On-Road Remote Sensing of Automobile Emissions in the Chicago Area: Year 4

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EXECUTIVE SUMMARY

The University of Denver has completed the first four years of a multi-year remote sensing study in the Chicago 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 the exhaust that would be observed by a tailpipe probe, corrected for water and any excess oxygen not involved in combustion. Mass emissions per mass or volume of fuel can also be determined. The system used in this study was 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.

The fourth year of this study involved four days of fieldwork conducted at the on-ramp from Algonquin Rd. to eastbound I-290 in northwest Chicago. A database was compiled containing 22,065 records for which the State of Illinois provided make and model year information. All of these records contained valid measurements for at least CO and CO_2, and 21,972 records contained measurements of HC and NO as well. The database, as well as others compiled by the University of Denver, can be found at www.feat.biochem.du.edu.

The mean CO, HC and NO emissions for the fleet measured in the fourth year of this study were 0.26%, 94 ppm (when offset is removed) and 316 ppm, respectively. These values are amongst the lowest we have observed for a statistically significant fleet, and are again considerably lower than those for fleets previously measured in the Chicago area.

Vehicle emissions as a function of vehicle specific power revealed that NO emissions show a positive dependence on specific power, while HC emissions show a negative dependence on specific power – the expected trends. Carbon monoxide emissions show a slight negative dependence on specific power in the range from –5 to 25 kW/tonne. This negative dependence of CO in less pronounced than previous years.

Using vehicle specific power, it was possible to adjust the emissions of the vehicle fleet measured in 2000, 1999 and 1998 to match the vehicle driving patterns of the fleet measured in 1997. After doing so, average emissions of all three pollutants of the current fleet were lower than the emissions of the 1997 fleet.

A model year adjustment was applied to 1983 to 1997 model year vehicles to track deterioration. It was observed that the average emissions of the fleet had declined, apparently more than offsetting expected emissions deterioration. It is possible that the recently implemented reformulated gasoline program caused this effect. Finally, an analysis of high emitters shows that there is significant overlap of vehicles that are high emitting for CO and HC.

INTRODUCTION

Many cities in the United States are in violation of the air quality standards established by the Environmental Protection Agency (EPA). Carbon monoxide (CO) levels become elevated primarily due to direct emission of the gas, and ground-level ozone, a major component of urban smog, is produced by the photochemical reaction of nitrogen oxides (NO_x) and hydrocarbons (HC). As of 1998, on-road vehicles were estimated to be the single largest source for the major atmospheric pollutants, contributing 60% of the CO, 44% of the HC, and 31% of the NO_x to the national emission inventory.[1]

For a description of the internal combustion engine and causes of pollutants in the exhaust see Heywood[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.

Control measures to decrease mobile source emissions in non-attainment areas include inspection and maintenance (I/M) programs, reformulated and 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. Colinear 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 a UV spectrometer. The UV unit is then capable of quantifying nitric oxide by measuring an absorbance band at 226.5 nm in the UV spectrum and comparing it to a calibration spectrum in the same region.

The exhaust plume path length and density of the observed plume are highly variable from vehicle to vehicle, and are 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 only measures directly 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. 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 as described below, the %HC values must first be multiplied by 2.0, assuming that the fuel used is regular gasoline. These percent emissions can be directly converted into mass emissions by the equations shown below.

gm CO/gallon = 5506•%CO/(15 + 0.285•%CO + 2.87•%HC)
gm HC/gallon = 8644•%HC/(15 + 0.285•%CO + 2.87•%HC)
gm NO/gallon = 5900•%NO/(15 + 0.285•%CO + 2.87•%HC)

These equations indicate that the relationship between concentrations of emissions to mass of emissions is quite linear, especially for CO and NO and at low concentrations for HC. Thus, the percent difference in emissions calculated from the concentrations of pollutants reported here is equivalent to a difference calculated from masses.

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

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

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

Quality assurance calibrations are performed twice daily in the field unless observed voltage readings or meteorological changes are judged to warrant more frequent calibrations. 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 local sources, 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 ±5% of the reading at higher concentrations. Appendix A gives a list of criteria for valid or invalid data.

The remote sensor is accompanied by a video system to record a freeze-frame image of the license plate of each vehicle measured. The emissions information for the vehicle, as well as a time and date stamp, is also recorded on the video image. The images are stored on videotape, so that license plate information may be incorporated into the emissions database during post-processing. A device to measure the speed and acceleration of vehicles driving past the remote sensor was also used in this study. The system consists of a pair of infrared emitters and detectors (Banner Industries) which generate a pair of infrared beams passing across the road, 6 feet apart and approximately 2 feet above the surface. Vehicle speed is calculated from the time that passes between the front of the vehicle blocking the first and the second beam. To measure vehicle acceleration, a second speed is determined from the time that passes between the rear of the vehicle unblocking the first and the second beam. From these two speeds, and the time difference between the two speed measurements, acceleration is calculated, and reported in mph/s. Appendix B defines the database format used for the data set.

The purpose of this report is to describe the remote sensing measurements made in the Chicago area in the fall of 2000, under CRC contract no. E-23-4. Measurements were made on four consecutive weekdays, from Monday, September 11 to Thursday, September 14 between the hours of 8:30 am and 7:00 pm. The measurement location used in this study was the on-ramp from Algonquin Rd. to eastbound I-290 (S.H. 53) in northwest Chicago. The setup of the cones and equipment was kept as close to that of the previous years to the extent that this was possible from marking that we had make on the road. Although this highway is officially designated as an east/west thoroughfare, traffic is actually traveling in a north/south direction at Algonquin Rd. A map of the measurement location is shown in Figure 1. The on-ramp serves both eastbound and westbound traffic on Algonquin Rd., and has an uphill grade of approximately 1.5°. Appendix C gives temperature and humidity data for the 1997, 1998, 1999 and 2000 studies from Chicago O'Hare Airport, approximately 6 miles southeast of the measurement site. This is the fourth year of a study to characterize motor vehicle emissions and deterioration in the Chicago area.

RESULTS AND DISCUSSION

Following the four days of data collection in September of 2000, the videotapes were read for license plate identification. Plates that appeared to be in-state and readable were sent to the State of Illinois to have the vehicle make and model year determined. The resulting database contained 22,065 records with make and model year information and valid measurements for at least CO and CO_2. The database and all previous databases compiled for CRC E-23-4 campaigns can be found at www.feat.biochem.du.edu. Most of these records also contain valid measurements for HC and NO as well. The validity of the attempted measurements is summarized in 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 CO_2 exceeds a preset limit (See Appendix A). The greatest loss of data in this process occurs during the plate reading process, when out-of-state vehicles and vehicles with unreadable plates (obscured, missing, dealer, out of camera field of view) are omitted from the database.

Table 1: Validity summary.

	CO	HC	NO
Attempted Measurements	27,943		
Valid Measurements Percent of Attempts	26,054 93.2%	25,924 92.8%	26,045 93.2%
Submitted Plates Percent of Attempts Percent of Valid Measurements	22,818 81.7% 87.6%	22,718 81.3% 87.6%	22,797 81.6% 87.5%
Matched Plates Percent of Attempts Percent of Valid Measurements Percent of Submitted Plates	22,065 79.0% 84.7% 96.7%	21,980 78.7% 84.8% 96.8%	22,057 78.9% 84.7% 96.8%

The percent validity of the 2000 measurements is very similar to the validity seen in the previous three years, with approximately 80% of attempted measurements being valid and plate matched.

Table 2 provides an analysis of the number of vehicles that were measured repeatedly, and the number of times they were measured. Of the 22,065 records used in this fleet analysis, 10,536 (48%) were contributed by vehicles measured once, and the remaining 11,529 (52%) records were from vehicles measured at least twice. A look at the distribution of measurements for vehicles measured five or more times showed that low or negligible emitters had more normally distributed emission measurements, while higher emitters had more skewed distributions of measurement values. For example, of the 107 vehicles that had five or more valid CO measurements, three had %CO>1: 1.2, 1.8, 5.6. These three vehicles' calculated variances in their measurements were 2.8, 3.2 and 7.5, respectively, while the average variance in the measurements of the other 104 vehicles was 0.12.

Table 2. Number of measurements of repeat vehicles.

Number of Times Measured	Number of Vehicles
1	10,536
2	2,655
3	1404
4	352
5	71
6	23
7	7
>7	6

Table 3 is the data summary; included are summaries of previous remote sensing databases collected by the University of Denver at the I-290 and Algonquin Rd. site. These other measurements were conducted in September of 1997, 1998 and 1999.

Compared to the fleets measured in 1997, 1998 and 1999, the fleet measured in the current study is considerably lower emitting. In fact, there seems to be an overall gradual decrease in the average emissions of all three major pollutants during the four years of study. This decrease may arise from technological advances in the emissions control systems of the modern fleet, since the average age of the fleet has gradually increased (Year of study – Mean model year). The current year's averages may be low due to other factors discussed below. Furthermore, the percent emissions from the dirtiest 10% of the fleet appear to be increasing in the current year. This observation lends weight to the postulate that technological advancements have made the new cars cleaner, and thus a greater percentage of the emissions come from the 10% of "broken" vehicles.

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. Since we assume the cleanest vehicles to emit next to nothing, such an approximation will only err slightly towards clean because the true offset will be a value somewhat less than the average of the cleanest model year and make. However, this procedure will adjust the data so that measurements from different years can be compared. For the Chicago data sets, offsets were determined to be 60, 70, 120, 80 ppm for yearly measurements conducted between 1997 and 2000, respectively. The offset subtraction has been performed here and later in the analysis where indicated.

Table 3. Data summary.

	2000	1999	1998	1997
Mean CO (%) (g/kg of fuel)	0.26 (32.8)	0.35 (44.2)	0.39 (49.0)	0.45 (55.8)
Median CO (%)	0.05	0.09	0.15	0.14
Percent of Total CO from Dirtiest 10% of the Fleet	69.1	63.0	60.2	60.2
Mean HC (ppm)* (g/kg of fuel)*	94 (1.9)	109 (2.2)	130 (2.6)	130 (2.6)
Median HC (ppm)	100	120	170	130
Percent of Total HC from Dirtiest 10% of the Fleet	48.3	47.3	57.5	43.8
Mean NO (ppm) (g/kg of fuel)	316 (4.5)	378 (5.3)	405 (5.7)	400 (5.5)
Median NO (ppm)	79	121	140	160
Percent of Total NO from Dirtiest 10% of the Fleet	55.2	51.1	46.8	46.6
Mean Model Year	1994.9	1994.3	1993.6	1992.7
Mean Speed (mph)	24.5	25.8	24.7	25.1
Mean Acceleration (mph/s)	0.48	0.23	0.78	0.05
*Indicates values that have been HC offset adjusted as described in text.				

Figure 2 shows the distribution of CO, HC and NO emissions by percent or ppm category from the data collected in Chicago in 2000. The black bars show the percentage of the fleet in a given emissions category, and the gray bars show the percentage of the total emissions contributed by the given category. This figure illustrates the skewed nature of automobile emissions, showing that the lowest emission category is occupied by no less than 75% of the fleet (for HC) and as much as 94% of the fleet (for CO). The fact that the cleanest 94% of the fleet is responsible for only 42% 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 during the other years of the study in Chicago and is represented by the consistent high values of percent of total emissions from the dirtiest 10% of the fleet (See Table 3). As was the case in 1999, the large number of negative values seen in the lowest hydrocarbon emission category (≤200 ppm) during 1997 and 1998 was not as significant in 2000. Thus, the lowest HC category in 2000 contributes significantly to the total emissions.

The inverse relationship between vehicle emissions and model year is shown in Figure 3, for data collected during each of the four years. The HC data have been offset adjusted here. The plot of NO emissions vs. model year rises rather sharply, at least compared to the plots for CO and HC, and then appears to level out in model years prior to 1989. This "leveling out" phenomenon has been observed previously,[5,9] and it has been proposed that the tendency for older vehicles to lose compression and operate under fuel-rich conditions negates the tendency for poor maintenance and catalyst deterioration to result in continually increasing NO emissions with age.

The tendency for the emissions of the most recent model year vehicles to appear remarkably high had been seen in previous years and reported elswhere,[10] and we have suggested that this is due to a plate matching artifact. It is possible that some older vehicles were sold in the time period between data collection (in September) and plate matching by the State of Illinois (April for 1997, January for 1998, December for 1999 and December for 2000), and replaced with new vehicles bearing the same license plate. This would result in some older vehicles (with comparatively higher emissions) appearing in the database as late model vehicles. With the 2000 database, however, the newest model year does not show increased emissions. The general downward trend of emissions as a function of model year continues into the newest model year. An examination of the databases reveals that the number of measurements in the newest model year category has decreased from more than 600 in 1997 to 116 in 2000. Some fraction of these 116 measurements then represents vehicles that were purchased in the time period between measurement and plate matching. It is probable that with so few older vehicles mistakenly labeled as new ones, the incidental lack of high emitters in the category has left the average emissions of the newest model year unaltered.

As originally shown by Ashbaugh et al.,[11] vehicle emissions by model year, with each model year divided into emission quintiles, were plotted for data collected in 2000. This resulted in the plots shown in Figure 4. The bars represent the mean emissions for each quintile, and do not account for the number of vehicles in each model year. This figure illustrates that the cleanest 40% of the vehicles, regardless of model year, make an essentially negligible contribution to the total fleet emissions. The results shown here demonstrate that vehicle age alone cannot be used as an indicator of vehicle emissions, and that all vehicles of a given model year do not have the same emissions. Note particularly that the lowest 20% of the oldest MY have emissions lower than the highest 20% of the 14 years newer vehicles.

An equation for determining the instantaneous power of an on-road vehicle has been proposed by Jimenez[12], which takes the form

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

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 in each of the four years' databases. This equation, in common with all dynamometer studies, does not include any load effects arising from road curvature. The emissions data were binned according to vehicle specific power, and illustrated in Figure 5. All of the specific power bins contain at least 100 measurements. As expected, NO emissions show a positive dependence on specific power while HC emissions show a negative dependence on specific power; again, the HC offsets have been subtracted. Carbon monoxide emissions also show a slight negative dependence on specific power in this range. This dependence is less pronounced in the current year's CO measurements, however. One can also see that average CO emissions are significantly reduced from previous years' measurements across the whole VSP range. The error bars included in the plot are standard errors of the mean of the daily averages. These uncertainties were generated for these γ-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.

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

	1997 (measured)	1997 (adjusted)	1998 (measured)	1998 (adjusted)	1999 (measured)	1999 (adjusted)	2000 (measured)	2000 (adjusted)
Mean CO (%)	0.43	**0.43**	0.38	**0.42**	0.35	**0.35**	0.26	**0.26**
Mean HC (ppm)	210	**130**	237	**161**	176	**108**	151	**103**
Mean NO (ppm)	393	**393**	396	**349**	364	**355**	311	**285**

Using vehicle specific power, it is possible to eliminate the influence of driving behavior from the mean vehicle emissions. Table 4 shows the mean emissions from all vehicles in the 1997, 1998, 1999 and 2000 databases with specific powers between –5 and 20 kW/tonne. Note that these emissions do not vary considerably from the mean emissions for the entire databases, as shown in Table 2. Also shown in Table 4 are the mean emissions for the 1998, 1999 and 2000 databases, adjusted for specific power. This correction is accomplished by applying the mean vehicle emissions for each VSP bin (between –5 and 20 kW/tonne) from a certain year's measurements to the vehicle distribution, by specific power, for each bin from 1997. A sample calculation, for the specific power adjusted mean NO emissions, is shown in Appendix D. It should be noted here that VSP values for all of the years of measurement in Chicago were recalculated using the most recent VSP equation during the generation of this current report. Readers may notice slight discrepancies in the averaged values from earlier reports.

In the case of CO and NO, the decrease in average emissions with time is even more pronounced with these adjusted values. The higher HC emissions for the 1998 data are indicative of a large offset during that year. Subsequent measurements in 1999 and 2000 seem to contain smaller offsets. The adjusted values for HC include subtraction of the offset. Because all VSP data are adjusted to the 1999 vehicle frequency distribution by VSP bin, the 1997 adjusted column is the same as the measured except for the 80 ppm offset has been subtracted from the average HC measurement.

A similar correction can be applied to a fleet of specific model year vehicles to track deterioration, provided we use as a baseline only model years measured in 1997. Table 5 shows the mean emissions for all vehicles from model year 1983 to 1997, as measured in each of the four years of the study. Applying the vehicle frequency distribution by model year from 1997 to the mean emissions by model year from 1998, 1999 and 2000 yields the model year adjusted fleet emissions. A sample calculation, for the model year adjusted mean NO emissions, is shown in Appendix E. The calculation indicates that, though some of the measured decrease in fleet average emissions is due to fleet turnover, the emissions of even older model years (83-97) measured previously seem to have decreased.

Table 5. Model year adjusted fleet emissions (MY 1983-1997 only).

	1997 (measured)	1997 (adjusted)	1998 (measured)	1998 (adjusted)	1999 (measured)	1999 (adjusted)	2000 (measured)	2000 (adjusted)
Mean CO (%)	0.45	**0.45**	0.44	**0.45**	0.43	**0.49**	0.37	**0.44**
Mean HC	214	**134**	260	**145**	200	**147**	189	**151**
Mean NO	409	**409**	451	**462**	463	**491**	440	**479**

Vehicle deterioration can be illustrated by Figure 6, which shows the mean emissions of the 1984 to 1999 model year fleet as a function of vehicle age. The first point for most model years was measured in 1997, the second point in 1998, etc. The HC offset has been subtracted here as well. Vehicle age was determined by the difference between the year of measurement and the vehicle model year. Most model years show a noticeable deterioration from one year to the next for NO emissions. In the case of CO emissions, however, every model year, except 1986 and 1989, shows a slight decrease in emissions with age. The average HC measurements for each model year have also decreased between 1999 and 2000 except for model years 1986, 1989, 1990 and 1991. Though this decrease may not prove to be statistically significant for each individual model year, the set of slopes from every model year is significant.

The various analyses of the data presented up to this point suggest a decrease in emissions from the previous year even when model year adjustment is conducted, in order to remove effects of fleet turnover. Some factor has decreased emissions, especially CO, at a rate which has more than overcome deterioration. We know of two phenomena which could have caused the fleet emissions to have the observed property: the full imposition of the new I/M program and the use of reformulated gasoline in the Chicago area. The I/M program was phased in during calendar years 1999 and 2000. An I/M program, if it were effective, would produce most of the observed results. In fact, an analysis of the I/M effect conducted in the Year 3 report,[13] when a fraction of the measured vehicles had undergone I/M testing, suggested CO and HC benefits of 7.1±2.2% and 13.5±5.8%, respectively, relative to Illinois's previous idle program.

In order to estimate this possible I/M benefit after the two-year phase-in, trends in the emissions as functions of year of measurement were determined. Only data from model years 1983-1995 were used. These plots are included in Figure 7. The error bars are standard errors of the mean of daily averages. The best-fit line was generated using data from 1997 through 1999. In 1999, only those vehicles that had not undergone I/M were included. The actual 2000 measurement is also included. In the case of HC, the yearly averages were adjusted for measurement offset. This analysis suggests that there was a 16.7±8.2% CO, 9.1±8.6% HC, and 14.4±9.8% NO decrease in model year 1983-1995 vehicles measured in 2000 compared to the trend observed from three previous years.

However, the decrease in emissions is also present in the four newest model years, which are exempt from I/M testing in the Illinois I/M program. For example, in the 1997 model year vehicles (for which we have a full four year record) there were 31.7±0.1% CO and 35.1±18.0% NO decreases in the average readings in 2000 compared to the trend from measurements in 1997, 1998 and 1999. The HC decrease turns out not to be significant in this subset of the data due to a fluctuating trend. The shorter records on 1998 and 1999 MY also appear to show reversed deterioration. A decrease in emissions of even the newest model year vehicles, which do not undergo I/M, suggests that another factor than I/M must be lowering the fleet emissions. Illinois' transition to reformulated gasoline by the time of the 2000 measurements is the only other possible cause of the decreased emissions of which we are aware. Emission reductions due to reformulated gasoline has been reported previously.[14] In view of the confusion caused by two programs, both of which are designed to lower on-road emissions, both starting in the same year, all we can conclude is that the data are compatible with all of the observed deterioration reversal coming from the fuel switch, but reductions caused by I/M can not be ruled out.

Another use of the on-road remote sensing data is to predict the effectiveness with which high emitter identification for one pollutant actually identifies high emissions for another pollutant. One can look at the high CO emitters and calculate that percentage of these is also high emitting for HC, 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 measurements of one pollutant is also in the top decile for another pollutant. These data are in Table 6; included in the analysis are only those readings that have valid readings for the pollutant in the column heading. The column heading is the pollutant whose top decile is being analyzed, and the values indicate the percentage of the fleet that is high emitting for the pollutants in the column and row headings. The values where the column and row headings are the same indicate the percentage that is high emitting in the one pollutant only. The "All" row gives the percentage of the readings that is high emitting in all three pollutants.

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

Top 10% Decile	CO	HC	NO
CO	5.6%	3.8%	1.3%
HC	3.8%	5.4%	1.7%
NO	1.3%	1.7%	7.8%
All	0.7%	0.7%	0.7%

Thus, the table shows that 3.8% of the measurements is in the top decile for both HC and CO; 1.3% of the measurements is high emitting for CO and NO; 5.6% of the measurements 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 6 values to percent of emissions. Table 7 shows that identification of the 5.6% of vehicles that are high emitting for CO only would identify an overall 38.7% of total measured on-road CO. More efficiently, identification of the 3.8% high CO and HC vehicles accounts for 26.2% of the total CO, 18.3% of the total HC.

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

Top 10% Decile	CO	HC	NO
CO	38.7%	18.3%	7.2%
HC	26.2%	26.1%	9.4%
NO	9.0%	8.2%	43.1%
All	4.8%	3.4%	3.9%

In the manner described in the Phoenix, Year 2 report[15], instrument noise was measured by looking at the slope of the negative portion of the log plots. Such plots were constructed for the three pollutants. Linear regression gave best fit lines whose slopes correspond to the inverse of the Laplace factor, which describes the noise present in the measurements. This factor must be viewed in relation to the average measurement for the particular pollutant to obtain a description of noise. The Laplace factors were found to be 540 ppm CO, 110 ppm HC and 40 ppm NO. These values indicate minimal relative noise in measurements of CO and NO and a small but 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.[15]

CONCLUSIONS

The University of Denver has completed the first four years of a multi-year remote sensing study of motor vehicle emissions and deterioration in the Chicago area. A database was compiled containing 22,065 records for which the State of Illinois provided make and model year information. All of these records contained valid measurements for at least CO and CO_2, and 21,972 records contained valid measurements for HC and NO as well. The mean CO, HC and NO emissions for the fleet measured in this study were 0.26%, 94 ppm and 316 ppm, respectively. The fleet emissions observed at the site in Chicago exhibited a skewed distribution, with most of the total emissions contributed by a relatively small percentage of the vehicles. Having collected data for four consecutive years at the same time and location, it was possible to show the deterioration of a specific model year fleet from one year to the next. It was seen that more recent model year vehicles have lower emissions quite independent of age. Unique to this data set was a decrease in emissions counter to the expected and previously observed deterioration of 1983-1997 model year vehicles. The same phenomenon was seen in newer model years. The recently implemented reformulated gasoline program may be the cause of these emission reductions. Continuing studies at the same site should allow further insight to be gained as to the effects of motor vehicle deterioration on fleet emissions. Data are available at www.feat.biochem.du.edu for the four years of measurement in Chicago and for other measurement campaigns undertaken by the University of Denver.

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The successful outcome of this project would not be possible without the assistance of Mr. Joe Kuta in the Illinois Department of Transportation, Division of Highways, District 1, Regional Permits Office, Mr. Dwight Menley in the Illinois Secretary of State's Office and Mrs. Annette Bishop whose plate reading skills are phenomenal. Comments from the various reviewers of this report were also invaluable.

ACRONYMS

CRC – Coordinating Research Council
EPA – Environmental Protection Agency
FID – Flame Ionization Detector
HC – Hydrocarbons
I/M – Inspection and Maintenance
IR - Infrared
MY- Model Year
NDIR – Non-Dispersive Infrared
UV - Ultraviolet
VSP – Vehicle Specific Power

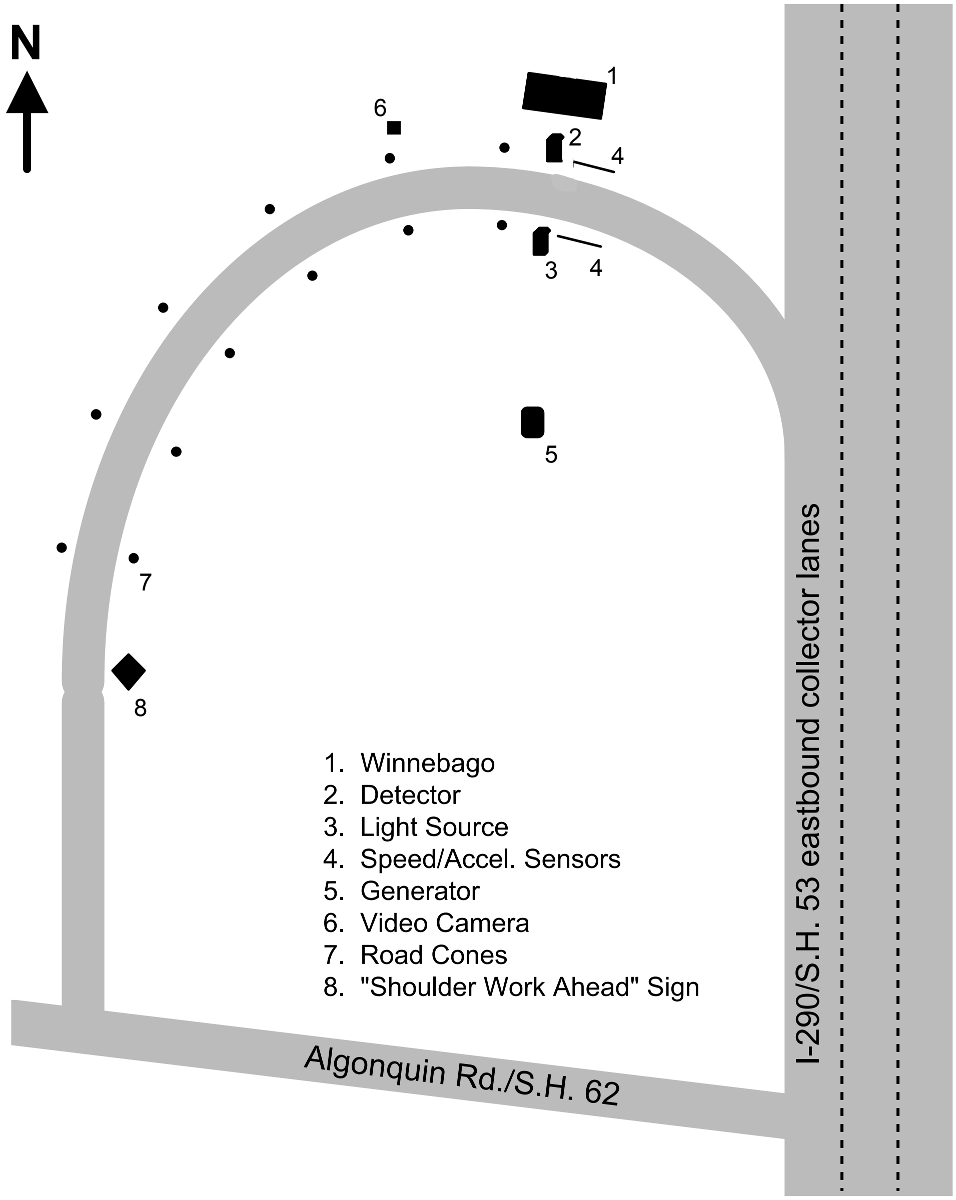

Figure 1. Area map of the on-ramp from Algonquin Road to eastbound I-290 in northwest Chicago, showing remote sensor configuration and safety equipment.

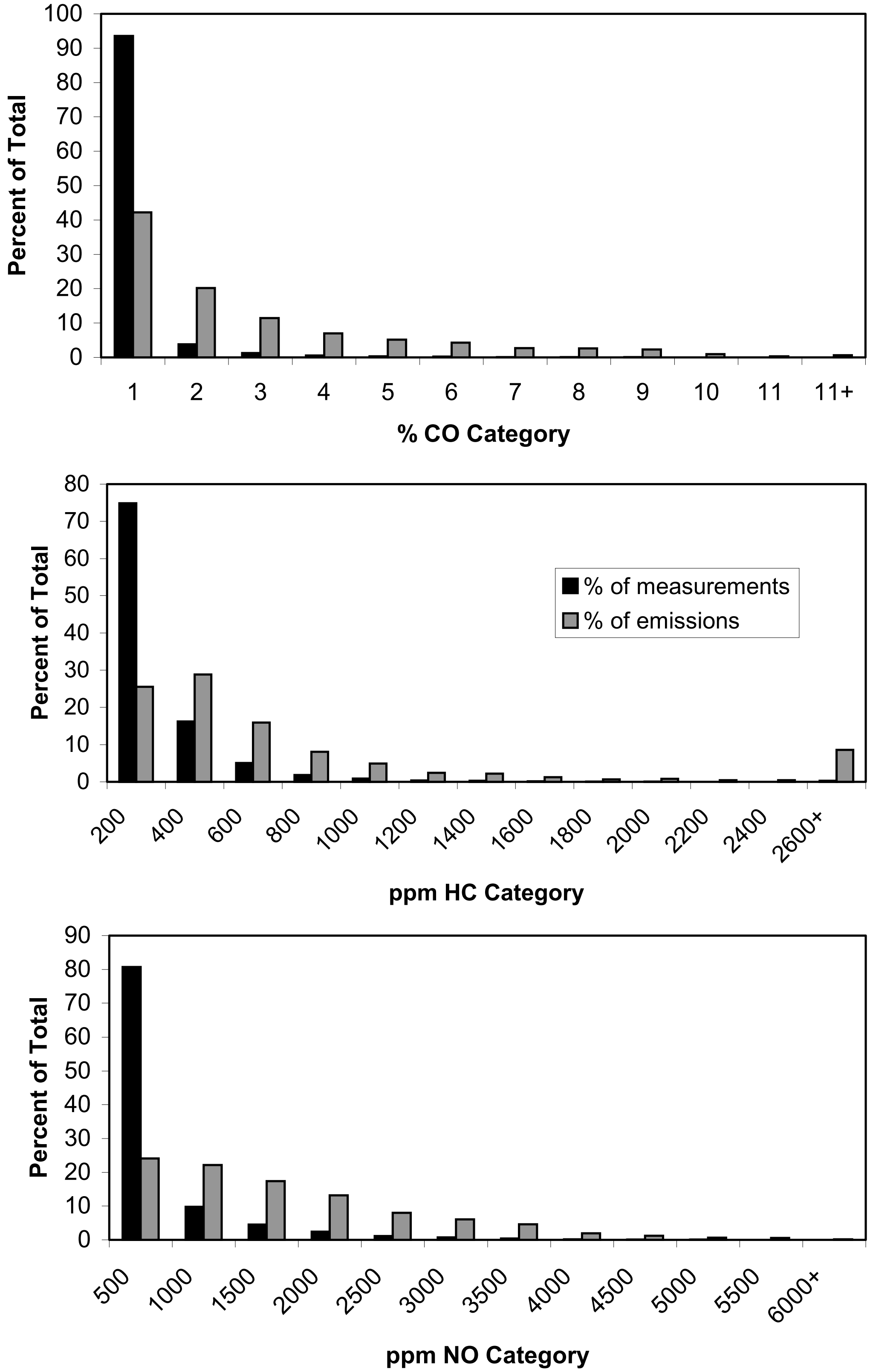

Figure 2. Emissions distribution showing the percentage of the fleet in a given emissions category (black bars) and the percentage of the total emissions contributed by the given category (gray bars).

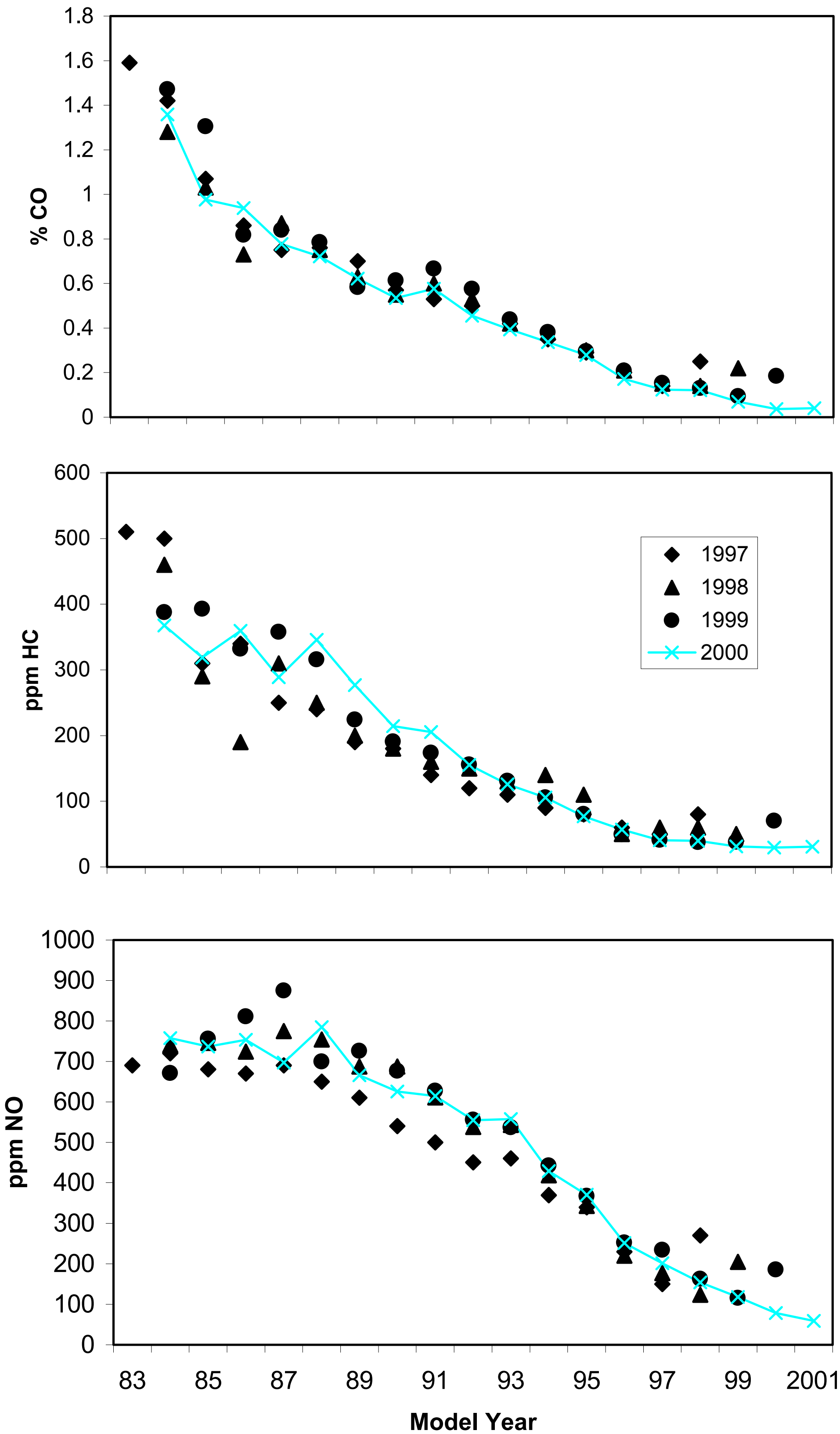

Figure 3. Mean vehicle emissions illustrated as a function of model year.

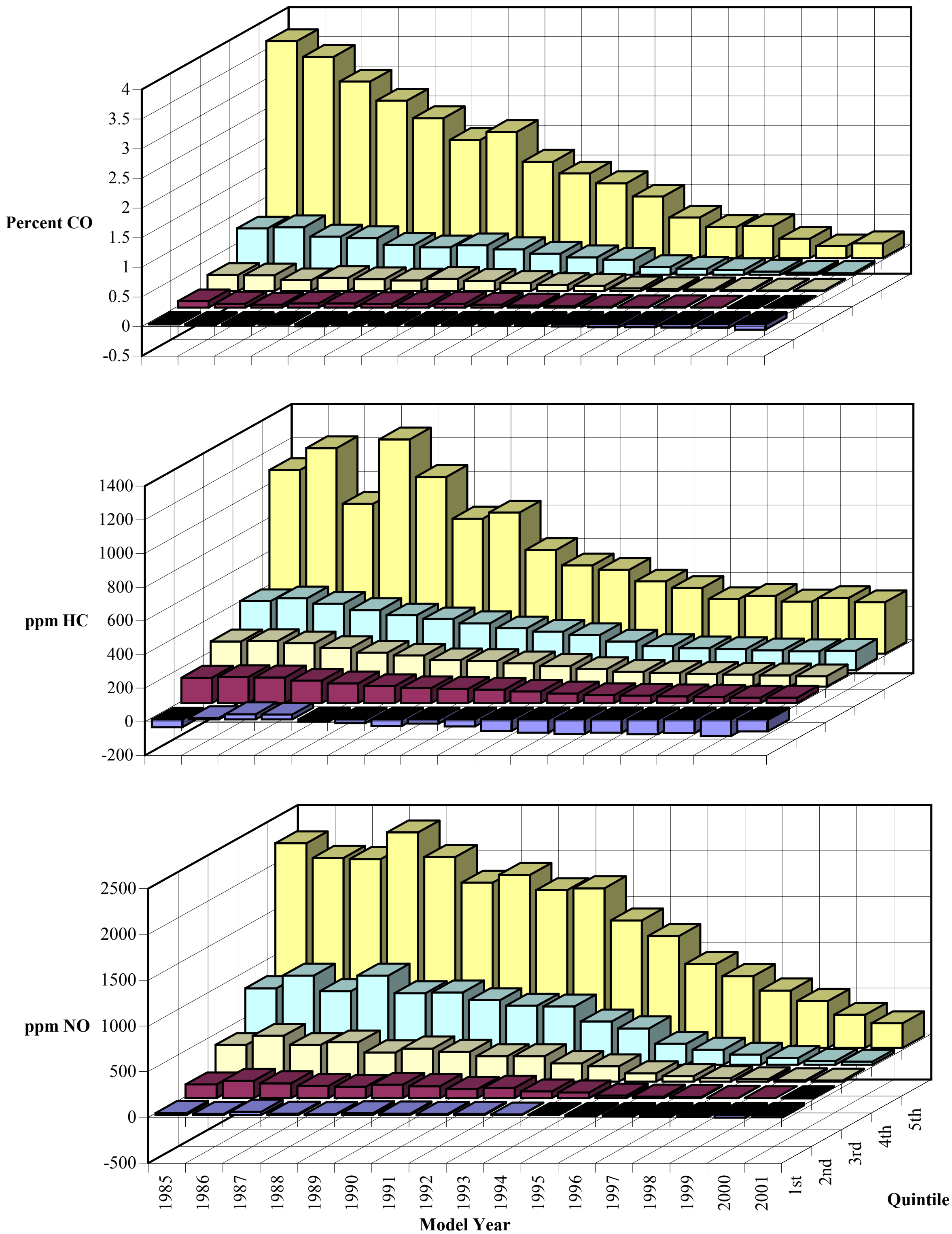

Figure 4. Vehicle emissions by model year, divided into quintiles.

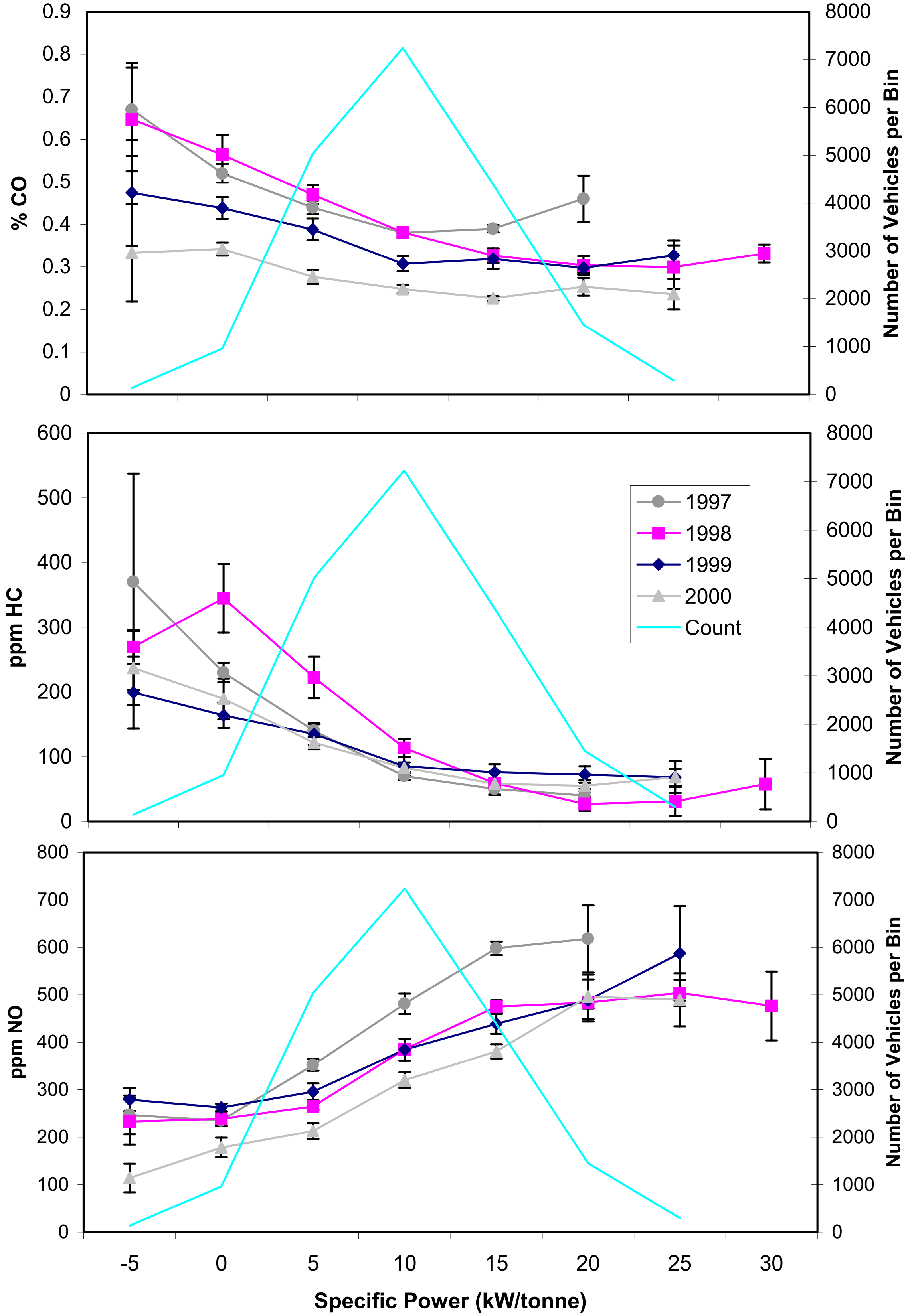

Figure 5. Vehicle emissions as a function of vehicle specific power. Error bars are standard errors of the mean from daily samples.

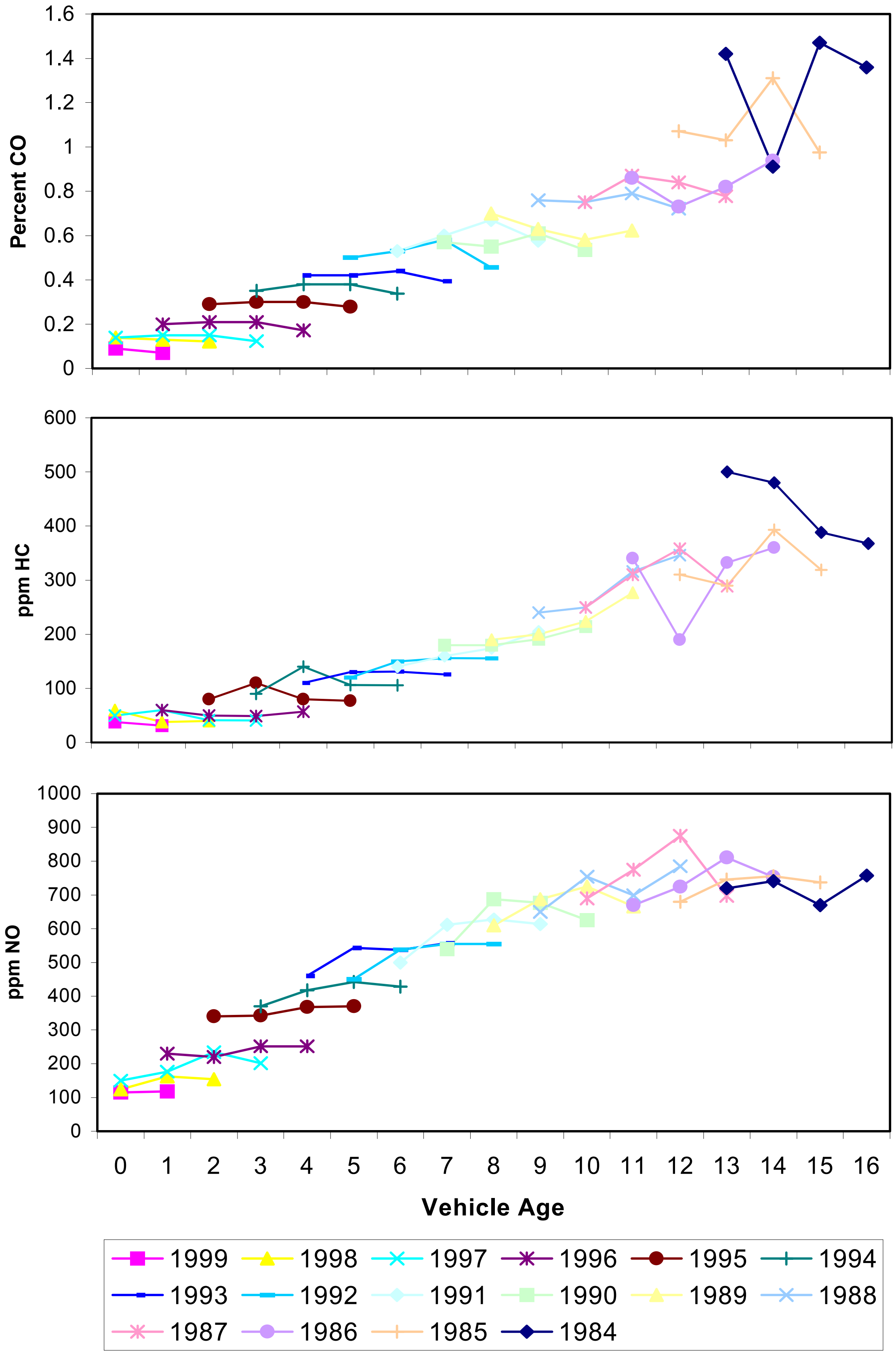

Figure 6. Mean vehicle emissions as a function of age, shown by model year.

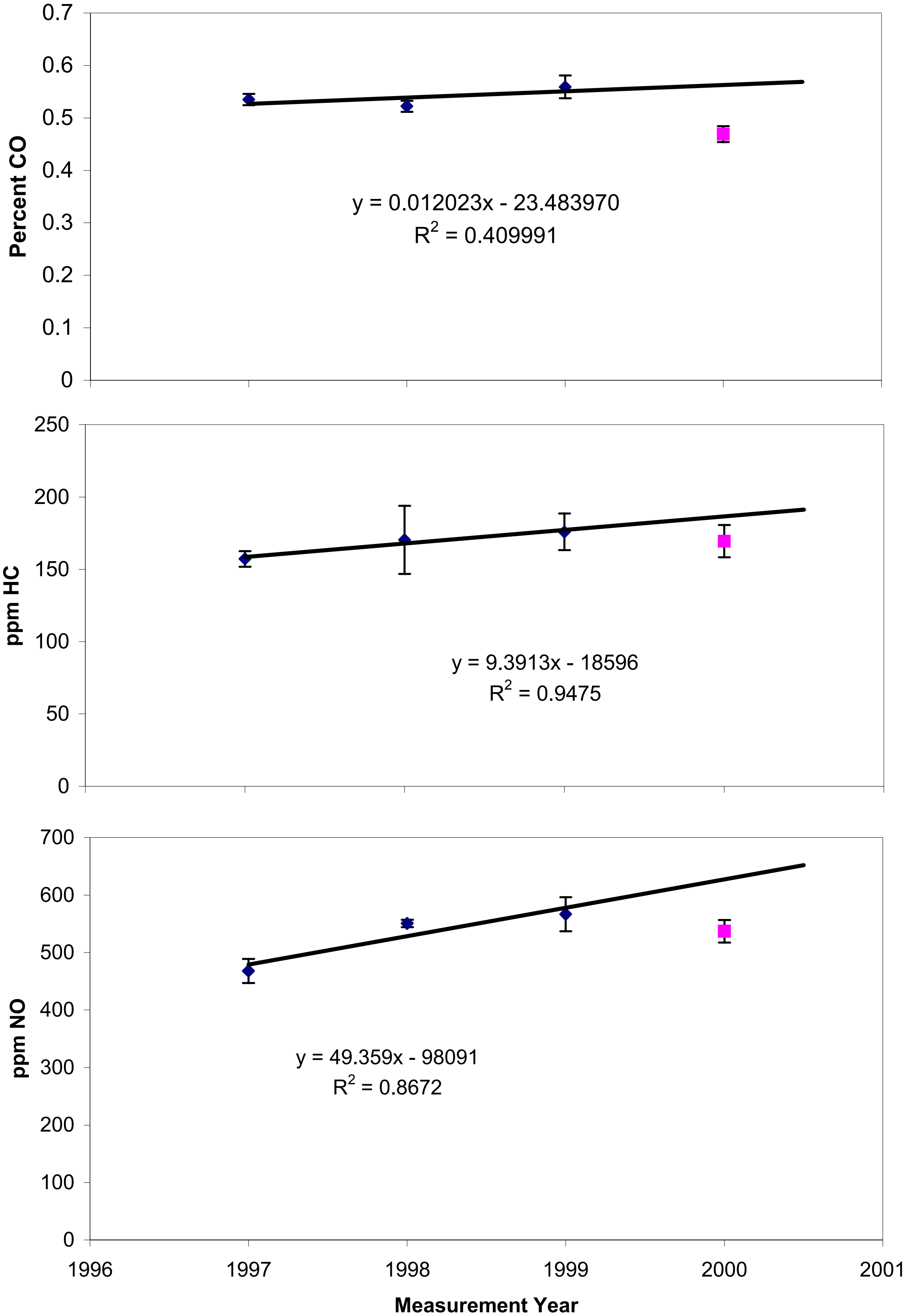

Figure 7. Trend in emissions as a function of measurement year (1997-1999). Measurements made in 2000 are also included. Data are from model year 1983-1995 vehicles only. Error bars are standard error of mean of daily averages.

LITERATURE CITED

1. *National Air Quality and Emissions Trends, 1998,* United States Environmental Protection Agency, Research Triangle Park, NC, 2000; EPA-454/R-00-003, pp. 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. Technol.* **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.

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.; AWMA: Pittsburg, PA, 1992; Vol. II, pp. 720-739.

9. Zhang, Y.; Stedman, D.H.; Bishop, G.A.; Guenther, P.L.; Beaton, S.P.; Peterson, J.E. *Environ. Sci. Technol.* **1993**, *27*, 1885.

10. Robert D. Stephens, *et al.* "The Michigan Remote Sensing Study: A Preliminary Review of Repair Induced Emissions Reductions", General Motors Corporation, 1993.

11. Ashbaugh, L.L; Croes, B.E.; Fujita, E.M.; Lawson, D.R. Presented at 13th North American Motor Vehicle Emissions Control Conference, 1990.

12. 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*, CA, 1999.

13. Pokharel, S.S.; Bishop, G.A.; Stedman, D.H. *On-Road Remote Sensing of Automobile Emissions in the Chicago Area: Year 3*, Final report to the Coordinating Research Council, contract E-23-4, 2000.

14. Kirchstetter, T.W.; Singer, B.C.; Harley, R.A; Kendall, G.R.; Traverse, M. *Environ. Sci. Technol.* **1999**, *33*, 318.

15. 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) beam block and unblock and then block again 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 database.

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

Invalid :

1) Insufficient plume to rear of vehicle relative to cleanest air observed in front or in the rear; at least five, 10ms averages >0.25% CO_2 in 8 cm path length. Often HD diesel trucks, bicycles.
2) too much error on CO/CO_2 slope, equivalent to $\pm$20% for %CO. >1.0, 0.2%CO for %CO<1.0.
3) reported %CO , <-1% or >21%. All gases invalid in these cases.
4) too much error on HC/CO_2 slope, equivalent to $\pm$20% for HC >2500ppm propane, 500ppm propane for HC <2500ppm.
5) reported HC <-1000ppm propane or >40,000ppm. HC "invalid".
6) too much error on NO/CO_2 slope, equivalent to $\pm$20% for NO>1500ppm, 300ppm for NO<1500ppm.
7) reported NO<-700ppm or >7000ppm. NO "invalid".

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

APPENDIX B: Explanation of the ill_00.dbf database.

The ill_00.dbf is a Microsoft Foxpro database file, and can be opened by any version of MS Foxpro, regardless of platform. The following is an explanation of the data fields found in this database:

License	Illinois 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; indicates the strength of the observed plume.
Speed_flag	Indicates a valid speed measurement by a “V”, an invalid by an “X”, and slow speed (excluded from the data analysis) by an “S”.
Speed	Measured speed of the vehicle, in mph.
Accel	Measured acceleration of the vehicle, in mph/s.
Ref_factor	Reference detector voltage. Used along with “CO2_factor” to observe calibration shifts.
CO2_factor	CO_2 detector voltage. Used along with “Ref_factor” to observe calibration shifts.
Lic_type	Value of 0 or 1. Indicates license plate type.
Exp_month	Indicates the month the current registration expires.

Exp_year	Indicates the year the current registration expires.
Address_2	Indicates the city, state, and zip code of the registrant's address.
Year	Model year of the vehicle.
Make	Manufacturer of the vehicle.
Body_style	Type of vehicle.
Vin	Vehicle identification number.
Owner_code	Unknown.
Make_abrv	Abbreviated manufacturer.

APPENDIX C: Temperature and Humidity Data

	Date (1997)									
	Sept. 15		Sept. 16		Sept. 17		Sept. 18		Sept. 19	
Hour	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0700	64	100	68	87	68	81	64	78	71	84
0800	69	78	71	84	69	70	71	68	-	-
0900	73	68	75	73	71	61	75	57	77	76
1000	75	68	78	71	75	46	77	46	78	73
1100	78	61	80	66	77	39	78	44	80	73
1200	80	57	84	60	78	38	82	36	82	69
1300	80	57	82	62	80	32	82	36	80	73
1400	80	57	84	60	80	29	82	36	77	76
1500	80	62	84	58	80	29	82	32	73	87
1600	78	66	82	58	80	27	80	32	71	93
1700	75	73	82	58	78	32	78	38	71	100
1800	73	78	80	68	78	38	77	39	71	93

	Date (1998)							
	Sept. 21		Sept. 22		Sept. 23		Sept. 24	
Hour	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0700	57	66	57	80	51	68	53	89
0800	59	62	62	72	55	54	55	83
0900	60	59	62	72	59	51	57	77
1000	64	51	64	67	60	49	59	72
1100	64	55	66	56	62	42	60	77
1200	64	55	62	67	64	39	64	72
1300	66	48	62	67	64	39	64	72
1400	64	60	64	60	64	36	66	67
1500	64	62	64	51	66	34	64	72
1600	64	62	62	60	66	36	64	72
1700	62	67	62	55	62	51	64	78
1800	62	67	59	53	55	61	62	83

	Date (1999)							
	Sept. 20		Sept. 21		Sept. 22		Sept. 23	
Hour	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0700	54	87	48	89	46	80	54	65
0800	55	80	49	80	54	56	58	56
0900	57	75	53	74	59	43	62	51
1000	60	62	57	67	63	37	70	42
1100	62	56	57	64	66	34	74	36
1200	62	52	59	58	66	33	77	31
1300	60	53	60	58	71	33	78	31
1400	60	50	59	56	72	32	79	31
1500	63	43	60	53	72	33	80	31
1600	62	43	59	58	72	33	78	36
1700	59	51	57	62	71	35	77	37
1800	58	60	55	69	67	40	75	40

	Date (2000)							
	Sept. 11		Sept. 12		Sept. 13		Sept. 14	
Hour	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0800	76	85	63	76	62	60	64	96
0900	79	79	65	70	66	50	63	93
1000	82	71	67	59	69	47	60	96
1100	84	66	68	53	71	44	65	81
1200	87	61	69	45	74	41	68	63
1300	77	73	71	41	76	39	70	53
1400	74	78	71	47	77	36	73	38
1500	66	95	70	46	78	36	72	38
1600	67	95	70	47	79	34	72	44
1700	68	89	68	47	77	36	71	42
1800	69	84	66	49	73	48	67	47
1900	69	87	64	52	64	70	64	52

APPENDIX D: Calculation of Vehicle Specific Power Adjusted Vehicle Emissions

1997 (Measured)	VSP Bin	Mean NO (ppm)	No. of Measurements	Total Emissions
	-5	236	225	53200
	0	224	1609	360090
	5	307	4985	1531000
	10	431	6146	2648020
	15	548	2624	1438060
	20	590	456	269180
			16045	6299550
			Mean NO (ppm)	**393**

1998 (Measured)	VSP Bin	Mean NO (ppm)	No. of Measurements	Total Emissions
	-5	233	137	31951
	0	239	784	187394
	5	265	3613	956613
	10	385	6685	2576433
	15	475	6012	2856195
	20	483	2392	1156320
			19623	7764906
			Mean NO (ppm)	**396**

1998 (Adjusted)	VSP Bin	'98 Mean NO (ppm)	'97 No. of Meas.	Total Emissions
	-5	233	225	52474
	0	239	1609	384588
	5	265	4985	1319877
	10	385	6146	2368700
	15	475	2624	1246616
	20	483	456	220436
			16045	5592691
			Mean NO (ppm)	**349**

APPENDIX E: Calculation of Model Year Adjusted Fleet Emissions

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**