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On-Road Remote Sensing of Automobile Emissions in the Chicago Area: Year 3

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EXECUTIVE SUMMARY

The University of Denver has completed the first three years of a five-year remote sensing study in the Chicago area. The remote sensor used in this study is capable of measuring the ratios of CO, HC, and NO to CO_2 in motor vehicle exhaust. From these ratios, we calculate the percent concentrations of CO, CO_2, HC and NO in the exhaust that would be observed by a tailpipe probe, corrected for water and any excess oxygen not involved in combustion. Mass emissions per mass or volume of fuel can also be determined. The system used in this study was configured to determine the speed and acceleration of the vehicle, and was accompanied by a video system to record the license plate of the vehicle.

The third year of this study involved four days of fieldwork conducted at the on-ramp from Algonquin Rd. to eastbound I-290 in northwest Chicago. A database was compiled containing 23,088 records for which the State of Illinois provided make and model year information. All of these records contained valid measurements for at least CO and CO_2, and 23,024 records contained measurements of HC and NO as well.

The mean CO, HC and NO emissions for the fleet measured in the third year of this study were 0.35%, 179 ppm and 378 ppm, respectively. These values are amongst the lowest we have observed for a statistically significant fleet, and are considerably lower than those for fleets previously measured in the Chicago area.

Vehicle emissions as a function of vehicle specific power revealed that NO emissions show a positive dependence on specific power, while HC emissions show a negative dependence on specific power – the expected trends. Carbon monoxide emissions show a slight negative dependence on specific power in the range from –5 to 30 kW/tonne.

Using vehicle specific power, it was possible to adjust the emissions of the vehicle fleet measured in 1999 and 1998 to match the vehicle driving patterns of the fleet measured in 1997. After doing so, the CO and NO emissions of the 1999 and 1998 fleets were lower than the emissions of the 1997 fleet. The HC emissions were found to have slightly increased.

A model year adjustment was applied to a fleet of specific model year vehicles to track deterioration. Using a fleet of 1983 to 1997 model year vehicles, the deterioration of the fleet was demonstrated as indicated by higher CO, HC and NO emissions. Finally, tracking of model year fleets through the three years of study showed that decreased emissions of newer model year vehicles are more an effect of technology than of age. In other words, emissions of newer cars appear to deteriorate very slowly with increasing age.

The unique nature of the 1999 data set, where Chicago was in the middle of a transition into a centralized and biennial IM240 emissions testing program, allowed for a IM benefit analysis. This analysis showed a small but significant decrease in average CO and HC emissions as a result of I/M. No significant decrease in NO was seen.

INTRODUCTION

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

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

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

The remote sensor used in this study was developed at the University of Denver for measuring the pollutants in motor vehicle exhaust, and has previously been described in the literature.[4,5] The instrument consists of a non-dispersive infrared (IR) component for detecting carbon monoxide, carbon dioxide (CO_2), and hydrocarbons, and a dispersive ultraviolet (UV) spectrometer for measuring nitric oxide. The source and detector units are positioned on opposite sides of the road in a bi-static arrangement. 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 an ultraviolet spectrometer. The UV unit is then capable of quantifying nitric oxide by measuring an absorbance band at 226.5 nm in the ultraviolet spectrum and comparing it to a calibration spectrum in the same region.

The exhaust plume path length and density of the observed plume are highly variable from vehicle to vehicle, and are dependant upon, among other things, the height of the vehicle's exhaust pipe, wind, and turbulence behind the vehicle. For these reasons, the remote sensor can only directly measure ratios of CO, HC or NO to CO_2. The ratios of CO, HC, or NO to CO_2, termed Q, Q' and Q'' respectively, are constant for a given exhaust plume, and on their own are useful parameters for describing a hydrocarbon combustion system. This study reports measured emissions as %CO, %HC and %NO in the exhaust gas, corrected for water and excess oxygen not used in combustion. However, these percent emissions can be directly converted into mass emissions by the equations shown below.

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

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

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

$$\frac{\text{moles pollutant}}{\text{moles C}} = \frac{\text{pollutant}}{CO + CO_2 + 3HC} = \frac{(\text{pollutant}/CO_2)}{(CO/CO_2) + 1 + 3(HC/CO_2)}$$

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.

Quality assurance calibrations are performed twice daily in the field unless observed voltage readings or meteorological changes are judged to warrant more frequent calibrations. A puff of gas containing certified amounts of CO, CO_2, propane and NO is released into the instrument's path, and the measured ratios from the instrument are then compared to those certified by the cylinder manufacturer (Praxair). These calibrations account for day-to-day variations in instrument sensitivity and variations in ambient CO_2 levels caused by local sources, atmospheric pressure and instrument path length. Since propane is used to calibrate the instrument, all hydrocarbon measurements reported by the remote sensor are as propane equivalents.

Studies sponsored by the California Air Resources Board and General Motors Research Laboratories have shown that the remote sensor is capable of CO measurements that are correct to within ±5% of the values reported by an on-board gas analyzer, and within ±15% for HC.[6,7] The NO channel used in this study has been extensively tested by the University of Denver, but we are still awaiting the opportunity to participate in an extensive blind study and instrument intercomparison to have it independently validated. Tests involving a late-model low-emitting vehicle indicate a detection limit (3σ) of 25 ppm for NO, with an error measurement of ±5% of the reading at higher concentrations. Appendix A gives a list of 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, are also recorded on the video image. The images are stored on videotape, so that license plate information may be incorporated into the emissions database during post-processing. A device to measure the speed and acceleration of vehicles driving past the remote sensor was also used in this study. The system consists of a pair of infrared emitters and detectors (Banner Industries) which generate a pair of infrared beams passing across the road, 6 feet apart and approximately 2 feet above the surface. Vehicle speed is calculated from the time that passes between the front of the vehicle blocking the first and the second beam. To measure vehicle acceleration, a second speed is determined from the time that passes between the rear of the vehicle unblocking the first and the second beam. From these two speeds, and the time difference between the two speed measurements, acceleration is calculated, and reported in mph/s. 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 1999, under CRC contract no. E-23-4. Measurements were made on four consecutive weekdays, from Monday, September 20 to Thursday, September 23. The measurement location used in this study was the on-ramp from Algonquin Rd. to eastbound I-290 (S.H. 53) in northwest Chicago. Although this highway is officially designated as an east/west thoroughfare, traffic is actually travelling in a north/south direction at Algonquin Rd. A map of the measurement location is shown in Figure 1. The on-ramp serves both eastbound and westbound traffic on Algonquin Rd., and has an uphill grade of approximately 1.5°. Appendix C gives temperature and humidity data for the 1997, 1998 and 1999 studies from Chicago O'Hare Airport, approximately 6 miles southeast of the measurement site. This is the third year of a study to characterize motor vehicle emissions and deterioration in the Chicago area.

RESULTS AND DISCUSSION

Following the four days of data collection in September of 1999, 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 23,088 records with make and model year information and valid measurements for at least CO and CO_2. Most of these records also contain valid measurements for HC and NO as well. The validity of the attempted measurements is summarized in Table 1. The table describes the data reduction process beginning with the number of attempted measurements and ending with the number of records containing both valid emissions measurements and vehicle registration information. An attempted measurement is defined as a beam block followed by a half second of data collection. If the data collection period is interrupted by another beam block from a close following vehicle, the measurement attempt is aborted and an attempt is made at measuring the second vehicle. In this case, the beam block from the first vehicle is not recorded as an attempted measurement. Invalid measurement attempts arise when the vehicle plume is highly diluted, or the reported error in the ratio of the pollutant to CO_2 exceeds a preset limit. See Appendix A. The greatest loss of data in this process occurs during the plate reading process, when out-of-state vehicles and vehicles with unreadable plates are omitted from the database.

Table 1: Validity summary.

	CO	HC	NO
Attempted Measurements	28,925		
Valid Measurements	26,809	26,722	26,790
Percent of Attempts	92.7%	92.4%	92.6%
Submitted Plates	23,769	23,672	23,721
Percent of Attempts	82.2%	81.8%	82.0%
Percent of Valid Measurements	88.7%	88.6%	88.5%
Matched Plates	23,088	23,024	23,072
Percent of Attempts	79.8%	79.6%	79.8%
Percent of Valid Measurements	86.1%	86.2%	86.1%
Percent of Submitted Plates	97.1%	97.3%	97.3%

The percent validity of the 1999 measurements is very similar to the validity seen in the previous two years, with approximately 80% of attempted measurements being valid and plate matched.

Table 2 is the data summary; included are summaries of previous remote sensing databases collected by the University of Denver at the I-290 and Algonquin Rd. site. These other measurements were conducted in September of 1997 and 1998.

Table 2. Data summary.

	1999	1998	1997
Mean CO (%) (g/kg of fuel)	0.35 (44.6)	0.39 (49.7)	0.45
Median CO (%)	0.09	0.15	0.14
Percent of Total CO from Dirtiest 10% of the Fleet	63.0	60.2	60.2
Mean HC (ppm) (g/kg of fuel)	179 (3.6)	250 (4.9)	210
Median HC (ppm)	120	170	130
Percent of Total HC from Dirtiest 10% of the Fleet	47.3	57.5	43.8
Mean NO (ppm) (g/kg of fuel)	378 (5.3)	405 (5.7)	400
Median NO (ppm)	121	140	160
Percent of Total NO from Dirtiest 10% of the Fleet	51.1	46.8	46.6
Mean Model Year	1994.3	1993.6	1992.7
Mean Speed (mph)	25.8	24.7	25.1
Mean Acceleration (mph/s)	0.23	0.78	0.05

Compared to the fleets measured in 1997 and 1998, the fleet measured in the current study is considerably lower emitting. This difference is most likely due to the technological advances in the emissions control systems of the modern fleet.

Figure 2 shows the distribution of CO, HC and NO emissions by percent or ppm category from the data collected in Chicago in 1999. The black bars show the percentage of the fleet in a given emissions category, and the gray bars show the percentage of the total emissions contributed by the given category. This figure illustrates the skewed nature of automobile emissions, showing that the lowest emission category is occupied by no less than 70% of the fleet (for NO) and as much as 90% of the fleet (for CO). The fact that the cleanest 91% of the fleet is responsible for only 40% of the CO emissions further demonstrates how the emissions picture can be dominated by a small number of high-emitting vehicles. The skewed distribution was also seen in the 1997 and 1998 data and is represented by the consistent high values of percent of total emissions from the dirtiest 10% of the fleet (See Table 2). The large number of negative values seen in the lowest hydrocarbon emission category (≤200 ppm) of previous years' data was not as significant in 1999. Thus, the lowest HC category in 1999 contributes significantly to the total emissions.

The inverse relationship between vehicle emissions and model year is shown in Figure 3, for data collected in 1997, 1998 and 1999. The plot of NO emissions vs. model year rises rather sharply, at least compared to the plots for CO and HC, and then appears to level out in model years prior to 1989. This "leveling out" phenomenon has been observed previously,[5,8] 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 emissions with age. The tendency for the emissions of the most recent model year vehicles to increase slightly has been reported previously,[9] and we believe this is due to a plate matching artifact. It is possible that some older vehicles were sold in the time period between data collection (in September) and plate matching by the State of Illinois (April for 1997, January for 1998 and December for 1999), and replaced with new vehicles bearing the same license plate. This would result in some older vehicles (with comparatively higher emissions) appearing in the database as late model vehicles.

Plotting vehicle emissions by model year for data collected in 1999, with each model year divided into emission quintiles, results in the plots shown in Figure 4. The bars represent the mean emissions for each quintile, and are not meant to account for the number of vehicles in each model year. This figure illustrates that the cleanest 40% of the vehicles, regardless of model year, make an essentially negligible contribution to the total fleet emissions. The results shown here demonstrate that vehicle age alone cannot be used as an indicator of vehicle emissions, and that all vehicles of a given model year do not have the same emissions.

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

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

where SP 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 1997, 1998 and 1999 databases. This equation, in common with all dynamometer studies, does not include any load effects arising from road curvature. The emissions data were binned according to vehicle specific power, and illustrated in Figure 5. All of the specific power bins contain at least 100 measurements. As expected, NO emissions show a positive dependence on specific power while HC emissions show a negative dependence on specific power. Carbon monoxide emissions also show a slight negative dependence on specific power in this range.

Table 3. Specific power adjusted fleet emissions (-5 to 20 kW/tonne only).

	1997	1998 (measured)	1998 (adjusted)	1999 (measured)	1999 (adjusted)
Mean CO (%)	0.43	0.38	0.42	0.35	0.41
Mean HC (ppm)	209	237	286	177	222
Mean NO (ppm)	394	397	347	359	287

Using vehicle specific power, it is possible to eliminate the influence of driving behavior from the mean vehicle emissions for the 1997, 1998 and 1999 databases. Table 3 shows the mean emissions from all vehicles in the 1997, 1998 and 1999 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 1997, 1998 and 1999 databases, as shown in Table 2. Also shown in Table 3 are the mean emissions for the 1998 and 1999 databases, adjusted for specific power. This correction is accomplished by applying the mean vehicle emissions for each specific power bin in Figure 5, for 1998 and 1999, to the vehicle distribution, by specific power, for each bin from 1997. A sample calculation, for the specific power adjusted mean NO emissions, is shown in Appendix D. It can be seen from Table 3 that the adjusted mean emissions for 1998 and 1999 are similar for CO to the 1997 fleet average, whereas the unadjusted means do not correlate as well.

In the case of NO, the unadjusted values do not show a trend with time, while the adjusted means show a decrease in emissions with time, as would be expected from technological improvements. These results also indicate that the higher mean NO emissions for the 1998 and 1999 fleets, as shown in Table 2, could be a result of the higher mean specific power. In fact, higher vehicle specific power has been seen at the Chicago site in each subsequent year (notice the 25 and 30 kW/tonne bins in 1999) and may be due to less congestion on I-290. Congestion on the highway, resulting from construction (1997) or high traffic volume (rush hour), causes back-ups on the ramp which lowers speed and acceleration.

The higher HC emissions for the adjusted 1998 data may be indicative of a problem with the HC channel of the instrument used in this study. We have subsequently discovered and rectified a power supply problem, which apparently interfered with the HC detector and cooler. Thus, the adjusted 1999 HC mean emission is lower than the adjusted 1998 mean. It is not as low as the original 1997.

A similar correction can be applied to a fleet of specific model year vehicles to track deterioration, provided we use as a baseline only model years measured in the 1997 study. Table 4 shows the mean emissions for all vehicles from model year 1983 to 1997, as measured in 1997, 1998 and 1999. Applying the vehicle distribution by model year from 1997 to the mean emissions by model year from 1998 and 1999 yields the model year adjusted fleet emissions. A sample calculation, for the model year adjusted mean NO emissions, is shown in Appendix E. Both the CO and NO emissions show a noticeable deterioration effect as expected. The HC emissions in 1999, however, seem to have decreased from 1998 and returned approximately to the same level as in 1997. This effect is most likely due to the cooling problem in the HC detector in 1998.

Table 4. Model year adjusted fleet emissions (MY 1983-1997 only).

	1997	1998 (measured)	1998 (adjusted)	1999 (measured)	1999 (adjusted)
Mean CO (%)	0.45	0.44	0.45	0.43	0.49
Mean HC (ppm)	214	260	265	200	217
Mean NO (ppm)	409	451	462	463	491

Vehicle deterioration can be illustrated by Figure 6, which shows the mean emissions of the 1984 to 1998 model year fleet as a function of vehicle age. The first point for each model year was measured in 1997, the second point in 1998, and the third in 1999. It should be noted again that the 1998 means for HC are offset high due to a detector problem during that study. Thus, these points are not very significant and are discarded in the following analysis. Vehicle age was determined by the difference between the year of measurement and the vehicle model year. Most model years show a noticeable deterioration from one year to the next for NO emissions. In the case of CO emissions, however, the six most recent model years show only a slight increase in emissions with age. Though this increase may not prove to be statistically significant for each individual model year, the set of slopes from every model year is significant. This slight rise is not nearly as great as the slope in emissions as a function of model year. Thus, the data seem to indicate that technological enhancements in more recent model years have brought and kept emissions down, and the slope in the plot of emissions versus model year is more a result of new technologies than of vehicle age.

Factors confounding this analysis would be variables that were not controlled among the three years of study, including ambient conditions such as temperature. Temperature, however, decreased from 1997 to 1998 and 1999. We have seen from an analysis of IM240 data that a decrease in ambient temperature tends to decrease CO and HC emissions. Thus, the fact that there was an increase in CO emissions for each model year during subsequent years of the study while at the same time temperatures decreased, indicates that the increase in emissions as a function of age is underestimated.

Finally, an Inspection and Maintenance (I/M) program benefit study was conducted with this year's data set. The data set from 1999 is unique because the on-road measurements were taken while the Chicago area was in transition from a centralized and biennial idle emissions testing program to a centralized and biennial IM240 program. Thus, vehicles passing the on-road measurement site may or may not have had to pass the IM240 test. A database containing records for the vehicles we had measured and which had undergone an IM240 test was obtained. Once the license plates were matched with the IM records, the vehicles that had been subject to the IM240 were easily discernable from those that had not. Most of the IM240 tested vehicles were even model years. The IM240 tested fleet also included some odd model year vehicles, which are apparently cars that have changed ownership. The newest model year vehicles (1996-) were not tested.

In the manner of a previous study in Denver,[11] the difference in average emissions between vehicles that had certainly undergone the IM240 test and all other vehicles was calculated. In order to calculate the uncertainty in these differences, each day of on-road measurement was treated as an independent sample, and analyzed using normal statistics. One complication was the difference in model year profile between the tested and untested fleets. To correct for this, a model year correction was applied as described above, where the untested fleet was subject to the model year distribution of the tested fleet.

This analysis gave the apparent benefit of IM240 over idle testing to be 7.1±2.2, 13.5±5.8 and –2.3±3.0 percent for CO, HC and NO, respectively. These figures indicate a small but significant emissions reduction benefit in terms of CO and HC, but no significant benefit in terms of NO emissions. Furthermore, these values are overestimates because emissions from the late model year vehicles (1996-) are not taken into account because of the model year adjustment. While the large number of new vehicles contributes a significant amount to the overall emissions of the fleet, the Illinois I/M program excludes these vehicles from testing. Thus, when a percent emissions reduction is calculated, a significant portion of existing emissions is left out. For the 1999 Chicago data set, model years 1983-1995 account for 78% of overall CO vehicle emissions, 67% of overall HC emissions and 75% of NO emissions. Taking this into account reduces the apparent IM240 benefit to 5.5% and 9.0% for CO and HC, respectively. Note that this analysis is on-road emissions for the specific fleet as measured at this site.

CONCLUSIONS

The University of Denver has completed the first three years of a five-year remote sensing study of motor vehicle emissions and deterioration in the Chicago area. A database was compiled containing 23,088 records for which the State of Illinois provided make and model year information. All of these records contained valid measurements for at least CO and CO_2, and 23,024 records contained valid measurements for HC and NO as well. The mean CO, HC and NO emissions for the fleet measured in this study were 0.35%, 179 ppm and 378 ppm, respectively. The fleet emissions observed at the site in

Chicago exhibited a skewed distribution, with most of the total emissions contributed by a relatively small percentage of the vehicles. Having collected data for three consecutive years at the same time and location, it was possible to show the deterioration of a specific model year fleet from one year to the next. It was seen that more recent model year vehicles have lower emissions quite independent of age. An analysis of IM effectiveness showed small but significant decreases in average CO and HC emissions as a result of IM240. Continuing studies at the same site should allow further insight to be gained as to the effects of motor vehicle deterioration on fleet emissions. Data are available on CD-ROM for 1997, 1998 and 1999 studies from CRC.

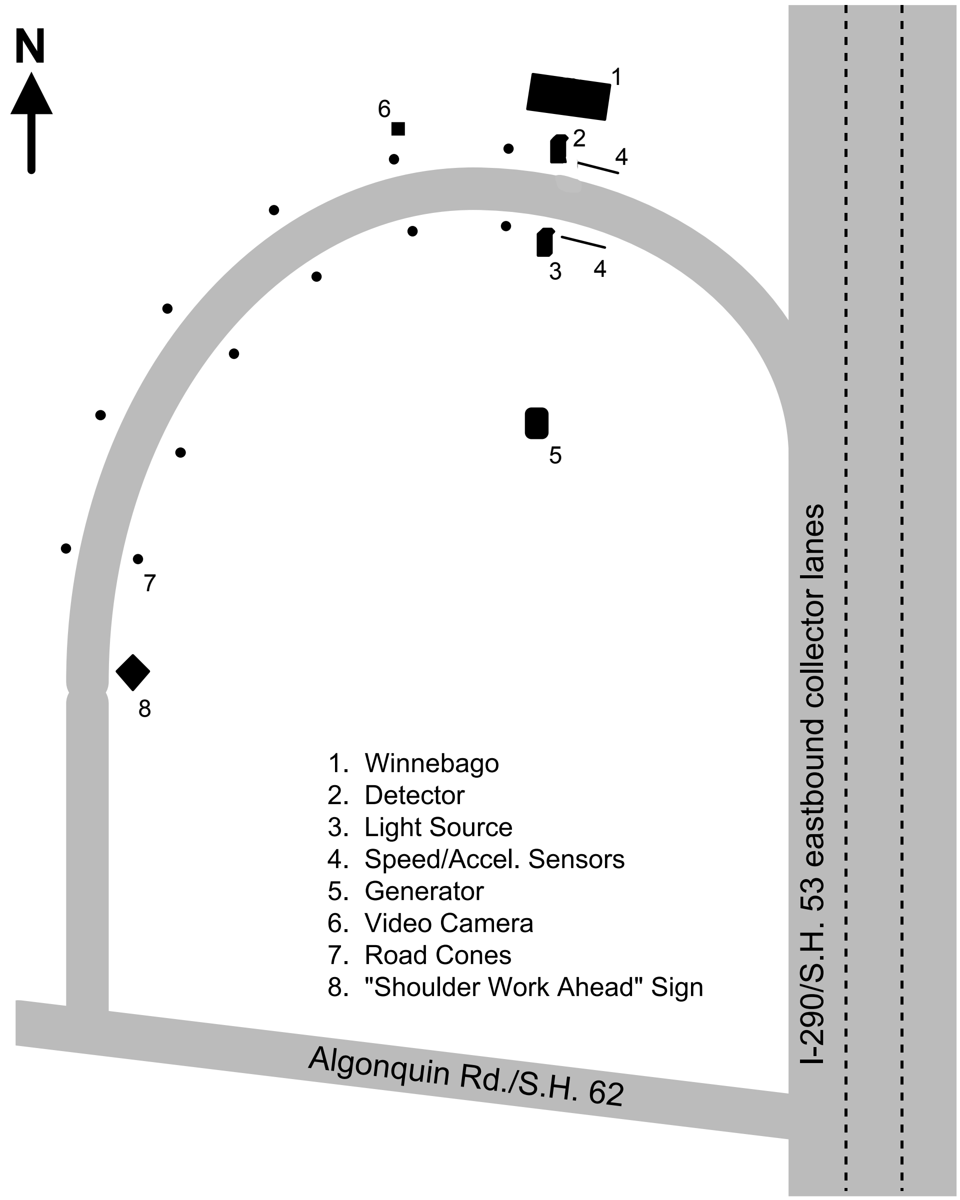

Figure 1. Area map of the on-ramp from Algonquin Road to eastbound I-290 in northwest Chicago, showing remote sensor configuration and safety equipment.

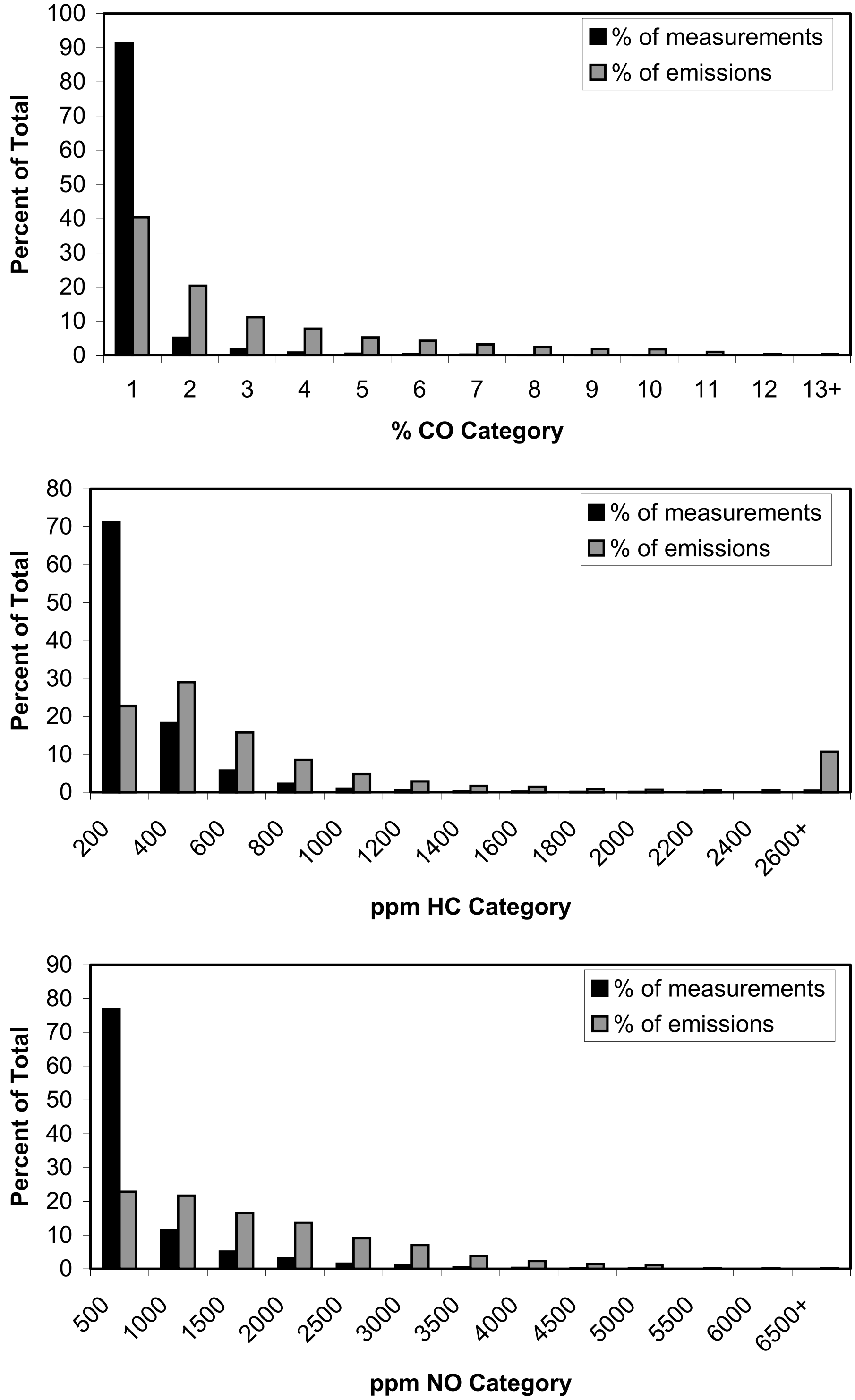

Figure 2. Emissions distribution showing the percentage of the fleet in a given emissions category (black bars) and the percentage of the total emissions contributed by the given category (gray bars).

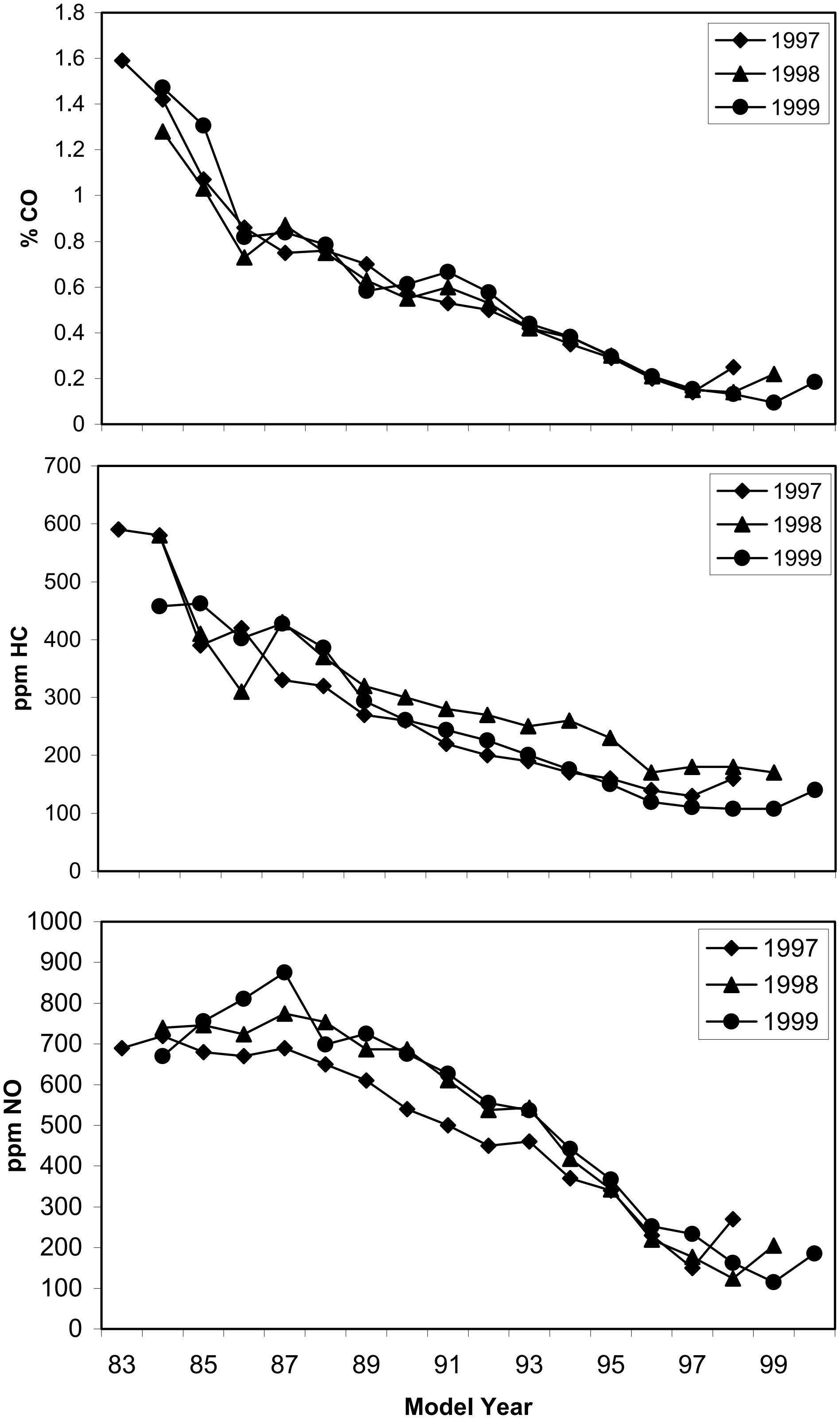

Figure 3. Mean vehicle emissions illustrated as a function of model year.

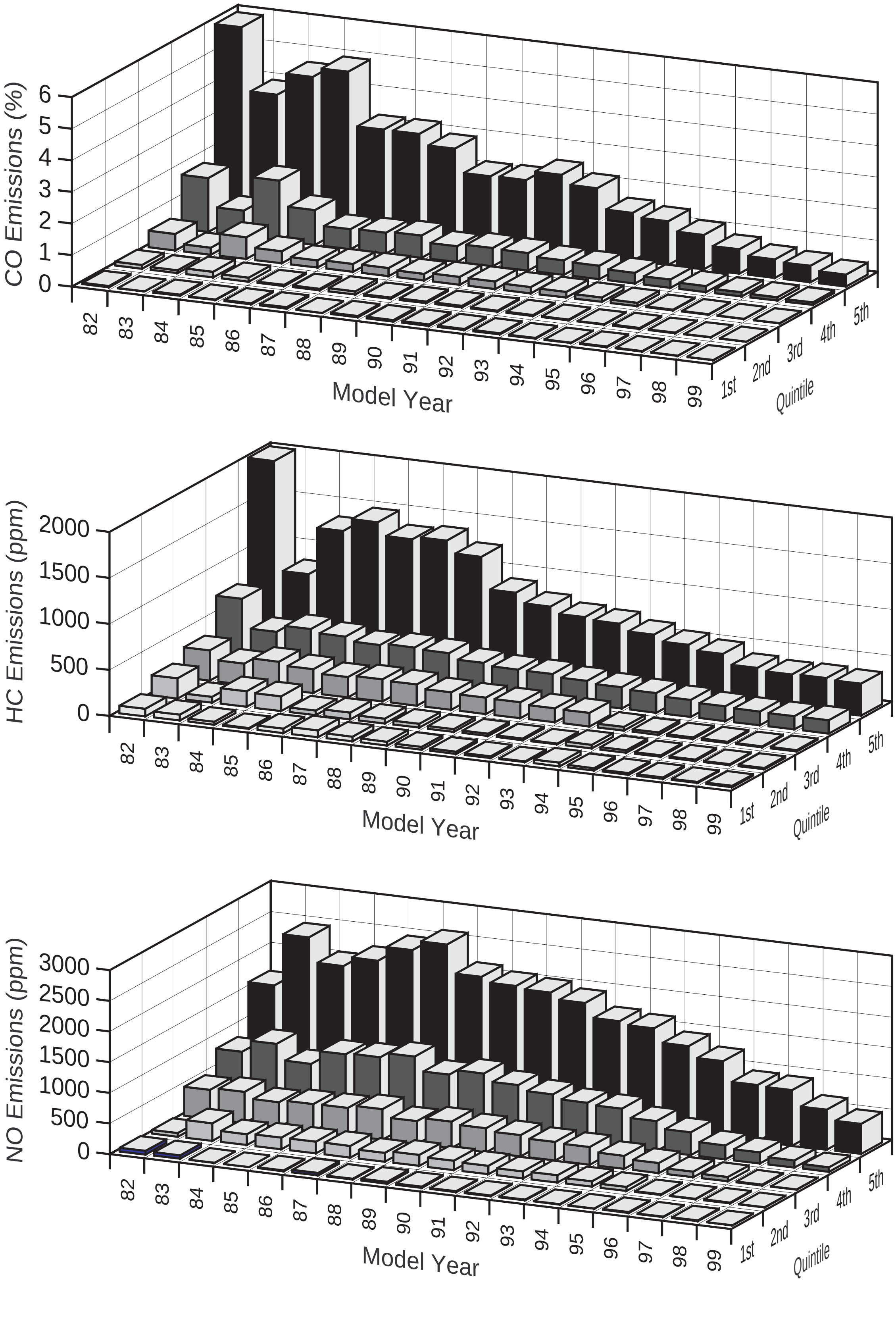

Figure 4. Vehicle emissions by model year, divided into quintiles.

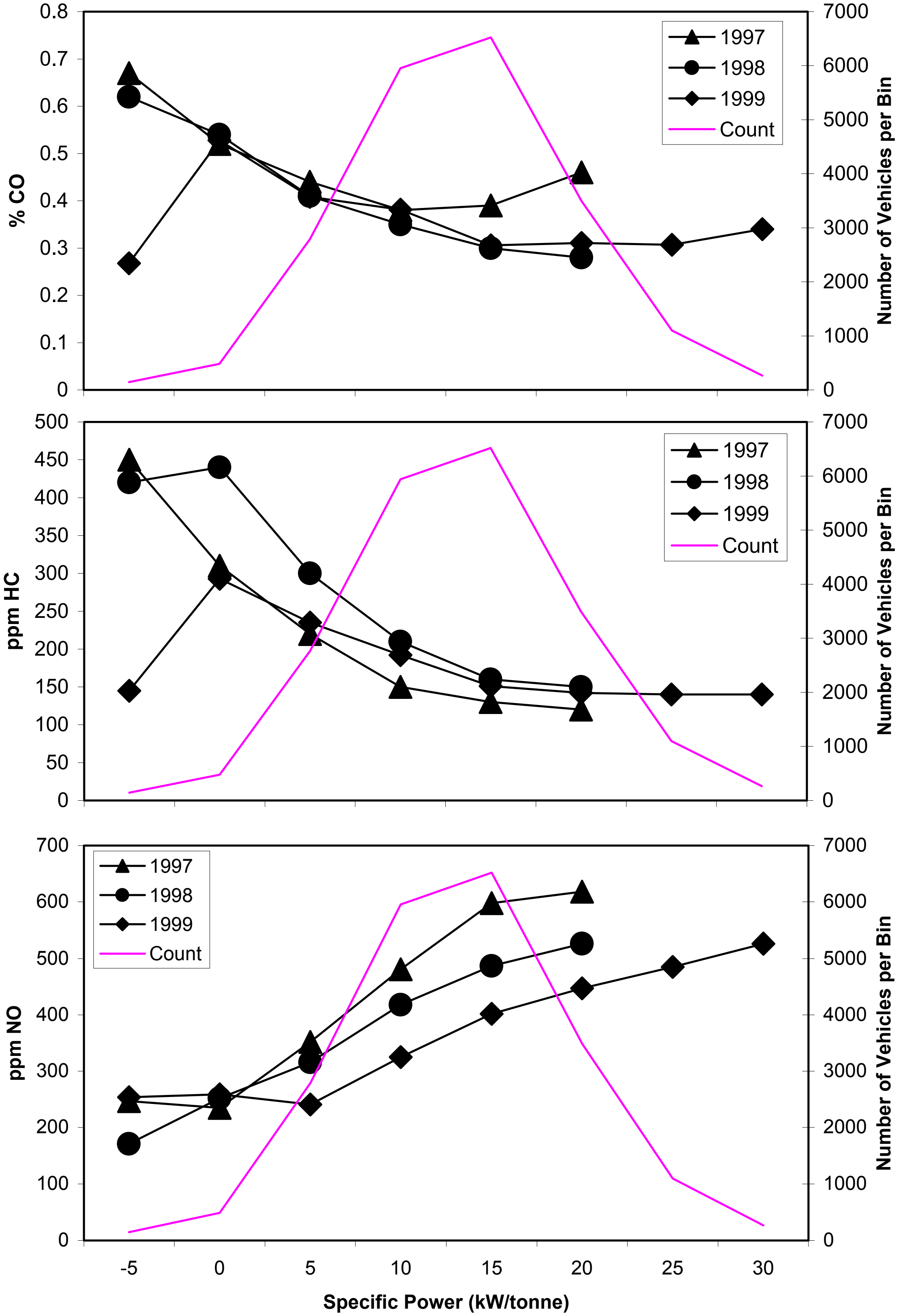

Figure 5. Vehicle emissions as a function of vehicle specific power.

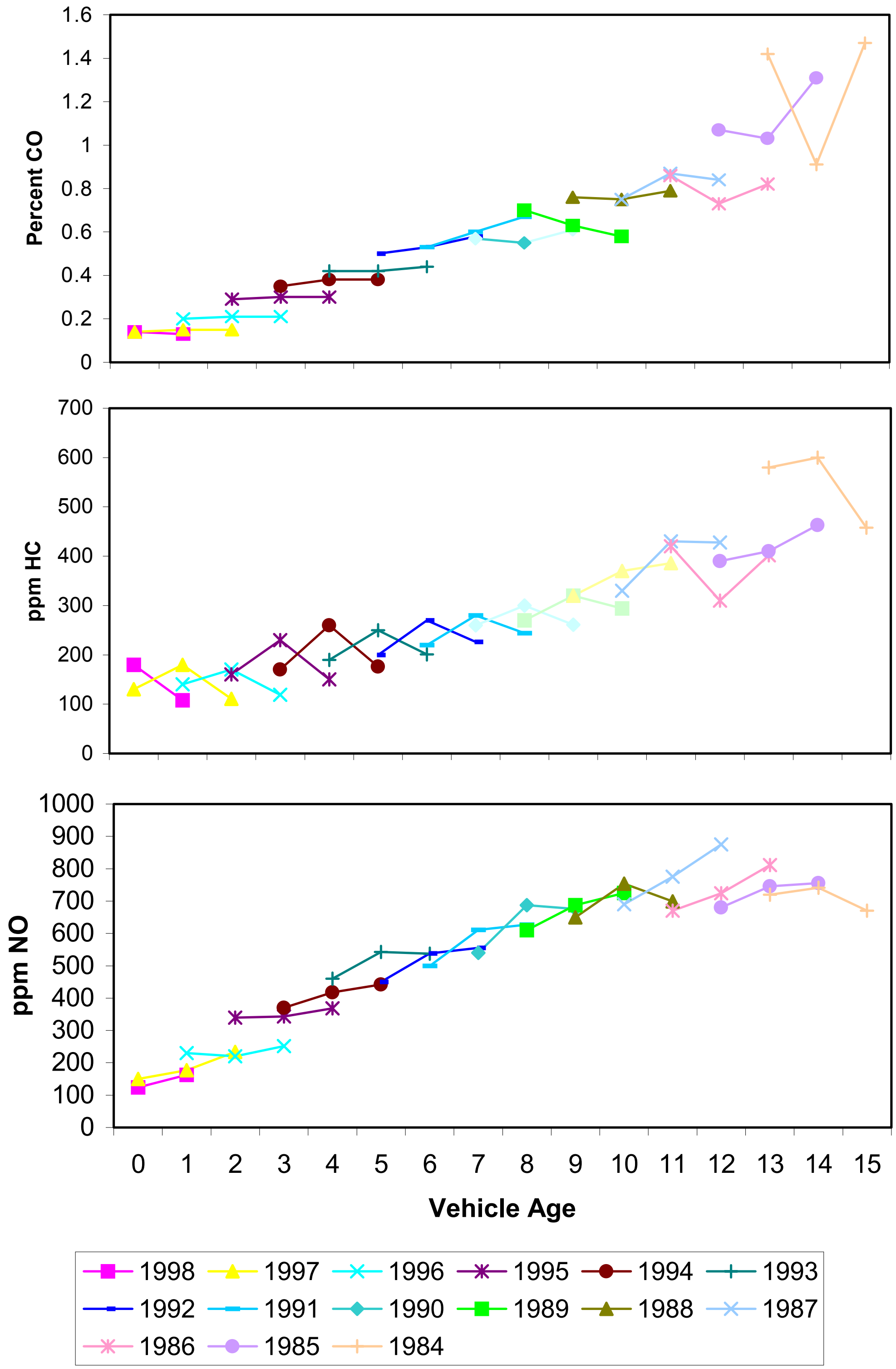

Figure 6. Mean vehicle emissions as a function of age, shown by model year.

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

Not measured:

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

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

Invalid :

1) Insufficient plume to rear of vehicle relative to cleanest air observed in front or in the rear; at least five, 10ms averages >0.25% CO_2 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_99.dbf database.

The ill_99.dbf is a Microsoft Foxpro database file, and can be opened by any version of MS Foxpro, regardless of platform. The following is an explanation of the data fields found in this database:

License	Illinois license plate
Date	Date of measurement, in standard format.
Time	Time of measurement, in standard format.
Percent_co	Carbon monoxide concentration, in percent.
Co_err	Standard error of the carbon monoxide measurement.
Percent_hc	Hydrocarbon concentration (propane equivalents), in percent.
Hc_err	Standard error of the hydrocarbon measurement.
Percent_no	Nitric oxide concentration, in percent.
No_err	Standard error of the nitric oxide measurement
Percent_co2	Carbon dioxide concentration, in percent.
Co2_err	Standard error of the carbon dioxide measurement.
Opacity	Opacity measurement, in percent.
Opac_err	Standard error of the opacity measurement.
Restart	Number of times data collection is interrupted and restarted by a close-following vehicle, or the rear wheels of tractor trailer.
Hc_flag	Indicates a valid hydrocarbon measurement by a “V”, invalid by an “X”.
No_flag	Indicates a valid nitric oxide measurement by a “V”, invalid by an “X”.
Opac_flag	Indicates a valid opacity measurement by a “V”, invalid by an “X”.
Max_co2	Reports the highest absolute concentration of carbon dioxide measured by the remote sensor; indicates the strength of the observed plume.
Speed_flag	Indicates a valid speed measurement by a “V”, an invalid by an “X”, and slow speed (excluded from the data analysis) by an “S”.
Speed	Measured speed of the vehicle, in mph.
Accel	Measured acceleration of the vehicle, in mph/s.
Lic_type	Unknown.
Exp_month	Indicates the month the current registration expires.
Exp_year	Indicates the year the current registration expires.
Address_2	Indicates the city, state, and zip code of the registrants’ address.
Year	Model year of the vehicle.

Make	Manufacturer of the vehicle.
Body_style	Type of vehicle.
Vin	Vehicle identification number.
Owner_code	Unknown.
Make_abrv	Abbreviated manufacturer.

APPENDIX C: Temperature and Humidity Data

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

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

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

APPENDIX D: Calculation of Vehicle Specific Power Adjusted Vehicle Emissions

1997 (Measured)	VSP Bin	Mean NO (ppm)	No. of Measurements	Total Emissions
	-5	247	228	56316
	-2.5	235	612	143820
	0	235	1506	353910
	2.5	285	2369	675165
	5	352	2972	1046144
	7.5	426	3285	1399410
	10	481	2546	1224626
	12.5	548	1486	814328
	15	598	624	373152
	17.5	572	241	137852
	20	618	92	56856
			15961	6281579
			Mean NO (ppm)	**394**

1998 (Measured)	VSP Bin	Mean NO (ppm)	No. of Measurements	Total Emissions
	-5	171	126	21546
	-2.5	231	259	59829
	0	252	753	189756
	2.5	246	1708	420168
	5	316	2369	748604
	7.5	374	3378	1263372
	10	418	3628	1516504
	12.5	470	3277	1540190
	15	487	2260	1100620
	17.5	481	1303	626743
	20	526	683	359258
			19744	7846590
			Mean NO (ppm)	**397**

1998 (Adjusted)	VSP Bin	‘98 Mean NO (ppm)	‘97 No. of Meas.	Total Emissions
	-5	171	228	38988
	-2.5	231	612	141372
	0	252	1506	379512
	2.5	246	2369	582774
	5	316	2972	939152
	7.5	374	3285	1228590
	10	418	2546	1064228
	12.5	470	1486	698420
	15	487	624	303888
	17.5	481	241	115921
	20	526	92	48392
			15961	5541237
			Mean NO (ppm)	**347**

APPENDIX 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**