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Chicago Year 7

On-Road Remote Sensing of Automobile Emissions in the Chicago Area: Year 7, September 2006

Final Report

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On-Road Remote Sensing of Automobile Emissions in the Chicago Area: Year 7, September 2006

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EXECUTIVE SUMMARY

The University of Denver has completed the nine years of a multi-year remote sensing study in the Chicago area, with measurements made in September of 1997 through 2000, 2002, 2004 and 2006. 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 seventh campaign of this study involved fieldwork on September 12 - 15, 2006, conducted at the on-ramp from Algonquin Rd. to eastbound I-290 in northwest Chicago. For the 2006 measurements, a database was compiled containing 22,200 records for which the State of Illinois provided makes and model year information. All of these records contain valid measurements for at least CO and CO_2. A total of 22,149 records contain valid measurements of CO, HC and NO. 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 seventh year of this study were 0.13% (16.1 g/kg), 58 ppm (when a 10ppm offset is removed, 2.2 g/kg) and 125 ppm (1.8 g/kg) respectively. Compared to the means measured in 1997 of 0.45% (55.8 g/kg), 130 ppm (when a 80ppm offset is removed, 5.3 g/kg) and 400 ppm (5.5 g/kg) these are overall reductions of 71% for CO, 55% for HC and 69% for NO. It is also notable that these reductions have occurred while the fleet has aged more than half a model year during this time. Some of the larger than normal drop in NO emissions this year may related to the cool and damp weather we had during the measurements this year (see Appendix C).

The fleet emissions observed at the site in Chicago exhibited a skewed distribution, with most of the total emissions contributed by a small percentage of the measurements. The skewness of the measurement distribution has markedly increased since 1997 when half of the emissions for CO, HC and NO were from 6.7%, 13.2% and 11.2% of the measurements. In 2006 half of the emissions for CO, HC and NO were from 3.2%, 2.6% and 4.6% of the measurements. This is a result of adding progressively lower emitting vehicles with each model year since 1997 and those vehicles maintaining those low emissions longer than prior models. Fleet emission levels for all three species continue to decline each year and there is emerging evidence that emission levels are better controlled during accelerations and decelerations as well. The NO emissions continue to show a steady decline at all VSP loads.

Having collected seven data sets over a nine year period at the same time and location, it is possible to show the "deterioration" of specific model year fleets from one year to the next. When we restrict the fleet to only those model years observed during the first measurements in 1997 the 1983-1997 model year vehicles have had rather flat emissions with age, counter to the traditionally expected view of emissions deterioration. Another way of phrasing this is that the

fleet fraction of gross emitters first seen in 1997 has remained the same for that model year grouping even though that original fleet has aged nine years and the remainder of that original fleet numbers on 4,238. It is unlikely that I/M or fuel programs are the reason for this observation. Continuing studies at the same site and at non I/M, non special fuels sites should allow further insight to be gained as to the extent that I/M programs and special fuels contribute to reducing motor vehicle fleet emissions deterioration compared with fleet turnover.

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 2002, on-road vehicles were estimated to be the single largest source for the major atmospheric pollutants, contributing 82% of the CO, 45% of the VOCs, and 56% 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 degree of effectiveness of these measures is still uncertain. 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 directly measures 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.

$$\text{gm CO/gallon} = 5506 \bullet \%CO/(15 + 0.285 \bullet \%CO + 2.87 \bullet \%HC)$$
$$\text{gm HC/gallon} = 8644 \bullet \%HC/(15 + 0.285 \bullet \%CO + 2.87 \bullet \%HC)$$
$$\text{gm NO/gallon} = 5900 \bullet \%NO/(15 + 0.285 \bullet \%CO + 2.87 \bullet \%HC)$$

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 grams pollutant per kilogram (g/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 (see 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 reported 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, six feet apart and approximately two 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 2006, under CRC Contract No. E-23-4. Measurements were made on four consecutive weekdays, from Tuesday, September 12, to Friday, September 15, between the hours of 9:00 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 equipment was installed on the ramp similarly to the remote sensing measurement studies conducted in the previous years utilizing paint markings made on the road. Although I-290 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 and a photograph of the site in Figure 2. The on-ramp serves both eastbound and westbound traffic on Algonquin Rd. via a traffic light controlled intersection. Appendix C gives temperature and humidity data for the 1997, 1998, 1999, 2000, 2002, 2004 and 2006 studies from Chicago O'Hare International Airport, located approximately six miles southeast of the measurement site. This is the seventh campaign in a nine year 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 2006, 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 22,200 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

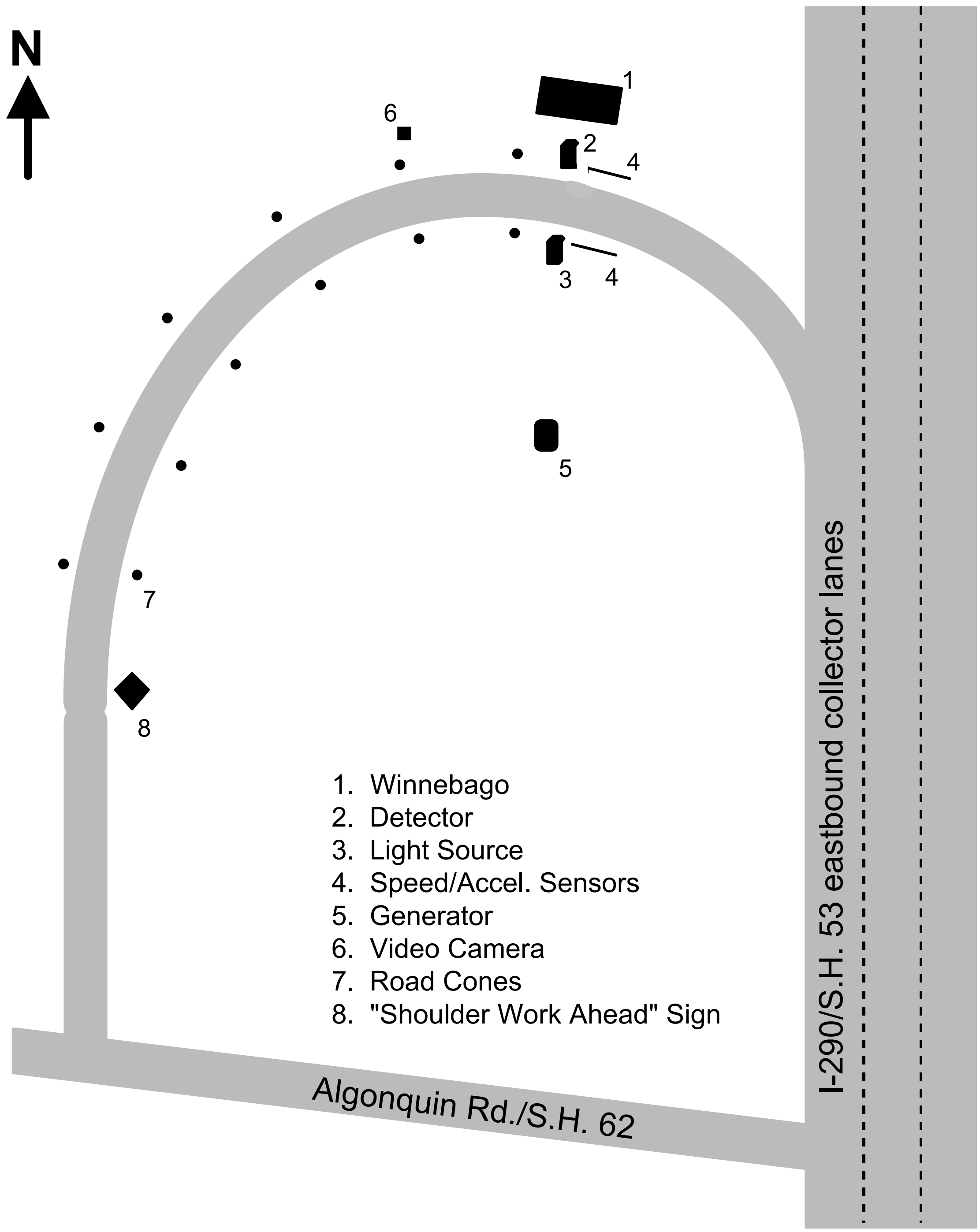

Figure 1. Area map of the on-ramp from Algonquin Road to eastbound I-290 in northwest Chicago, showing remote sensor configuration and safety equipment.

Figure 2. A photograph looking east at the Algonquin Rd. monitoring site and remote sensing setup.

Table 1. Validity Summary.

	CO	HC	NO
Attempted Measurements	28,057		
Valid Measurements Percent of Attempts	25,906 92.3%	25,838 92.1%	25,897 92.3%
Submitted Plates Percent of Attempts Percent of Valid Measurements	22,929 81.7% 88.5%	22,885 81.6% 88.6%	22,920 81.7% 88.5%
Matched Plates Percent of Attempts Percent of Valid Measurements Percent of Submitted Plates	22,200 79.1% 85.7% 96.8%	22,158 79.0% 85.8% 96.8%	22,191 79.1% 85.7% 96.8%

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 2 provides an analysis of the number of vehicles that were measured repeatedly, and the number of times they were measured. Of the 22,200 records used in this analysis, 10,572 (48%) were contributed by vehicles measured once, and the remaining 11,628 (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 70 vehicles that had five or more valid CO measurements only two had mean %CO>1 (1.4 and 1.5% respectively). These two vehicles' calculated variances in their measurements were 0.6 and 11.5, while the average variance in the measurements of the other 68 vehicles was 0.06. This observation is expected in view of the known large variability in the emissions of high emitting vehicles regardless of the emission testing method.[9]

Table 2. Number of measurements of repeat vehicles.

Number of Times Measured	Number of Vehicles	Percent of Measurements
1	10,572	47.6%
2	2,306	20.8%
3	1,309	17.7%
4	674	12.1%
5	45	1.0%
6	18	0.5%
7	4	0.1%
>7	3	0.2%

Table 3 is the data summary; included are summaries of all 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, 1999, 2000, 2002 and 2004.

Mean fleet emissions continue to decrease at the Algonquin Rd. site and the change in mean model year lagged the amount of elapsed time. As noted in previous years, the percentage of emissions from the dirtiest 10% of the measurements continues to increase, which is consistent with the observation that newer vehicles remain lower emitting longer than previous models. Afternoon traffic levels in 2006 were similar to the higher volumes observed in 1997 - 2000 and 2004. These higher traffic volumes increase the number of observed accelerations brought about by congestion on the ramp during the afternoon.

Table 3. Data summary.

Study Year	1997	1998	1999	2000	2002	2004	2006
Mean CO (%) (g/kg of fuel)	0.45 (55.8)	0.39 (49.0)	0.35 (44.2)	0.26 (32.8)	0.23 (28.9)	0.17 (21.5)	0.13 (16.1)
Median CO (%)	0.14	0.15	0.09	0.05	0.07	0.04	0.02
Percent of Total CO from Dirtiest 10% of the Fleet	60.2%	60.2%	63.0%	69.1%	68.0%	70.1%	77.7%
Mean HC (ppm)* (g/kg of fuel)* Offset (ppm)	130 (5.3) 80	130 (5.3) 120	109 (4.5) 70	94 (3.9) 60	80 (3.2) 10	72 (2.8) 20	58 (2.2) 10
Median HC (ppm)*	50	50	50	40	40	30	30
Percent of Total HC from Dirtiest 10% of the Fleet	43.8%	57.5%	47.3%	48.3%	65.6%	87.6%	96.0%
Mean NO (ppm) (g/kg of fuel)	400 (5.5)	405 (5.7)	378 (5.3)	316 (4.5)	262 (3.7)	236 (3.3)	125 (1.8)
Median NO (ppm)	160	140	121	79	52	39	14
Percent of Total NO from Dirtiest 10% of the Fleet	46.6%	46.8%	51.1%	55.2%	60.0%	63.9%	73.5%
Mean Model Year	1992.7	1993.6	1994.3	1994.9	1997.4	1999.2	2001.0
Mean Speed (mph)	25.1	24.7	25.8	24.5	24.2	24.3	23.9
Mean Acceleration (mph/s)	0.1	0.8	0.2	0.5	-0.4	0.4	0.4
Mean VSP (kw/tonne) Slope (degrees)	5.3 1.5°	9.3 1.5°	6.0 1.5°	7.9 1.5°	-6.9 1.0°	6.0 1.0°	5.9 1.0°
*Indicates values that have been HC offset corrected as described in text.							

The average HC values here have been adjusted 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. Calculation of the offset is accomplished by computing the mode and means of the newest model year vehicles, and assuming that these vehicles emit negligible levels of hydrocarbons, using the lowest of either of these values as the offset. The offset adjustment subtracts this value from all of the hydrocarbon data. Since we assume the cleanest vehicles to emit little hydrocarbons, 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. This adjustment facilitates comparisons with the other E-23 sites and or different collection years for the same site. The offset correction has been performed here and later in other analyses where indicated.

Figure 3 shows the distribution of CO, HC and NO emissions by percent category from the data collected in Chicago in 2006. The black bars show the percentage of the fleet in a given emission category, and the shaded bars show the percentage of the total emissions contributed in that

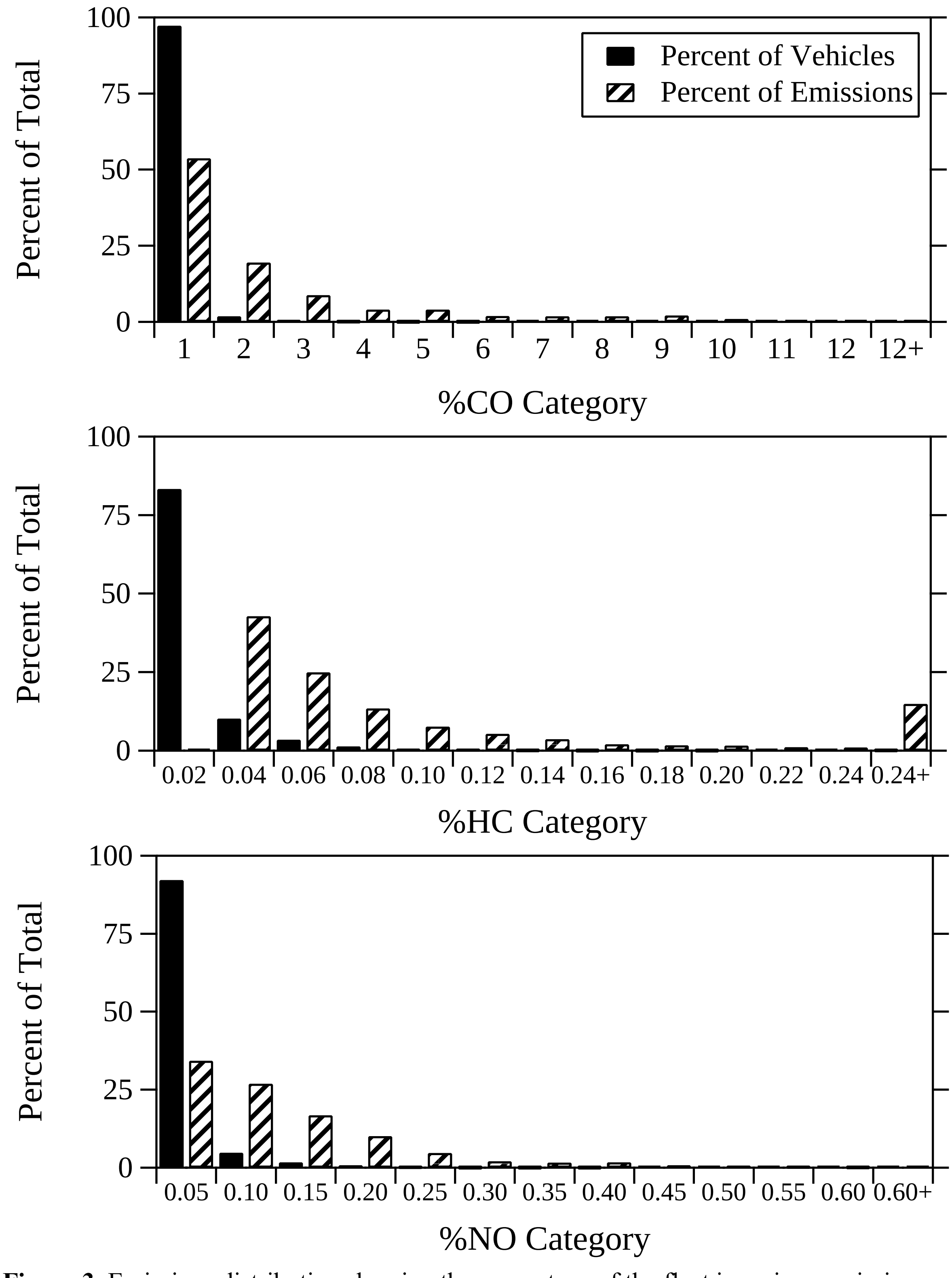

Figure 3. Emissions distribution showing the percentage of the fleet in a given emissions category (black bars) and the percentage of the total emissions contributed by the given category (shaded bars).

category. This figure illustrates the skewed nature of automobile emissions, showing that the lowest emission category is occupied by no less than 83% of the measurements (for HC) and as much as 97% of the measurements (for CO). The fact that the cleanest 97% of the measurements is responsible for only 54% 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).

The inverse relationship between vehicle emissions and model year is shown in Figure 4, for data collected during each of the seven campaigns. The HC data have been offset adjusted here. The NO emissions are now becoming more like the CO and HC plots where the newest model year vehicle show little or no emissions deterioration indicating that the reduction capabilities of modern catalyst are lasting longer. The NO emissions vs. model year now take between thirteen and fourteen model years before they level out. This "leveling out" phenomenon has been observed previously,[5,10] 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.

There are small upward spikes in HC and NO emissions for the 2007 model year vehicles in this data set but not for CO. In past data sets this increase in emissions by the newest vehicles has been suggested to be due to a plate-matching artifact. A second observation is that the downward emissions trend with model year appears to be leveling out for all three species, albeit at very low emission levels. This again could be the result of limitations in emissions control systems and/or we are running into the noise limits of the detector and its ability to measure a true zero. The NO emissions measured this year are dramatically lower than previous years. Some of this reduction may be attributable to the cool and damp weather that we experienced this year (see Appendix C).

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 2006. This resulted in the plots shown in Figures 5 - 7. The bars in the top graphs represent the mean emissions for each quintile. The middle graphs give the fraction of the fleet for each model year. The bottom graphs are a product of the first two graphs and display the fraction of the total emissions by quintiles and model year. The bottom graphs illustrates that while older vehicles generally have higher mean emissions, their lack of numbers mean they are less important in the overall air quality picture. The bottom graphs also illustrate that the cleanest 60% of the measurements, regardless of model year, make an essentially negligible contribution to the total emissions. The large accumulations of negative emissions in the first two quintiles are the result of ever decreasing emission levels. Our instrument is designed such that when measuring a true zero emission plume, half of the readings will be negative and half will be positive. As the lowest emitting segments of the fleets continue to dive toward zero emissions, the negative emission readings will continue to grow toward half of the measurements. For HC, the newest model years are nearly at that stage now.

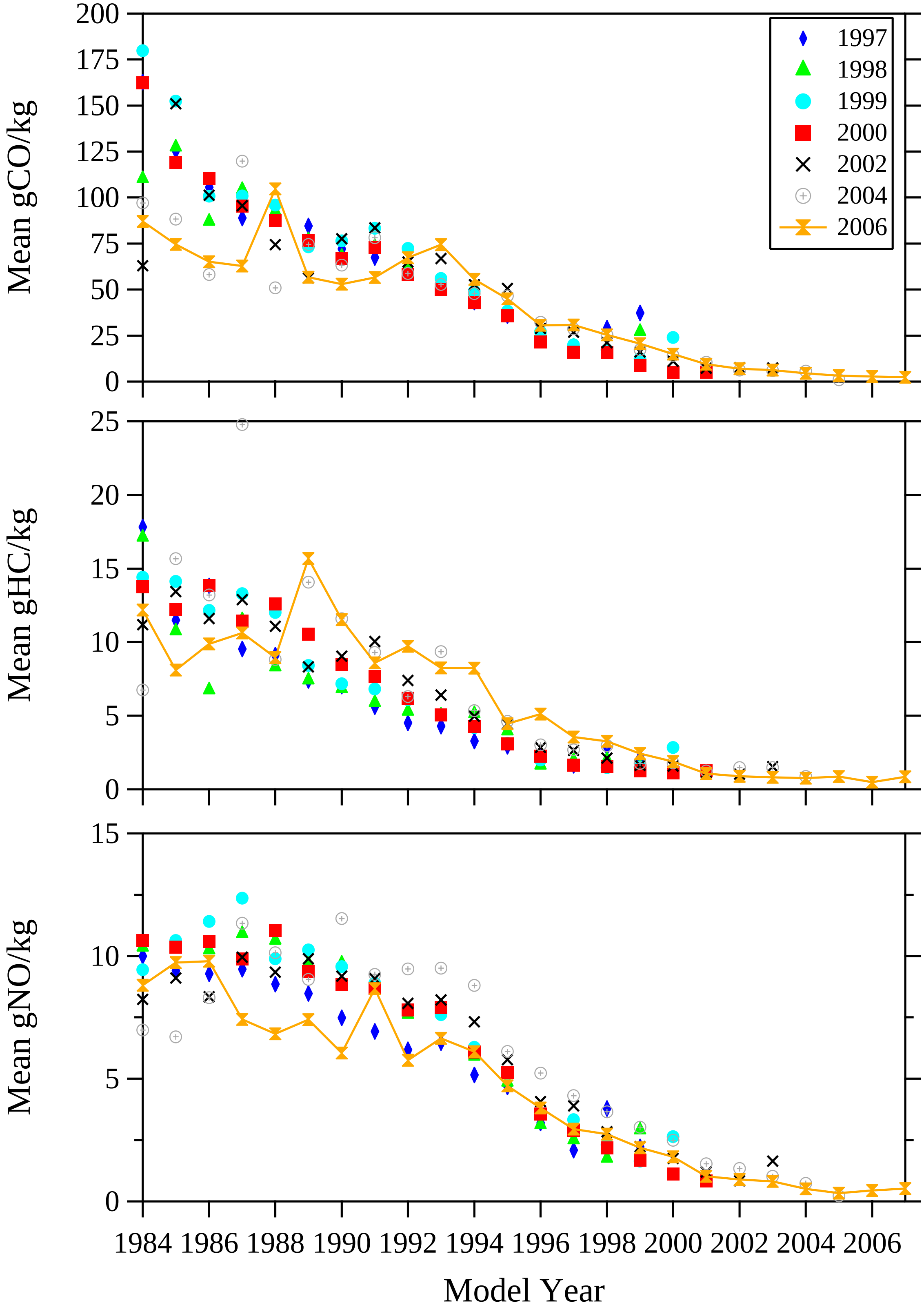

Figure 4. Mean vehicle emissions illustrated as a function of model year. HC data have been offset adjusted as described in the text.

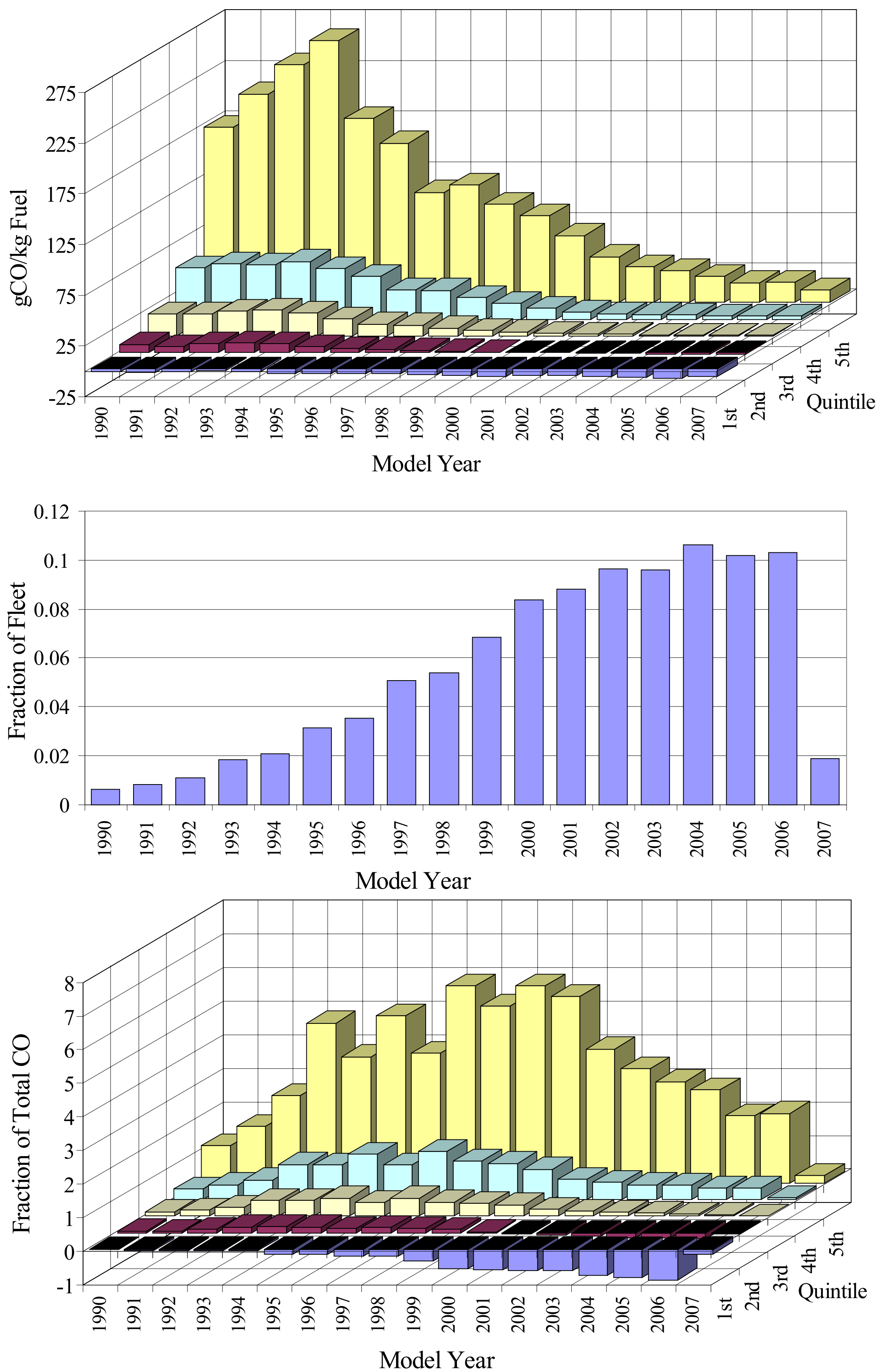

Figure 5. 2006 CO emissions by model year and quintile (top), fleet distribution (middle) and their product showing the total fractional CO emissions by model year and quintile (bottom).

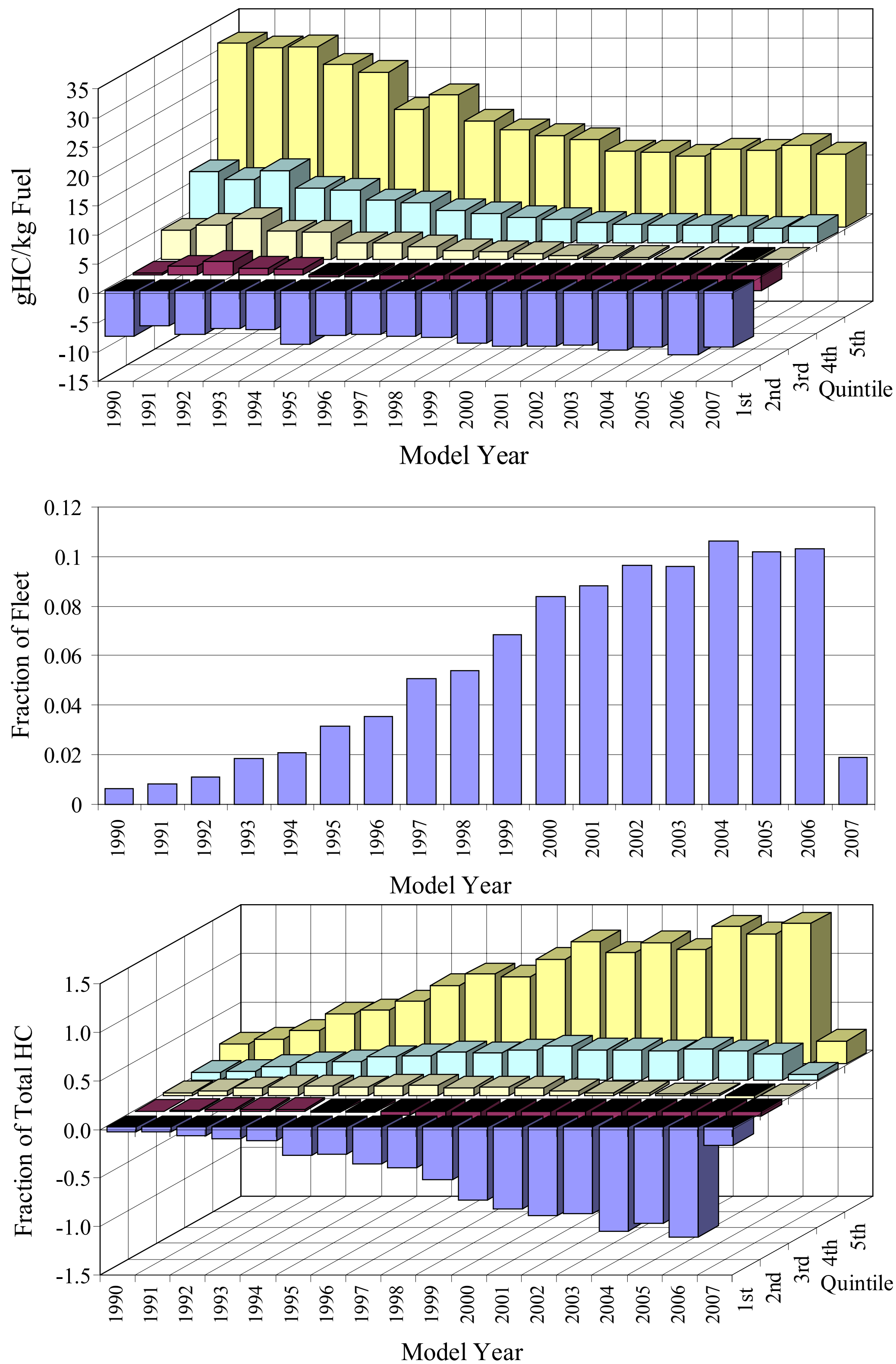

Figure 6. 2006 HC emissions by model year and quintile (top), fleet distribution (middle) and their product showing the total fractional HC emissions by model year and quintile (bottom).

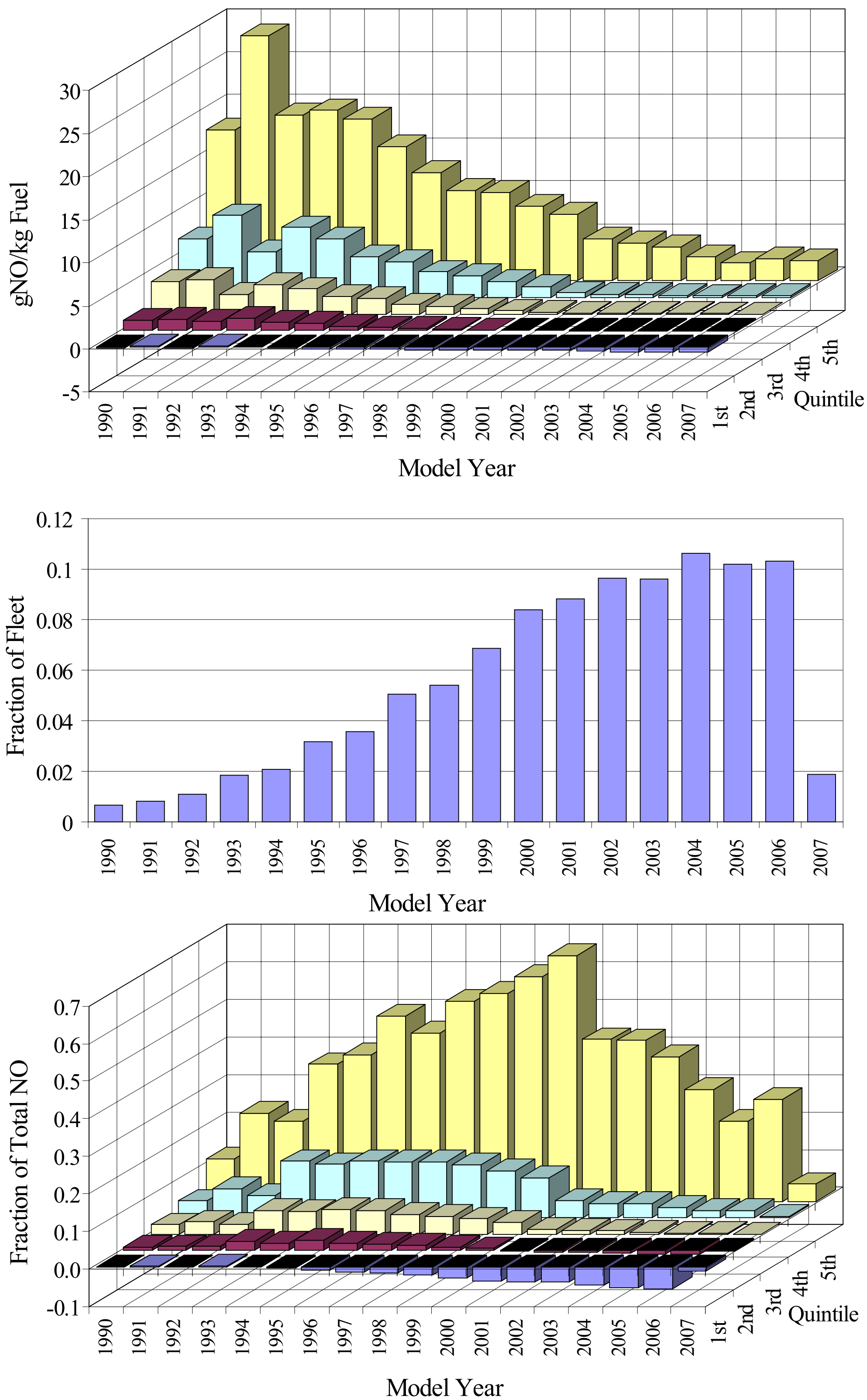

Figure 7. 2006 NO emissions by model year and quintile (top), fleet distribution (middle) and their product showing the total fractional NO emissions by model year and quintile (bottom).

Figures 5 - 7 can also be used to get a picture of federal compliance standards. The on-road data are measured as mass emissions per kg of fuel. It is not possible to determine mass emissions per mile for each vehicle because the instantaneous gasoline consumption (kg/mile) is not known. An approximate comparison with the fleet average emissions shown in Figures 5 - 7 can, however, be carried out. To make this comparison, we assume a fuel density of 0.75 kg/L and an average gas mileage for all model years of 23mpg. The Tier 1, 100,000 mile standards for CO, HC, and NO are 4.2, 0.31, and 0.6 gm/mi, respectively. With the above assumptions, these correspond to 34, 2.5, and 4.9 gm/kg, respectively. Inspection of the top graphs in Figures 5 - 7 shows that significant fractions, especially of the newer vehicles, are measured with on-road emissions well below these standards. Also note that the means in Table 3 are also well below these standards, although the fleet average age is only approximately 5 years.

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

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

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. Derived from dynamometer studies, and necessarily an approximation, the first term represents the work required to climb the gradient, the second term is the $f = ma$ work to accelerate the vehicle, the third is an estimated friction term, and the fourth term represents aerodynamic resistance. Using this equation, vehicle specific power was calculated for all measurements in each of the seven year's 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 8. All of the specific power bins contain at least 100 measurements and the HC data have been offset adjusted

As expected, NO emissions show a positive dependence on vehicle specific power and while the data are similar to the previous years, there is a noticeable downward trend in all three emissions. All three species emissions are lower and in general are showing less dependence on specific power than previous years. The error bars included in the plot are standard errors of the mean calculated from 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 an independent measurement of the emissions at that VSP. Normal statistics were then applied to these daily averages.

Using VSP, it is possible to reduce the influence of driving behavior from the mean vehicle emissions. Table 4 shows the mean emissions from all vehicles in the 1997, 1998, 1999, 2000, 2002, 2004 and 2006 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 3. Also shown in Table 4 are the mean emissions for the 1998, 1999, 2000, 2002, 2004 and 2006 databases, adjusted for vehicle specific power to match the 1997 VSP distribution.

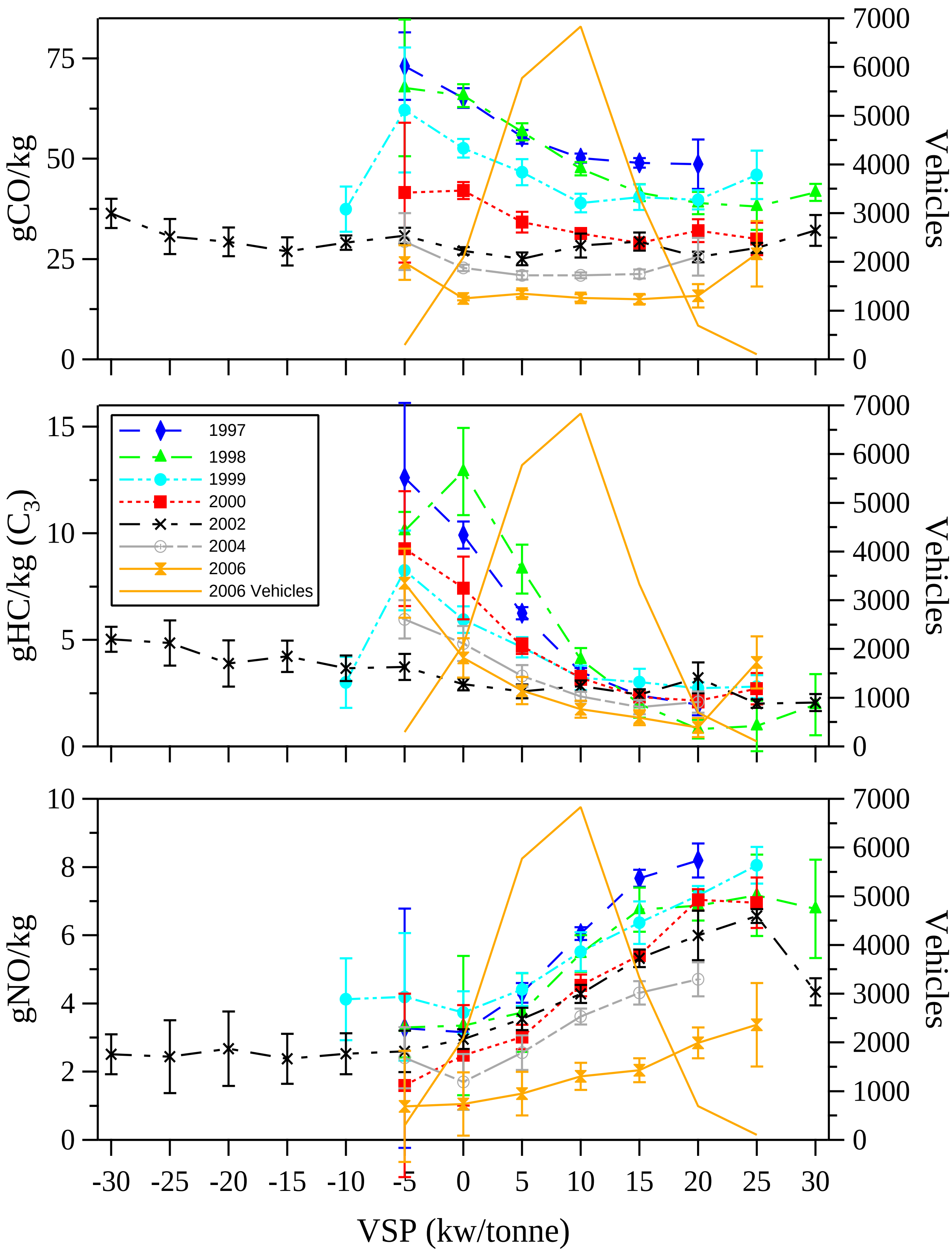

Figure 8. Vehicle emissions as a function of vehicle specific power for all of the Chicago E-23 data sets. Error bars are standard errors of the mean calculated from daily samples. The solid line without markers is the vehicle count profile for the 2006 data set.

Table 4. Vehicle specific power adjusted fleet emissions (-5 to 20 kw/tonne only) with standard errors of the means calculated using daily averages.

Means	1997 measured (adjusted)	1998 measured (adjusted)	1999 measured (adjusted)	2000 measured (adjusted)	2002 measured (adjusted)	2004 measured (adjusted)	2006 measured (adjusted)
gCO/kg	53.4 ± 1.0 (53.4 ± 1.0)	47.2 ± 1.3 (51.2 ± 1.4)	43.7 ± 2.3 (43.3 ± 2.3)	32.2 ± 0.9 (33.1 ± 0.9)	27.7 ± 1.2 (27.3 ± 1.2)	21.4 ± 0.8 (21.4 ± 0.8)	15.7 ± 0.9 (15.7 ± 0.9)
gHC/kg[a]	8.2 ± 0.2 (4.9 ± 0.2)	9.2 ± 0.6 (5.9 ± 0.4)	6.9 ± 0.5 (4.0 ± 0.3)	3.0 ± 0.2 (4.0 ± 0.3)	3.3 ± 0.3 (2.7 ± 0.2)	3.7 ± 0.3 (2.9 ± 0.3)	2.7 ± 0.5 (2.3 ± 0.5)
gNO/kg	5.5 ± 0.3 (5.5 ± 0.3)	5.6 ± 0.1 (4.9 ± 0.1)	5.2 ± 0.3 (5.2 ± 0.3)	4.4 ± 0.2 (4.0 ± 0.2)	3.9 ± 0.2 (4.1 ± 0.2)	3.3 ± 0.1 (3.2 ± 0.1)	1.7 ± 0.1 (1.7 ± 0.1)

[a]HC adjusted emissions are offset corrected as described in the text.

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 vehicle specific power, for each bin from 1997. A sample calculation, for the vehicle 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.

Because all VSP data are adjusted to the 1997 vehicle frequency distribution by VSP bin, the 1997 adjusted values are the same as the measured values except for the HC data that include an extra calculation to adjust for the yearly HC offset. Each measurement year's adjusted values for HC in Table 4 include this additional adjustment. In the case of CO and NO, the decrease in average emissions with time shows less noise than the HC data. The higher noise in the VSP adjusted HC emissions data is a direct reflection of the year to year changes in the calculated HC offsets.

A similar normalization can be applied to a fleet of specific model year vehicles to track deterioration, provided we use as a baseline only the model years measured in 1997. A sample calculation, for the model year adjusted mean NO emissions, is shown in Appendix E. Table 5 shows the mean emissions for all vehicles from model year 1983 to 1997, as measured in each of the seven years. Applying the vehicle frequency distribution by model year from 1997 to the mean emissions by model year from the later studies yields the model year adjusted fleet emissions. The calculation indicates that, though some of the measured decrease in fleet average emissions is due to fleet turnover, the emissions of even the older model years (1983-1997) measured previously seem to have not increased significantly. The lack of emissions deterioration over a growing period of time is likely the result of a large number of factors and not just the imposition of reformulated fuels, as discussed in previous CRC reports, and as observed on-road by Kirchstetter et al.[13] We surmise, however, that we may be beginning to observe the effect whereby the best maintained 1983-1997 vehicles last longer than their

Table 5. Model year adjusted fleet emissions (MY 1983-1997 only). Errors are standard errors of the means calculated from the daily means.

Means	1997 measured (adjusted)	1998 measured (adjusted)	1999 measured (adjusted)	2000 measured (adjusted)	2002 measured (adjusted)	2004 measured (adjusted)	2006 measured (adjusted)
gCO/kg	53.0 ± 0.9 (53.0 ± 0.9)	52.0 ± 0.8 (53.3 ± 0.8)	53.8 ± 1.9 (57.1 ± 2.0)	46.4 ± 1.4 (51.2 ± 1.6)	50.6 ± 2.0 (56.8 ± 2.2)	46.3 ± 1.9 (53.3 ± 2.1)	46.2 ± 2.1 (52.8 ± 2.4)
gHC/kg[a]	8.1 ± 0.2 (4.8 ± 0.2)	4.9 ± 1.2 (5.0 ± 0.6)	5.0 ± 0.6 (5.4 ± 0.4)	5.1 ± 0.3 (5.6 ± 0.4)	5.4 ± 0.5 (6.3 ± 0.5)	5.7 ± 0.4 (7.4 ± 0.6)	6.2 ± 1.3 (7.6 ± 1.5)
gNO/kg	5.6 ± 0.3 (5.6 ± 0.3)	6.3 ± 0.1 (6.4 ± 0.1)	6.6 ± 0.3 (6.8 ± 0.3)	6.2 ± 0.2 (6.6 ± 0.2)	6.4 ± 0.3 (7.0 ± 0.3)	7.0 ± 0.3 (7.7 ± 0.3)	4.9 ± 0.3 (5.7 ± 0.4)
Number of Vehicles	18,251	19,319	16,639	13,394	9,372	6,220	4,238

[a]HC emissions are offset corrected for all of the years adjusted data.

neglected counterparts. The fact that this fleet is now about one quarter the size it was when measured in 1997 makes this hypothesis at least somewhat plausible.

Vehicle deterioration can also be illustrated by Figure 9, which shows the mean emissions of the 1984 to 2006 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 defined as the difference between the year of measurement and the vehicle model year. Two features of this analysis stand out. The first is the gap between the 1996 and newer model year vehicles and the older fleets. There were significant changes in the motor vehicle emissions regulations for the 1996, most notably the introduction of two additional oxygen sensors to monitor catalyst efficiency as part of the OBDII monitoring system. These additional oxygen sensors allow the manufacturers to correct for any drift that occurs with the manifold oxygen sensor that is used to maintain the engine's air to fuel ratio setting.[14] This seems to be reflected in a noticeable gap between 1995 and older vehicles and 1996 and newer vehicles shown in Figure 9.

The second feature, common to much of the E-23 data, is that each model year shows very little deterioration with age, but each model year has higher emissions than its newer neighbor. The various analyses of the data presented up to this point suggest small increases in emissions from the previous years, even when model year adjustments were made to remove effects of fleet turnover. This lack of the expected deterioration also shows up clearly in Figure 9. Only the NO plot in Figure 9 shows the traditional view of emissions deterioration where fleet emissions creep upwards with age. However, even the NO plot only shows this trend for about fifteen years at which time emissions level out and then decrease after that. Are we wrong to expect fleet average deterioration by age, or are there factors at work suppressing the deterioration that would otherwise be observed?

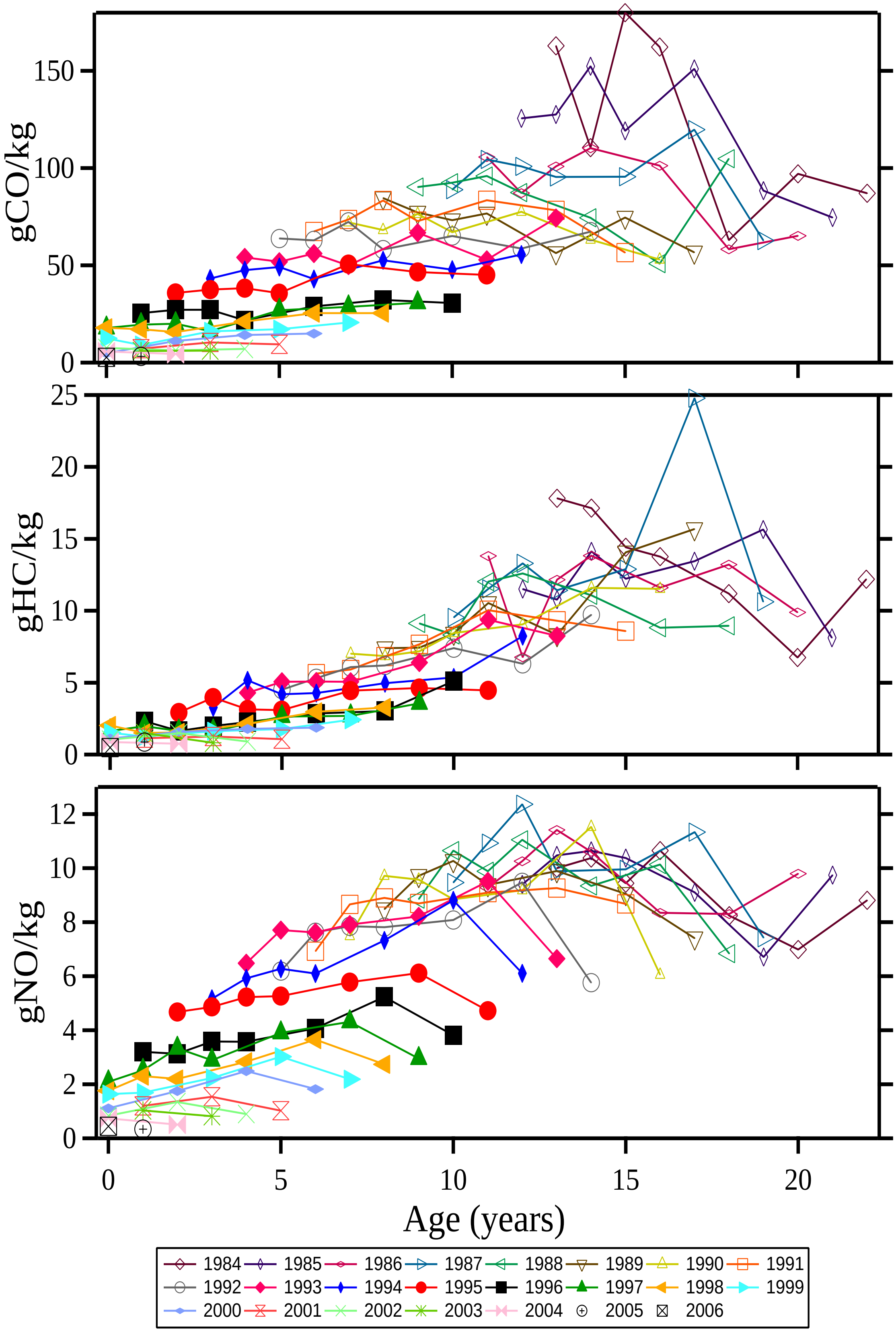

Figure 9. Mean vehicle emissions as a function of age, shown by model year.

We can imagine several programs and processes that may contribute to the overall fleet emissions: the Chicago area I/M program, the use of reformulated gasoline and the "natural" loss of the least well maintained vehicles as fleet's age. The enhanced I/M program was phased in during calendar years 1999 and 2000. If the I/M program were effective, it would produce some, but not all, of the observed results. In fact, an analysis of the I/M effect was conducted in the Year 3 report[15], 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. The fact that the same emissions behavior is seen in the newest model years that are not subject to I/M until their fifth model year indicates that I/M effectiveness is certainly not the whole story. It is also difficult to construct a story whereby fuel changes could somehow stop vehicle emissions deterioration.

Another use of the on-road remote sensing data is to predict the effectiveness with which high emitter identification for one pollutant actually predicts high emissions for another pollutant. One can look at the high CO emitters (as defined as the top emissions decile) and calculate what percentage of these are also high emitting for HC, for example. This type of analysis would allow a calculation of the maximum 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 all three pollutants. 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 are high emitting in all three pollutants. Thus, the table shows that 2.1% of the measurements are in the top decile for both HC and CO; 1.3% of the measurements are high emitting for CO and NO; 5.7% of the measurements are high CO emitters only.

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

Top 10% Decile	CO	HC	NO
CO	5.7%	2.1%	1.3%
HC	2.1%	6.3%	0.7%
NO	1.3%	0.7%	7.1%
All		0.9%	

The preceding analysis gives the percent of vehicle overlap but does not directly give emissions overlap. In order to assess the overlap, one must convert the Table 6 values to percent of emissions. This number is a maximum because the normal variability of emissions readings, particularly from high emitters[9], has not been included in this analysis. Table 7 shows that identification of the 5.7% of the measurements that are high emitting for CO only would identify an overall 35.8% of total measured on-road CO. More efficiently, identification of the 2.1% high CO and HC measurements accounts for more than a quarter of the total CO and HC emissions from these data.

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

Top 10% Decile	CO	HC	NO
CO	35.8%	27.4%	7.0%
HC	27.9%	53.0%	4.8%
NO	9.0%	5.1%	51.1%
All	7.5%	10.4%	8.3%

Most vehicles are low emitting and show little emissions variability when measured more than once. Vehicles that have one high reading often have other readings that vary widely.[9] This effect has also been observed from multiple FTP and IM240 tests. The evidence from pullover studies in California is that even one high reading identifies vehicles that have a >90% probability of failing an alternative I/M test if performed immediately.[16] These vehicles also have a high probability of showing evidence of tampered or defective emission control equipment.[7,17] Because of this variability in the emissions of broken cars, the emissions distribution obtained from any snapshot of fleet emissions (remote sensing or annual I/M testing) is bound to be more skewed than were one able to monitor the emissions of all vehicles at all times. This phenomenon does not affect the means measured by these snapshots but it does imply that the overlap and high emitter fractions in the tables above would show less skewness were one able to fully characterize all vehicles and their variability.

In the manner described in the Phoenix, Year 2 report[18], 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 4.3, 4.8, and 0.3 for CO, HC and NO, respectively. These values indicate standard deviations of 6.0 g/kg (0.05%), 6.7 g/kg (162 ppm) and 0.4 g/kg (35 ppm) for individual measurements of CO, HC and NO, respectively. These values indicate minimal relative noise in measurements of CO and NO and a small but significant amount of noise in the HC measurements. In terms of uncertainty in average values reported here, the numbers are reduced by a factor of the square root of the number of measurements. For example, with averages of 100 measurements, which is the low limit for number of measurements per bin, the uncertainty reduces by a factor of 10. Thus, the uncertainties in the averages reduce to 0.6 g/kg, 0.7 g/kg, and 0.04 g/kg, respectively.

CONCLUSIONS

The University of Denver has completed the seventh campaign of a multi-year remote sensing study of motor vehicle emissions and deterioration in the Chicago area, with measurements made in 1997 through 2000, 2002, 2004 and in 2006. A database was compiled containing 22,200 records for which the State of Illinois provided makes and model year information. All of these records contained valid measurements for at least CO and CO_2, and 21,149 records contained valid measurements for HC and NO as well.

The mean CO, HC and NO emissions for the fleet measured in this study was 0.13% (16.1 g/kg), 58 ppm (when a 10ppm offset is removed, 2.2 g/kg) and 125 ppm (1.8 g/kg), 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 measurements. Emission levels for all three species continue to decline and there is some evidence that levels are better controlled across a wider VSP range than past fleets. The CO and HC emissions are remarkably flat over the ±20 kw/tonne VSP range and the NO emissions are showing a steady decline in emission levels, particularly at the higher VSP loads.

Having collected seven data sets over a nine year period at the same time and location, it is possible to show the "deterioration" of specific model year fleets from one year to the next. When we restrict the fleet to only those model years observed during the first measurements in 1997 the 1983-1997 model year vehicles have had rather flat emissions with age, counter to the traditionally expected view of emissions deterioration. Another way of phrasing this is that the fleet fraction of gross emitters first seen in 1997 has remained the same even though that original fleet has aged nine years and only one quarter of the original fleet size is no longer observed in the current measurements. It is unlikely that I/M or fuel programs are the reason for this observation. Continuing studies at the same site and at non I/M, non special fuels sites should allow further insight to be gained as to the extent I/M programs and special fuels contribute to reducing motor vehicle fleet emissions deterioration compared with fleet turnover. Data are available at www.feat.biochem.du.edu for the seven measurement campaigns in Chicago and for other measurement campaigns undertaken by the University of Denver.

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ACRONYMS

CO – Carbon monoxide
CO_2 – Carbon dioxide
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
NO – Nitric Oxide
S.H.53 – State Highway 53
UV - Ultraviolet
VSP – Vehicle Specific Power

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_2006.dbf database.

The ill_2006.dbf is a Microsoft Foxpro database file, and can be opened by any version of MS Foxpro or Filemaker Pro regardless of platform and MS Access. 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 Indicates license plate type, 0 (standard passenger plate), 1 (anything but passenger plates) and 2 (temporary). This field should not be used to distinguish cars from trucks as the plate type is not always indicative of the vehicle.

Exp_month	Indicates the month the current registration expires.
Exp_year	Indicates the year the current registration expires.
Vin	Vehicle identification number.
Year	Model year of the vehicle.
Make	Manufacturer of the vehicle.
Body_style	Type of vehicle.
Address	Indicates the city, state, and zip code of the registrant's address.
Owner_code	Illinois DMV ownership codes (1 – individual, 2 – multiple individuals same last name, 3 – multiple individuals different last names, 4 – corporate owner, 5 – combined corporate and individual, 6 – multiple corporate ownership, 7 – local government, 8 – state government and 9 – Federal government).
Make_abrv	Abbreviated manufacturer.

APPENDIX C: Temperature and Humidity Data from Chicago O'Hare Int. Airport.

	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

	Date (2002)									
	Sept. 16		Sept. 17		Sept. 18		Sept. 19		Sept. 20	
Hour	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0700	57	90	60	84	62	100	73	96	71	94
0800	63	70	66	72	64	93	74	94	70	100
0900	67	55	71	63	68	87	75	94	70	100
1000	69	55	74	60	70	76	76	91	70	100
1100	70	53	75	52	72	73	77	90	71	96
1200	72	50	77	50	72	79	76	97	70	90
1300	73	44	76	52	75	79	79	88	69	87
1400	75	40	79	47	78	74	79	82	69	90
1500	75	42	79	42	79	74	78	85	69	87
1600	76	39	77	45	79	74	78	79	69	87
1700	74	41	74	52	78	74	79	77	69	84
1800	67	57	73	57	77	79	77	79	67	87

	Date (2004)							
	Sept. 20		Sept. 21		Sept. 22		Sept. 23	
Hour	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0800	63	54	67	61	69	57	70	61
0900	67	47	72	46	73	50	75	50
1000	71	42	75	37	76	43	79	44
1100	72	41	77	35	78	37	80	39
1200	74	38	80	34	78	37	81	38
1300	76	33	80	34	80	35	83	37
1400	77	28	81	32	80	35	84	35
1500	78	29	82	28	78	40	84	32
1600	77	30	81	30	80	38	84	33
1700	75	39	80	33	76	43	82	34
1800	71	49	70	55	68	63	78	39
1900	67	59	67	59	70	57	76	42

	Date (2006)							
	Sept. 12		Sept. 13		Sept. 14		Sept. 15	
Hour	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)	T (°F)	RH (%)
0751	67	93	60	93	64	70	65	87
0851	68	93	60	93	66	70	69	76
0951	68	90	61	93	68	68	72	66
1051	68	97	61	90	71	61	72	59
1151	68	97	62	84	71	64	77	52
1251	70	90	62	87	71	64	75	52
1351	70	87	63	84	71	61	77	50
1451	71	84	62	87	72	57	78	47
1551	68	93	63	81	71	61	74	60
1651	66	90	63	81	69	66	73	64
1751	65	90	63	81	67	68	71	68
1851	65	90	62	81	65	75	69	76

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**

Note that the Mean NO readings listed here have been rounded to the nearest ppm values which results in the Total Emissions column appearing to not be a direct multiplication product. The -5 to 20 kw/tonne bins are chosen to preclude any "off-cycle" emissions.

The object of this adjustment is to have the 1998 fleet's emissions calculated as if they drove (VSP wise) like the 1997 fleet. This is accomplished by first binning and averaging the 1997 and 1998 data (the top two tables). We then combine the mean NO values from the 1998 fleet with the numerical VSP bin distribution from the 1997 fleet in the bottom table. The product of these two columns is summed and the sum total emissions are divided by the number of 1997 vehicles to produce the 1998 adjusted mean NO average. For this example, it shows that the 1998 fleet when driven like the 1997 fleet has lower NO emissions than the 1997 fleet.

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**

APPENDIX F: Field Calibration Record.

1997				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
9/15	9:35	1.42	1.35	1.07
9/15	14:30	1.26	1.18	0.94
9/16	9:20	1.33	1.25	1.02
9/16	12:40	1.12	1.08	0.86
9/17	8:10	1.39	1.27	1.11
9/17	11:55	1.19	1.12	0.97
9/18	8:15	1.49	1.41	1.20
9/18	12:30	1.15	1.10	0.86
9/19	11:00	1.24	1.16	0.95

1998				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
9/21	8:15	1.38	1.26	1.21
9/21	13:00	1.31	1.17	1.15
9/22	7:40	1.48	1.36	1.46
9/22	11:40	1.26	1.15	1.27
9/23	8:00	1.64	1.52	1.26
9/23	10:45	1.32	1.25	1.13
9/24	9:00	1.46	1.33	1.41
9/24	12:30	1.30	1.19	1.12

1999				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
9/20	9:50	1.32	1.05	1.21
9/20	14:30	1.25	0.99	1.15
9/21	8:15	1.45	1.19	1.46
9/21	10:30	1.33	1.07	1.27
9/22	8:30	1.47	1.13	1.32
9/22	11:10	1.22	1.01	1.201
9/23	8:15	1.46	1.16	1.41
9/23	10:30	1.25	0.97	1.12

2000				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
9/11	8:50	1.22	0.94	1.22
9/11	11:20	1.12	0.87	1.10
9/11	18:05	1.28	0.98	1.35
9/12	8:35	1.29	0.99	1.49
9/13	8:10	1.41	1.11	1.38
9/13	10:35	1.18	0.94	1.13
9/14	8:25	1.36	1.03	1.49
9/14	10:25	1.35	1.07	1.49
9/14	12:35	1.19	0.93	1.25

2002				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
9/16	11:10	1.35	1.07	1.59
9/17	9:35	1.52	1.19	1.82
9/17	12:00	1.35	1.07	1.46
9/18	9:00	1.51	1.19	1.67
9/18	12:45	1.36	1.07	1.44
9/19	9:20	1.59	1.31	1.60
9/19	12:35	1.39	1.16	1.40
9/20	12:30	1.31	1.17	1.68

2004				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
9/20	9:00	1.66	1.45	1.47
9/20	11:15	1.37	1.14	1.26
9/21	8:45	1.58	1.32	1.35
9/21	11:10	1.31	1.11	1.19
9/22	8:00	1.77	1.50	1.58
9/22	10:00	1.39	1.19	1.23
9/23	8:00	2.24	1.66	1.87
9/23	10:00	1.43	1.22	1.27

2006				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
9/12	9:05	1.69	1.41	1.52
9/13	10:00	1.58	1.30	1.51
9/13	11;50	1.75	1.38	1.48
9/13	13:50	1.48	1.20	1.19
9/14	8:00	1.59	1.30	1.41
9/14	11:00	1.43	1.19	1.22
9/15	8:00	2.32	1.91	2.35
9/15	9:30	1.69	1.42	1.56
9/15	11:15	1.46	1.22	1.31