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On-Road Remote Sensing of Automobile Emissions in the Phoenix Area: Year 6, November 2006

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On-Road Remote Sensing of Automobile Emissions in the Phoenix Area: Year 6, November 2006

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EXECUTIVE SUMMARY

The University of Denver conducted a five-day remote sensing study in the Phoenix, AZ area in the fall of 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 mass emissions per kg (or gallon) of fuel and the percent concentrations of CO, CO_2, HC and NO in motor vehicle exhaust which would be observed by a tailpipe probe, corrected for water and any excess oxygen not involved in combustion. The system used in this study was also configured to determine the speed and acceleration of the vehicle, and was accompanied by a video system to record the license plate of the vehicle.

Five days of fieldwork (November 13-17, 2006) were conducted on the uphill exit ramp from Hwy 202 / Sky Harbor Blvd. Westbound to Hwy 143 Southbound in Phoenix, AZ. A database was compiled containing 21,782 records for which the State of Arizona provided makes and model year information. All of these records contained valid measurements for at least CO and CO_2, and 21,731 contained valid measurements for HC and NO as well. Of these measurements, 8,873 (41%) were of vehicles measured only once. The rest were of vehicles measured at least twice. Analysis of these repeat vehicles showed that high emitters have skewed emissions distributions while low emitters have more normally distributed emissions. The database, as well as others compiled by the University of Denver, can be found at www.feat.biochem.du.edu.

This was the sixth year of a multi-year continuing study to characterize motor vehicle emissions and deterioration in the Phoenix area. However, because of the non-ideal driving mode at the site in the first year (1998), a new ramp similar to the Denver, Chicago and L.A. Basin sites had been used in 1999, 2000, 2002, 2004 and was again used this year. The mean percent CO, HC, and NO were determined to be 0.11%, 0.0056%, and 0.0203%, (13.9 g/kg, 2.2 g/kg and 2.9 g/kg) respectively. The fleet emissions measured in this study exhibit a gamma distribution, with the dirtiest 10% of the fleet responsible for 81%, 87%, and 70% of the CO, HC, and NO emissions, respectively.

The 2006 data show the least dependence on vehicle specific power (VSP) of any of the previous data sets. CO, HC and NO emissions are at low levels across the entire VSP range. Using VSP, the emissions of the vehicle fleet measured in 2006 were VSP adjusted to match the vehicle driving patterns of the fleet measured in 1998. Despite the fact that the current site has a higher averaged VSP than the 1998 site, the emissions are now lower than the 1998 measurements. This trend is more difficult to discern in the model year adjustments since the fleet has aged 8 years in the process and we are comparing two different sites. If we restrict our comparison to the current site, observed increases in this analysis are no larger than the estimated errors, and emission deterioration in the fleet is very small at worst.

Tracking of model year fleets through six measurements indicates that the rate of emissions deterioration continues to slow. The observed increases in emissions only slightly exceeded the standard errors of the mean, despite the age of the fleet increasing by 8 years. An analysis of high emitting vehicles showed that there is considerable

overlap of CO and HC high emitters; for instance, 1.7% of the fleet emits 25% of the total CO and 19% of the total HC. The noise levels in the CO, HC and NO measurement channels were determined to be low, compared with previous campaigns.[16]

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 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]

According to Heywood[2], carbon monoxide emissions from automobiles are at a maximum when the air/fuel ratio is rich of stoichiometric, and are caused solely by a lack of adequate air for complete combustion. Hydrocarbon emissions are also maximized with a rich air/fuel mixture, but are slightly more complex. When ignition occurs in the combustion chamber, the flame front cannot propagate within approximately one millimeter of the relatively cold cylinder wall. This results in a quench layer of unburned fuel mixture on the cylinder wall, which is scraped off by the rising piston and sent out the exhaust manifold. With a rich air/fuel mixture, this quench layer simply becomes more concentrated in HC, and thus more HC is sent out the exhaust manifold by the rising pistons. There is also the possibility of increased HC emissions with an extremely lean air/fuel mixture when a misfire can occur and an entire cylinder of unburned fuel mixture is emitted into the exhaust manifold. Nitric oxide (NO) emissions are maximized at high temperatures when the air/fuel mixture is slightly lean of stoichiometric, and are limited during rich combustion by a lack of excess oxygen and during extremely lean combustion by low flame temperatures. In most vehicles, practically all of the on-road NO_x is emitted in the form of NO.[2] Properly operating modern vehicles with three-way catalysts are capable of partially (or completely) converting engine-out CO, HC and NO emissions to CO_2, H_2O and N_2.[2]

Control measures to decrease mobile source emissions in non-attainment areas include inspection and maintenance (I/M) programs, oxygenated fuel mandates, and transportation control measures, but the effectiveness of these measures remains questionable. Many areas remain in non-attainment, and with the new 8-hour ozone standards introduced by the EPA in 1997, many locations still violating the standard may have great difficulty reaching attainment.[3]

The remote sensor used in this study was developed at the University of Denver for measuring the pollutants in motor vehicle exhaust, and has previously been described in the literature.[4,5] The instrument consists of a non-dispersive infrared (IR) component for detecting carbon monoxide, carbon dioxide (CO_2), and hydrocarbons, and a dispersive ultraviolet (UV) spectrometer for measuring nitric oxide. The source and detector units are positioned on opposite sides of the road in a bi-static arrangement. Collinear beams of IR and UV light are passed across the roadway into the IR detection unit, and are then focused through a dichroic beam splitter, which serves to separate the beams into their IR and UV components. The IR light is then passed onto a spinning polygon mirror, which distributes the light across the four infrared detectors: CO, CO_2, HC and reference.

The UV light is reflected off the surface of the beam splitter and is focused into the end of a quartz fiber-optic cable, which transmits the light to an ultraviolet spectrometer. The UV unit is then capable of quantifying nitric oxide by measuring an absorbance band at 226.5 nm in the ultraviolet spectrum and comparing it to a calibration spectrum at the same wavelength.

The exhaust plume path length and the density of the observed plume are highly variable from vehicle to vehicle, and are dependent upon, among other things, the height of the vehicle's exhaust pipe, wind, and turbulence behind the vehicle. For these reasons, the remote sensor can only directly measure ratios of CO, HC or NO to CO_2. The ratios of CO, HC, or NO to CO_2, termed Q, Q' and Q", respectively, are constant for a given exhaust plume; and, on their own, are useful parameters for describing a hydrocarbon combustion system. The remote sensor used in this study reports the %CO, %HC and %NO in the exhaust gas, corrected for water and excess oxygen not used in combustion. The %HC measurement is a factor of two smaller than an equivalent measurement by an FID instrument.[6] Thus, in order to calculate mass emissions, the %HC values in the equations below would be RSD measured values multiplied by 2. These percent emissions can be directly converted into mass emissions per gallon by the equations shown below.

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

These equations indicate that the relationship between concentrations of emissions to mass of emissions is almost linear, especially for CO and NO and at the typical low concentrations for HC. Thus, the percent differences in emissions calculated from the concentrations of pollutants reported here are equivalent to differences calculated from the fuel-based mass emissions of the pollutants.

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

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

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

Quality assurance calibrations are performed as dictated in the field by the atmospheric conditions and traffic volumes. A puff of gas containing certified amounts of CO, CO_2, propane and NO is released into the instrument's path, and the measured ratios from the instrument are then compared to those certified by the cylinder manufacturer (Praxair).

These calibrations account for day-to-day variations in instrument sensitivity and variations in ambient CO_2 levels caused by atmospheric pressure and instrument path length. Since propane is used to calibrate the instrument, all hydrocarbon measurements reported by the remote sensor are as propane equivalents.

Studies sponsored by the California Air Resources Board and General Motors Research Laboratories have shown that the remote sensor is capable of CO measurements that are correct to within ±5% of the values reported by an on-board gas analyzer, and within ±15% for HC.[7,8] The NO channel used in this study has been extensively tested by the University of Denver. Tests involving a late-model low-emitting vehicle indicate a detection limit (±3σ) of 25 ppm for NO, with an error measurement of ±5% of the reading at higher concentrations. Appendix A gives a list of the criteria for valid/invalid data.

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

The purpose of this report is to describe the remote sensing measurements made in the Phoenix, AZ area in November 2006, under CRC contract no. E-23-9. Measurements were made for 5 consecutive weekdays, from Monday, Nov. 13 to Friday, Nov. 17, conducted on the uphill exit ramp from Hwy 202 / Sky Harbor Blvd. Westbound to Hwy 143 Southbound in Phoenix, AZ. This intersection is just east of Sky Harbor Airport, and the ramp consists of a rather large loop approximately a mile long. The instrument was located as far up the ramp as possible (described as location A in previous reports). The uphill road grade was 1.3°. A map of the measurement location is shown in Figure 1. Measurements were generally made between the hours of 6:00 and 17:00. This was the sixth year of a multi-year campaign to characterize motor vehicle emissions and deterioration in the Phoenix area.

RESULTS AND DISCUSSION

Following the five days of data collection in November 2006, the pictures were read for license plate identification. Plates which appeared to be in state and readable were sent to the State of Arizona to be matched against registration records. The resulting

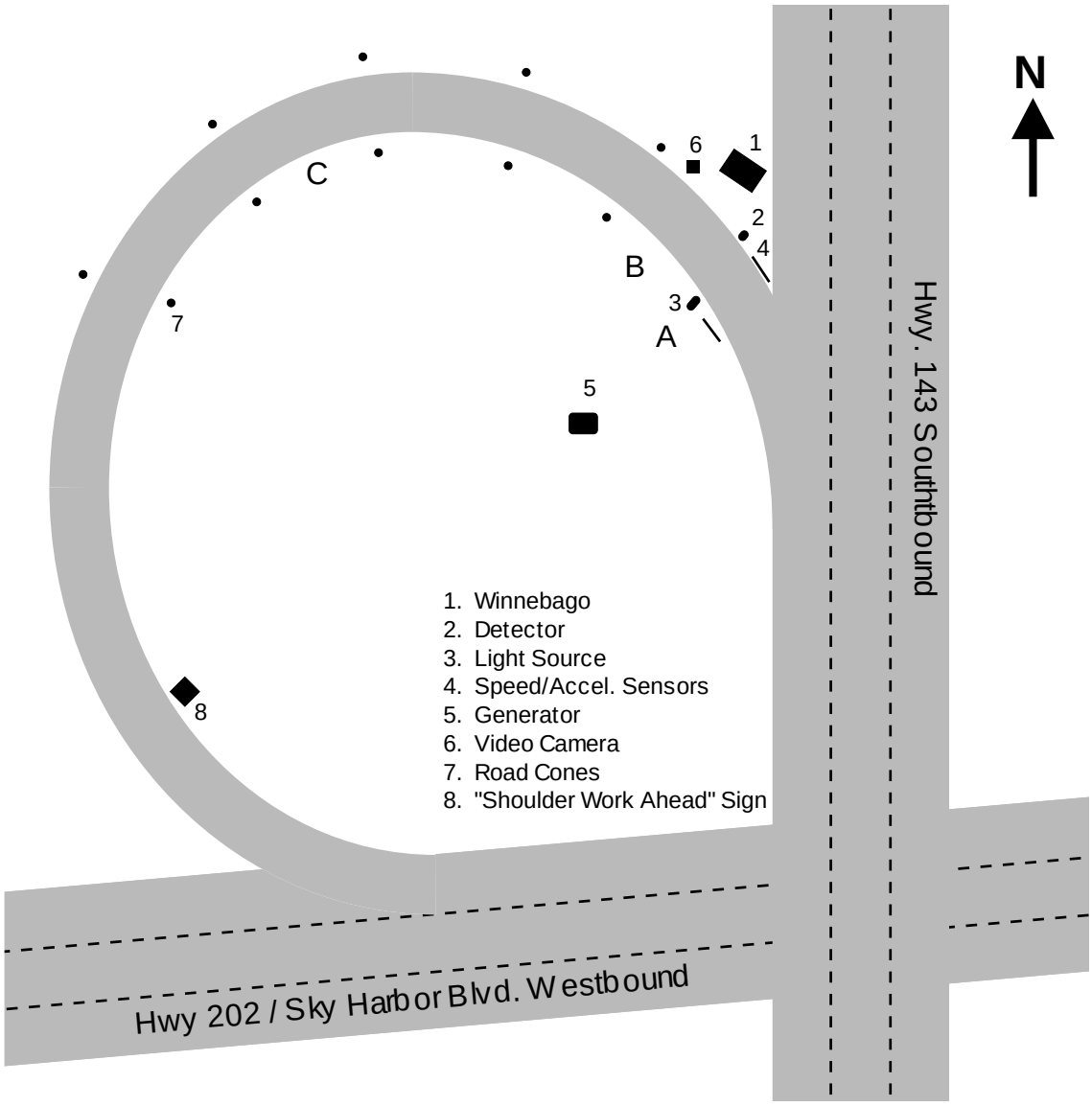

Figure 1. Layout of the on-ramp from Highway 202 to Highway 143 in the Phoenix area.

database contains 21,782 records with registration information and valid measurements for at least CO and CO_2. Most of these records also contained valid measurements for HC and NO (see Table 1). The complete structure of the database and the definition of terms are included in Appendix B. The temperature and humidity record from nearby Sky Harbor Airport is included in Appendix C.

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

Table 1. Data Collection Summary.

	CO	HC	NO
Attempted Measurements	29,127		
Valid Measurements	27,067	27,014	27,050
Percent of Attempts	92.9%	92.7%	92.9%
Submitted Plates	23,086	23,047	23,069
Percent of Attempts	79.3%	79.1%	79.3%
Percent of Valid Measurements	85.3%	85.3%	85.3%
Matched Plates	21,782	21,746	21,767
Percent of Attempts	74.8%	74.7%	74.8%
Percent of Valid Measurements	80.5%	80.5%	80.5%
Percent of Submitted Plates	94.4%	94.5%	94.4%

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 additional losses are from the usual sources such as trailer hitches that obstruct the view of the license plate.

Table 2 provides an analysis of the number of vehicles that were measured repeatedly, and the number of times they were measured. Of the 21,782 records used in this fleet analysis, 8,873 (41%) were contributed by vehicles measured once, and the remaining 12,909 (59%) 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 mean or negligible emitters had nearly normally distributed emission measurements, while higher mean emitters had more skewed distributions, as shown previously by Bishop, *et al.*[9] For example, of the 403 vehicles that had five or more valid CO measurements, ten had mean %CO > 1: 1.1, 1.1, 1.2, 1.2, 1.3, 1.3, 1.3, 1.7, 2.5 and 2.5. These ten vehicles' calculated variances in their measurements were 1.7, 3.1, 1.4, 1.1, 2.5, 0.9, 0.1, 4.4, 2.6 and 1.2 respectively, while the average variance in the measurements of the other 393 vehicles was 0.04.

Table 2. Number of measurements of repeat vehicles.

Number of Times Measured	Number of Vehicles
1	8,873
2	2,044
3	1,223
4	760
5	343
6	45
7	8
>7	7

Table 3 is the data summary; included is the summary of the previous remote sensing data collected by the University of Denver at the older site in the Phoenix area in the fall of 1998 and the 1999, 2000, 2002, 2004 and 2006 data from the current site. The dramatic

Table 3. Data summary.

Study Year	1998[a]	1999[b]	2000	2002	2004	2006
Mean CO (%) (g/kg of fuel)	0.28 (34.4)	0.31 (38.3)	0.27 (34.2)	0.22 (27.3)	0.18 (22.9)	0.11 (13.9)
Median CO (%)	0.07	0.06	0.05	0.05	0.04	0.02
Percent of Total CO from Dirtiest 10% of the Data	70.7%	77.8%	75.5%	72.3%	76.3%	80.9%
Mean HC (ppm)* (g/kg of fuel)* Offset (ppm)	110 (3.9) 80	85 (3.0) 50	99 (3.8) -60	66 (2.6) 40	49 (1.8) 40	56 (2.2) 60
Median HC (ppm)*	10	40	70	30	20	20
Percent of Total HC from Dirtiest 10% of the Data	65.5%	79.0%	71.1%	77.5%	71.5%	86.6%
Mean NO (ppm) (g/kg of fuel)	360 (5.1)	572 (8.1)	448 (6.4)	327 (4.6)	245 (3.5)	203 (2.9)
Median NO (ppm)	120	167	99	63	43	23
Percent of Total NO from Dirtiest 10% of the Data	56.0%	49.1%	52.6%	57.4%	63.0%	69.8%
Mean Model Year	1993.3	1994.0	1995.3	1997.4	1999.4	2001.4
Mean Speed (mph)	37.2	34.6	34.0	34.7	36.1	35.6
Mean Acceleration (mph/s)	-0.7	1.2	1.1	2.2	1.9	1.3
Mean VSP (kw/tonne) Slope (degrees)	2.7 2.1°	17.5 1.3°/1.4°	16.6 1.3°	25.1 1.3°	23.7 1.3°	18.2 1.3°

[a]Data collected at different Phoenix site, exit ramp from I-10W to US 143N.
[b]Data collected at current ramp but at two different locations on the ramp.
*Indicates values that have been HC offset adjusted as described in text.

reductions in on-road vehicle emissions can be seen between 1998 and 2006. Despite the current monitoring site's higher mean accelerations and VSP's, the raw measurements continue to decrease and are now well below even the lower load 1998 data.

The fleet measured in 2006 continues to show a steady decrease in mean emissions for CO and NO from the previous four years of measurement at the Highway 202 site. We believe that the HC data is also trending down but systematic noise in our measurements precludes that trend from being smooth. The average HC values here have been adjusted for comparison purposes only to remove an artificial offset in the measurements. This offset, restricted to the HC channel, has been reported in earlier CRC E-23 reports. Calculation of the offset is accomplished by computing the mode and means of the newest model year vehicles and assuming these vehicles emit negligible levels of hydrocarbons, using the lowest of either of these values as the offset. The offset is then subtracted from all of the hydrocarbon data. Since we assume the cleanest vehicles to emit little hydrocarbons, such an adjustment 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 subtraction has been performed here and later in the analysis where indicated.

Figure 2 shows the distribution of CO, HC, and NO emissions by percent category from the data collected in this study. The solid bars show the percentage of the fleet in a given emission category, and the hatched bars show the percentage of the total emissions contributed by that category. This figure illustrates the skewed nature of automobile emissions; the lowest emission category for each of three pollutants is occupied by no less than 82% of the measurements (for HC). The lowest emission categories for CO and NO contain 98% and 86% of the measurements, respectively. The fact that the cleanest 98% of the measurements are responsible for only 50% of the CO emissions further demonstrates how the emissions picture can be dominated by a small number of high emitters. This skewed distribution was also seen in all of the previous years and is reflected in the high values of percent of total emissions from the dirtiest 10% of the data (see Table 3).

The inverse relationship between vehicle emissions and model year has been observed at a number of locations around the world, and Figure 3 shows that the fleet in the Phoenix area, during all six years of measurement, is not an exception.[4] 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 has been observed previously,[5, 10] and is likely due to the tendency for older vehicles to lose compression and operate under fuel-rich conditions, both factors resulting in lower NO emissions.

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 4 - 6. 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. The results shown here continue to demonstrate that broken emissions control equipment has a greater impact on fleet emissions than vehicle age.

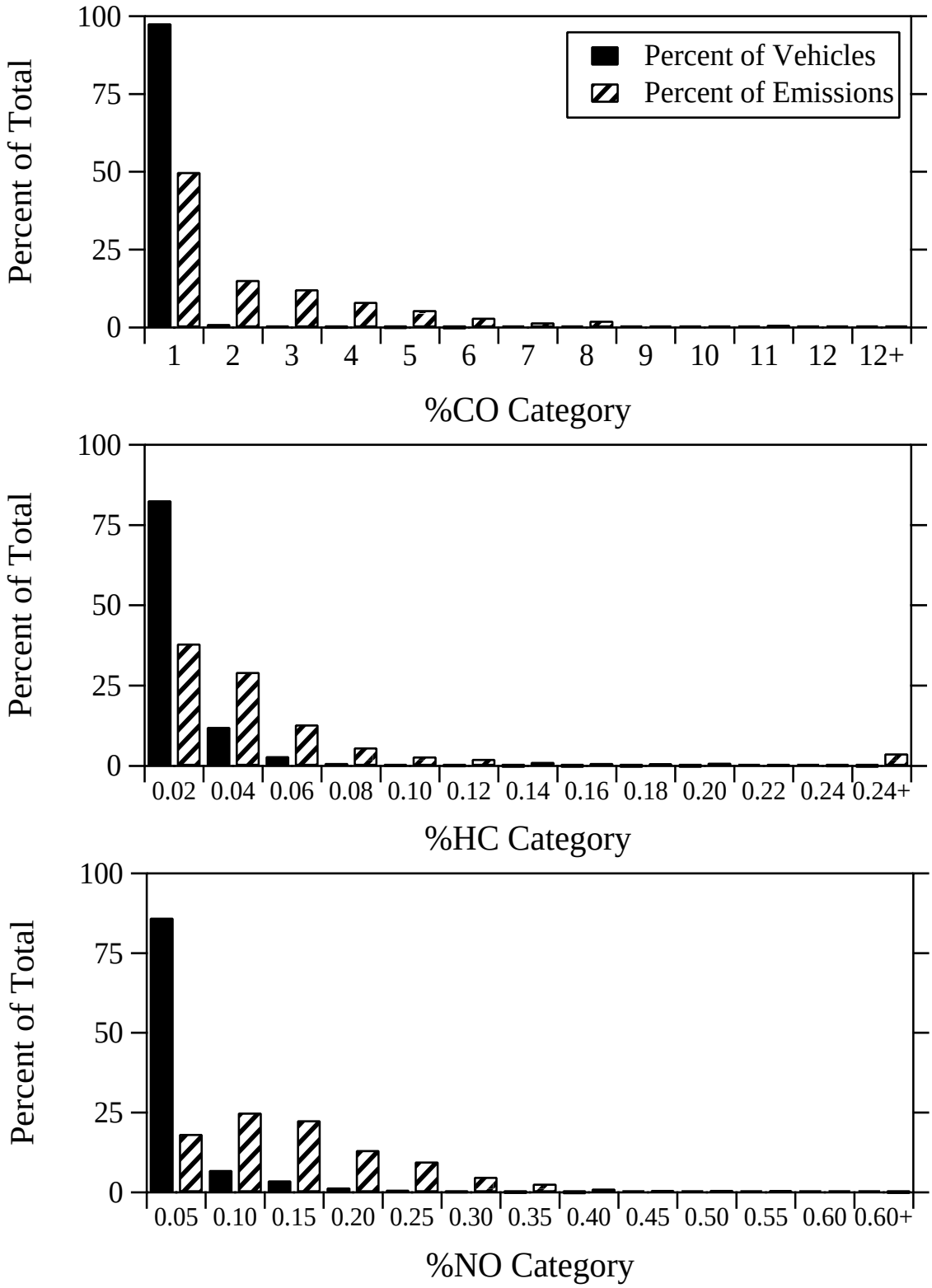

Figure 2. Emissions distribution showing the percentage of the fleet in a given emission category (black bars) and the percentage of the total emissions contributed by the given category (hatched bars).

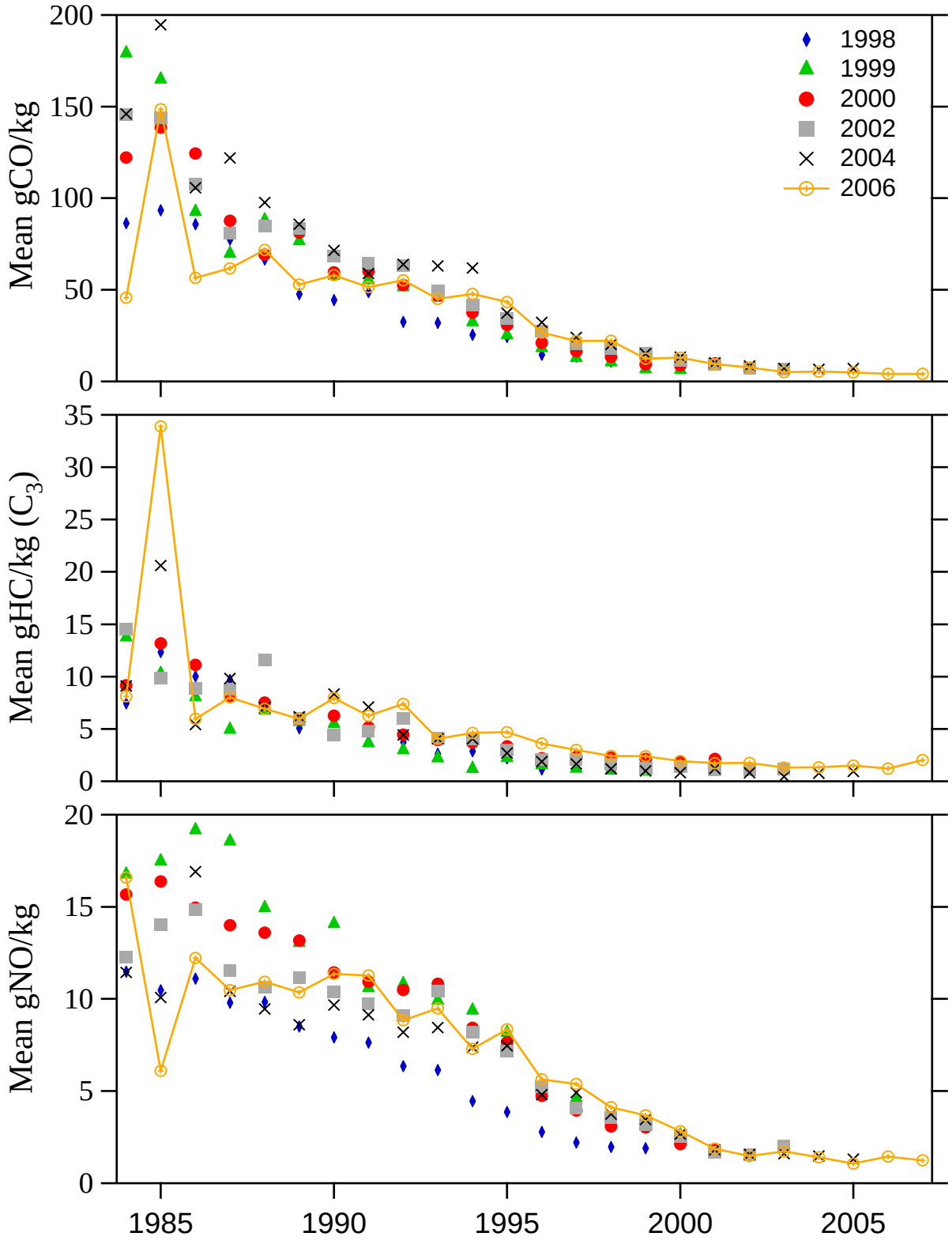

Figure 3. Mean vehicle emissions illustrated as a function of model year. HC data have been offset adjusted as described in the text.

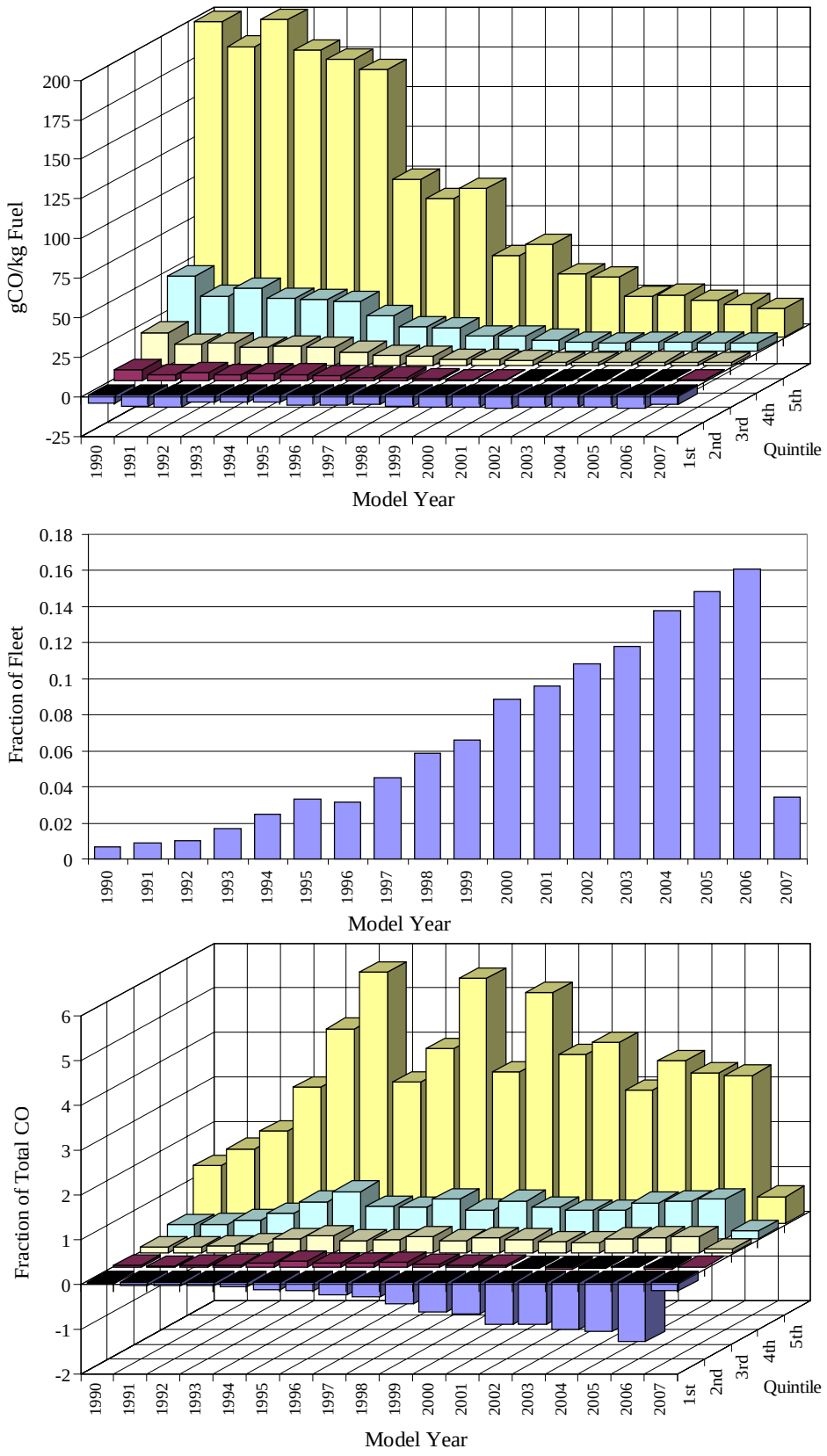

Figure 4. 2006 CO emissions by model year and quintile (top), fleet distribution (middle) and their product showing the total fractional CO emissions by model year and quintile (bottom).

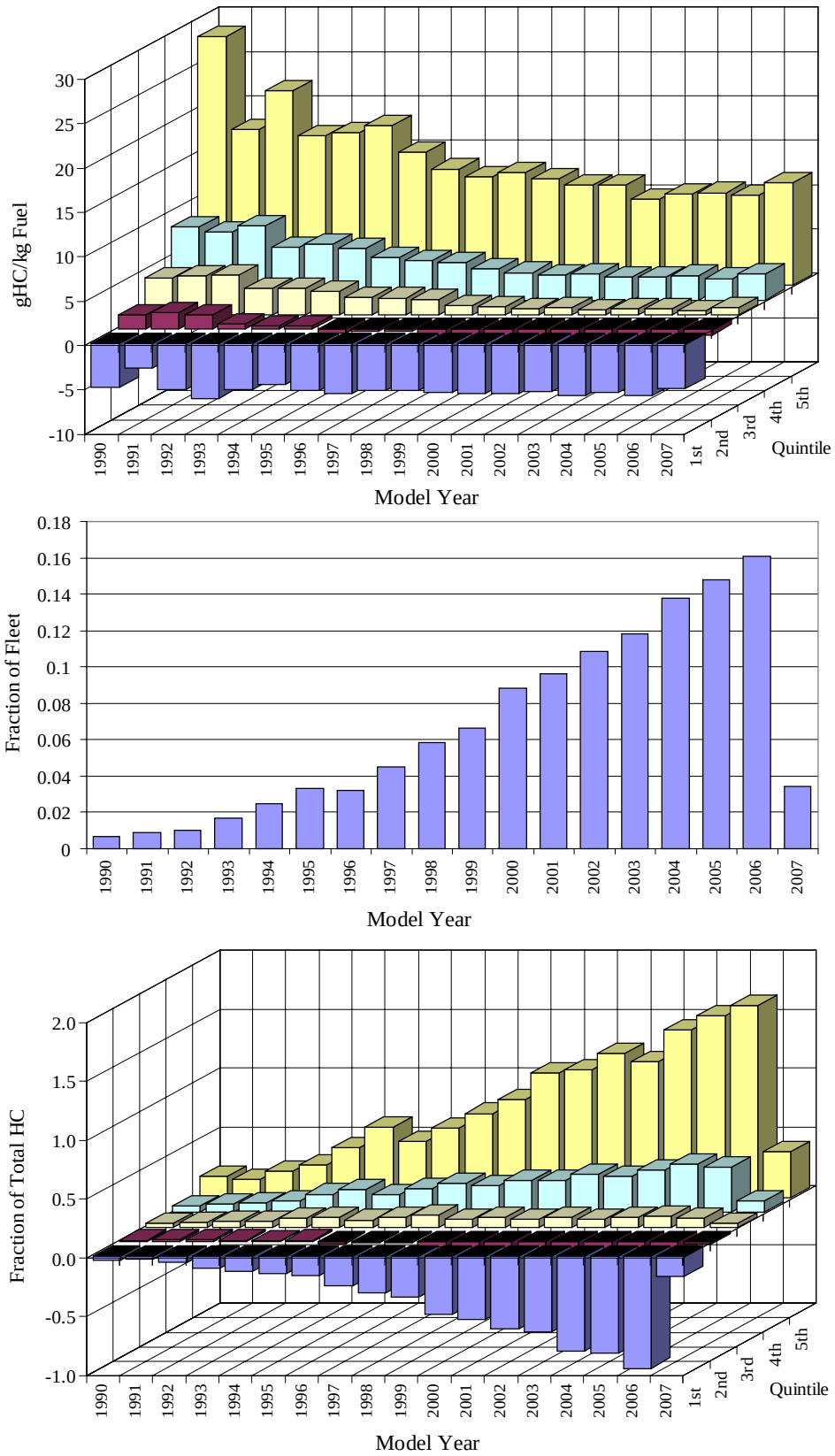

Figure 5. 2006 HC emissions by model year and quintile (top), fleet distribution (middle) and their product showing the total fractional HC emissions by model year and quintile (bottom).

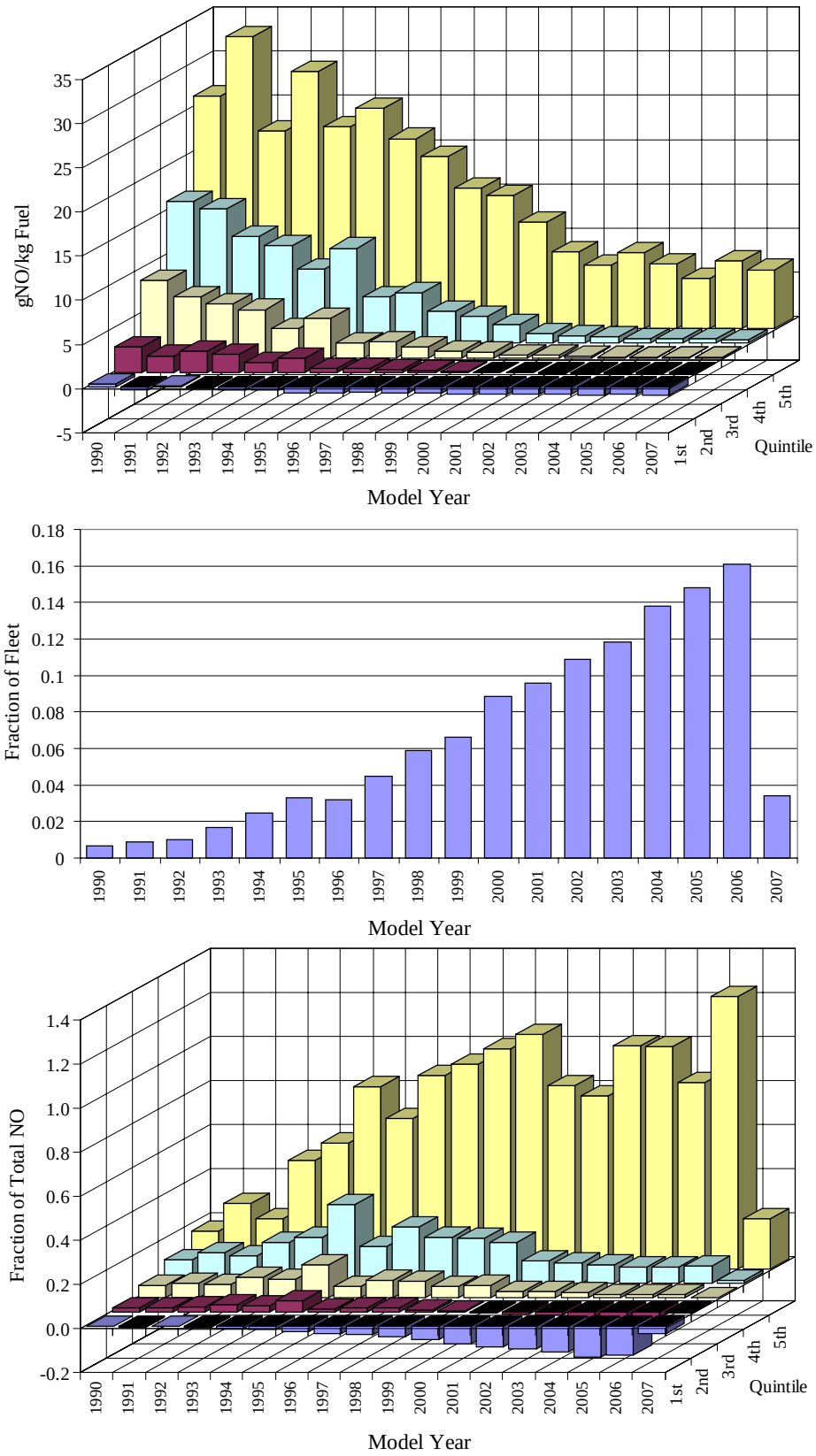

Figure 6. 2006 NO emissions by model year and quintile (top), fleet distribution (middle) and their product showing the total fractional NO emissions by model year and quintile (bottom).

Figures 4 - 6 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 4 - 6 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 4 - 6 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

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

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. Using this equation, vehicle specific power was calculated for all measurements in the database. The emissions data were binned according to vehicle specific power, and illustrated in Figure 7. The solid line in the figure provides the number of measurements in each bin for the 2006 data. The 2006 data show the least dependence on VSP of any of the previous data sets. All of the species are remarkably flat across the VSP range with only slight rises at the VSP levels that in past years showed larger increases. These observations are probably the result of a number of factors that influence vehicle emissions. This could possibly include the continued improvement in emissions systems durability and lower national tailpipe standards through the 50-state certification program.

Using vehicle specific power, it is possible to eliminate some of the influence of load and of driving behavior from the mean vehicle emissions for the 1998, 1999, 2000, 2002, 2004 and 2006 databases. Table 4 shows the mean emissions from vehicles in the 1998 database, from vehicles measured at the two locations in 1999 and from vehicles in 2000, 2002, 2004 and 2006 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. This correction is accomplished by applying the mean vehicle emissions for each specific power bin in Figure 7, for each of the two locations in 1999, the 2000, 2002, 2004 and the 2006 measurements, to the vehicle distribution by specific power, for each bin from 1998. A sample calculation, for the specific power adjusted mean NO emissions in Chicago in 1998, is shown in Appendix D. The uncertainty values in the table are standard errors of the means determined from the daily averages. Table 4 shows the mean VSP adjusted emissions during the five years have been steadily decreasing since the 1999 data set. The current measurements are the lowest to date, most likely due to the robust emissions durability of the newer model year vehicles entering the Phoenix fleet.

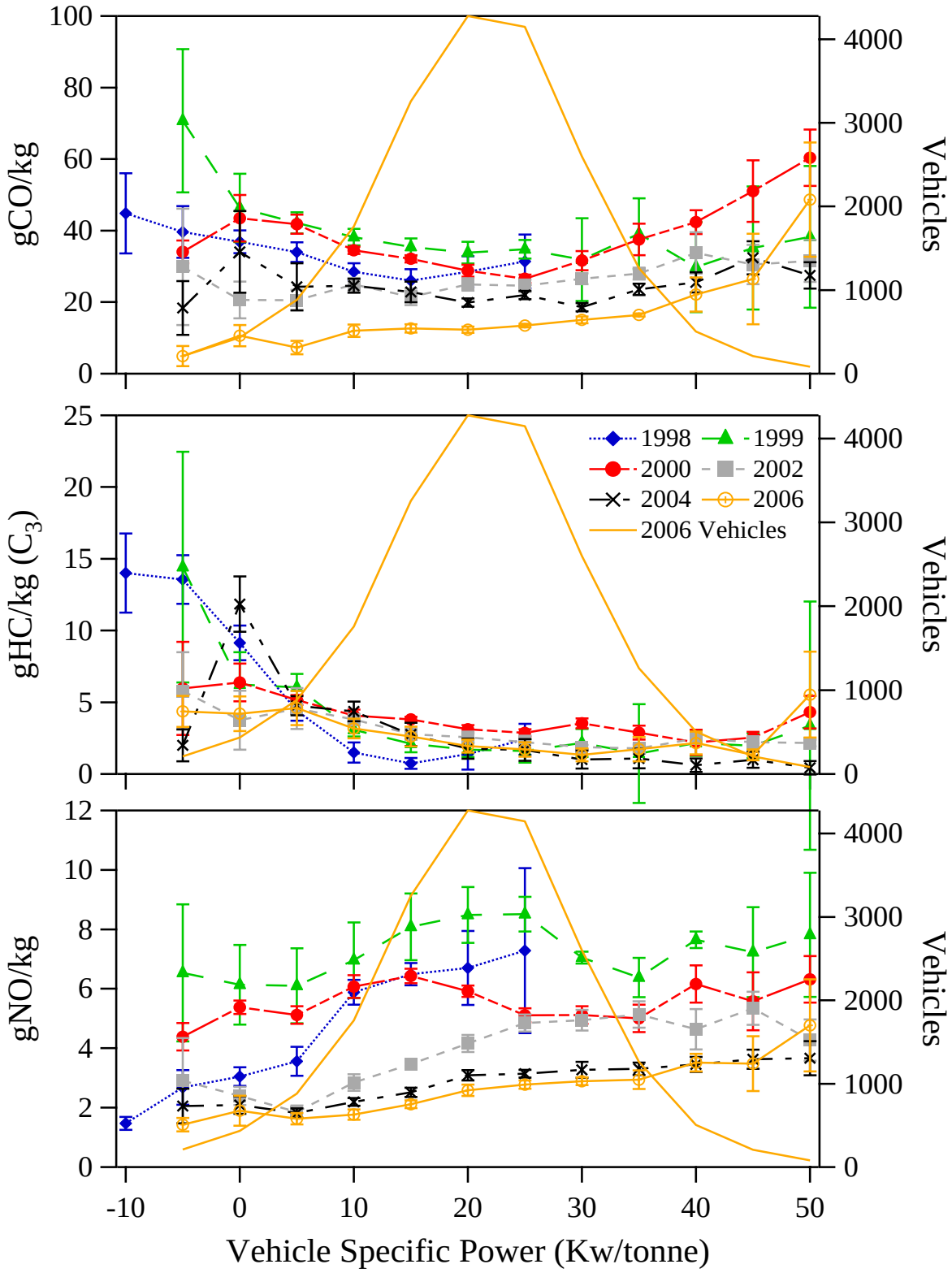

Figure 7. Vehicle emissions as a function of vehicle specific power for the all of the Phoenix E-23 data sets. Error bars are standard errors of the mean calculated from daily samples. The solid line without markers is the vehicle count profile for the 2006 data set.

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

Means	1998[a] measured (adjusted)	1999[b] measured (adjusted)	2000[c] measured (adjusted)	2002 measured (adjusted)	2004 measured (adjusted)	2006 measured (adjusted)
gCO/kg	31.5 ± 2.5 (31.5 ± 2.5)	37.8 ± 1.5 (42.3 ± 1.7)	33.0 ± 0.9 (36.7 ± 1.0)	23.6 ± 2.0 (23.0 ± 1.9)	22.7 ± 1.8 (24.8 ± 2.1)	11.6 ± 0.9 (10.3 ± 0.8)
gHC/kg[d]	6.5 ± 1.4 (3.2 ± 1.2)	5.3 ± 0.4 (4.2 ± 0.5)	1.4 ± 0.3 (4.5 ± 0.4)	4.7 ± 0.4 (3.7 ± 0.4)	4.4 ± 0.6 (4.5 ± 0.5)	5.2 ± 0.6 (3.4 ± 0.7)
gNO/kg	5.2 ± 0.2 (5.2 ± 0.2)	7.5 ± 1.2 (7.0 ± 1.1)	6.0 ± 0.2 (5.8 ± 0.2)	3.6 ± 0.2 (2.8 ± 0.1)	3.8 ± 0.2 (2.2 ± 0.1)	2.2 ± 0.1 (1.9 ± 0.1)

[a]Data collected at different Phoenix site, exit ramp from I-10W to US 143N.
[b]Data collected at current ramp but at two different locations on the ramp.
[c]Data presented from location A only.
[d]HC emissions are offset adjusted for all of the years adjusted data.

A correction similar to the VSP adjustment can be applied to a fleet of specific model year vehicles to look at model year deterioration, provided we use as a baseline only model years measured in the 1998 study. This restriction reduces the number of vehicles in the calculation for each subsequent year and that fleet size is listed at the bottom of the table. Table 5 shows the mean emissions for all vehicles from model years 1984 to 1999, as measured in 1998, 1999, 2000, 2002, 2004 and 2006. Applying the vehicle distribution by model year from 1998 to the mean emissions by model year from each of the other three years of measurement yields the model year adjusted fleet emissions. What deterioration that is occurring in this fleet is small with only the CO emissions showing an increase that is outside the error limits given. The HC and now the NO emissions have flattened out and do not show a statistically significant deterioration effect. An expanded sample calculation, for the model year adjusted mean NO emissions in Chicago in 1998, is shown in Appendix E.

Table 5. Model year adjusted fleet emissions (MY 1984-1999 only). Errors are standard error of the means calculated using the daily means.

Means	1998 Measured (Adjusted)	1999 Measured (Adjusted)	2000 Measured (Adjusted)	2002 Measured (Adjusted)	2004 Measured (Adjusted)	2006 Measured (Adjusted)
gCO/kg	29.4 ± 3.2 (29.4 ± 3.2)	34.0 ± 1.0 (37.6 ± 1.1)	34.6 ± 0.9 (39.9 ± 1.1)	36.8 ± 1.1 (44.6 ± 1.3)	40.3 ± 1.2 (51.4 ± 1.6)	31.2 ± 0.9 (40.2 ± 1.2)
gHC/kg[a]	6.5 ± 1.3 (3.1 ± 1.2)	4.6 ± 0.5 (2.7 ± 0.5)	1.2 ± 0.3 (4.0 ± 0.3)	4.9 ± 0.3 (3.9 ± 0.4)	4.6 ± 0.6 (3.8 ± 0.8)	3.9 ± 0.5 (5.0 ± 0.2)
gNO/kg	4.7 ± 0.2 (4.7 ± 0.2)	7.8 ± 1.0 (8.4 ± 1.1)	6.9 ± 0.3 (7.7 ± 0.3)	6.3 ± 0.3 (7.2 ± 0.4)	5.9 ± 0.3 (6.9 ± 0.3)	6.2 ± 0.2 (7.5 ± 0.2)
Number of Vehicles	16,947 11,675 11,371	17,427	16,463	13,355	9,164	5,729

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

Vehicle deterioration can also be illustrated by Figure 8, which shows the mean emissions of the 1984 to 2007 model year fleet as a function of vehicle age. The first point for each model year was measured in 1998, the second in 1999, the third in 2000, the fourth in 2002 the fifth in 2004 and the sixth in 2006. Vehicle age is determined by the difference between the year of measurement and the vehicle model year. Since the measurements are taken in November, the model year that matches the measurement year are considered one year old because the following model year vehicle has already been released for most manufacturers. The analysis is somewhat confounded by differences in measurement location during the three years of measurement. This is especially noticeable in the highly load dependent pollutant - NO - which measured low in 1998 at the first location. As more data are collected, what is most striking is how the first four to six years of age the mean CO, HC and NO emissions show very small amounts if any emissions deterioration. 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 and no doubt are contributing to the low deterioration rates.[13]

Another use of the on-road remote sensing data is to predict the abundance of vehicles that are high emitting for more than one pollutant measured. One can look at the high CO emitters (as defined as the top emissions decile) and calculate what percent of these are also high HC emitters, for example. This type of analysis would allow a calculation of HC emission benefits resulting from fixing all high CO emitters. To this extent, we have analyzed our data to determine what percent of the top decile of emitters of one pollutant are also in the top decile for another. These data are in Table 6; included in the analysis are only those vehicles that have valid readings for all three pollutants. The column heading is the pollutant whose top decile is being analyzed, and the values indicate what percentage of the data are high emitters only for the pollutants in the column and row headings. Where the column and row headings are the same, the values indicate the percentage that is high emitting in only that pollutant. The sum of these three bins gives the percentage that is high emitting for any pollutant. The "All" row gives the percentage of the data that are high emitting in all three pollutants. Thus 1.7% of the measurements are in the top decile for both HC and CO but not NO; 1.2% are high emitting for CO and NO but not HC; 6.5% are only high CO emitters.

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

Top 10% Decile	CO	HC	NO
CO	6.5%	1.7%	1.2%
HC	1.7%	6.8%	0.9%
NO	1.2%	0.9%	7.3%
All	0.6%		

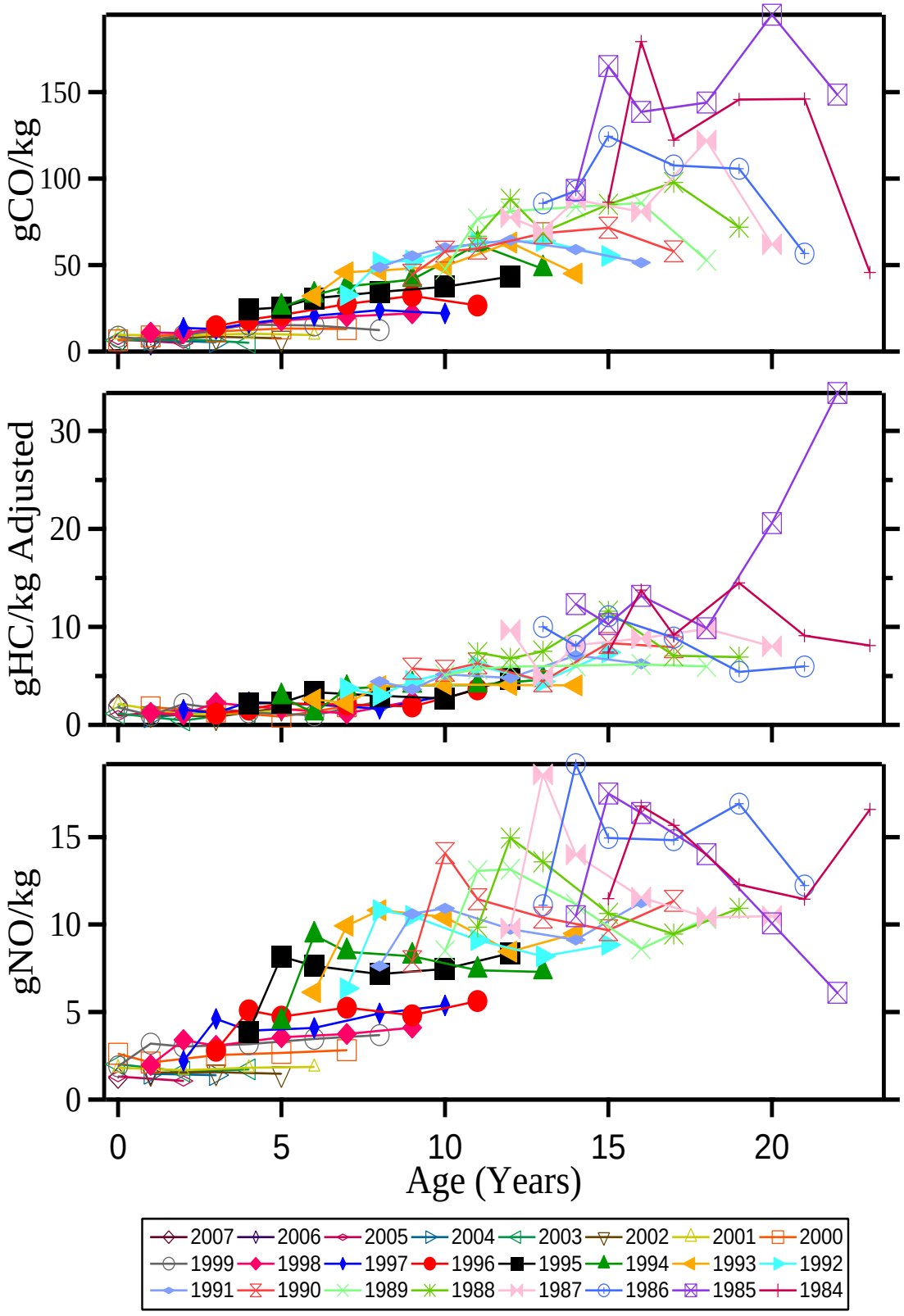

Figure 8. Mean vehicle emissions as a function of age, shown by model year. Included are data from the sites in 1998, 1999, 2000, 2002, 2004 and 2006.

The preceding analysis gives the percent of vehicle overlap but does not directly give emissions overlap. To assess the emissions 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 6.5% of the measurements that are in the top CO decile would identify an overall 43% of the total measured on-road CO. More efficiently, identification of the 1.7% of the measurements that are in the top decile for both CO and HC accounts for 25% of the total CO and 19% of the total on-road HC from these data.

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

Top 10% Decile	CO Emissions	HC[a] Emissions	NO Emissions
CO	43%	19%	8%
HC	25%	55%	7%
NO	7%	6%	50%
All	5%	6%	5%

[a]HC data used has been offset adjusted

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.[14] These vehicles also have a high probability of showing evidence of tampered or defective emission control equipment.[7, 15] 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[16], 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 5.5, 3.7, and 0.4 for CO, HC and NO, respectively. These values indicate standard deviations of 7.8 g/kg (0.06%), 5.3 g/kg (124 ppm) and 0.6 g/kg (50 ppm) for individual measurements of CO, HC and NO, respectively. These levels are consistent with the low noise level as discussed in a previous Phoenix report.[16] 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 0.8 g/kg, 0.5 g/kg, and 0.06 g/kg, respectively.

CONCLUSION

The University of Denver successfully completed the sixth year of a multi-year remote sensing study in Phoenix. Five days of fieldwork (November 13-17, 2006) were conducted on the uphill exit ramp from Hwy 202 / Sky Harbor Blvd. Westbound to Hwy 143 Southbound in Phoenix, AZ. A database was compiled containing 21,782 records for which the State of Arizona provided makes and model year information. All of these records contained valid measurements for at least CO and CO_2, and 21,731 contained valid measurements for HC and NO as well. Of these measurements, 8,873 (41%) were of vehicles measured only once. The rest were of vehicles measured at least twice. Analysis of these repeat vehicles showed that high emitters have skewed emissions distributions while low emitters have more normally distributed emissions.

The mean measurements for CO, HC, and NO were determined to be 13.9 gCO/kg, 2.2 gHC/kg, and 2.9 gNO/kg, respectively with an average model year of 2001.4. As expected, the fleet emissions observed in this study exhibited a typical skewed distribution, with the dirtiest 10% of the fleet contributing 81%, 87%, and 70% of the CO, HC, and NO emissions, respectively. An analysis of emissions as a function of model year showed a typical inverse relationship.

The 2006 data show the least dependence on VSP of any of the previous data sets. CO, HC and NO emissions are at low levels across the entire VSP range. Using vehicle specific power, the emissions of the vehicle fleet measured in 2006 were VSP adjusted to match the vehicle driving patterns of the fleet measured in 1998. Despite the fact that the current site has a higher averaged VSP than the 1998 site, the emissions are now lower than the 1998 measurements. This trend is more difficult to discern in the model year adjustments since the fleet has aged 8 years in the process and we are comparing two different sites. If we restrict our comparison to the current site, observed increases in this analysis are no larger than the estimated errors, and emission deterioration in the fleet is very small at worst.

Tracking of model year fleets through six measurements indicates that the rate of emissions deterioration continues to slow. The observed increases in emissions only slightly exceeded the standard errors of the mean, despite the age of the fleet increasing by 8 years. An analysis of high emitting vehicles showed that there is considerable overlap of CO and HC high emitters, for instance 1.7% of the fleet emits 25% of the total CO and 19% of the total HC. The noise levels in the CO, HC and NO measurement channels were determined to be low, compared with previous campaigns.[16]

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LITERATURE CITED

1. *National Air Quality and Emissions Trends Report, 2003 Special Studies Edition*, United States Environmental Protection Agency, Research Triangle Park, NC, 2003; EPA-454/R-03-005.

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**, *32*, 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: Pittsburgh, PA, 1992; Vol. II, pp. 720-739.

9. Bishop, G.A.; Stedman, D.H.; Ashbaugh, L.L. *J. Air Waste Manage. Assoc.*, **1996**, 46:667-675.

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

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. White, V. A.; Javaherian, H., *Internal Combustion Engine Air/Fuel Ratio Regulation*, US Patent 5,392,598, issued 28 February 1995.

14. Burnette, A.; Manne, G. In *Proceedings of the 16th CRC On-Road Vehicle Emissions Workshop*, CA, 2006.

15. *Remote Sensing Device High Emitter Identification with Confirmatory Roadside Inspection*, Bureau of Automotive Repair, Engineering and Research Branch, Final Report 2001-06, 2001.

16. Pokharel, S.S.; Bishop, G.A.; Stedman, D.H. *On-Road Remote Sensing of Automobile*

Emissions in the Phoenix Area: Year 2, Final report to the Coordinating Research Council, Contract E-23-4, 2000.

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

Not measured:

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

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

Invalid :

1) insufficient plume to rear of vehicle relative to cleanest air observed in front or in the rear; at least five, 10ms >160ppmm CO_2 or >400 ppmm CO. (0.2 %CO_2 or 0.5% CO in an 8 cm cell. This is equivalent to the units used for CO_2 max.) Often HD diesel trucks, bicycles.

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

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

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

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

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

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

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

A restart is an occurrence of a beam block within the 0.5 s exhaust data acquisition time. Data analysis is restarted using the clean air data collected in advance of the first blocking event. High clearance pickups typically generate one restart.

APPENDIX B: Explanation of the Az_2006.dbf database.

The Az_2006.dbf is a Microsoft FoxPro database file, and can be opened by any version of MS FoxPro. The file can be read by a number of other database management programs as well, and is available on CD-ROM or from www.feat.biochem.du.edu. The following is an explanation of the data fields found in this database:

License	Arizona license plate.
Date	Date of measurement, in standard format.
Time	Time of measurement, in standard format.
Percent_co	Carbon monoxide concentration, in percent.
Co_err	Standard error of the carbon monoxide measurement.
Percent_hc	Hydrocarbon concentration (propane equivalents), in percent.
Hc_err	Standard error of the hydrocarbon measurement.
Percent_no	Nitric oxide concentration, in percent.
No_err	Standard error of the nitric oxide measurement.
Percent_co2	Carbon dioxide concentration, in percent.
Co2_err	Standard error of the carbon dioxide measurement.
Opacity	Opacity measurement, in percent.
Opac_err	Standard error of the opacity measurement.
Restart	Number of times data collection is interrupted and restarted by a close-following vehicle, or the rear wheels of tractor trailer.
Hc_flag	Indicates a valid hydrocarbon measurement by a “V”, invalid by an “X”.
No_flag	Indicates a valid nitric oxide measurement by a “V”, invalid by an “X”.
Opac_flag	Indicates a valid opacity measurement by a “V”, invalid by an “X”.
Max_co2	Reports the highest absolute concentration of carbon dioxide measured by the remote sensor over an 8 cm path; indicates plume strength.
Speed_flag	Indicates a valid speed measurement by a “V”, an invalid by an “X”, and slow speed (excluded from the data analysis) by an “S”.
Speed	Measured speed of the vehicle, in mph.
Accel	Measured acceleration of the vehicle, in mph/s.
Ref_factor	Reference factor.
CO2_factor	CO2 factor.
Tag_name	File name for the digital picture of the vehicle.
Plate_key	Coded plate type.

Vin	Vehicle identification number.
Category	Coded vehicle category.
Make	Manufacturer of the vehicle.
Year	Model year.
Fuel	Fuel type G (gasoline), D (diesel) and N (natural gas).
Weight	Gross vehicle weight.
County	Arizona county vehicle is registered in.
City	Registrant's mailing city.
Zipcode	Registrant's mailing zip code.
Reg_St	Registrant’s mailing state.
Emis_type	Code for tested vehicle emissions type.
Init_test	8 digit date of initial emissions test.
Date_pass	8 digit date of passing emissions test.
Result_cd	Coded result of emissions test.
Waiver	Waiver status, codes are blank and Y.
Emis_area	Unsure, codes are A, B and blank.
Exp_date	License expiration date.

APPENDIX C: Temperature and Humidity Data.

Phoenix 1998 Temperature and Humidity Data								
Time	11/16 °F	11/16 %RH	11/17 °F	11/17 %RH	11/18 °F	11/18 %RH	11/19 °F	11/19 %RH
6:56	53	61	55	49	50	54	48	66
7:56	55	57	56	49	53	49	50	61
8:56	61	46	60	41	58	41	55	45
9:56	65	40	66	33	63	35	60	38
10:56	70	35	69	31	66	34	64	33
11:56	74	28	72	26	70	30	67	30
12:56	77	26	75	23	73	29	69	25
13:56	79	24	77	21	75	26	71	24
14:56	80	23	79	19	75	25	71	24
15:56	81	22	78	19	74	24	72	24
16:56	79	24	77	21	72	24	70	26

Phoenix 1999 Temperature and Humidity Data										
Time	11/15 °F	11/15 %RH	11/16 °F	11/16 %RH	11/17 °F	11/17 %RH	11/18 °F	11/18 %RH	11/19 °F	11/19 %RH
5:56	60.1	46	63	37	60.1	42	57	53	55.9	46
6:56	61	44	63	37	59	42	57	51	55	49
7:56	64	41	63	41	62.1	38	57.9	50	57	45
8:56	70	27	69.1	29	66	32	63	41	60.1	39
9:56	77	20	75	23	71.1	26	64.9	42	66.9	32
10:56	81	19	79	21	75	23	69.1	38	70	30
11:56	84	17	82.9	19	78.1	22	71.1	34	72	31
12:56	88	16	84.9	18	80.1	21	73.9	32	75	30
13:56	88	16	86	17	84	19	75	30	77	30
14:56	90	15	87.1	17	82.9	20	75.9	30	77	31
15:56	90	16	88	16	82.9	22	75.9	30	78.1	28
16:56	89.1	16	87.1	17	81	23	75	31	77	28

Phoenix 2000 Temperature and Humidity Data										
Time	11/13 °F	11/13 %RH	11/14 °F	11/14 %RH	11/15 °F	11/15 %RH	11/16 °F	11/16 %RH	11/17 °F	11/17 %RH
5:56	43	34	47	33	45	34	41	32	42	31
6:56	41	35	46	32	43	36	40	32	43	30
7:56	46	31	48	35	46	36	43	31	43	33
8:56	50	28	53	33	50	37	47	30	50	27
9:56	54	27	58	34	53	31	52	28	54	22
10:56	58	29	61	32	56	29	54	27	56	21
11:56	58	27	63	34	57	24	58	26	58	21
12:56	62	25	64	35	61	27	60	20	58	18
13:56	62	24	66	37	60	28	62	20	62	16
14:56	63	23	66	36	63	24	62	18	63	16
15:56	64	21	65	34	62	21	63	18	63	14
16:56	64	21	64	34	61	21	61	19	62	16

Phoenix 2002 Temperature and Humidity Data										
Time	11/18 °F	11/18 %RH	11/19 °F	11/19 %RH	11/20 °F	11/20 %RH	11/21 °F	11/21 %RH	11/22 °F	11/22 %RH
5:56	50	39	52	34	64	21	62	25	60	26
6:56	50	39	49	39	64	23	58	31	58	28
7:56	53	37	52	35	66	21	62	28	57	33
8:56	58	30	58	30	70	18	69	23	62	28
9:56	62	24	62	22	74	15	76	14	68	22
10:56	69	17	67	15	76	16	80	11	76	16
11:56	73	13	71	13	80	13	83	9	79	15
12:56	75	12	73	12	83	12	84	9	80	13
13:56	76	11	76	10	83	11	85	9	84	11
14:56	77	10	78	9	86	10	87	8	85	10
15:56	77	10	80	9	85	11	87	8	84	10
16:56	76	12	77	10	84	11	86	8	83	10

Phoenix 2004 Temperature and Humidity Data										
Time	11/15 °F	11/15 %RH	11/16 °F	11/16 %RH	11/17 °F	11/17 %RH	11/18 °F	11/18 %RH	11/19 °F	11/19 %RH
5:56	55	62	53	83	53	77	55	77	55	69
6:56	60	46	54	80	53	74	56	72	54	72
7:56	61	44	56	75	55	72	56	72	56	67
8:56	64	38	59	67	59	62	61	58	59	60
9:56	65	37	62	58	62	58	64	52	62	56
10:56	68	36	66	50	67	49	68	47	66	49
11:56	69	38	69	44	67	49	70	42	69	42
12:56	60	72	70	41	69	44	71	41	69	42
13:56	60	75	70	41	71	41	72	40	71	38
14:56	63	65	71	36	72	38	74	37	73	33
15:56	62	73	72	38	72	40	74	37	73	32
16:56	60	84	71	41	71	36	72	40	71	35

Phoenix 2006 Temperature and Humidity Data										
Time	11/13 °F	11/13 %RH	11/14 °F	11/14 %RH	11/15 °F	11/15 %RH	11/16 °F	11/16 %RH	11/17 °F	11/17 %RH
5:51	54	47	54	42	55	36	53	27	54	29
6:51	54	49	53	41	57	25	53	31	53	30
7:51	55	43	54	40	57	25	54	30	56	26
8:51	56	42	58	35	66	13	61	19	60	24
9:51	58	39	63	29	68	11	66	16	67	17
10:51	64	28	66	25	70	10	73	9	72	13
11:51	67	25	70	19	72	9	75	8	75	11
12:51	71	22	72	19	75	7	78	7	77	10
13:51	72	20	76	18	79	5	79	7	78	9
14:51	73	20	74	20	79	5	80	6	82	7
15:51	74	18	73	21	80	5	80	6	81	7
16:51	72	19	73	22	79	5	80	6	81	7

APPENDIX D: Sample Calculation of Vehicle Specific Power Adjusted Vehicle Emissions using data from Chicago 1997 and 1998.

1997 (Measured)	VSP Bin	Mean NO (ppm)	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)	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 Measurements	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: Sample Calculation of Model Year Adjusted Fleet Emissions using data from Chicago 1997 and 1998

1997 (Measured)	Model Year	Mean NO (ppm)	No. of Measurements	Total Emissions
	83	690	398	274620
	84	720	223	160560
	85	680	340	231200
	86	670	513	343710
	87	690	588	405720
	88	650	734	477100
	89	610	963	587430
	90	540	962	519480
	91	500	1133	566500
	92	450	1294	582300
	93	460	1533	705180
	94	370	1883	696710
	95	340	2400	816000
	96	230	2275	523250
	97	150	2509	376350
			17748	7266110
			Mean NO (ppm)	**409**
1998 (Measured)	Model Year	Mean NO (ppm)	No. of Measurements	Total Emissions
	83	740	371	274540
	84	741	191	141531
	85	746	331	246926
	86	724	472	341728
	87	775	557	431675
	88	754	835	629590
	89	687	1036	711732
	90	687	1136	780432
	91	611	1266	773526
	92	538	1541	829058
	93	543	1816	986088
	94	418	2154	900372
	95	343	2679	918897
	96	220	2620	576400
	97	177	3166	560382
			20171	9102877
			Mean NO (ppm)	**451**
1998 (Adjusted)	Model Year	'98 Mean NO (ppm)	'97 No. of Meas.	Total Emissions
	83	740	398	294520
	84	741	223	165243
	85	746	340	253640
	86	724	513	371412
	87	775	588	455700
	88	754	734	553436
	89	687	963	661581
	90	687	962	660894
	91	611	1133	692263
	92	538	1294	696172
	93	543	1533	832419
	94	418	1883	787094
	95	343	2400	823200
	96	220	2275	500500
	97	177	2509	444093
			17748	8192167
			Mean NO (ppm)	**462**

APPENDIX F: Field Calibration Record.

1999				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
11/15	12:05	1.02	.91	.76
11/16	6:55	1.02	1.06	.98
11/16	10:00	.99	.80	.84
11/17	6:00	1.37	1.04	1.03
11/17	12:28	1.1	.99	.92
11/18	5:50	1.4	1.1	.98
11/18	13:00	1.18	1.0	.98
11/19	6:00	1.47	1.18	1.08
11/19	13:00	1.14	.95	.82

2000				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
11/13	8:00	1.48	1.22	1.68
11/13	12:30	1.04	0.96	1.06
11/14	6:00	1.47	1.25	1.66
11/14	12:30	1.18	1.00	1.29
11/15	5:40	1.62	1.33	1.76
11/15	12:45	1.17	0.98	1.23
11/16	5:35	1.52	1.30	1.68
11/16	12:20	1.24	1.10	1.50
11/17	6:00	1.76	1.55	2.34
11/17	11:07	1.27	1.11	1.66

2002				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
11/18	6:15	1.538	1.26	0.097
11/18	10:30	1.16	0.98	1.49
11/19	5:40	1.61	1.28	1.74
11/19	10:30	1.32	1.07	1.52
11/20	5:40	1.19	0.98	1.37
11/20	10:30	1.05	0.84	1.276
11/21	5:40	1.25	1.03	1.83
11/21	10:10	1.04	0.85	1.42
11/21	12:30	0.98	0.83	1.17
11/22	5:50	1.40	1.12	1.91
11/22	11:15	1.05	0.88	1.30

2004				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
11/15	7:10	1.37	1.07	2.3
11/15	11:10	1.17	0.92	1.16
11/16	6:10	1.66	1.33	2.5
11/16	10:15	1.27	1.04	1.63
11/17	5:55	1.53	1.18	2.6
11/17	9:05	1.56	1.22	2.25
11/17	12:40	1.18	0.96	1.75
11/18	5:40	1.47	1.2	1.94
11/18	9:20	1.37	1.07	1.73
11/18	13:10	1.10	0.9	1.56
11/19	5:40	1.6	1.23	2.64
11/19	9:40	1.26	0.98	1.87
11/19	12:15	1.23	0.93	1.73

2006				
Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
11/13	5:55	1.6	1.2	1.2
11/13	12:30	1.25	0.96	0.92
11/14	5:45	1.4	1.1	1.24
11/14	12:20	1.06	0.88	1.04
11/15	6:00	1.4	1.14	1.36
11/15	10:40	1.2	0.95	1.2
11/16	5:50	1.6	1.3	1.7
11/16	10:00	1.4	1.1	1.4
11/16	12:55	1.05	0.87	1.0
11/17	6:55	1.75	1.4	1.5
11/17	9:10	1.37	1.0	1.21