

University of Denver

Digital Commons @ DU

Fuel Efficiency Automobile Test Publications

Fuel Efficiency Automobile Test Data Repository

2002

On-Road Remote Sensing of Automobile Emissions in the Los Angeles Area: Year 3 (Riverside)

Sajal S. Pokharel

Gary A. Bishop

Donald H. Stedman

Follow this and additional works at: https://digitalcommons.du.edu/feat_publications

Digital Commons
Part of the [Environmental Chemistry Commons](#)
Commons

Network

Logo

On-Road Remote Sensing of Automobile Emissions in the Los Angeles Area: Year 3 (Riverside)

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

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

June 2002

Prepared for:

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

EXECUTIVE SUMMARY

The University of Denver conducted the third year of a multi-year remote sensing study in the Los Angeles, CA area. The remote sensor used in this study is capable of measuring the ratios of CO, HC, and NO to CO₂ in motor vehicle exhaust. From these ratios, we calculate the percent concentrations of CO, CO₂, 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.

Eight days of fieldwork between June 6 and 13, 2001, were conducted on the uphill exit ramp from 91N to 60W in Riverside, CA. A database was compiled containing 19,800 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 CO₂, 19,761 contained measurements for HC and 19,783 for NO data. The database, along with earlier databases and reports, can be found at www.feat.biochem.du.edu.

The mean emissions for CO, HC, and NO were determined to be 0.39%, 100 ppm, and 400 ppm, respectively, with an average model year of 1994.5. The mean emissions in gm/kg of fuel consumed for CO, HC and NO were 48.3, 2.0 and 5.6. The fleet emissions measured in this study exhibit a gamma distribution, with the dirtiest 10% of the fleet responsible for 74%, 66%, and 52% of the CO, HC, and NO emissions, respectively.

The majority of measurements (66%) at this location were of vehicles measured once. The remaining 34% of the measurements were of vehicles measured at least twice. By removing all of the repeat measurements from the database and allowing each vehicle to appear only once, we have shown that these repeat measurements are not skewing the results and that the full database is statistically representative of the actual fleet at the measurement site.

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. The adjustment did not significantly alter the 2001 measurements because of the similarity in VSP profiles between 1999 and 2001.

A model year adjustment was applied to a fleet of specific model year vehicles to track deterioration. Only NO emissions displayed fleet deterioration with this adjustment. Tracking of individual model years during the three years of measurements showed little deterioration in terms of CO for the most recent model years. In fact, model year was a greater determinant of CO emissions than age. An analysis of high emitting vehicles showed that there is considerable overlap of CO and HC high emitters. Finally, an analysis of measurement uncertainty indicated minimal noise in all three pollutants.

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 the single largest source for the major atmospheric pollutants, contributing 60% of the CO, 44% of the HC, and 31% of the NO_x to the national emission inventory.¹

According to Heywood², 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 occurs 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 wavelength region.

The exhaust plume path length and density of the observed plume are highly variable from vehicle to vehicle, and are dependent upon, among other things, the height of the vehicle's exhaust pipe, wind, and turbulence behind the vehicle. For these reasons, the remote sensor can only directly measure ratios of CO, HC or NO to CO₂. The ratios of CO, HC, or NO to CO₂, termed Q, Q' and Q'' respectively, are constant for a given exhaust plume, and on their own are useful parameters for describing a hydrocarbon combustion system. This study reports measured emissions as %CO, %HC and %NO in the exhaust gas, corrected for water and excess oxygen not used in combustion. The %HC measurement is a factor of two smaller than an equivalent measurement by an FID instrument.⁶ Thus, in order to calculate mass emissions the %HC values measured by RSD must be multiplied by 2. These percent emissions can be directly converted into mass emissions per gallon or kilogram of fuel used. We now prefer to use the g/kg of fuel conversion since they do not require any assumptions about the fuel density. These equations are:

$$\text{gm CO/kg} = (28 \times \% \text{CO} / \% \text{CO}_2 / (\% \text{CO} / \% \text{CO}_2 + 1 + 6 \times \% \text{HC} / \% \text{CO}_2)) / 0.014$$

$$\text{gm HC/kg} = (44 \times \% \text{HC} / \% \text{CO}_2 / (\% \text{CO} / \% \text{CO}_2 + 1 + 6 \times \% \text{HC} / \% \text{CO}_2)) / 0.014$$

$$\text{gm NO/kg} = (30 \times \% \text{NO} / \% \text{CO}_2 / (\% \text{CO} / \% \text{CO}_2 + 1 + 6 \times \% \text{HC} / \% \text{CO}_2)) / 0.014$$

where the 28, 44 and 30 are grams/mole for CO, HC (as propane) and NO, respectively, and 0.014 is the kg of fuel per mole of carbon assuming gasoline is stoichiometrically CH₂. It turns out that gm/kg of fuel calculations are very insensitive to the small changes observed in the carbon to hydrogen ratio because in all cases the majority of the fuel mass is the (measured) carbon component. Gm/gallon calculations are effected linearly by changes in fuel density which are however also quite small.

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, CO₂, 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 CO₂ levels caused by atmospheric pressure and instrument path length. Since propane is used to calibrate the instrument, all hydrocarbon measurements reported by the remote sensor are as propane equivalents.

Studies sponsored by the California Air Resources Board and General Motors Research Laboratories have shown that the remote sensor is capable of CO measurements that are correct to within ±5% of the values reported by an on-board gas analyzer, and within ±15% for HC.^{7,8} The NO channel used in this study has been extensively tested by the University of Denver, 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 $\pm 5\%$ 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, 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 Los Angeles, CA area in June 2001, under CRC Contract No. E-23-4. Measurements were made for 8 days between Wednesday, June 6 and Wednesday, June 13 on the uphill exit ramp (slope of 4.35°) from 91N to 60W in Riverside, CA (see Figure 1). The site measurements were generally made between the hours of 9:30 and 18:00. The physical locations of the source and detector units are marked with paint on the pavement to enable the exact relocation of the equipment in the following years. This was the third year of a multi-year study to characterize motor vehicle emissions and deterioration in the Los Angeles area.

RESULTS AND DISCUSSION

Following the eight days of data collection in June 2001, the videotapes were read for license plate identification. Plates which appeared to be in-state and readable were sent to the California Bureau of Automotive Repair to be matched against registration records approximately 3 months after the measurements. The resulting database contained 19,800 records with registration information and valid measurements for at least CO and CO₂. The database can be found at www.feat.biochem.du.edu. Most of these records also contained valid measurements for HC and NO (see Table 1). The table describes the data reduction process beginning with the number of attempted measurements and ending with the number of records containing both valid emissions measurements and vehicle registration information. An attempted measurement is defined as a beam block followed by a half second of data collection. If the data collection period is interrupted by another beam block from a close following vehicle, the measurement attempt is aborted and an attempt is made at measuring the second vehicle. In this case, the beam block from the first vehicle is not recorded as an attempted measurement. Invalid measurement attempts arise when the vehicle plume is highly diluted, or the reported error in the ratio of the pollutant to CO₂ exceeds a preset limit (see Appendix A). The

complete structure of the database and the definition of terms are included in Appendix B. The temperature and humidity data were recorded manually at the site during the measurements and are listed in Appendix C.

Table 1. Validity summary.

	CO	HC	NO
Attempted Measurements	26,009		
Valid Measurements	24,381	24,300	24,358
Percent of Attempts	93.7%	93.4%	93.7%
Submitted Plates	20,969	20,915	20,946
Percent of Attempts	80.6%	80.4%	80.5%
Percent of Valid Measurements	86.0%	86.1%	86.0%
Matched Plates	19,800	19,761	19,783
Percent of Attempts	76.1%	76.0%	76.1%
Percent of Valid Measurements	81.2%	81.3%	81.1%
Percent of Submitted Plates	94.4%	94.5%	94.4%

The layout and grade at this site are almost identical to the sampling site which we are using in Denver, CO. All of the traffic at this site consists of fully warmed up vehicles operating under a well controlled, loaded driving mode resulting in a high successful measurement rate for all species. One difference between this site and the one in Denver is that the traffic volume is much lower (400 to 500 vehicles per hour versus 1200 to 2000 vehicles per hour) and the resulting lack of congestion on the Riverside ramp produces vehicle specific powers which are rarely negative. The other major difference at this site was the high temperatures experienced during the data collection (see Appendix C). Many days saw the temperatures reach the 90's, and it would be expected that most of the vehicles so equipped would be using air conditioning at most all of the data collection times.

Table 2 is the data summary; included is the summary of the previous remote sensing database collected by the University of Denver at this site. These other measurements were conducted in May/June 2000 and June/July 1999.

Compared to the fleets measured in 1999 and 2000, the fleet measured in the current study is considerably lower emitting for CO. This difference has been found to be statistically significant with the t-test when each day's average emissions are considered independent measures. NO emissions have also decreased from 2000 but not as low as 1999 levels. These differences in NO from current year averages were found to not be statistically significant. Average vehicle age and speed have stayed constant, while acceleration has decreased significantly.

Table 2. Data summary.

	2001	2000	1999
Mean CO (%) (g/kg of fuel)	0.39 (48)	0.50 (62)	0.55 (67)
Median CO (%) (g/kg of fuel)	0.06 (6.7)	0.07 (9.3)	0.09 (12)
Percent of Total CO from Dirtiest 10% of Fleet	74.2	73.0	69.6
Mean HC (ppm)* (g/kg of fuel)*	100 (2.0)	130 (2.6)	150 (3.0)
Median HC (ppm)* (g/kg of fuel)*	50 (1.0)	60 (1.2)	60 (1.2)
Percent of Total HC from Dirtiest 10% of Fleet	66.3	78.3	52.8
Mean NO (ppm) (g/kg of fuel)	400 (5.6)	420 (6.0)	370 (5.2)
Median NO (ppm) (g/kg of fuel)	88 (1.2)	100 (1.4)	100 (1.3)
Percent of Total NO from Dirtiest 10% of Fleet	52.3	50.5	51.1
Mean Model Year	1994.5	1993.3	1992.4
Mean Speed (mph)	24.0	23.7	24.1
Mean Acceleration (mph/s)	-0.29	0.65	0.43
*The values have been HC offset adjusted as described in text.			

The average HC values here have been adjusted so as to remove an artificial offset in the measurements. This offset, restricted to the HC channel, has been reported in earlier CRC E-23-4 reports, but diagnosis has proved difficult. In the absence of a true diagnosis of the problem, we propose a remedy to remove the offset and obtain data which can be compared from the several years of study. This adjustment is to subtract a predetermined offset from the averaged data. The offset is determined as the average emissions of the cleanest model year and make of vehicles from each data set. By offset subtraction we force the cleanest fleet to zero emissions, but the true HC average of this clean fleet is probably slightly greater than zero. Thus, we are subtracting somewhat too

much and making averages slightly cleaner than actual. However, this procedure will adjust the data so that measurements from different years can be compared.

The make/model year groups chosen to represent the cleanest fleet for offset determination are restricted to those containing at least 200 measurements. The groups with the lowest average emissions are not always the same during the different years of measurement. Instead, the groups tend to be up to three year old model years from one or more of the following makes: Chevrolet, Ford, and Toyota. For example, in this year's data set the 2001 Chevrolet and 2001 Ford groups had the lowest average emissions - essentially zero. Thus, no offset was assumed. The 1999 and 2000 datasets, however, exhibited offsets of 50 ppm and -10 ppm respectively. The offset subtraction has been performed here and later in the analysis where indicated. The t-test reveals that the decreases in offset-adjusted averages emissions from 1999 to 2000 and from 2000 to 2001 are significant.

Table 3. Number of measurements on repeat vehicles.

Number of Times Measured	Number of Vehicles
1	12,978
2	1,688
3	551
4	242
5	78
6	40
7	9
8+	14
Total	15,600

Table 3 provides an analysis of the number of vehicles that were measured repeatedly, and the number of times they were measured. Of the 19,800 records used in this fleet analysis, 12,978 (66%) were contributed by vehicles measured once, and the remaining 6,822 (34%) records were from vehicles measured at least twice. A look at the distribution of measurements for vehicles measured seven 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.

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 shaded bars show the percentage of the total emissions contributed by the given category. This figure illustrates the skewed nature (gamma distributed) of automobile emissions, showing that the lowest emission category for each of three pollutants is occupied by no less than 75% of the fleet (for NO), and as much as 90% of the fleet (for CO). The fact that the cleanest 90% of the vehicles 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. The skewed distribution was also seen in the 1999 data and 2000 and is represented by the consistent high values of percent of total emissions from the dirtiest 10% of the fleet (see Table 2).

Figure 3 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 HC data contain a significant portion of negative readings. These negative values are a result of noise in the HC channel which become insignificant when data are averaged over 50 or more measurements (as in this report). Measurement noise is discussed further below.

The inverse relationship between vehicle emissions and model year has been observed at a number of locations around the world, and Figure 4 shows that the fleet reported in this study is not an exception.⁴ The trends in the current measurements are very similar to those seen in 1999 and 2000. The plot of %NO versus model year appears to be nearly linear and does not show any asymptotic tendencies at either age extreme when compared to the plots for CO and HC. The increased NO emissions for the 1999 model year has been previously shown to be due to the high percentage of diesel vehicles present in that model year fleet.⁹ The HC offset has been corrected in this plot.

Plotting vehicle emissions by model year, with each model year divided into emission quintiles results in the plots shown in Figure 5. 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 1991¹⁰. The results shown here continue to demonstrate that broken emissions control equipment has a greater impact on fleet emissions than vehicle age.

An equation for determining the instantaneous power of an on-road vehicle has been proposed by Jimenez¹¹, which takes the form

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

where VSP is the vehicle specific power in kW/metric tonne, *slope* is the slope of the roadway (in degrees), *v* is vehicle speed in mph, and *a* is vehicle acceleration in mph/s. Using this equation, vehicle specific power was calculated for all measurements with valid speed and acceleration in the database. The emissions data were binned according to VSP, and illustrated in Figure 6. HC offset correction has been applied. The solid line in Figure 6 shows the number of measurements in each bin from the 2001 data set. The 1999 and 2000 data are also included. The 2001 profiles are less pronounced with both the HC and CO plots being rather insensitive to VSP. While these results are somewhat different from what was observed in 1999 and 2000, they correspond to VSP profiles at the other E-23 sites. The error bars included in the plot are standard errors of the mean. These uncertainties were generated for these gamma distributed data sets by applying the central limit theorem. Each day's average emission for a given VSP bin was assumed to

be an independent measurement of the emissions at that VSP. Normal statistics were then applied to these daily averages.

The NO plot displays less of the undulating behavior observed in the previous two years at the site. However, the rather pronounced dependence of NO on VSP, seen in Chicago and Denver sites, continues to be absent at this site. The phenomenon may be related to the abundance of higher emitting trucks at low VSP as described in the CRC Phoenix: Year 2 report.¹²

Another factor that may be interfering with the VSP analysis is the recently observed dependence of vehicle age on VSP. In other words, average model year of vehicles in the different VSP groupings is not constant. Figure 7 illustrates the data. Since NO emissions are dependent on age, even during the early years of a vehicle, the older vehicles at lower VSP cause the average NO emissions of those VSP groups to be higher. This effect further confounds the NO versus VSP profile.

Using vehicle specific power, it is possible to eliminate the influence of load and of driving behavior from the mean vehicle emissions for the 1999, 2000 and 2001 databases. Table 4 shows the mean emissions from vehicles in the 1999 and 2000 with specific powers between 0 and 35 kW/tonne. Included are the 95% confidence intervals obtained by treating each day's average as independent measurements. The HC averages have been offset adjusted. Note that these emissions do not vary considerably from the mean emissions for the entire databases, as shown in Table 2. Also shown in Table 4 are the mean emissions for the 2000 and 2001 measurements adjusted for specific power. This correction is accomplished by applying the mean vehicle emissions for each specific power bin in Figure 5 for 2000 and 2001, 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 1998, is shown in Appendix E. It can be seen from Table 4 that the VSP adjustment does not significantly change the average emissions in 2001. This is consistent with the fact that the VSP distribution in 2001 was very similar to that of 1999.

Table 4. Specific power adjusted fleet emissions (0 to 35 kW/tonne only).

	1999	2000 (measured)	2000 (adjusted)	2001 (measured)	2001 (adjusted)
Mean CO (%)	0.53±0.03	0.48±0.02	0.50±0.02	0.38±0.02	0.39±0.02
Mean HC (ppm)	156±13	126±4	136±4	100±9	100±9
Mean NO (ppm)	345±33	396±27	395±27	373±33	384±33

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 1999. Table 5 shows the mean emissions for all vehicles from

model years 1983 to 1999, as measured in 1999, 2000 and 2001. Applying the vehicle distribution by model year from 1999 to the mean emissions by model year from 2000 and 2001 yields the model year adjusted fleet emissions. A sample calculation, for mean NO emissions in Chicago in 1998, is shown in Appendix F. In this analysis, a deterioration effect is seen only in average NO and even this is within the uncertainty. CO and offset adjusted HC emissions seem to remain relatively constant during three years of measurement when model year adjusted.

Table 5. Model year adjusted fleet emissions (MY 1983-1999 only).

	1999	2000 (measured)	2000 (adjusted)	2001 (measured)	2001 (adjusted)
Mean CO (%)	0.46 ± 0.03	0.43 ± 0.02	0.48 ± 0.02	0.42 ± 0.02	0.46 ± 0.02
Mean HC (ppm)	127 ± 13	112 ± 4	117 ± 4	107 ± 9	118 ± 9
Mean NO (ppm)	344 ± 33	424 ± 27	439 ± 27	443 ± 33	472 ± 33

Vehicle deterioration can be illustrated by Figure 8, which shows the mean emissions of the 1983 to 2001 model year fleet as a function of vehicle age. The first point for each model year was measured in 1999, the second point in 2000 and the third in 2001. Vehicle age was determined by the difference between the year of measurement and the vehicle model year. The most recent model years (up to 5 years old) show negligible deterioration from one year to the next for CO emissions. In fact, for most of the fleet, model year is a better determinant than age of CO emissions.

The NO measurements also show a significant deterioration effect. NO emissions increase with age for almost every model year shown in Figure 8. The offset adjusted HC emissions are a combination of deterioration with age and model year differences.

The current data set contained 700 measurements of vehicles that were also measured in 2000 and 1999. The average emissions of these vehicles are given in Table 6. HC offset correction has been applied. The deterioration trend of this set of vehicles is opposite that of the trend of the entire measured fleets. Though the repeat fleet has been aging one year between each successive measurement, the whole fleet has remained approximately seven years old through the three years. Therefore, individual vehicles are deteriorating while overall fleet emissions are improving. Thus, fleet turnover is leading to reduced emissions in successive years of measurement.

Table 6. Average emissions of vehicles measured during all three years of measurement.

	2001	2000	1999
CO (%)	0.40	0.37	0.27
HC (ppm)	95	90	90
NO (ppm)	430	380	310
Age	7.5	6.5	5.5

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 7; 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 7: Percent of all vehicles that are high emitting.

Top 10% Decile	CO	HC	NO
CO	4.7%	4.3%	0.3%
HC	4.3%	3.4%	1.6%
NO	0.3%	1.6%	7.4%
All	0.8%	0.7%	0.8%

Thus, the table shows that 4.3% of the fleet are in the top decile for both HC and CO but not NO; 0.3% of the fleet is high emitting for CO and NO but not HC; 4.7% of the fleet are high CO emitters only.

Table 8: Percent of total emissions from high emitting vehicles.

Top 10% Decile	CO	HC	NO
CO	34.9%	39.2%	1.6%
HC	32.0%	23.1%	8.4%
NO	2.2%	10.9%	38.7%
All	5.9%	4.8%	4.2%

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 7 values to percent of emissions. Table 8 shows that identification of the 4.7% of vehicles that are high emitting for CO only would identify an overall 34.9% of total measured on-road CO. More efficiently, identification of the 4.3% high CO and HC vehicles accounts for 32.0% of the total CO, 39.2% of the total HC.

In the manner described in the Phoenix, Year 2 report¹², instrument noise was measured by looking at the slope of the negative portion of the log plots. Such plots were constructed for the three pollutants. Linear regression gave best fit lines whose slopes correspond to the inverse of the Laplace factor, which describes the noise present in the measurements. This factor must be viewed in relation to the average measurement for the particular pollutant to obtain a description of noise. The Laplace factors were found

to be 0.034, 0.011 and 0.005 for CO, HC and NO, respectively. These values indicate standard deviations of 0.048%, 160 ppm and 70 ppm for individual measurements of CO, HC and NO, respectively. In terms of uncertainty in average values reported here, the numbers are reduced by a factor of the square root of the number of measurements included in each average. For example, with averages of 100 measurements, which is the low limit for number of measurements per bin, the uncertainty reduces by a factor of 10. Thus, the uncertainties in the averages reduce to 0.005%, 16 ppm and 7 ppm for CO, HC and NO, respectively. This HC noise puts these HC measurements in the lower of the two HC noise groups reported earlier.¹²

CONCLUSION

The University of Denver successfully completed the third year of a multi-year remote sensing study in the Los Angeles area to investigate trends and other characteristics of on-road emissions. Eight days of fieldwork (June 6 - June 13, 2001) were conducted on the uphill exit ramp from 91N to 60W in Riverside, CA. A database was compiled containing 19,800 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 CO₂, and 19,761 contained measurements for HC and 19,783 contained NO data.

The mean measurements for CO, HC, and NO were determined to be 0.39%, 100 ppm and 400 ppm, respectively, with an average model year of 1994.5. The mean emissions in gm/kg of fuel consumed for CO, HC and NO were 48, 2.0 and 5.6. As expected, the fleet emissions observed in this study exhibited a typical gamma distribution, with the dirtiest 10% of the fleet contributing 74%, 66%, and 52% of the CO, HC, and NO emissions, respectively. Of the 19,800 records in the database 34% arise from vehicles measured more than once. An analysis of emissions as a function of model year showed a typical inverse relationship. Measured emissions were rather insensitive to vehicle specific power this year. Small minima for CO and HC emissions were observed at approximately 15 kW/tonne. More striking is the lack of a straightforward relationship between NO emissions and vehicle specific power at this location. This feature in the relationship may be related to varying car/truck ratios at different VSP and/or lack of congestion at this site. Tracking of vehicle deterioration indicated that age is less of a factor than model year for CO emissions. An analysis of high emitting vehicles has shown that there is significant CO and HC high emitter overlap. Finally, the calculated noise in the measurements was minimal for all three pollutants.

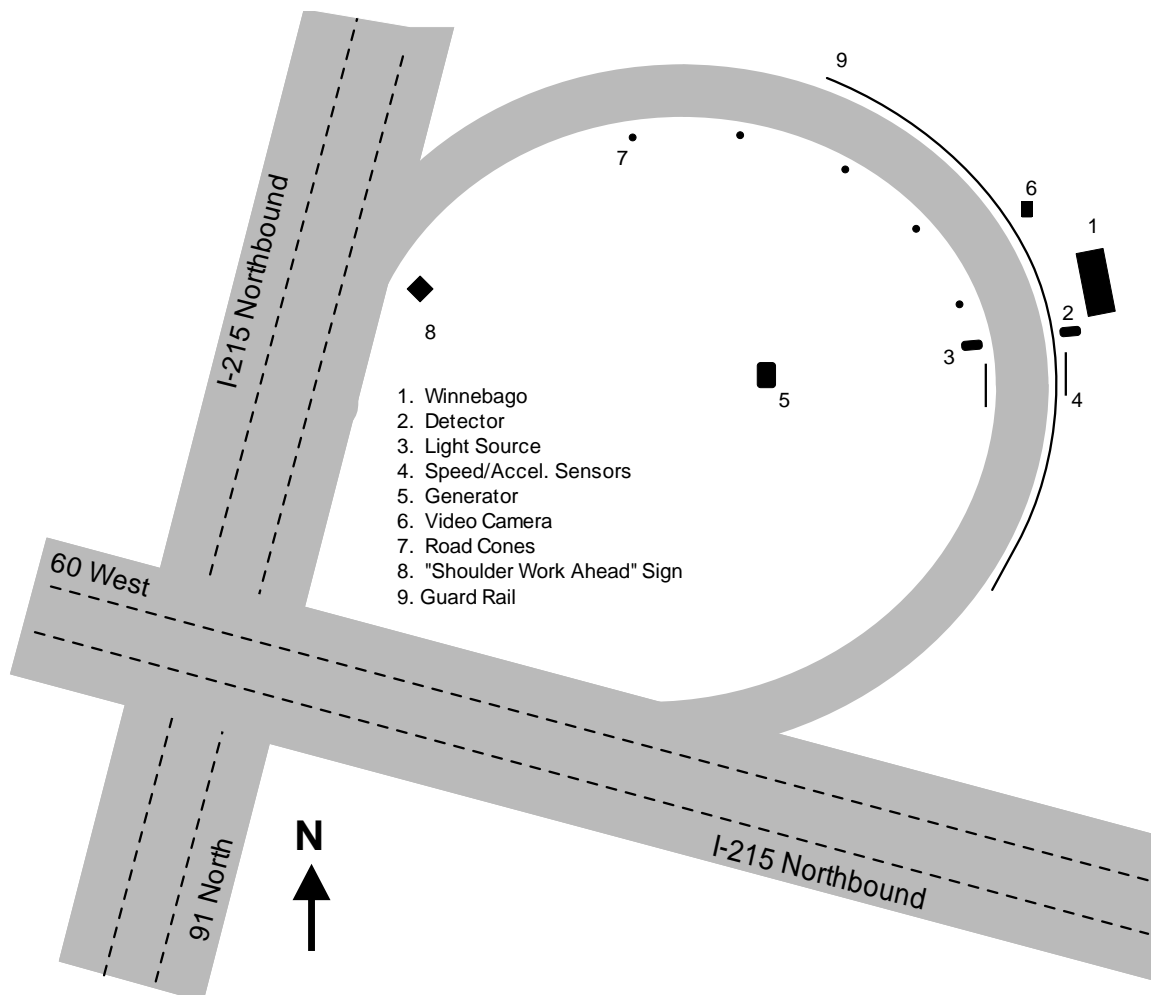


Figure 1. Schematic representation of the remote sensing site in Riverside, CA.

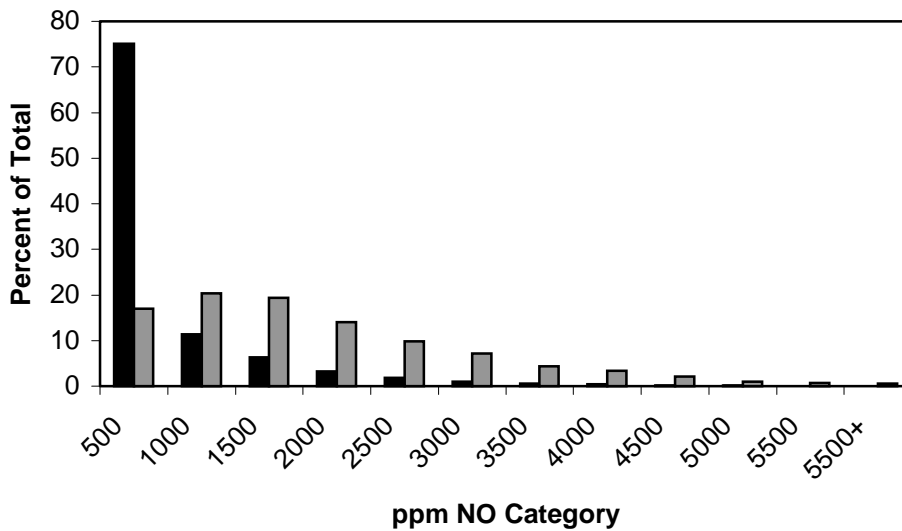
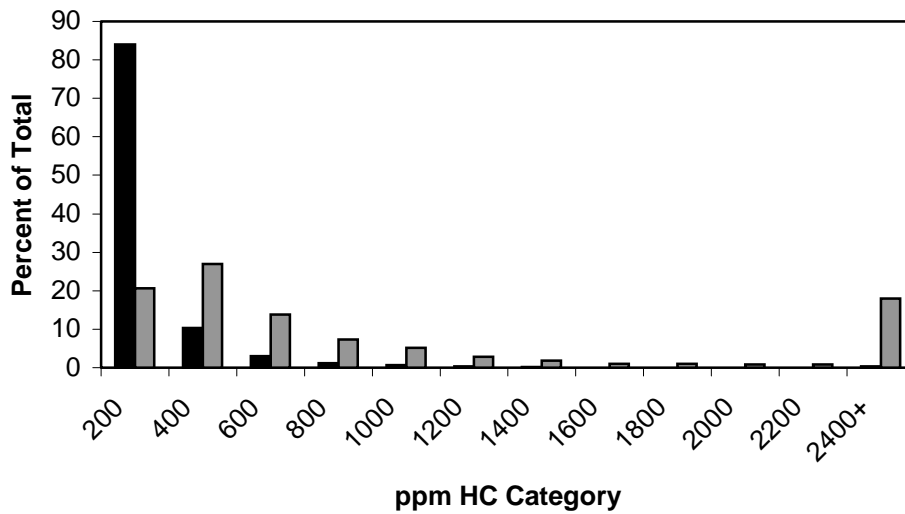
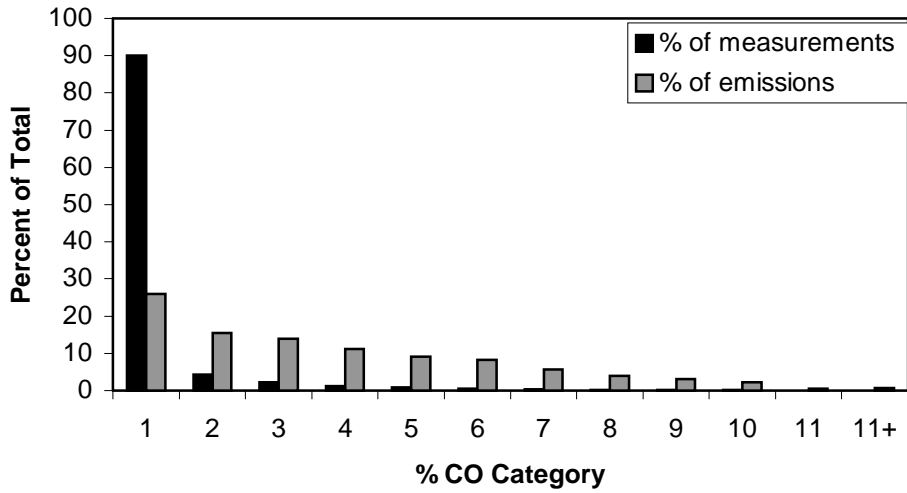


Figure 2. Emissions distributions showing the percentage of the fleet in a given emissions category (solid bars) and the percentage of the total emissions contributed (shaded bars).

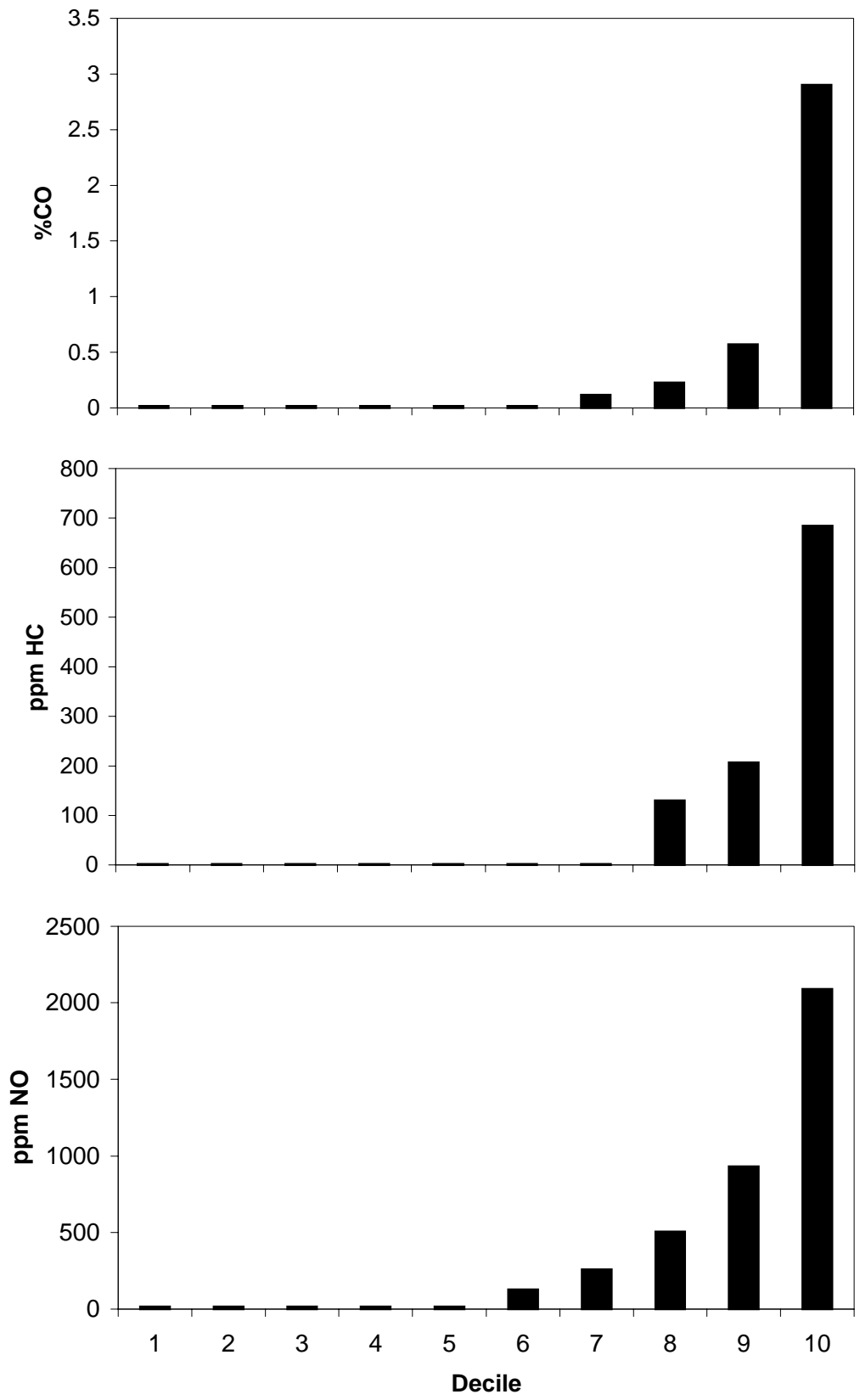


Figure 3. Fleet emissions organized into decile bins.

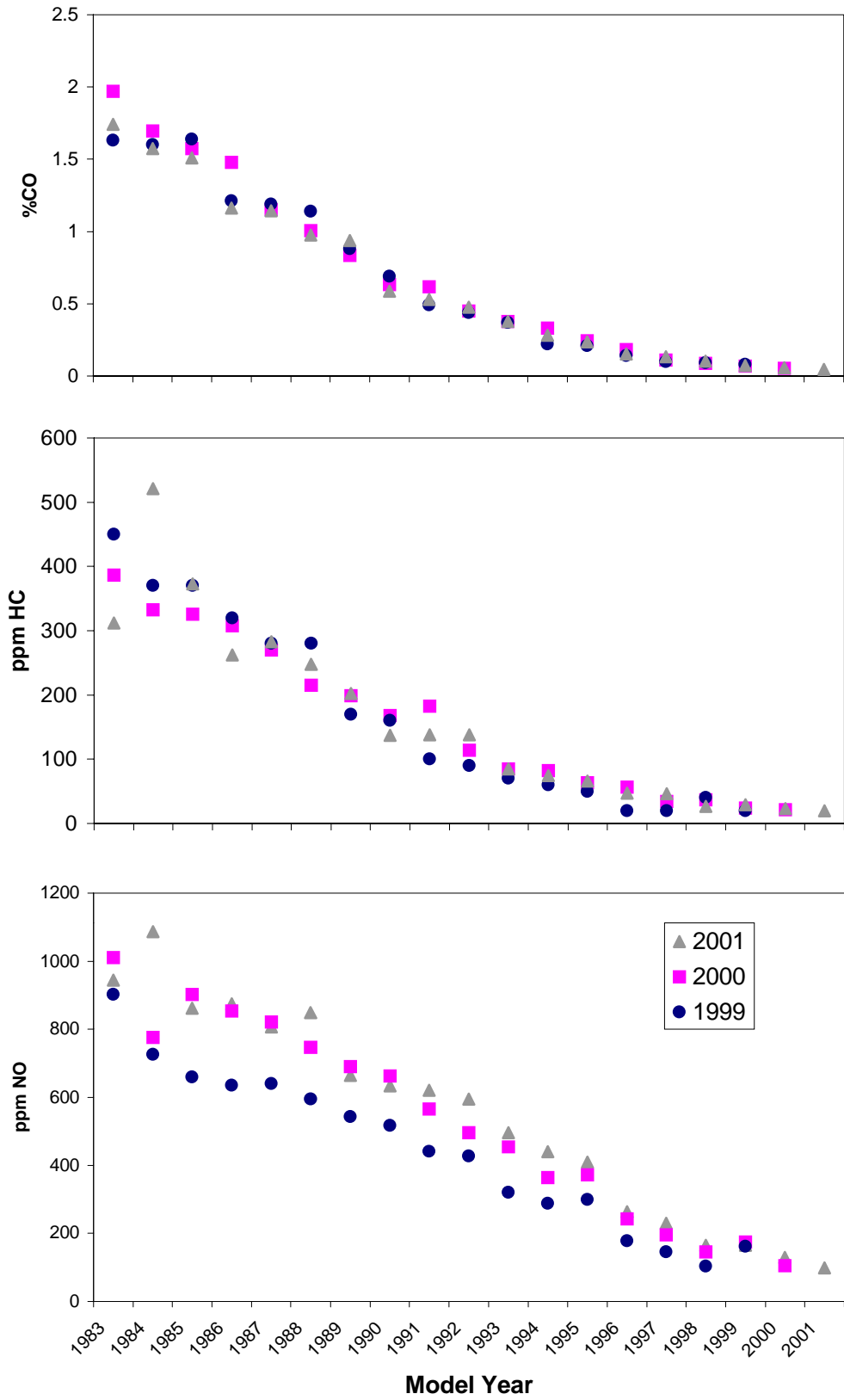


Figure 4. Mean emissions for three measurement years illustrated as a function of model year.

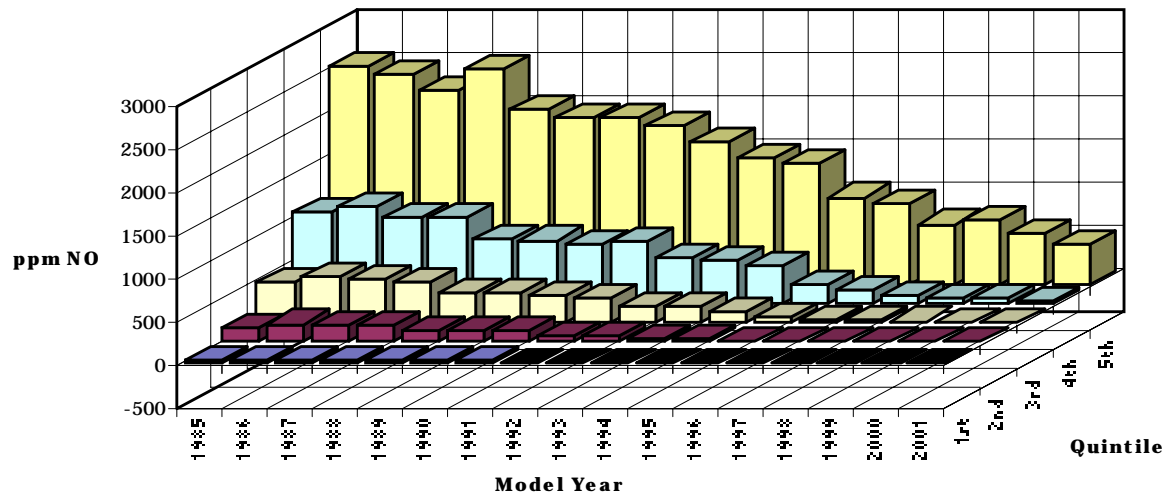
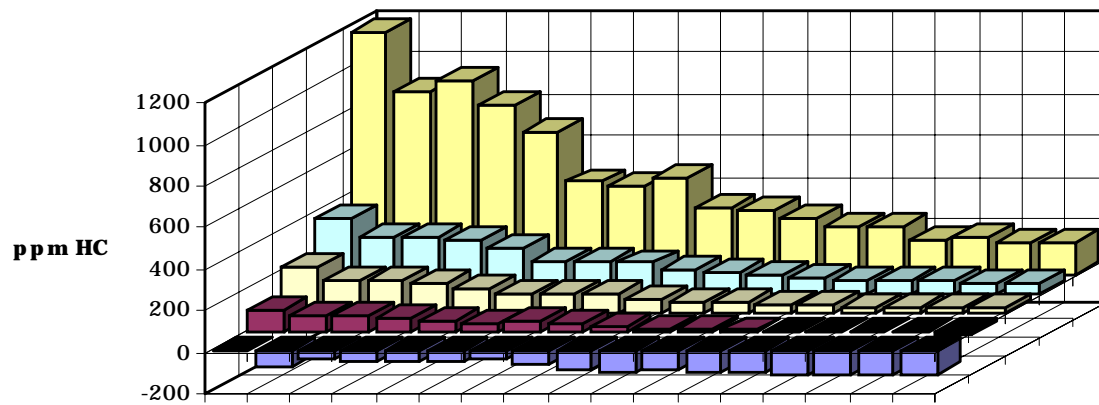
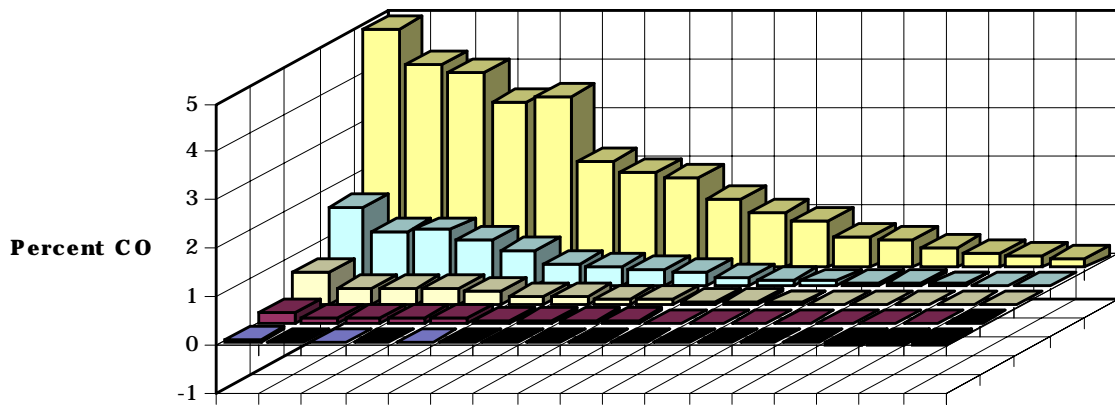


Figure 5. Vehicle emissions for three measured pollutants by model year, divided into quintiles.

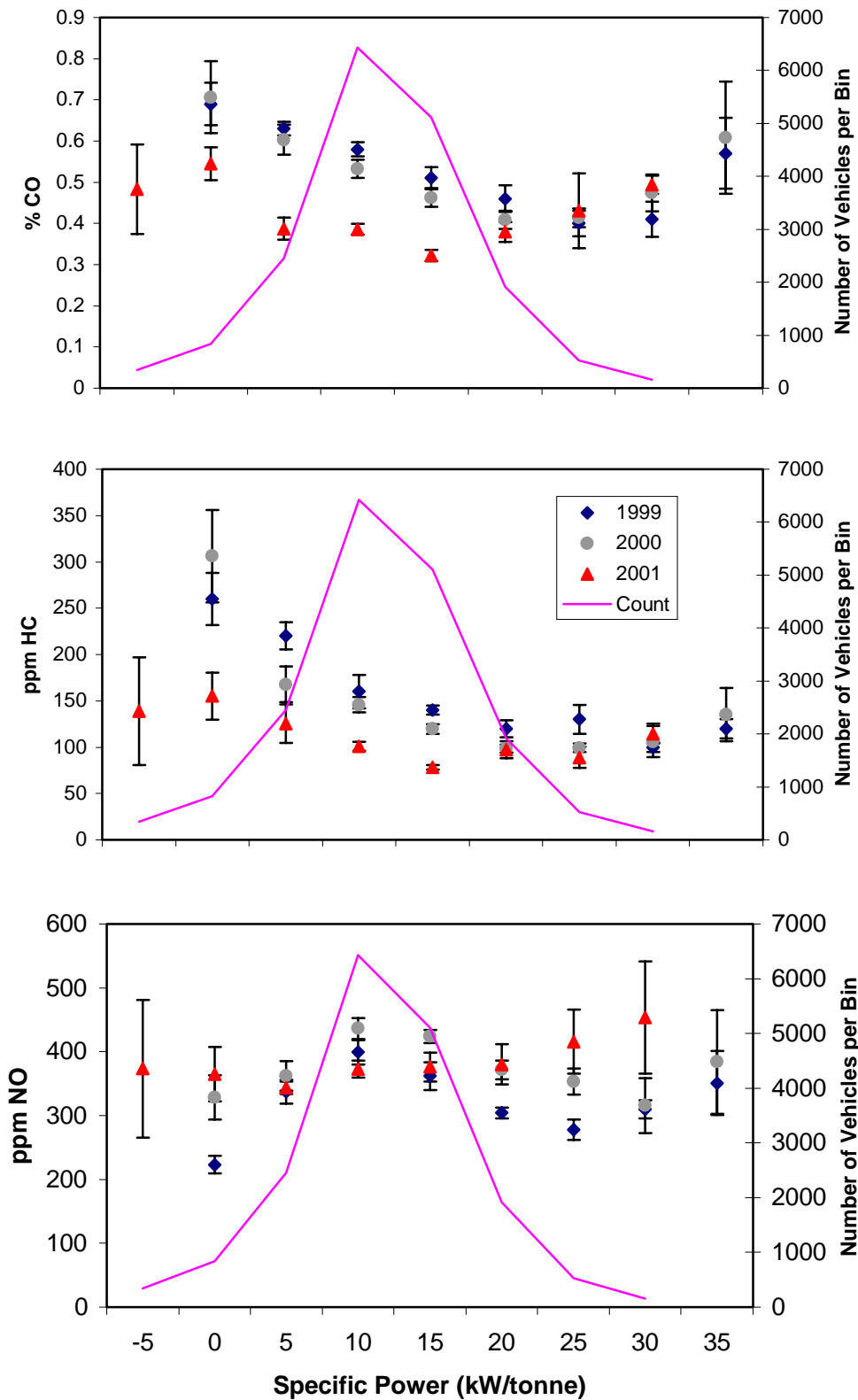


Figure 6. Vehicle specific power (lines with markers) for the three measured emission species during the three years of measurement. The solid line shows the number of vehicles averaged into each vehicle specific power bin for 2001 averages. Error bars are standard errors of the means of daily averages.

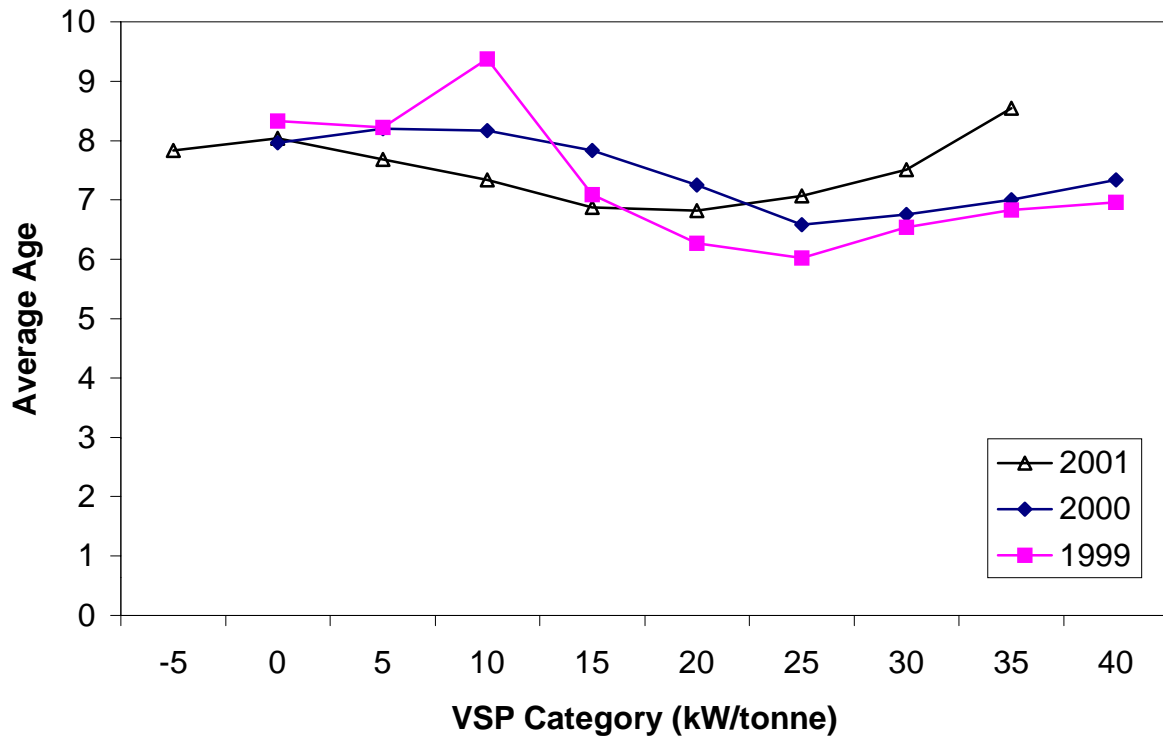


Figure 7. Average age as a function of VSP category for the three years of measurement.

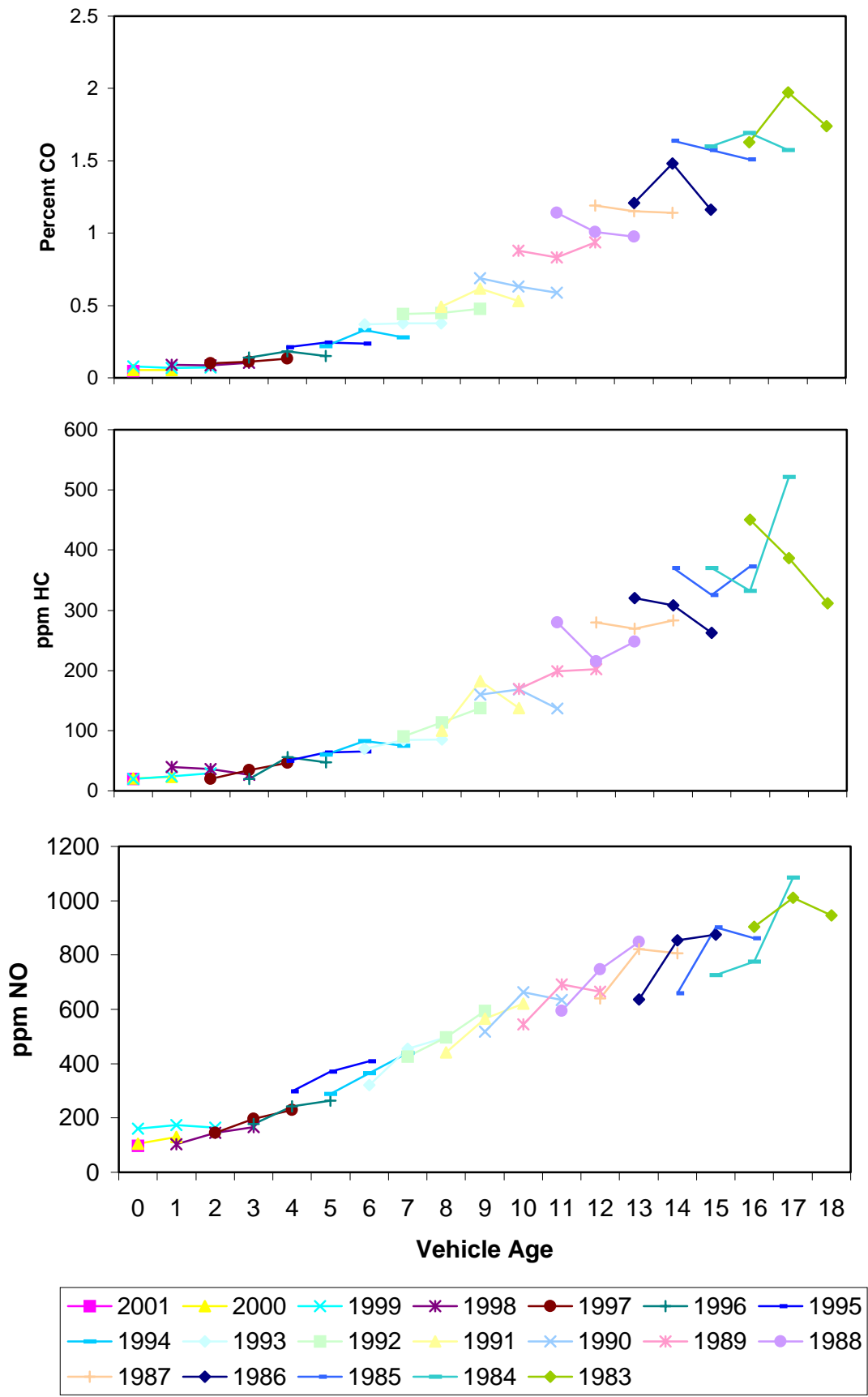


Figure 8. Mean vehicle emissions as a function of age, shown by model year.

LITERATURE CITED

1. *National Air Quality Emissions Trends, 1998*, United States Environmental Protection Agency, Research Triangle Park, NC, **2000**; EPA-454/R-00-003, p. 11.
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.*, **1999**, 49, 1463- 1468.
6. Singer, B.C.; Harley, R.A.; Littlejohn, D.; Ho, J.; Vo, T. *Environ. Sci. Technol.* **1998**, 27, 3241.
7. Lawson, D.R.; Groblicki, P.J.; Stedman, D.H.; Bishop, G.A.; Guenther, P.L. *J. Air & Waste Manage. Assoc.* **1990**, 40, 1096.
8. 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.
9. Pokharel, S.S.; Bishop, G.A.; Stedman, D.H. *On-Road Remote Sensing of Automobile Emissions in the Los Angeles Area: Year 2*, Final report to the Coordinating Research Council, Contract E-23-4, **2000**.
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. *On-Road Remote Sensing of Automobile Emissions in the Phoenix Area: Year 2*, Final report to the Coordinating Research Council, Contract E-23-4, **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 averages $>200\text{ppmm CO}_2$ or $>400\text{ppmm CO}$. ($0.25\% \text{CO}_2$ or $0.5\% \text{CO}$ 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 $\% \text{CO}$. >1.0 , $0.2\% \text{CO}$ for $\% \text{CO} < 1.0$.
- 3) reported $\% \text{CO}$, $< -1\%$ or $> 21\%$. All gases invalid in these cases.
- 4) too much error on HC/CO_2 slope, equivalent to $\pm 20\%$ for $\text{HC} > 2500\text{ppm}$ propane, 500ppm propane for $\text{HC} < 2500\text{ppm}$.
- 5) reported $\text{HC} < -1000\text{ppm}$ propane or $> 40,000\text{ppm}$. HC “invalid”.
- 6) too much error on NO/CO_2 slope, equivalent to $\pm 20\%$ for $\text{NO} > 1500\text{ppm}$, 300ppm for $\text{NO} < 1500\text{ppm}$.
- 7) reported $\text{NO} < -700\text{ppm}$ or $> 7000\text{ppm}$. 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 $100\text{mph} > \text{speed} > 5\text{mph}$ and $14\text{mph/s} > \text{accel} > -13\text{mph/s}$ and there are no restarts, or there is one restart and exactly two blocks and unblocks in the time buffer.

APPENDIX B: Explanation of the LA_01.dbf database.

The La_01.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 , FTP or at www.feat.biochem.du.edu. 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”.
Speed	Measured speed of the vehicle, in mph.
Accel	Measured acceleration of the vehicle, in mph/s.
Vin	Vehicle identification number.
Make	Manufacturer of the vehicle.
Exp_date	License expiration date.
Body_style	DMV designated body type.
Zip	Registrant's mailing zip code.

County California county number vehicle is registered in.
Year Vehicle model year.
Fuel Fuel type G (gasoline), D (diesel) and N (natural gas).
GVW Gross vehicle weight.
Smog_due Date next smog check test is required.

APPENDIX C: Temperature and Humidity Data

2000

Date	Time	Temperature	Humidity
5/30	14:07	87	50
	15:07	86	50
	16:07	84	50
	17:07	81	54
	18:09	78	61
	18:35	77	63
5/31	9:51	69	66
	10:51	71	73
	11:51	74	67
	12:12	77	63
	12:12	80	58
	14:12	84	55
	15:12	84	46
	16:12	86	44
	17:12	84	48
18:12	80	53	
6/1	9:52	69	80
	10:52	74	69
	11:52	80	60
	13:08	85	47
	14:08	90	37
	15:08	92	34
	16:08	93	36
	17:08	89	42
18:08	85	46	
6/2	9:50	78	60
	10:50	80	54
	11:50	87	37
	13:00	91	28
	14:00	91	37
	16:00	90	35
	17:00	89	35
	18:00	85	38
6/3	10:00	78	47
	11:00	82	34
	12:00	87	30
	13:00	89	28
	14:00	91	26
	15:00	93	31
	16:00	93	26
	17:00	92	30
18:00	87	36	

Date	Time	Temperature	Humidity
6/4	9:56	80	32
	10:56	83	33
	11:56	86	32
	12:56	91	30
	13:56	92	32
	14:56	92	37
	15:56	92	40
	16:56	89	42
	17:56	86	45
6/5	9:59	79	58
	10:59	83	53
	11:59	86	44
	12:59	90	32
	13:59	93	36
	14:59	93	34
	15:59	93	29
	16:59	91	32
17:59	87	38	
6/6	9:50	80	43
	10:50	84	36
	11:50	87	30
	12:50	91	20
	13:50	94	25
	15:17	93	26
	15:50	93	26
	16:50	92	25
17:50	88	25	

2001

Date	Time	Temperature	Humidity
6/6	10:49	74	74
	11:49	80	66
	12:54	83	59
	13:49	88	53
	14:49	91	49
6/7	9:46	77	68
	10:46	82	66
	11:46	85	58
	12:46	89	53
	13:46	91	51
	14:46	93	47
6/8	9:56	76	78
	10:56	81	70
	11:56	87	58
	12:58	91	51
	13:56	93	50
	14:57	93	49
	16:01	92	49
	16:57	91	51
	17:57	88	52
6/9	9:43	71	90
	10:43	77	79
	11:49	84	67
	12:43	88	57
	13:43	93	43
	14:43	93	42
	15:43	92	42
	16:45	91	46
6/10	9:34	68	85
	10:34	72	72
	11:34	79	56
	12:36	85	44
	13:34	88	31
	13:53	89	27
	14:53	89	31
	15:53	89	31
	16:53	88	28

Date	Time	Temperature	Humidity
6/11	9:30	75	66
	10:30	77	61
	11:30	80	57
	12:30	83	44
	13:30	87	44
	13:37	86	44
	14:37	86	40
	15:37	87	43
	16:37	86	43
6/12	17:37	84	40
	9:44	66	80
	10:44	68	73
	11:44	73	69
	12:45	71	66
	13:44	73	62
	14:51	73	64
	15:59	72	66
	16:58	71	68
6/13	17:58	70	70
	9:37	68	69
	10:38	69	68
	11:37	73	60
	12:37	76	57
	12:57	76	55
	13:57	80	51
	14:57	82	50
	15:57	80	53
16:57	79	54	

APPENDIX D: 2001 Field Calibration Record.

Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	CO ₂ /Ref Voltage Ratio
6/6	10:40	1.50	1.21	1.47	0.79
6/7	9:40	1.50	1.24	1.49	0.79
6/8	9:50	1.50	1.28	1.51	0.92
	14:00	1.29	1.13	1.15	1.00
6/9	9:40	1.53	1.27	1.54	0.90
	14:00	1.24	1.06	1.12	0.97
6/10	9:30	1.60	1.30	1.75	0.83
	13:50	1.27	1.09	1.20	0.90
6/11	9:25	1.59	1.35	1.58	0.94
	13:35	1.25	1.10	1.11	1.02
6/12	9:40	1.56	1.35	1.57	0.97
	14:00	1.44	1.26	1.44	1.03
6/13	9:30	1.42	1.26	1.55	1.02
	12:55	1.31	1.16	1.35	1.05

**APPENDIX E: Calculation of Vehicle Specific Power Adjusted
Vehicle Emissions (Chicago 1997-8 data)**

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 (Chicago 1997-8 data)

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