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

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EXECUTIVE SUMMARY

The University of Denver conducted the second year of a five 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 CO_2 in motor vehicle exhaust. From these ratios, we calculate 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.

Eight days of fieldwork between May 30 and June 6, 2000 were conducted on the uphill exit ramp from 91N to 60W in Riverside, CA. A database was compiled containing 23,303 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, 23,230 contained measurements for HC and 23,285 for NO data. The database, along with earlier databases and reports, can be found at www.feat.biochem.du.edu.

The mean percent CO, HC, and NO were determined to be 0.50%, 0.012%, and 0.042%, respectively with an average model year of 1993.3. The mean emissions in gm/kg of fuel consumed for CO, HC and NO were 61.7, 2.2 and 6.0. The fleet emissions measured in this study exhibit a gamma distribution, with the dirtiest 10% of the fleet responsible for 73%, 78%, and 51% of the CO, HC, and NO emissions, respectively.

The majority of measurements (62%) at this location were of vehicles measured once. The remaining 38% 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 2000 to match the vehicle driving patterns of the fleet measured in 1999. After doing so, slight improvement in CO emissions was seen. The HC and NO data seemed to contain other factors that confounded the analysis.

A model year adjustment was applied to a fleet of specific model year vehicles to track deterioration. Using a fleet of 1983 to 1999 model year vehicles, the deterioration of the fleet was demonstrated for CO and HC. Tracking of model year fleets through the two years of study showed that decreased CO emissions of newer model year vehicles are more an effect of technology than of age. In other words, emissions of newer cars appear to deteriorate very slowly with increasing age. An analysis of high emitting vehicles showed that there is considerable overlap of CO and HC high emitters.

INTRODUCTION

Many cities in the United States are in violation of the air quality standards established by the Environmental Protection Agency (EPA). Carbon monoxide (CO) levels become elevated primarily due to direct emission of the gas; and ground-level ozone, a major component of urban smog, is produced by the photochemical reaction of nitrogen oxides (NO_x) and hydrocarbons (HC). As of 1996, on-road vehicles were the single largest source for the major atmospheric pollutants, contributing 60% of the CO, 29% of the HC, and 31% of the NO_x to the national emission inventory.[1]

According to Heywood[2], carbon monoxide emissions from automobiles are at a maximum when the air/fuel ratio is rich of stoichiometric, and are caused solely by a lack of adequate air for complete combustion. Hydrocarbon emissions are also maximized with a rich air/fuel mixture, but are slightly more complex. When ignition occurs in the combustion chamber, the flame front cannot propagate within approximately one millimeter of the relatively cold cylinder wall. This results in a quench layer of unburned fuel mixture on the cylinder wall, which is scraped off by the rising piston and sent out the exhaust manifold. With a rich air/fuel mixture, this quench layer simply becomes more concentrated in HC, and thus more HC is sent out the exhaust manifold by the rising piston. There is also the possibility of increased HC emissions with an extremely lean air/fuel mixture, when a misfire 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 CO_2. The ratios of CO, HC, or NO to CO_2, termed Q, Q' and Q'' respectively, are constant for a given exhaust plume, and on their own are useful parameters for describing a hydrocarbon combustion system. This study reports measured emissions as %CO, %HC and %NO in the exhaust gas, corrected for water and excess oxygen not used in combustion. However, these percent emissions can be directly converted into mass emissions per gallon 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:

$$\text{gm CO/kg} = (28 \times \%CO/\%CO_2 / (\%CO/\%CO_2 + 1 + 3\times\%HC/\%CO_2)) / 0.014$$

$$\text{gm HC/kg} = (44 \times \%HC/\%CO_2 / (\%CO/\%CO_2 + 1 + 3\times\%HC/\%CO_2)) / 0.014$$

$$\text{gm NO/kg} = (30 \times \%NO/\%CO_2 / (\%CO/\%CO_2 + 1 + 3\times\%HC/\%CO_2)) / 0.014$$

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 CH_2. 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, CO_2, propane and NO is released into the instrument's path, and the measured ratios from the instrument are then compared to those certified by the cylinder manufacturer (Praxair). These calibrations account for day-to-day variations in instrument sensitivity and variations in ambient CO_2 levels caused by atmospheric pressure and instrument path length. Since propane is used to calibrate the instrument, all hydrocarbon measurements reported by the remote sensor are as propane equivalents.

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Laboratories have shown that the remote sensor is capable of CO measurements that are correct to within ±5% of the values reported by an on-board gas analyzer, and within ±15% for HC.[6,7] The NO channel used in this study has been extensively tested by the University of Denver, but we are still awaiting the opportunity to participate in an extensive blind study and instrument intercomparison to have it independently validated. Tests involving a late-model low-emitting vehicle indicate a detection limit (±3σ) of 25 ppm for NO, with an error measurement of ±5% of the reading at higher concentrations. Appendix A gives a list of the criteria for valid/invalid data.

The remote sensor is accompanied by a video system to record a freeze-frame image of the license plate of each vehicle measured. The emissions information for the vehicle, as well as a time and date stamp, 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 May/June 2000, under CRC contract no. E-23-4. Measurements were made for 8 days between Tuesday, May 30 and Tuesday, June 6 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 19:00. 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 second year of a 5-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 May/June of 2000, 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 23,303 records with registration information and valid measurements for at least CO and CO_2. 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 I). 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 CO_2 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	28,046		
Valid Measurements Percent of Attempts	26,564 94.7%	26,454 94.3%	26,537 94.6%
Submitted Plates Percent of Attempts Percent of Valid Measurements	24,896 88.8% 93.7%	24,812 88.5% 93.8%	24,876 88.7% 93.7%
Matched Plates Percent of Attempts Percent of Valid Measurements Percent of Submitted Plates	23,303 83.1% 87.7% 93.6%	23,230 82.8% 87.8% 93.6%	23,285 83.0% 87.7% 93.6%

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 upper 90's and it would be expected that most of the vehicles so equipped would be using air conditioning at 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 June/July of 1999.

Table 2. Data summary.

	2000	1999
Mean CO (%) (g/kg of fuel)	0.50 (62)	0.55 (67)
Median CO (%) (g/kg of fuel)	0.07 (9.3)	0.09 (12)
Percent of Total CO from Dirtiest 10% of Fleet	73.0	69.6
Mean HC (ppm) (g/kg of fuel)	120 (2.2)	200 (4.1)
Median HC (ppm) (g/kg of fuel)	50 (1.0)	110 (2.4)
Percent of Total HC from Dirtiest 10% of Fleet	78.3	52.8
Mean NO (ppm) (g/kg of fuel)	420 (6.0)	370 (5.2)
Median NO (ppm) (g/kg of fuel)	100 (1.4)	100 (1.3)
Percent of Total NO from Dirtiest 10% of Fleet	50.5	51.1
Mean Model Year	1993.3	1992.4
Mean Speed (mph)	23.7	24.1
Mean Acceleration (mph/s)	0.65	0.43

Compared to the fleets measured in 1999, the fleet measured in the current study is considerably lower emitting for HC. NO emissions, however, seem to have increased in the current year. These differences have been found to be statistically significant with the t-test when each day's average emissions was considered an independent measure. No significant difference was found between the CO means for the two years. Average vehicle age and speed have stayed constant, while acceleration has increased.

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 73% of the fleet (for NO), and as much as 89% of the fleet (for HC). The fact that the cleanest 88% of the vehicles are responsible for only 21% 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 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 are peculiar because they contain a large portion of negative readings. These negative values are a result of high levels of noise in the HC channel and are 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. 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. Unlike data collected in Chicago, only the NO emissions show a tendency for the mean emissions to increase slightly for the 1999 model year[8] during both years of measurement. The appearance of this increase during both of the measurements, and not in model year 2000 vehicles measured in 2000, indicates that the high NO emissions seen in 1999 measurements for 1999 model year vehicles is not an artifact of license plate matching, since in California most license plates (non-personalized) stay with the vehicle. Instead, there appears to be a real increase in NO emissions for 1999 model year vehicles, perhaps due to change in emissions control technology or fleet make-up in the 1999 model year vehicles.

In fact, an analysis of the 1999 measurement data had revealed that the model year 1999 fleet consisted of 127 out of 1,372 (9.3%) vehicles listed as diesel compared with only 2.8% in the 1998 model year fleet. The model year with the next highest percentage of diesels was model year 1995 with 5% and the average for the entire database was 4%. Thus, it was concluded that the observed emissions increase in the newest model year is not related to that observed in the Chicago measurements but due to the fleet makeup: more new diesels were purchased in 1999. The current measurements in 2000 support this conclusion as the model year 1999 fleet contains the highest percentage of diesels (7.2%), while the 1998 and 2000 model year vehicles contain 2.2% and 3.3% diesels, respectively. When all the diesel vehicles are removed from the 2000 measurements (triangles on the NO plot), the increased NO of 1999 model year vehicles disappears.

Figure 4 also includes the average emissions by model year measured in 1999.

Comparison of the two profiles reveals that we have an offset problem that is most evident in the 1999 HC measurements. Each specific model year seems to emit higher amounts of HC in 1999 than in 2000. This is the opposite of what would be expected since a given model year vehicle is older in 2000. Further evidence for this offset is the fact that the newest model year in 1999 emits a significant amount of HC, while the expectation is minimal emissions, as seen in 2000. We attempt to correct for this offset by assuming the average measured emissions of the newest model year vehicles is zero. The offset found in the newest MY was then subtracted from the other model year bins to give inset plot shown in Figure 4. The adjusted HC profile is what was expected with the 2000 average measurements slightly higher for the newer model years.

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 1991[9]. The results shown here continue to demonstrate that broken emissions control equipment has a greater impact on fleet emissions than vehicle age. Again, however, the HC data are somewhat difficult to interpret as a large number of negative values cause the first quintile averages to be less than zero.

An equation for determining the instantaneous power of an on-road vehicle has been proposed by Jimenez[10], which takes the form

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

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. The solid line in Figure 6 shows the number of measurements in each bin from the 2000 data set. Both 1999 and 2000 data are included. The 1999 profiles are less pronounced with both the HC and NO plots being rather flat, and only at very high vehicle specific powers is an increase in emissions for CO and NO observed. In 2000, however, the plots are more pronounced for CO and HC and show the expected negative dependence on VSP. Only at very high VSP (>25 kW/tonne) does commanded power enrichment cause emissions to increase again. Lack of congestion at this site eliminates almost all vehicles that have a negative vehicle specific power (only 603 vehicles out of 20,408 with valid speeds or 3.0%), and thus very few decelerations are observed at this ramp. The error bars included in the plot are standard errors of the mean. These uncertainties were generated for these •-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 rise in NO concentrations at low vehicle specific powers cannot be explained by the presence of diesels, as there were even fewer diesels measured in 2000. The phenomenon may be related to the abundance of trucks at low VSP as described in the CRC Phoenix: Year 2 report.[11] The variation of the car to truck ratio as a function of VSP in Riverside is evident in Figure 7. The variation in car/truck ratio and the quite different NO emission profile with VSP of cars and trucks (see Figure 8) gives rise to the undulating overall NO profile seen in Figure 6. The Phoenix and Riverside sites, which show this unexpected NO versus VSP curve, also show very large car/truck ratio differences as a function of VSP. Both phenomena may arise from the fact that these two sites show less traffic congestion than the Chicago and Denver E-23 sites.

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 9 illustrates the data. Since NO emissions are dependent on age, especially 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.

Table 3. Number of measurements on repeat vehicles.

Number of Times Measured	Number of Vehicles
1	14,560
2	1,907
3	678
4	328
5	179
6	78
7	12
8	5
>8	5

Table 3 provides an analysis of the number of vehicles that were measured repeatedly, and the number of times they were measured. Of the 23,303 records used in this fleet analysis, 14,560 (62%) were contributed by vehicles measured once, and the remaining 8,743 (38%) records were from vehicles measured at least twice. A look at the distribution of measurements for vehicles measured eight 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.

The current data set contained 6413 measurements of vehicles that were also measured in 1999. The average emissions of these vehicles are given in Table 4. The deterioration trend of this set of vehicles is opposite that of the trend of the entire measured fleets. However, 49% of vehicles measured as having CO emissions >1.0% in 1999 also had CO > 1.0% in 2000. In terms of HC, this high emitter (>0.05%) conservation rate was 34% and 70% for NO (>0.1%).

Table 4. Average emissions of vehicles measured during both years of measurement.

	2000	1999
CO (%)	0.43	0.41
HC (ppm)	160	92
NO (ppm)	490	570

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 and 2000 databases. Table 5 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. Note that these emissions do not vary considerably from the mean emissions for the entire 1999 and 2000 databases, as shown in Table 2. Also shown in Table 5 are the mean emissions for the 2000 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, 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 5 that the mean VSP adjusted emissions in 2000 is not significantly different for CO from the 1999 fleet average. In the cases of the other two pollutants, however, VSP adjustment does not account for the differences in average emissions. Average HC is lower in 2000 and average NO is higher. As discussed previously, the HC discrepancy is most likely a result of an HC measurement offset problem in 1999 that was subsequently corrected in 2000.

Table 5. Specific power adjusted fleet emissions (0 to 35 kW/tonne only).

	1999	2000 (measured)	2000 (adjusted)
Mean CO (%)	0.53 ± 0.03	0.48 ± 0.02	0.50 ± 0.02
Mean HC (ppm)	206 ± 13	116 ± 4	126 ± 4
Mean NO (ppm)	345 ± 33	396 ± 27	395 ± 27

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 6 shows the mean emissions for all vehicles from model year 1983 to 1999, as measured in 1999 and 2000. Applying the vehicle distribution by model year from 1999 to the mean emissions by model year from 2000 yields the model year adjusted fleet emissions. A sample calculation, for mean NO emissions in Chicago in 1998, is shown in Appendix F. Both CO and NO emissions show a slight deterioration effect upon model year adjustment. In the case of NO, model year adjustment seems to increase the average emissions to a value much greater than would be expected due to deterioration. The HC average emissions, however, still suffer from the offset, and model year correction does not account for the discrepancy.

Table 6. Model year adjusted fleet emissions (MY 1983-1999 only).

	1999	2000 (measured)	2000 (adjusted)
Mean CO (%)	0.46 ± 0.03	0.43 ± 0.02	0.48 ± 0.02
Mean HC (ppm)	177 ± 13	102 ± 4	107 ± 4
Mean NO (ppm)	344 ± 33	424 ± 27	439 ± 27

Vehicle deterioration can be illustrated by Figure 10, which shows the mean emissions of the 1983 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 point in 2000. Vehicle age was determined by the difference between the year of measurement and the vehicle model year. The most recent model years (up to 4 years old) show a small deterioration from one year to the next for CO emissions. The deterioration rate seems to increase in the model years that are 5 years old and older, but becomes confounded by noise at older model years, as fewer vehicles of those model years are measured.
In the case of HC emissions, there is an apparent decrease in emissions with age; this, again, is caused by the offset in the 1999 measurements. The NO measurements also show a significant deterioration effect. NO emissions seem to increase with age for every model year shown in Figure 10. This apparent deterioration is greater than is expected, however. One interesting feature of the NO plot is that the two model years with significantly higher percentage of diesel vehicles, 1995 and 1999, are easily distinguishable in the plot as they have considerably higher average NO emissions during both years of measurement.

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

Top 10% Decile	CO	HC	NO
CO	5.4%	4.2%	0.7%
HC	4.2%	4.3%	1.7%
NO	0.7%	1.7%	7.9%
All	0.3%	0.3%	0.3%

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 8: Percent of total emissions from high emitting vehicles.

Top 10% Decile	CO	HC	NO
CO	39.4%	33.0%	3.5%
HC	30.6%	33.8%	8.6%
NO	5.1%	13.3%	39.9%
All	2.2%	2.4%	1.5%

Thus, the table shows that 4.2% of the fleet are in the top decile for both HC and CO but not NO; 0.7% of the fleet is high emitting for CO and NO but not HC; 5.4% of the fleet are high CO emitters only.

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 5.4% of vehicles that are high emitting for CO only would identify an overall 39.4% of total measured on-road CO. More efficiently, identification of the 4.2% high CO and HC vehicles accounts for 30.6% of the total CO, 33.0% of the total HC.

In the manner described in the Phoenix, Year 2 report[11], 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 520 ppm CO, 140 ppm HC and 50 ppm NO. These values indicate minimal relative noise in measurements of CO and NO but a significant amount of noise in the HC measurements. This HC noise puts these HC measurements in the lower of the two HC noise groups reported earlier.[11] This noise in the HC channel accounts for the abundance of negative HC readings seen in the various analyses above.

CONCLUSION

The University of Denver successfully completed the second year of a 5-year remote sensing study in the Los Angeles area to investigate trends and other characteristics of on-road emissions. Eight days of fieldwork (May 30 - June 6, 2000) were conducted on the uphill exit ramp from 91N to 60W in Riverside, CA. A database was compiled containing 23,303 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 23,230 contained measurements for HC and 23,285 contained NO data.

The mean measurements for CO, HC, and NO were determined to be 0.50%, 0.012% and 0.042%, respectively with an average model year of 1993.3. The mean emissions in gm/kg of fuel consumed for CO, HC and NO were 61.7, 2.2 and 6.0. As expected, the fleet emissions observed in this study exhibited a typical gamma distribution, with the dirtiest 10% of the fleet contributing 73%, 78%, and 51% 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 fuel specific CO and HC emissions are at a minimum at approximately 20 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.

Of the 23,303 records in the database 38% arise from vehicles measured more than once. VSP and model year corrections account for some of the differences in measured emissions between this year and 1999, but a HC offset apparent in 1999 is absent in 2000. Finally, an analysis of high emitting vehicles has shown that there is significant CO and HC high emitter overlap.

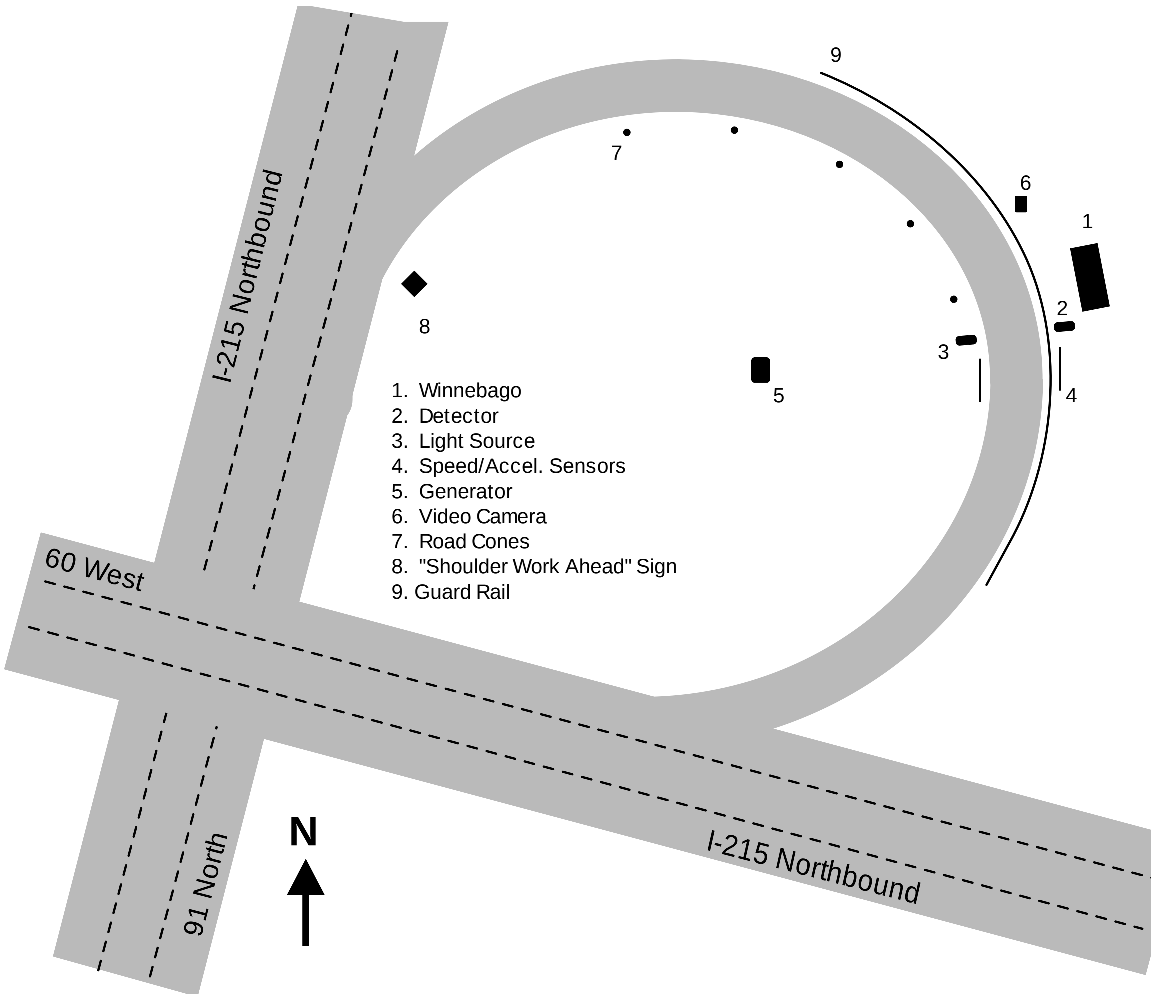

Figure 1. Schematic representation of the remote sensing site in Riverside, CA.

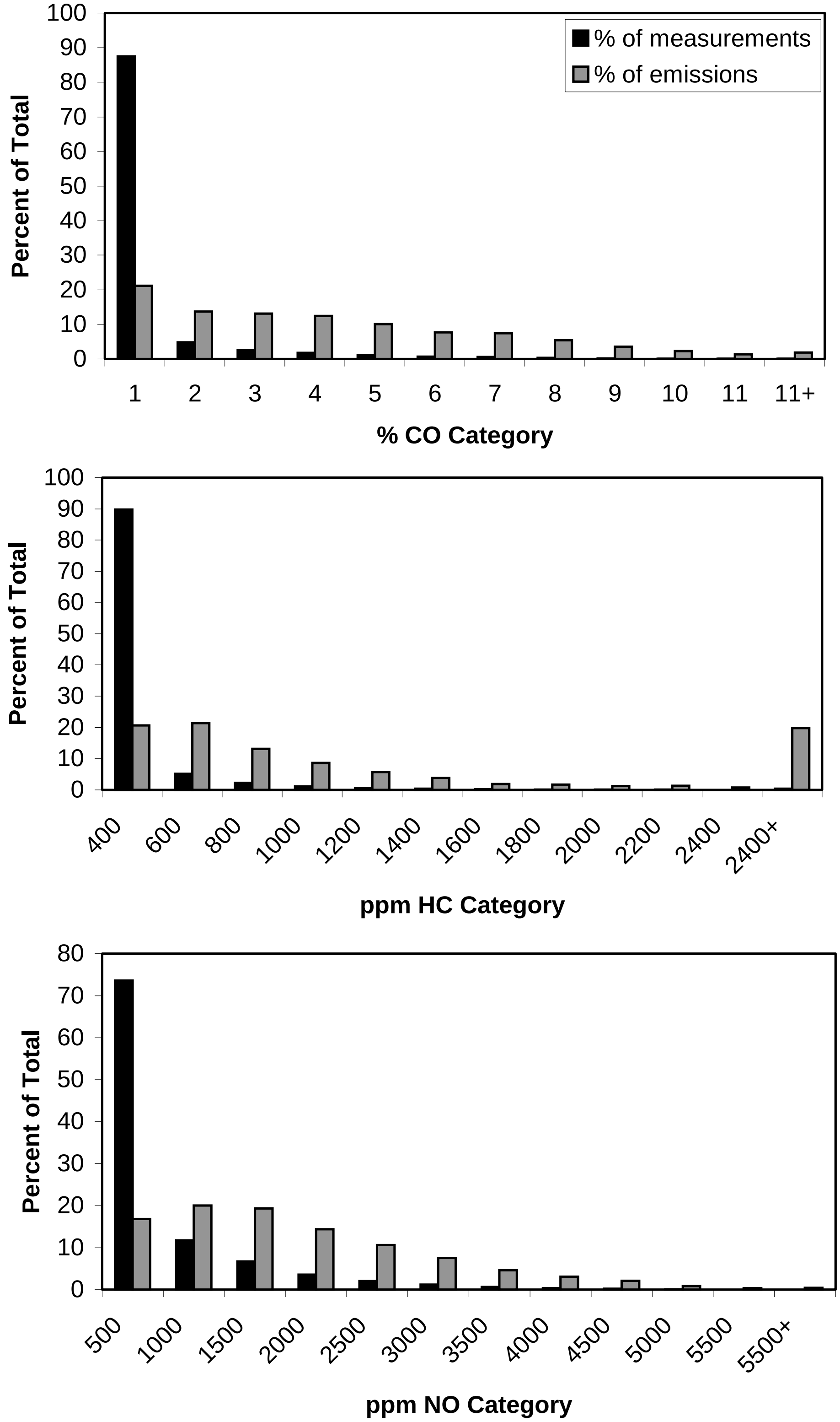

Figure 2. Emissions distributions showing the percentage of the fleet in a given emissions category (solid bars) and the percentage of the total emissions contributed (shaded bars).

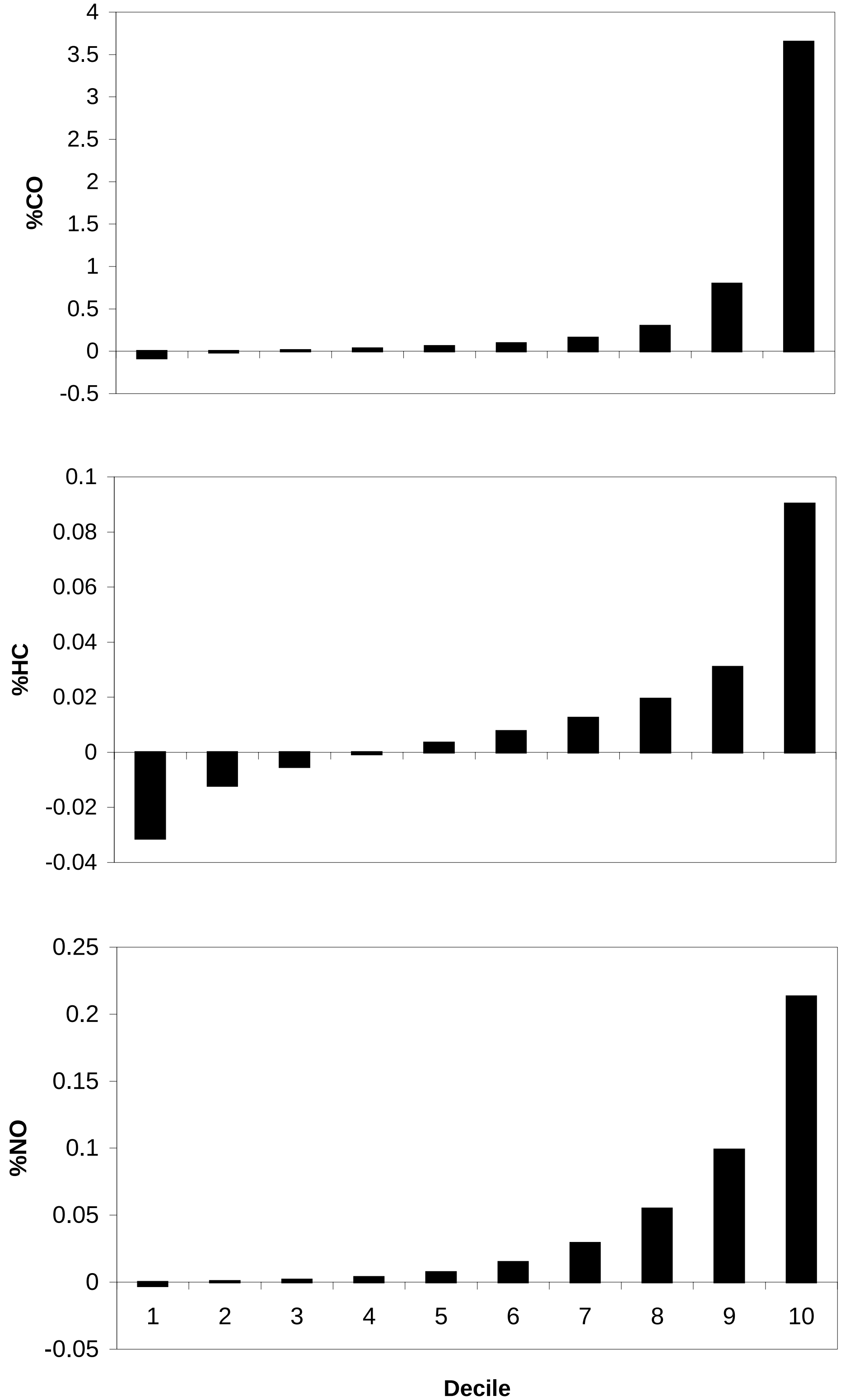

Figure 3. Fleet emissions organized into decile bins.

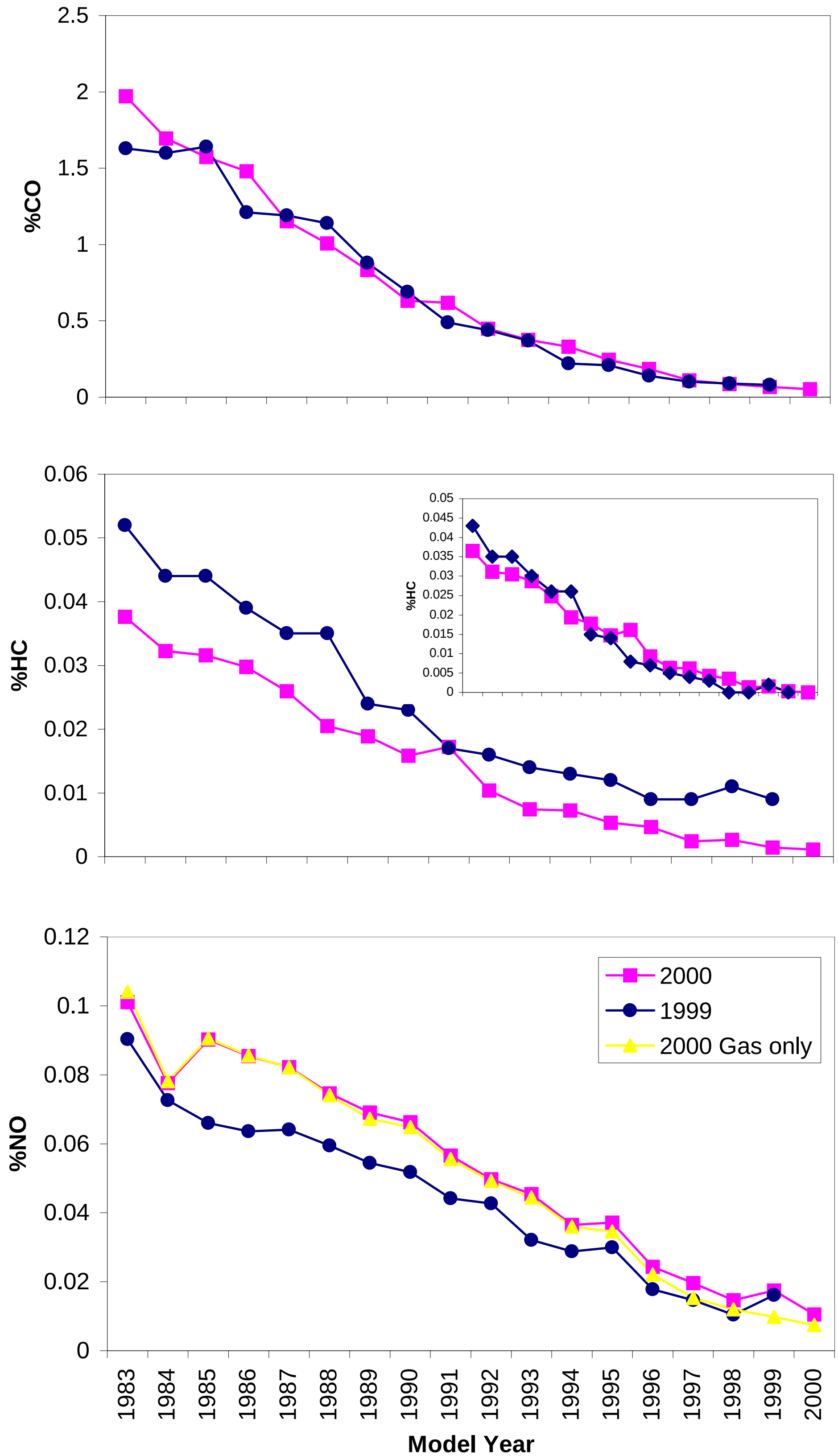

Figure 4. Mean emissions for two measurement years illustrated as a function of model year. The lines connecting the points are only a visual aid.

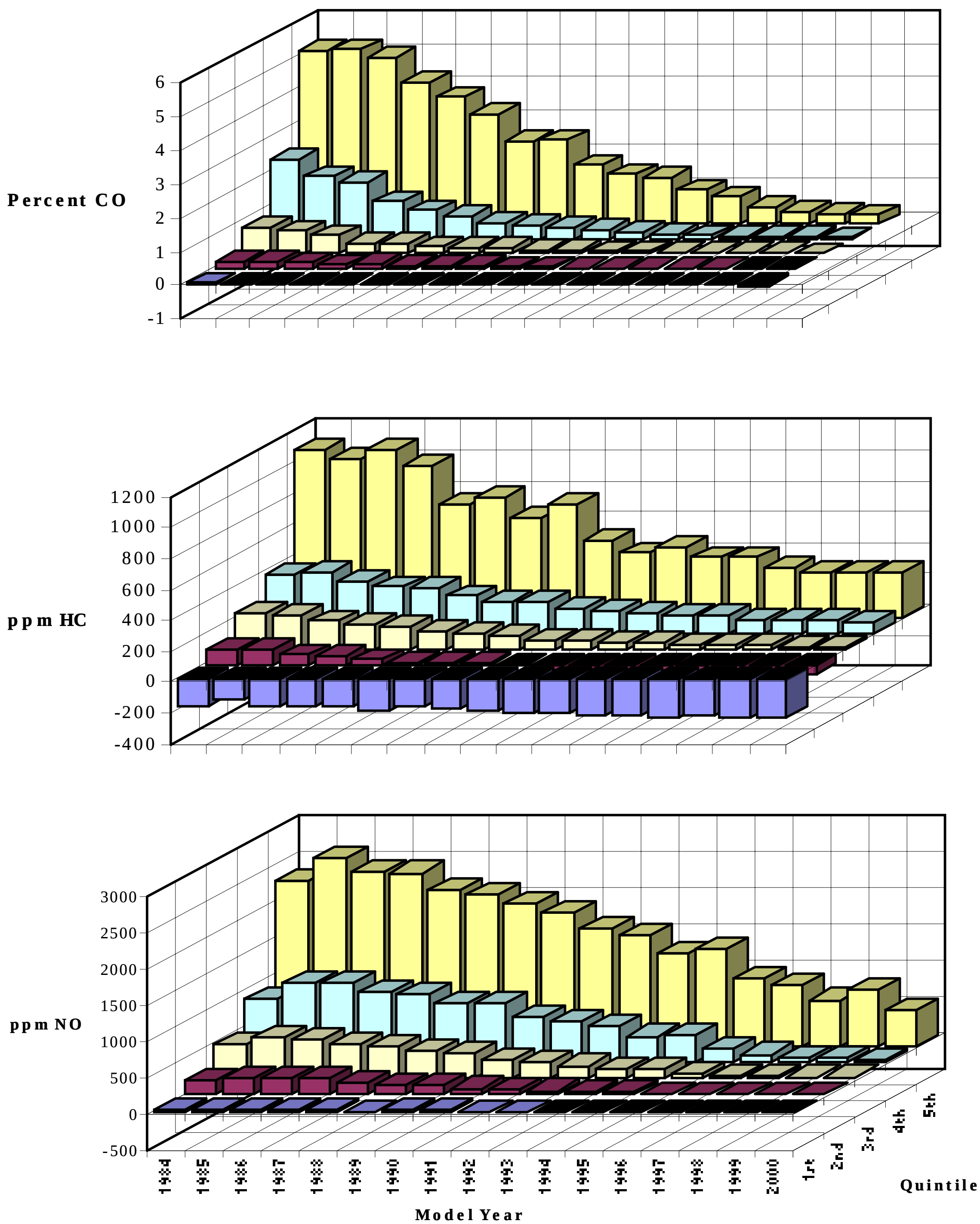

Figure 5. Vehicle emissions for three measured pollutants by model year, divided into quintiles.

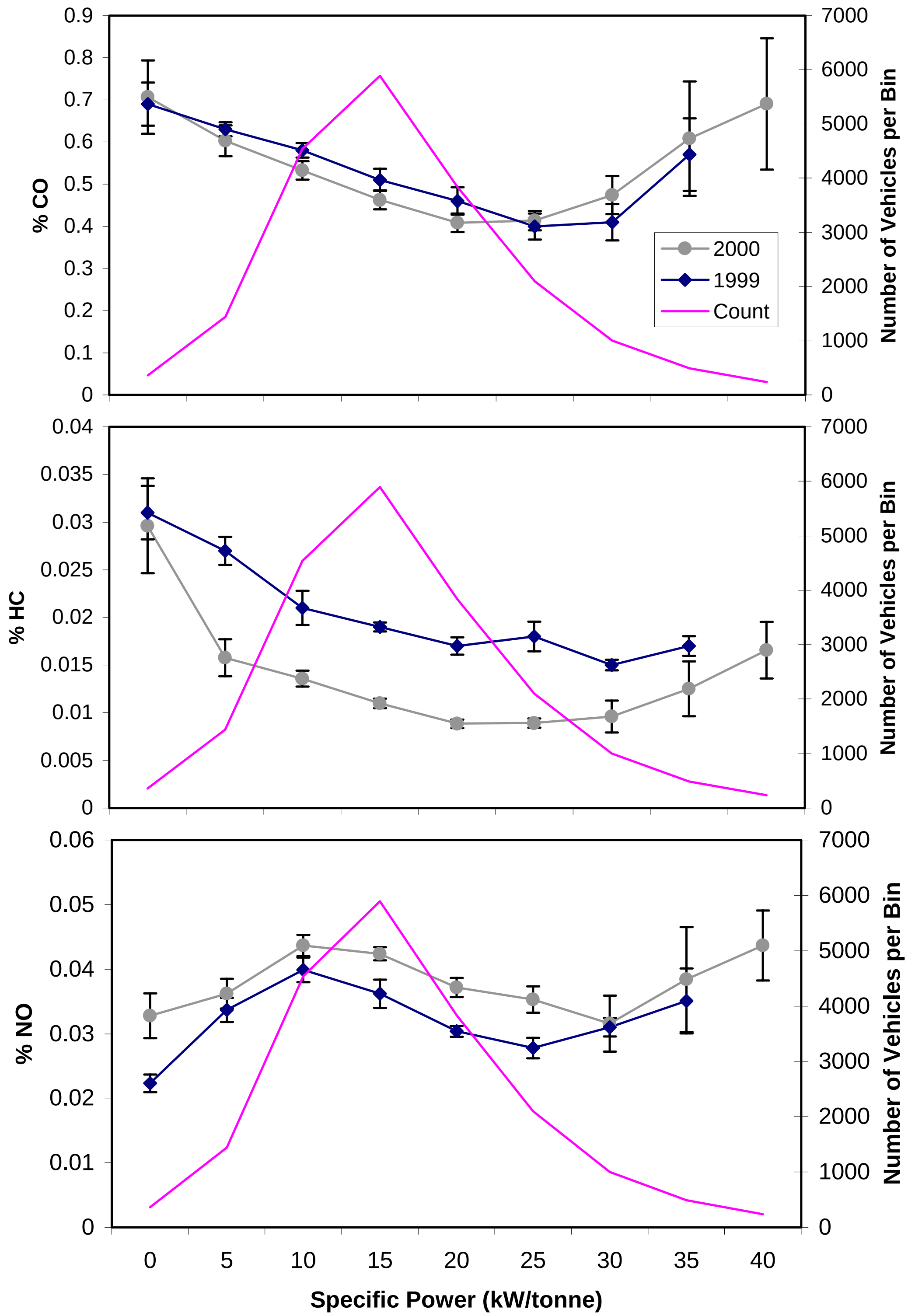

Figure 6. Vehicle specific power (lines with markers) for the three measured emission species during the two years of measurement. The solid line shows the number of vehicles averaged into each vehicle specific power bin.

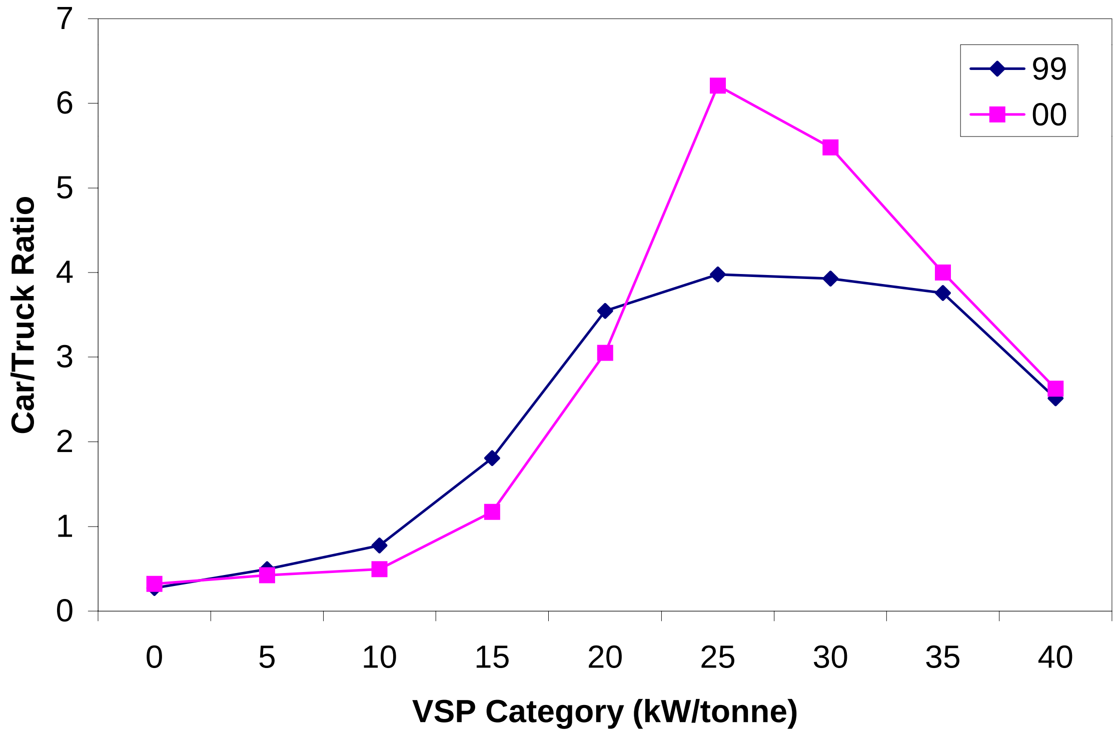

Figure 7. Plot of the car to truck ratio as a function of VSP category for the two years of measurement in LA.

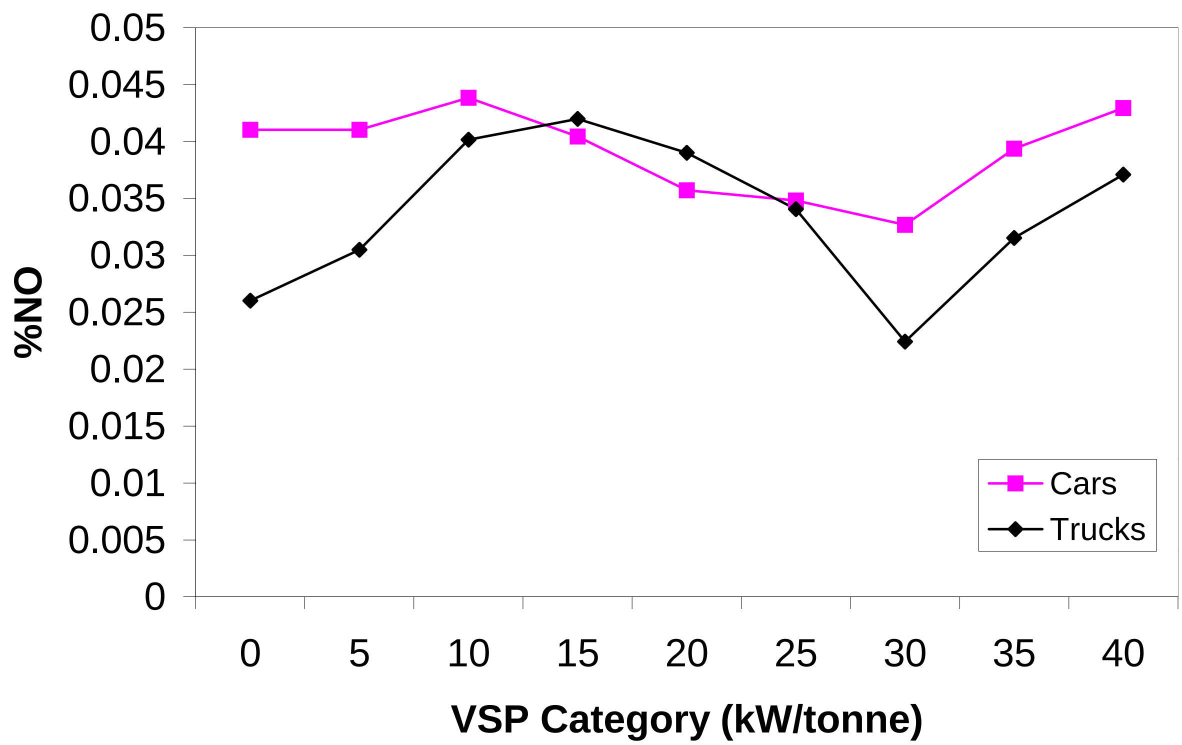

Figure 8. Average %NO as a function of VSP category, separated into cars and trucks from 2000 data.

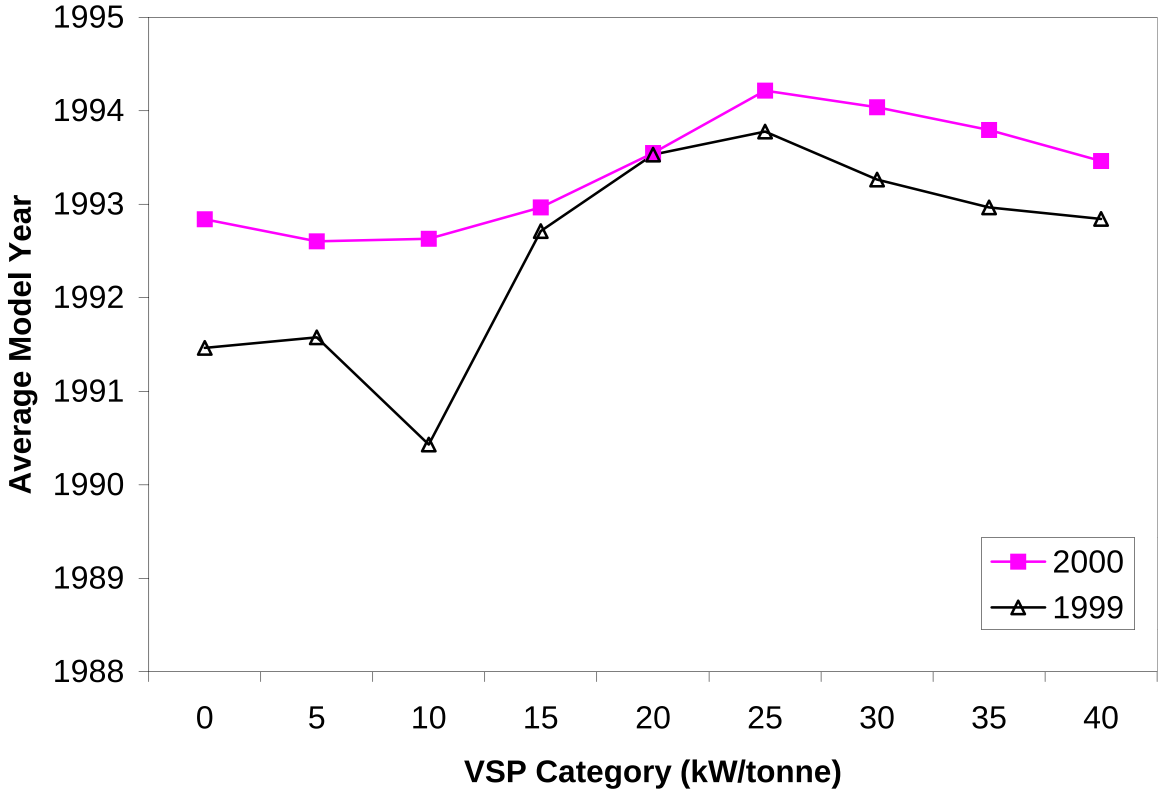

Figure 9. Average model year as a function of VSP category for the two years of measurement.

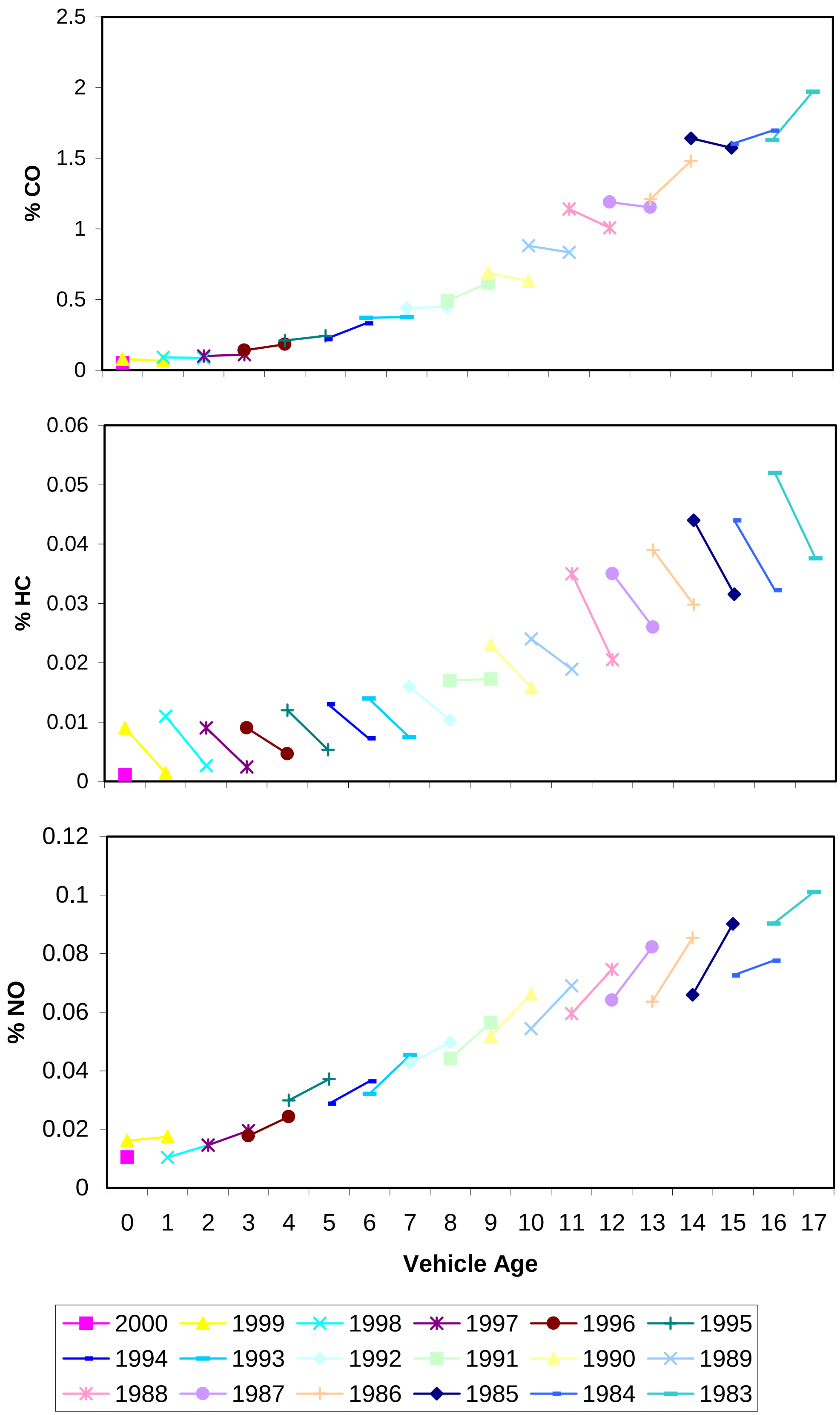

Figure 10. Mean vehicle emissions as a function of age, shown by model year.

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

Not measured:

1) vehicle with less than 0.5 seconds clear to the rear. Often caused by elevated pickups and trailers causing a “restart” and renewed attempt to measure exhaust. The restart number appears in the data base.

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

Invalid :

1) insufficient plume to rear of vehicle relative to cleanest air observed in front or in the rear; at least five, 10ms averages > 0.25% CO_2 or >0.5% CO in an 8cm cell. Often HD diesel trucks or pedestrians.

2) too much error on CO/CO_2 slope, equivalent to $\pm$20% for %CO. >1.0, 0.2%CO for %CO<1.0.

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

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

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

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

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

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

APPENDIX B: Explanation of the LA_00.dbf database.

The La_00.dbf is a Microsoft FoxPro database file, and can be opened by any version of MS FoxPro. The file can be read by a number of other database management programs as well, and is available on CD-ROM or FTP. The following is an explanation of the data fields found in this database:

License	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.
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: 2000 Temperature and Humidity Data

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

APPENDIX D: 2000 Field Calibration Record.

Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor	CO_2/Ref Voltage Ratio
5/30	14:00	1.27	1.17	1.32	0.84
5/31	9:51	1.61	1.31	1.42	0.79
5/31	12:00	1.39	1.14	1.15	0.83
6/1	9:50	1.57	1.27	1.29	0.77
6/1	13:00	1.32	1.18	1.21	0.86
6/2	9:50	1.58	1.44	1.71	0.81
6/2	11:55	1.35	1.20	1.34	0.88
6/3	10:00	1.44	1.27	1.52	0.82
6/3	11:00	1.41	1.25	1.39	0.83
6/3	14:20	1.27	1.17	1.34	0.85
6/4	9:55	1.44	1.30	1.66	0.81
6/4	14:35	1.31	1.19	1.39	0.84
6/5	9:55	1.56	1.40	1.62	0.84
6/5	12:05	1.33	1.21	1.37	0.91
6/6	9:50	1.50	1.31	1.40	0.82
6/6	12:10	1.31	1.16	1.19	0.85

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**