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

**Mitchell J. Williams, Gary A. Bishop and Donald H. Stedman**

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

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**Coordinating Research Council, Inc.**
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## EXECUTIVE SUMMARY

The University of Denver conducted a five-day remote sensing study in the LaBrea, California area in October of 2001. 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, October 15-19, 2001, were conducted as vehicles entered I-10 eastbound frontage road from LaBrea Blvd. in west Lost Angles basin. A database was compiled containing 26,975 records. Of these records the State of California provided make and model year information on 20,319 which contained valid measurements for at least CO and $CO_2$, and most 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 0.44%, 0.015%, and 0.041%, respectively. The emissions measurements in this study exhibit a gamma distribution, with the dirtiest 10% of the measurements responsible for 72.4%, 64.5%, and 56.7% of the CO, HC, and NO emissions, respectively. The HC readings contain a 21 ppm offset, which has been taken into account in all comparisons. The offset was determined by looking at the Model Year 2000 Ford vehicles. For the 1999 study, the Model Year 1999 Mercedes Benz vehicles that were used to estimate an offset of 17 ppm of HC. Appendix G shows an alternate offset calculation.

This was the fourth year of a multi-year continuing study to characterize motor vehicle emissions and deterioration in the Los Angles area. However, because of the low traffic volumes and reconstruction at the Riverside site, a new ramp similar to the Denver and Chicago sites was used this year. The California Inspection and Maintenance Review Committee used this site and this instrument in 1999, and those data have been made available to E-23 and are included in this report.

Vehicle emissions as a function of vehicle specific power revealed that NO emissions show a flat dependence on specific power when speed and acceleration are measured after emissions. HC emissions show a negative dependence on specific power – the expected trends. CO emissions show a slight positive dependence on specific power in the range from 5 to 30 kW/tonne.

Using vehicle specific power, it was possible to adjust the emissions of the vehicle fleet measured in 2001 to match the vehicle driving patterns of the fleet measured in 1999. After doing so, it was seen that the emissions measured in the current year are lower than those measured during 1999. Model year adjustments gave equivocal results. Previously reported emissions data from Riverside, CA give almost identical results from the fleet.

An analysis of high emitting vehicles showed that there is considerable overlap of CO and HC high emitters, for instance 4% of the measurements contribute 45% of the total CO and 38% of the total HC. The noise levels in the CO, HC and NO measurement channels were determined to be minimal compared to the standard error of the mean measurements.

## INTRODUCTION

Many cities in the United States are in violation of the air quality standards established by the Environmental Protection Agency (EPA). Carbon monoxide (CO) levels become elevated primarily due to direct emission of the gas; and ground-level ozone, a major component of urban smog, is produced by the photochemical reaction of nitrogen oxides ($NO_x$) and hydrocarbons (HC). As of 1998, on-road vehicles were estimated to be the single largest source for the major atmospheric pollutants, contributing 60% of the CO, 44% of the HC, and 31% of the NO 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 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 CO, carbon dioxide ($CO_2$), and HC, and a dispersive ultraviolet (UV) spectrometer for measuring NO. The source and detector units are positioned on opposite sides of the road in a bi-static arrangement. 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 coefficient of the %HC values in the equations below has been multiplied by 2. This correction factor has been taken into account in the following equations. Thus, the reported percent emissions can be directly converted into mass emissions per gallon by the equations shown below.

$$\text{gm CO/gallon} = 5506\times\%CO/(15 + 0.285\times\%CO + 5.74\times\%HC)$$
$$\text{gm HC/gallon} = 17288\times\%HC/(15 + 0.285\times\%CO + 5.74\times\%HC)$$
$$\text{gm NO/gallon} = 5900\times\%NO/(15 + 0.285\times\%CO + 5.74\times\%HC)$$

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:

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

Next, moles of pollutant are converted to grams by multiplying by molecular weight (e.g., 44 g/mole for HC since propane is measured), and the moles of carbon in the exhaust are converted to kilograms by multiplying (the denominator) by 0.014 kg of fuel per mole of carbon in fuel, assuming gasoline is stoichiometrically $CH_2$. Again, the $HC/CO_2$ ratio must use two times the reported HC (as above) because the equation depends upon carbon mass balance and the NDIR HC reading is about half a total carbon FID reading.[6]

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, vehicle exhaust buildup 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 (±3σ) of 25 ppm for NO, with an error measurement of ±5% of the reading at higher concentrations. The on-road remote sensing data compared to IM240 data for the same region. Both data sets were converted to average fuel-based emissions by model year in grams per kilogram. In all cases the correlation coefficients $r^2$ exceed 0.95. 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, are also recorded on the video image. The images are stored on videotape, so that license plate information may be incorporated into the emissions database during post-processing. A device to measure the speed and acceleration of vehicles driving past the remote sensor was also used in this study. The system consists of a pair of infrared emitters and detectors (Banner Industries), which 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 LaBrea, California area in October 2001, under CRC contract no. E23-7. Measurements were made for 5 consecutive weekdays, from Monday, Oct. 15th to Friday, Oct. 19th, conducted on the uphill ramp. This intersection is just west of the location where LaBrea Blvd. passes under I-10. The instrument was located as far up the ramp as possible, the same location as was used during the IMRC measurements in 1999. The uphill grade at the measurement location is 3.5%. Measurements were generally made between the hours of 6:00 and 17:00. This was the fourth year of a multi-year E-23 study to characterize motor vehicle emissions and deterioration in the L.A. Basin area.

## RESULTS AND DISCUSSION

Following the five days of data collection in October 2001, the videotapes were read for license plate identification. Plates which appeared to be in state and readable were sent to the State of California to be matched against registration records. The resulting database contained 20,319 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 1). The complete structure of the database and the definition of terms are included in Appendix B. The temperature and humidity record from nearby Los Angeles International Airport (LAX) is included in Appendix C.

**Table 1**: Validity summary (2001).

| | CO | HC | NO |
|---|---|---|---|
| Attempted Measurements | 26,975 | | |
| Valid Measurements | 24,751 | 24,614 | 24,632 |
| Percent of Attempts | 91.8% | 91.3% | 91.3% |
| Submitted Plates | 21,219 | 21,151 | 21,219 |
| Percent of Attempts | 78.7% | 78.4% | 78.7% |
| Percent of Valid Measurements | 85.7% | 85.9% | 86.1% |
| Matched Plates | 20,319 | 20,262 | 20,234 |
| Percent of Attempts | 75.3% | 75.1% | 75.0% |
| Percent of Valid Measurements | 82.1% | 82.3% | 82.2% |
| Percent of Submitted Plates | 95.8% | 95.8% | 95.4% |

The greatest loss occurs during the license plate reading process where hitches, trailers, etc. obstruct the view of the license plate.

Table 2 provides an analysis of the number of vehicles that were measured repeatedly, and the number of times they were measured. Of the 20,319 records used in this 2001 fleet analysis, 12,003 (59.1%) were contributed by vehicles measured once, and the remaining 8,316 (40.9%) 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 2**: Number of measurements of repeat vehicles

| Number of Times Measured | 2001 | 1999 |
|---|---|---|
| 1 | 12,003 | 12,583 |
| 2 | 1,755 | 1,586 |
| 3 | 741 | 602 |
| 4 | 393 | 261 |
| 5 | 164 | 50 |
| 6 | 17 | 11 |
| 7 | 4 | 0 |
| > 7 | 7 | 2 |

Table 3 is the data summary; included is the summary of the previous remote sensing database collected by the IMRC at the same site at LaBrea in the Fall of 1999. Since the site of measurement during the two years was the same, one can compare these fleet averages. The fleet measured in 2001 seems to have lower average CO, HC, and NO emissions than 1999.

The average HC values 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. In the absence of a true fix 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. The increase in HC from one model year to the next that correlates with IM240 data is preserved, as is the emissions distribution. However, this procedure, attempts to adjust the data so that the average of measurements from different years can be compared. A new method for analyzing the data to extract these artificial HC offsets is described in Appendix G. This method seems to work better to explain the data, which is (with the current analysis method) difficult to interpret.

The make/model year groups chosen are restricted to those containing at least 50 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 this particular study, 2000 Fords were chosen as the offset standards and gave an average offset of 21 ppm.

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 measurements 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 measured fleet (for NO), and as much as 79% and 93% of the measured fleet (for CO and HC, respectively). The fact that the cleanest 79% of the measurements are responsible for only 26% 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 1999 and is represented by the consistent high values of percent of total emissions from the dirtiest 10% of the fleet (see Table 3).

**Table 3**: Overall Fleet Data Summary

| | 2001 | 1999 |
|---|---|---|
| Mean CO (%)<br>(g/kg of fuel) | 0.44<br>(56.2) | 0.58<br>(73.6) |
| Median CO (%) | 0.06 | 0.09 |
| Percent of Total CO from Dirtiest 10% of the Fleet | 72.4 | 67.4 |
| Mean HC (ppm)†<br>(g/kg of fuel)† | 125†<br>(5.02) | 230†<br>(9.2) |
| Median HC (ppm)† | 39 | 79 |
| Percent of Total HC from Dirtiest 10% of the Fleet† | 61.6 | 54.9 |
| Mean NO (ppm)<br>(g/kg of fuel) | 411<br>(5.6) | 475<br>(6.5) |
| Median NO (ppm) | 72 | 100 |
| Percent of Total NO from Dirtiest 10% of the Fleet | 54.9 | 51.5 |
| Mean Model Year | 1994.4 | 1992.4 |
| Mean Speed (mph) | 18.3 | 17.6 |
| Mean Acceleration (mph/s) | 1.4 | 1.42 |

†HC offset corrected.

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 LaBrea area, during the two 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 two factors. The first is the tendency for older vehicles to lose compression and operate under fuel-rich conditions resulting in lower NO emissions. The second is more rapid NO catalyst deterioration. Unlike data collected in Chicago from 1997-1999, the LaBrea 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 California, 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 et al. 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. It is also noteworthy that the pre-1984 fleet has a similar emissions profile to 1984 and 1985 model year fleets. The greatest exception to this observation is the highest quintile for NO, which is off because of such a small sample of cars. There are only 177 measured cars in the bin, thus the largest quintile only samples 34 vehicles.

Figure 7 shows the total contribution of each quintile in Figure 6 as a function of the overall fleet population. It is interesting to see relatively numerous pre-1984 emissions, as well as the top 20% of the 3-19 year old vehicles.

An equation for determining the instantaneous power of an on-road vehicle has been proposed by Jimenez et al.[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 8. The pale line in the Figure provides the number of measurements in each bin. As expected, HC emissions show a negative dependence on specific power in the VSP range of 5 to 25 kW/tonne. At values above 20 kW/tonne, CO emissions increase in the 2001 measurements, while HC values level off. The general VSP profiles of CO and HC emissions are consistent during the two years of measurement. The NO profile is curious, showing little dependence on VSP. This was the same in the Riverside studies.

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 1999 and 2001 databases. Table 4 shows the mean emissions from vehicles in the 1999 database, from vehicles measured at the two locations in 1999 and from vehicles in 2001 with specific powers between 5 and 25 kW/tonne. Note that these emissions do not vary considerably from the mean emissions for the entire databases, as shown in Table 3. Also shown in Table 4 are the mean emissions for the 1999 location and the 2001 fleet adjusted for specific power. This correction is accomplished by applying the mean vehicle emissions for each specific power bin in Figure 8, for each of the location in 1999 and the 2001 measurements, to the vehicle distribution, by specific power, for each bin from 1999. A sample calculation, for the specific power adjusted mean NO emissions in Chicago in the 1999 report, 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 VSP difference between 1999 and 2001 is small and that the mean VSP adjusted emissions from 2001 and are significantly smaller than 1999.

**Table 4:** Specific power adjusted fleet emissions (5 to 25 kW/tonne only)

| | 1999 | 2001 | 2001(adjusted) |
|---|---|---|---|
| Mean CO (%) | 0.56 ± 0.02 | 0.43 ± 0.02 | .43 ± 0.02 |
| Mean HC[†] (ppm) | 227 ± 8 | 141 ± 19 | 145 ± 19 |
| Mean NO (ppm) | 462 ± 24 | 394 ± 32 | 392 ± 32 |

[†]HC values are offset corrected

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 1999 study. Table 5 shows the mean emissions for all vehicles from model years 1984 to 2000, as measured in 1999 and 2001. 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 years adjusted mean NO emissions in Chicago in 1998, is shown in Appendix E. The emissions do not show a statistically significant deterioration effect except for NO. A better understanding of deterioration in the L.A. area fleet will be attained with further measurements at the current site.

**Table 5.** Model year adjusted fleet emissions (MY 1984-2000 only).

| | 1999 | 2001 | 2001 (adjusted) |
|---|---|---|---|
| Mean CO (%) | 0.49 ± 0.02 | 0.37 ± 0.02 | .49 ± 0.02 |
| Mean HC[†] (ppm) | 205 ± 19 | 122 ± 8 | 162 ± 8 |
| Mean NO (ppm) | 439 ± 32 | 380 ± 24 | 500 ± 24 |

[†]HC values are offset corrected

Vehicle deterioration can also be illustrated by Figure 9, which shows the mean emissions of the 1984 to 2000 model year fleet as a function of vehicle age. The first point for each model year was measured in 1999 and the second in 2001. Vehicle age was determined by the difference between the year of measurement and the vehicle model year. The CO and NO look as expected, in that most model years deteriorate as they get older. The fluctuation among the oldest model years for CO is unexpected but the numbers are small. HC shows essentially all model year bins with inverse deterioration, which almost certainly is evidence that the HC offset calculated in this report is incorrect in one or the other relationship to the offset calculated in one or the other year of data. Appendix G shows the first application of a new and probably preferable offset estimation procedure.

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 measurements that are high emitting. (2001)

| Top 10% Decile | CO | HC | NO |
|---|---|---|---|
| CO | 3.7% | 4.0% | 0.2% |
| HC | 4.0% | 2.3% | 1.8% |
| NO | 0.2% | 1.8% | 7.0% |
| All | 0.9% | 0.9% | 0.9% |

Thus, the table shows that 4.0% of the fleet are in the top decile for both HC and CO but not NO; 0.2% of the of the fleet is high emitting for CO and NO but not HC; 3.7% of the fleet are high CO emitters only.

**Table 7**: Percent of total measured emissions from high emitting vehicles. (2001)

| Top 10% Decile | CO | HC | NO |
|---|---|---|---|
| CO | 21.3% | 37.7% | 1.2% |
| HC | 45.2% | 13.3% | 11.3% |
| NO | 1.02% | 7.6 % | 38.0% |
| All | 3.9% | 4.4% | 4.5% |

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 37.7% of HC and 1.2% of NO emissions. More efficiently, identification of the 4.0% high CO and HC vehicles accounts for 45.2% of the total CO and 37.7% of the total on-road HC.

In the manner described in the Phoenix, Year 2 report[14], instrument noise was measured by looking at the logarithmic slope of the negative portion of the emissions histograms. 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 and its estimated uncertainty for the particular pollutant to obtain a description of noise. The Laplace factors were found to be 0.074, 0.013 and 0.0019 for CO, HC and NO, respectively. These values indicate standard deviations of 0.104%, 184 ppm and 27 ppm for individual measurements of CO, HC and NO, respectively. These numbers for individual measurement noise go as a factor of √2 times the Laplace factor. 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 the usual number of measurements per bin, the uncertainty reduces by a factor of 10. Thus, the uncertainties in the averages reduced to 0.01%, 18 ppm and 3 ppm, respectively. This HC noise puts these HC measurements in the lower of the two HC noise groups reported earlier.[14]

Other studies performed by this group have looked at emissions in Riverside, CA[15] that is in the L.A. Basin, and exhibits relatively few statistically significant differences from the LaBrea site used in this study. Table 8 below shows a summary of the comparison of the LaBrea and Riversides sites during the 1999 and 2001 studies of both sites. It seems fairly clear that during the two years of study, the two sites are very similar. For the Riverside site, the average speeds are higher and acceleration is lower (in one case negative) but the overall VSPs are similar and are similarly distributed. VSPs are similar and the emissions inventories seem to match quite well.

**Table 8**: Riverside vs. LaBrea Study Results

| | LaBrea 2001 | Riverside 2001[15] | LaBrea 1999 | Riverside 1999[15] |
|---|---|---|---|---|
| Mean CO (%) (g/kg of fuel) | 0.44 (56.2) | 0.39 (48) | 0.58 (73.6) | 0.55 (67) |
| Median CO (%) | 0.06 | 0.06 | 0.09 | 0.09 |
| Percent of Total CO from Dirtiest 10% of the Fleet | 72.4 | 74.2 | 67.4 | 69.6 |
| Mean HC (ppm)† (g/kg of fuel) † | 125† (5.02) | 100† (4.13ξ) | 230† (9.2) | 150† (6.18ξ) |
| Median HC (ppm) † | 39 | 50 | 79 | 60 |
| Percent of Total HC from Dirtiest 10% of the Fleet† | 61.6 | 66.3 | 54.9 | 52.8 |
| Mean NO (ppm) (g/kg of fuel) | 411 (5.6) | 400 (5.6) | 475 (6.5) | 370 (5.2) |
| Median NO (ppm) | 72 | 88 | 100 | 100 |
| Percent of Total NO from Dirtiest 10% of the Fleet | 54.9 | 52.3 | 51.5 | 51.1 |
| Mean Model Year | 1994.4 | 1994.5 | 1992.4 | 1992.4 |
| Mean Speed (mph) | 18.3 | 24 | 17.6 | 24.1 |
| Mean Acceleration (mph/s) | 1.4 | -0.29 | 1.42 | 0.43 |

†HC offset corrected. ξData from Reference 15 published previously as gm/gallon

## CONCLUSION

The University of Denver successfully completed the second year of a multi-year remote sensing study in LaBrea. Five days of fieldwork (October 15-19, 2001) were conducted on the uphill entrance ramp from LaBrea Blvd. Southbound to I-10 Eastbound in LaBrea, CA. A database was compiled containing 20,319 records for which the State of California provided make and model year information. All of these records contained valid measurements for at least CO and $CO_2$, and 20,262 and 20,234 contained measurements for HC and NO, respectively. Of these measurements, 12,003 (79%) were of vehicles measured only once. The rest were of vehicles 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 0.44%, 125 ppm and 411 ppm, respectively with an average model year of 1994.4. As expected, the measured emissions observed in this study exhibited a typical skewed distribution, with the dirtiest 10% contributing 72%, 62%, and 55% 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. Unexpected was the relationship between NO emissions and vehicle specific power, showing little correlation with VSPs between 5-25. VSP normalization resulted in emissions that were significantly lower during the 2001 measurement.

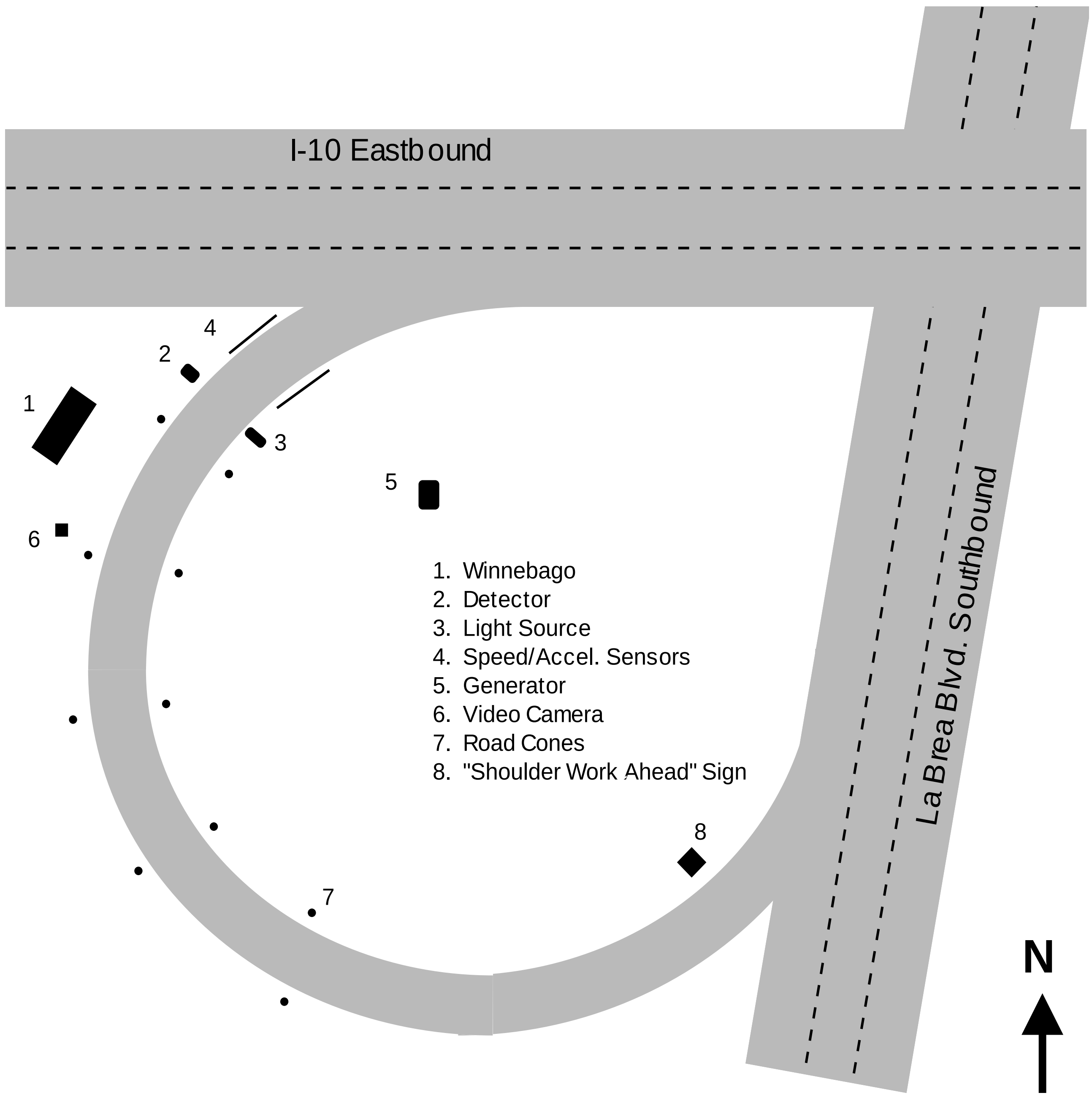


**Figure 1**: Area map of the on-ramp from Southbound LaBrea Blvd. to Eastbound I-10. The location and safety equipment configuration was for all five days of measurements.

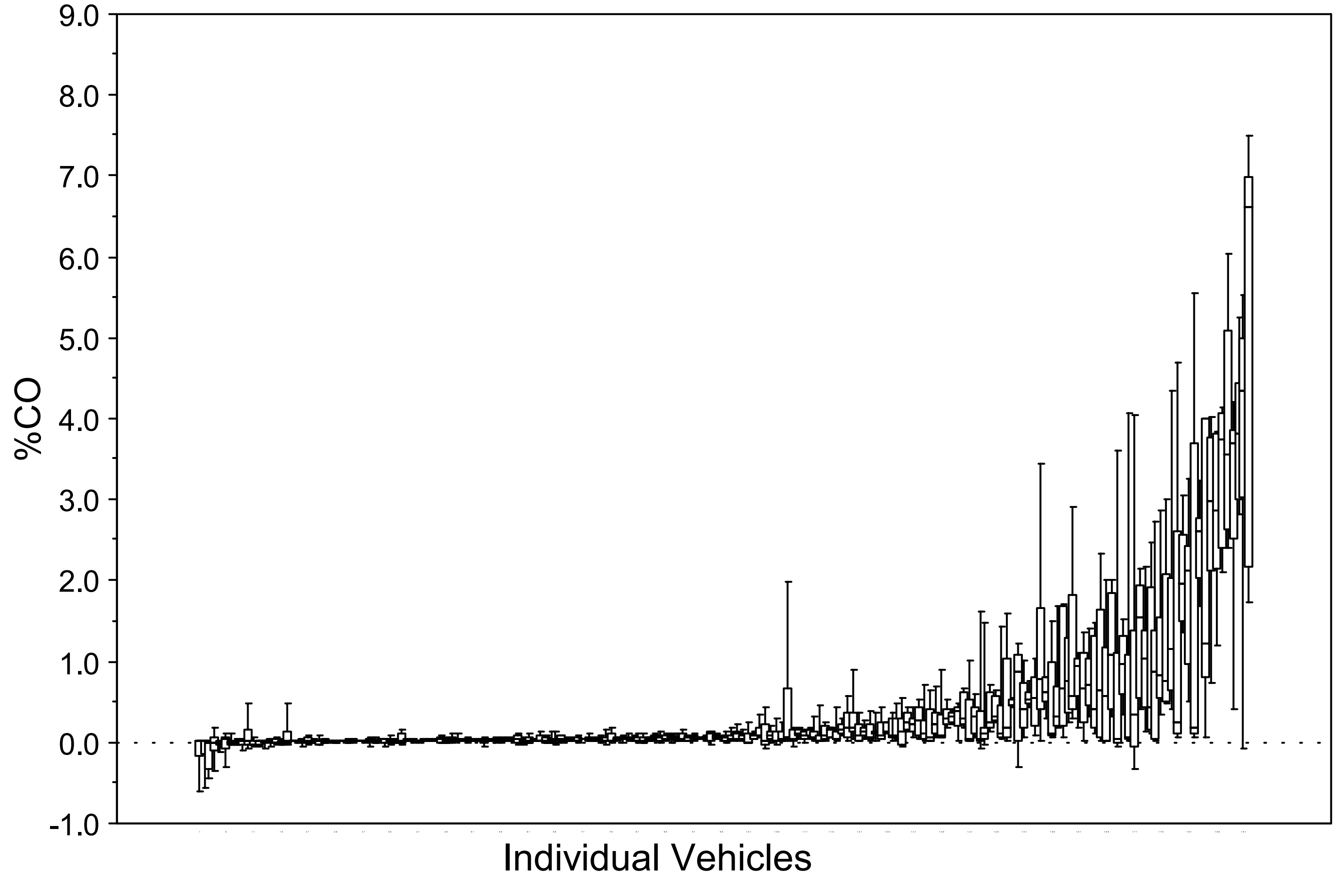


**Figure 2.** Box and Whisker plot illustrating clustering of CO measurements of vehicles measured five or more times, sorted according to average percent CO. For most vehicles, each horizontal line represents one of the five readings. Vehicles which have at least one measurement above 1% (high emitters) tend to have most other measurements clustered nearer zero. There is one notable exception, which repeatedly measures above 2.6% CO. Even this vehicle, however, exhibits a skewed distribution of CO measurements.

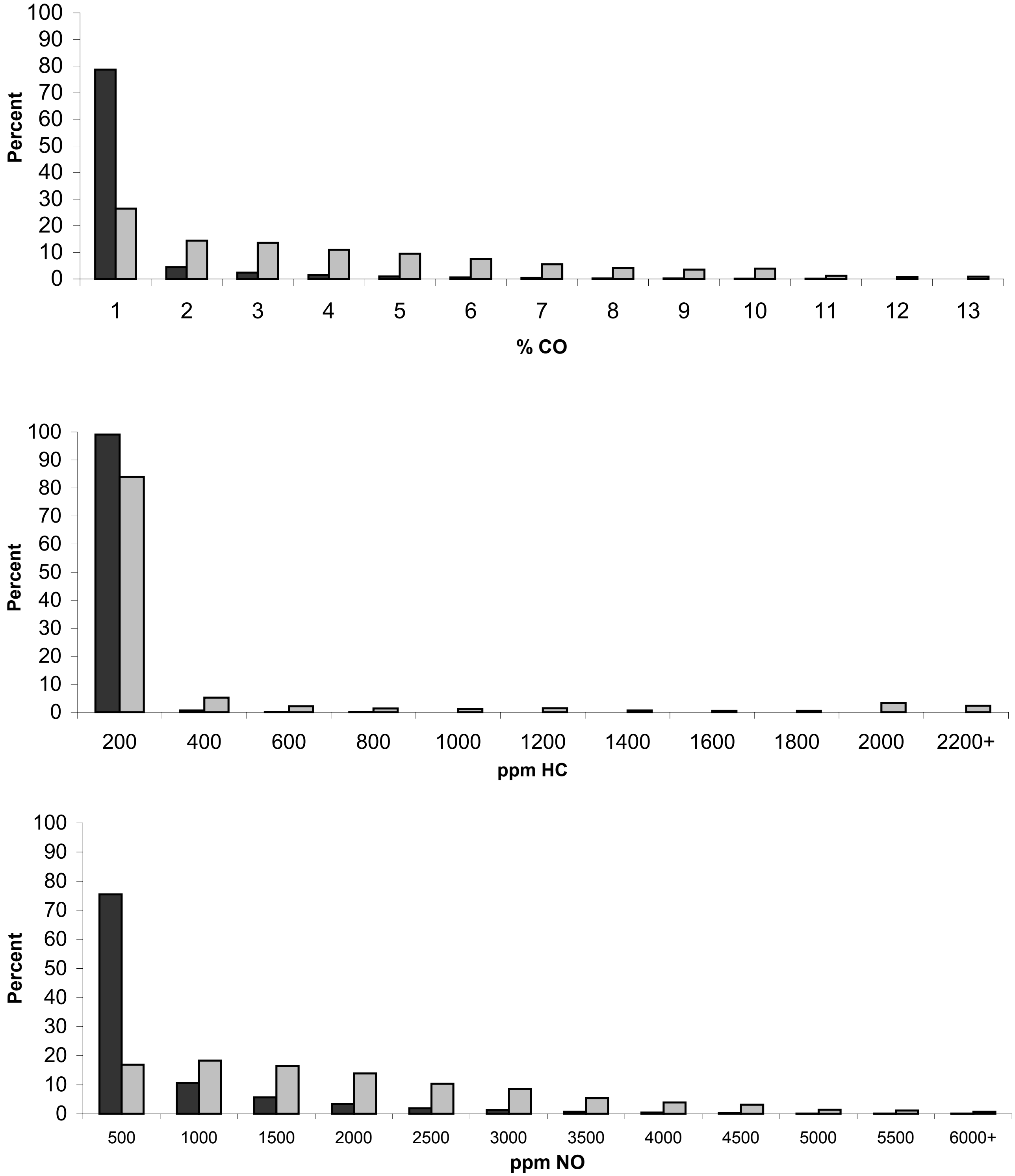


**Figure 3.** Emissions distribution showing the percentage of the measurements in a given emissions category (black bars) and the percentage of the total emissions contributed by the given category (white bars).

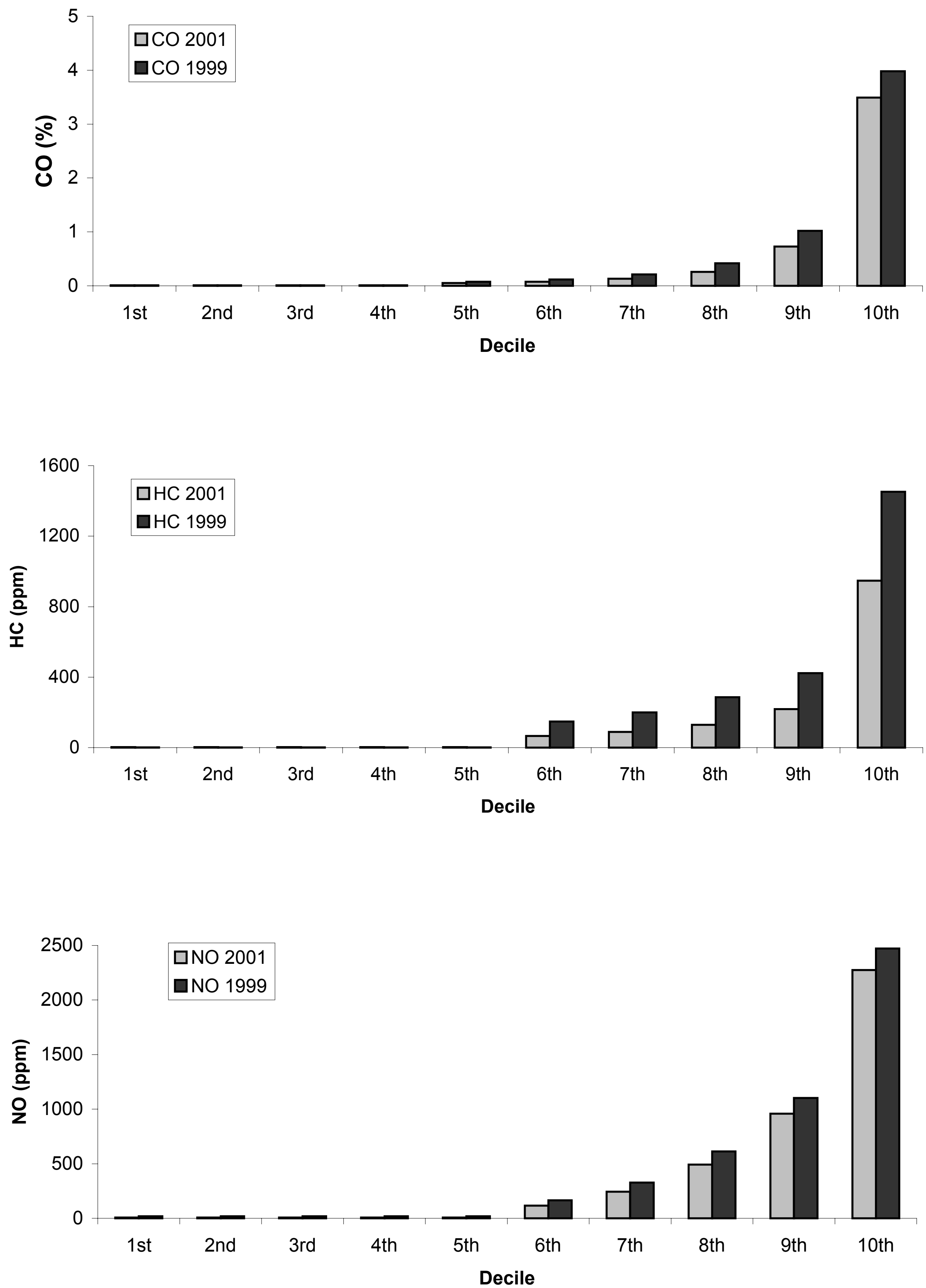


**Figure 4.** Fleet emissions organized into decile bins.

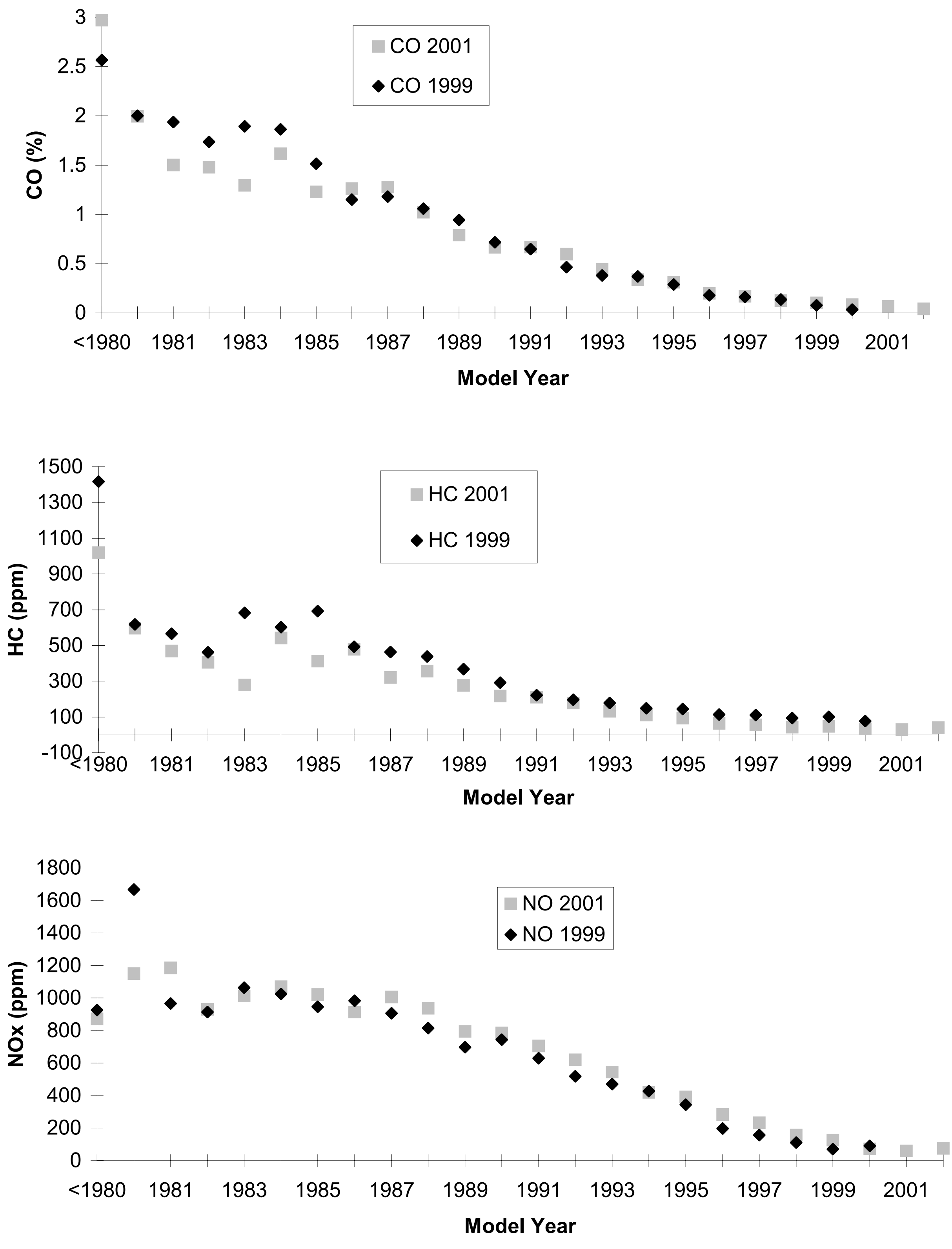


**Figure 5.** Mean vehicle emissions illustrated as a function of model year. Both years of measurement at the LaBrea site are included.

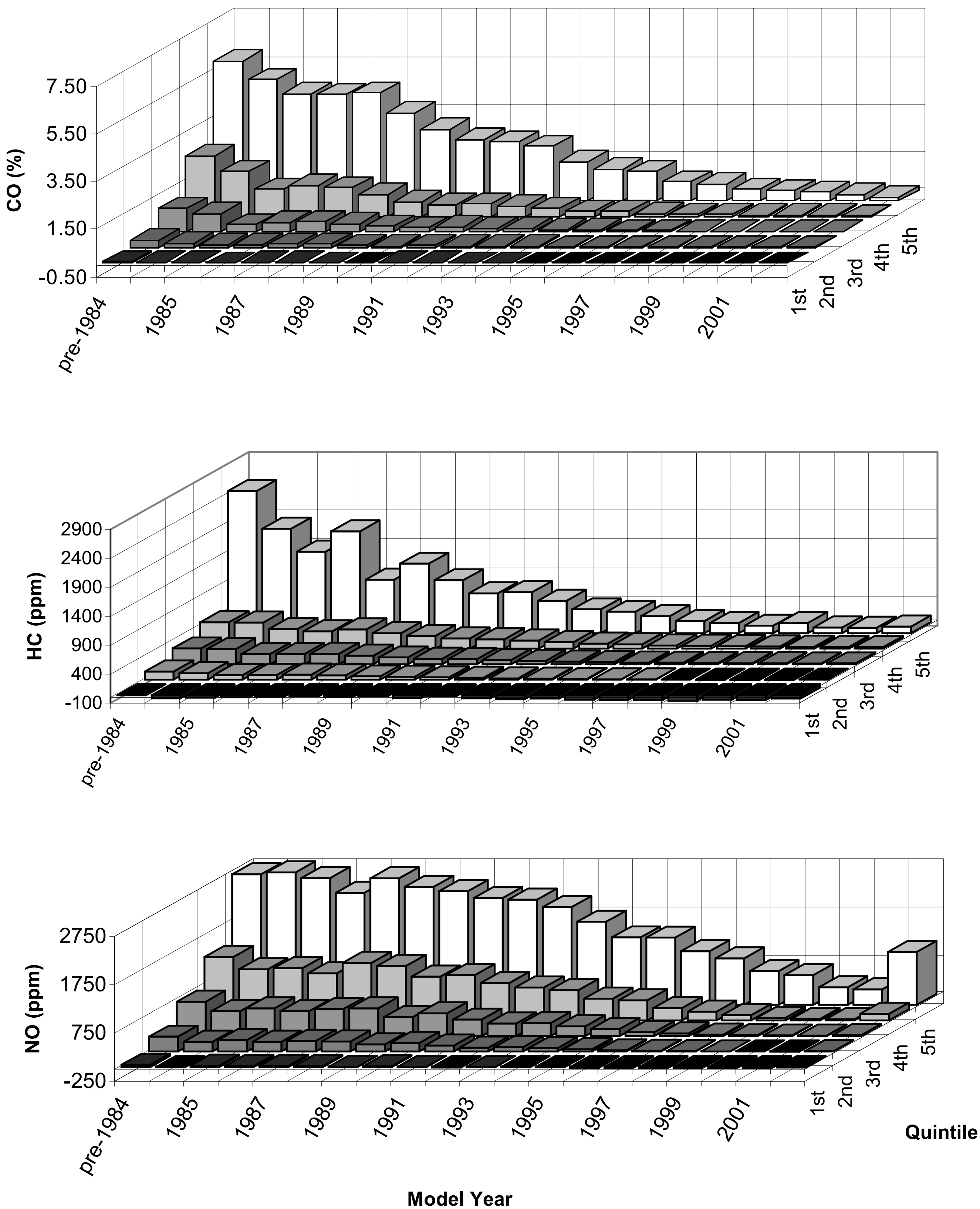


**Figure 6.** Vehicle emissions by model year, divided into quintiles. Negative averages are indicated by black bars.

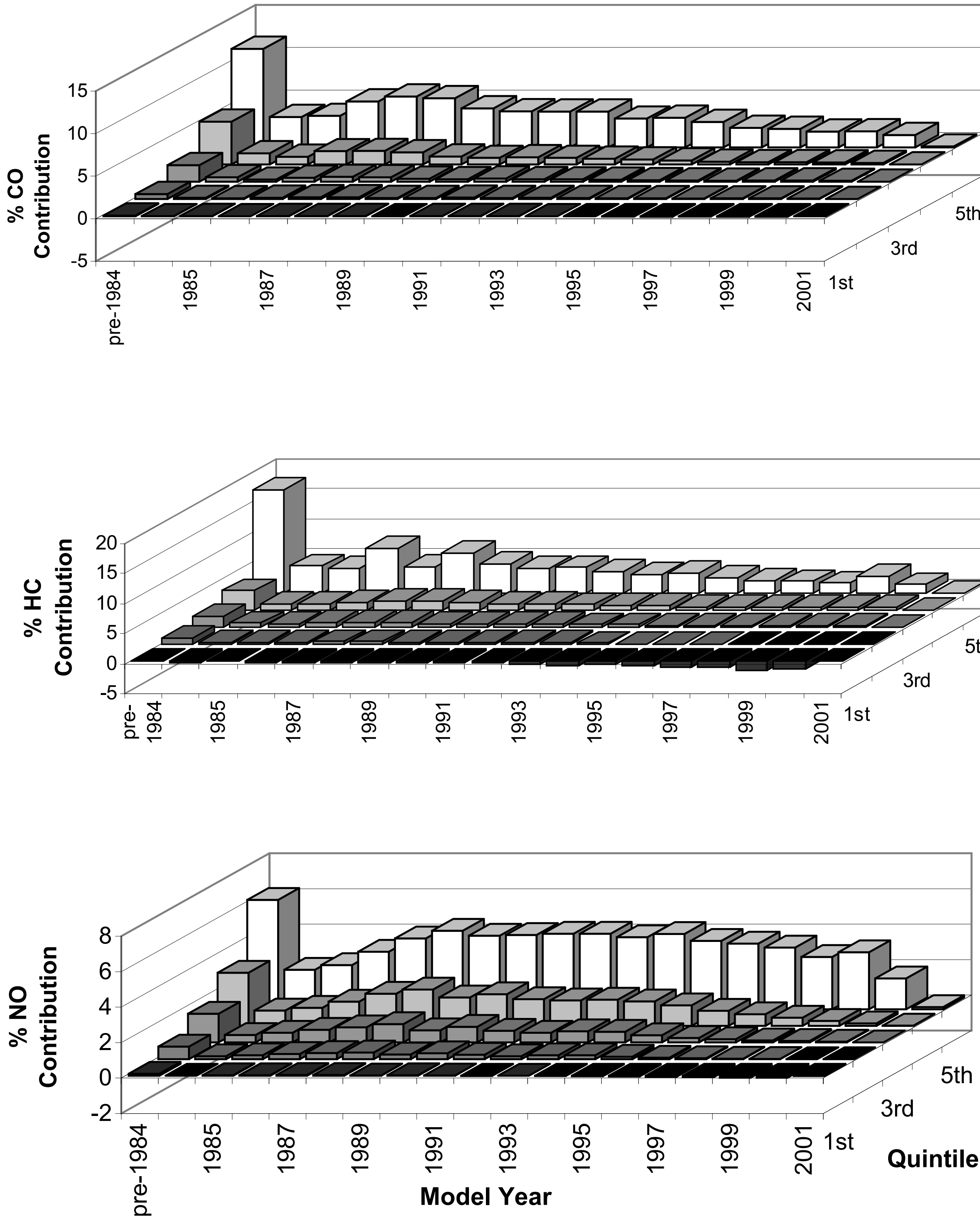


**Figure 7.** Percent of total emissions from a given model year quintile. This is Figure 6 taking into account the number of vehicles in each model year quintile from the 2001 study.

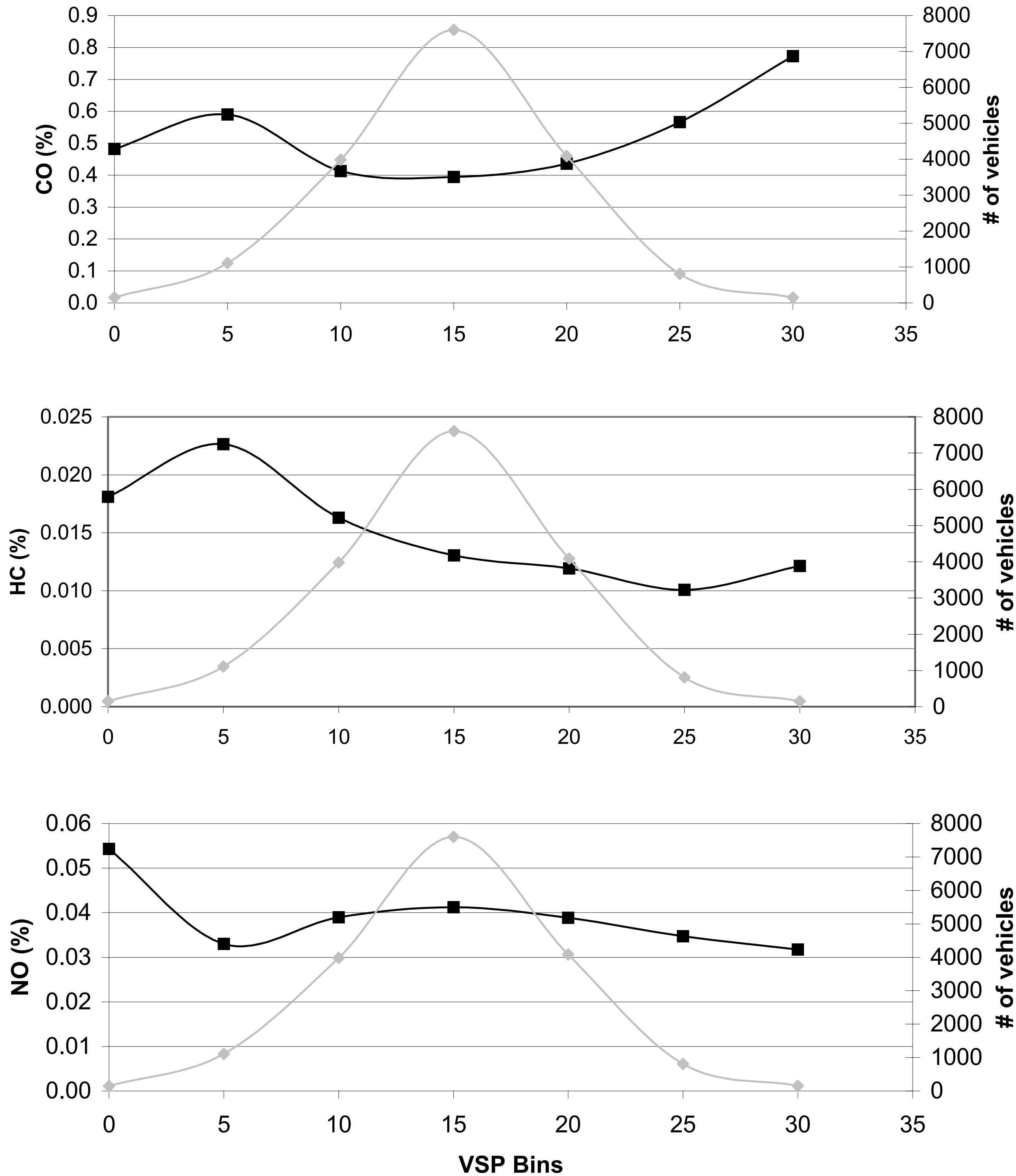


**Figure 8.** Vehicle emissions as a function of vehicle specific power/Number of vehicles per VSP bin.

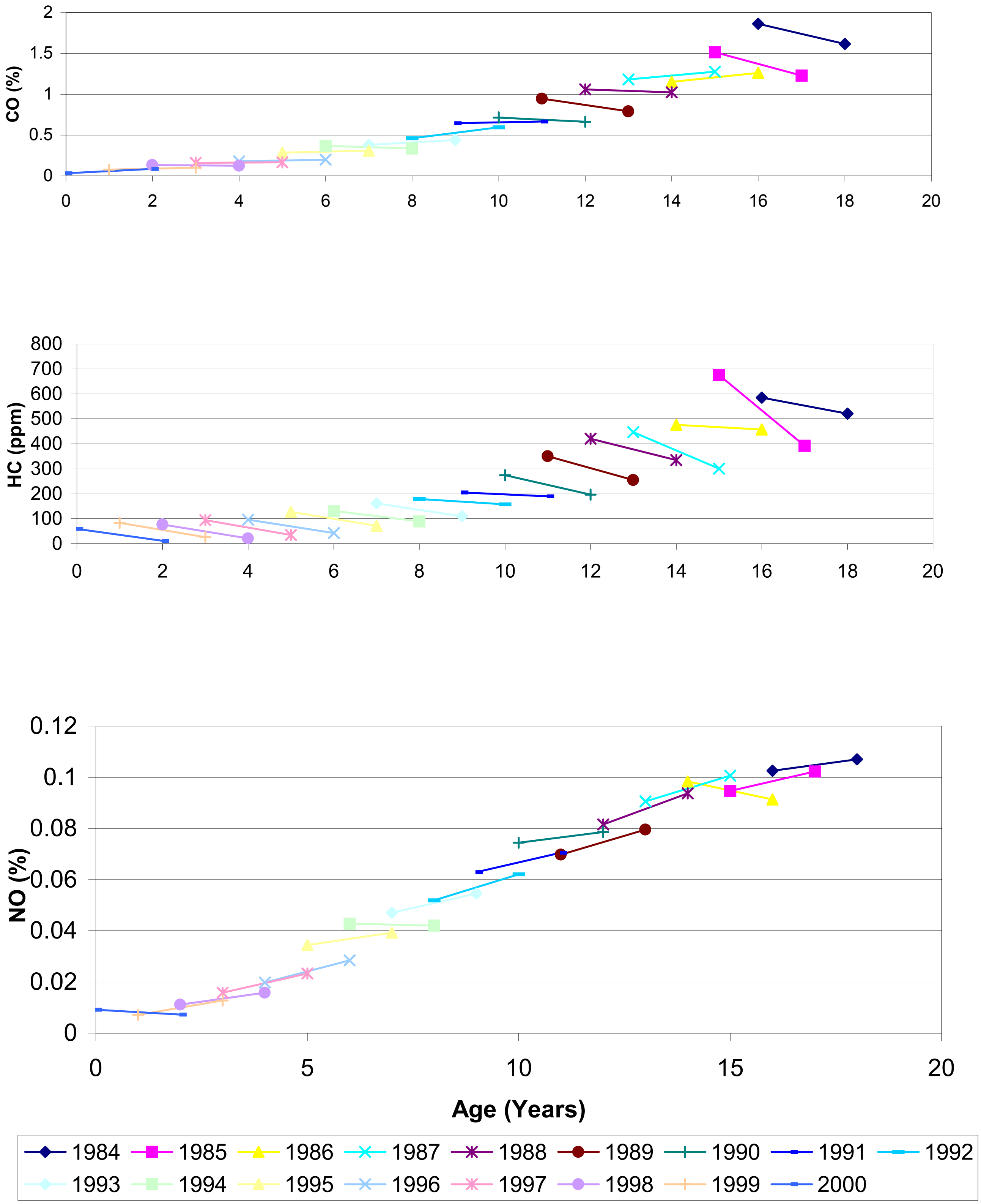


**Figure 9.** Mean vehicle emissions as a function of age, shown by model year. Included are data from the site in 1999 (first point) and 2001 (second point).

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

Not measured:

1) Block and unblock with less than 0.5 seconds clear to the rear. Caused by very close tailgating or by elevated pickups and trailers causing a "restart" and renewed attempt to measure exhaust.* The restart number appears in the database.

2) vehicle which drives completely through during the 0.4 seconds "thinking" time (relatively rare).

Invalid :

1) insufficient plume to rear of vehicle relative to cleanest air observed in front or in the rear; at least five, 10ms >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 $\pm$20% for %CO. >1.0, 0.2%CO for %CO<1.0.

3) reported %CO , <-1% or >21%. All gases invalid in these cases.

4) too much error on HC/$CO_2$ slope, equivalent to $\pm$20% for HC >2500ppm propane, 500ppm propane for HC <2500ppm.

5) reported HC <-1000ppm propane or >40,000ppm. HC "invalid".

6) too much error on NO/$CO_2$ slope, equivalent to $\pm$20% for NO>1500ppm, 300ppm for NO<1500ppm.

7) reported NO<-700ppm or >7000ppm. NO "invalid".

Speed/Acceleration valid only if at least two blocks and two unblocks in the time buffer and all blocks occur before all unblocks on each sensor and the number of blocks and unblocks is equal on each sensor and 100mph>speed>5mph and 14mph/s>accel>-13mph/s and there are no restarts, or there is one restart and exactly two blocks and unblocks in the time buffer.

*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 labrea01.dbf database.**

The labrea01.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** | California 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. |
| **Vin** | Vehicle identification number. |
| **Make** | Manufacturer of the vehicle. |
| **Year** | Model year. |
| **Exp_date** | License expiration date. |

| | |
|---|---|
| **Body_style** | DMV designated body style |
| **Zip** | Registrant's mailing zip code. |
| **DMV_first** | Year of first vehicle entry in California DMV records. |
| **County** | California county number vehicle is registered in. |
| **Fuel** | Fuel type G (gasoline), D (diesel) and N (natural gas). |
| **Weight** | Gross vehicle weight. |
| **Smog_type** | Type of Smog Check inspection |
| **Smog_due** | Date next Smog Check is due. |

## APPENDIX C: Temperature and Humidity Data.

***As Recorded at Los Angles International Airport**

**LaBrea 1999 Temperature and Humidity Data**

| Time | 11/09 °F | 11/09 %RH | 11/10 °F | 11/10 %RH | 11/11 °F | 11/11 %RH | 11/12 °F | 11/12 %RH | 11/13 °F | 11/13 %RH |
|---|---|---|---|---|---|---|---|---|---|---|
| 5:50 | 54 | 87 | 53 | 93 | 52 | 89 | 58 | 93 | 56 | 100 |
| 6:50 | 55 | 80 | 55 | 83 | 57 | 75 | 57 | 100 | 57 | 100 |
| 7:50 | 57 | 78 | 57 | 81 | 60 | 70 | 59 | 96 | 58 | 100 |
| 8:50 | 60 | 72 | 61 | 70 | 63 | 65 | 59 | 90 | 59 | 93 |
| 9:50 | 63 | 68 | 64 | 63 | 67 | 59 | 62 | 84 | 61 | 84 |
| 10:50 | 66 | 61 | 65 | 66 | 68 | 59 | 61 | 87 | 61 | 84 |
| 11:50 | 68 | 55 | 65 | 70 | 68 | 61 | 62 | 84 | 61 | 84 |
| 12:50 | 67 | 66 | 64 | 75 | 68 | 63 | 61 | 84 | 62 | 81 |
| 13:50 | 64 | 73 | 64 | 75 | 69 | 57 | 62 | 81 | 62 | 81 |
| 14:50 | 64 | 75 | 64 | 70 | 67 | 66 | 62 | 84 | 62 | 81 |
| 15:50 | 62 | 81 | 64 | 68 | 65 | 76 | 61 | 87 | 62 | 81 |
| 16:50 | 61 | 84 | 63 | 73 | 63 | 81 | 61 | 90 | 61 | 87 |

**LaBrea 2001 Temperature and Humidity Data**

| Time | 10/15 °F | 10/15 %RH | 10/16 °F | 10/16 %RH | 10/17 °F | 10/17 %RH | 10/18 °F | 10/18 %RH | 10/19 °F | 10/19 %RH |
|---|---|---|---|---|---|---|---|---|---|---|
| 8:03 | 64 | 90 | 62 | 90 | 61 | 90 | 62 | 93 | 64 | 84 |
| 9:03 | 67 | 87 | 66 | 81 | 63 | 87 | 65 | 78 | 67 | 76 |
| 10:03 | 68 | 79 | 69 | 73 | 65 | 78 | 70 | 64 | 69 | 73 |
| 11:03 | 71 | 73 | 70 | 71 | 67 | 73 | 69 | 73 | 68 | 76 |
| 12:03 | 68 | 68 | 67 | 79 | 67 | 73 | 70 | 68 | 66 | 78 |
| 13:03 | 69 | 76 | 69 | 73 | 66 | 75 | 69 | 70 | 66 | 78 |
| 14:03 | 69 | 76 | 68 | 76 | 67 | 76 | 70 | 66 | 63 | 84 |
| 15:03 | 67 | 76 | 68 | 76 | 66 | 78 | 68 | 70 | 64 | 84 |
| 16:03 | 65 | 84 | 66 | 81 | 65 | 81 | 67 | 79 | 63 | 87 |
| 17:03 | 63 | 87 | 64 | 90 | 63 | 87 | 64 | 87 | 63 | 87 |
| 18:03 | 63 | 93 | 63 | 90 | 62 | 90 | 63 | 90 | 62 | 90 |

## 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**.

| 2001 (FEAT 3002) | | | | |
|---|---|---|---|---|
| Date | Time | CO Cal Factor | HC Cal Factor | NO Cal Factor |
| 10/15 | 8:00 | 1.56 | 1.40 | 2.01 |
| 10/15 | 13:00 | 1.22 | 1.05 | 1.26 |
| 10/16 | 7:00 | 1.47 | 1.25 | 1.85 |
| 10/16 | 15:30 | 1.23 | 1.02 | 1.39 |
| 10/17 | 7:00 | 1.47 | 1.50 | 2.30 |
| 10/17 | 12:50 | 1.39 | 1.12 | 1.53 |
| 10/18 | 8:30 | 2.17 | 1.87 | 2.67 |
| 10/18 | 10:55 | 1.63 | 1.46 | 2.02 |
| 10/19 | 7:55 | 1.68 | 1.39 | 1.42 |
| 10/19 | 10:09 | 1.50 | 1.26 | 1.31 |

## APPENDIX G: Alternative HC Offset Calculation

In Figure 9b of this report, the HC shows negative or no deterioration of the fleet for almost all model years of car. This is counterintuitive, as fleets should not get cleaner as they get older, certainly not the newest model years. The problem seems to lie in the fact that the calculation of HC offsets for the FEAT 3000 unit is an inexact science. The procedure for calculating offsets (described in the text of this report) is taking the lowest mean for a group of > 50 vehicles based on make and model year. No rigorous statistical treatment has been performed to determine for a given population of cars in the study vs. what is the smallest statistically significant population of cars. Basically, what is the smallest number of cars we can average and still have a statistically significant sub-population within the fleet? We have recently proposed that the mode (most frequently observed) HC value for each model year (or for the whole data set) is a better HC offset. This scheme is demonstrated in this appendix. The 2001 data has the fleet mode HC at 40 ppm; the cleanest model year was the 1999 fleet with a 30 ppm mode. The fact that the difference is only 10 ppm is an encouraging statistic in itself. The 1999 data had a measured fleet mode of 70 ppm. For 1999 we do not yet have a data set that includes both HC to the nearest 10 ppm and model year. We therefore used the 70 ppm fleet offset for the 1999 data. The 30 ppm offset was used for 2001. The following is Figure 7 revised with these new offsets. The good news is that the deterioration by MY, especially for the newest MYs, looks sensible and appropriate. The bad news is that the 70 ppm offset has caused the newest four MY in the 1999 data set to have unrealistic negative HC means, although all have absolute values less than the reported instrument noise.