On-Road Remote Sensing of Automobile Emissions in the Chicago Area: Year 1

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EXECUTIVE SUMMARY

The University of Denver conducted a five-day remote sensing study in the Chicago area in the fall of 1997. The remote sensor used in this study is capable of measuring the ratios of CO, HC, and NO to CO_2 in motor vehicle exhaust. From these ratios, we calculate the percent concentrations of CO, CO_2, HC and NO in motor vehicle exhaust which would be observed by a tailpipe probe, corrected for water and any excess oxygen not involved in combustion. The system used in this study was also configured to determine the speed and acceleration of the vehicle, and was accompanied by a video system to record the license plate of the vehicle.

Five days of fieldwork were conducted at the on-ramp from Algonquin Rd. to southbound I-290 in west Chicago. A database was compiled containing 18,320 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 more than 17,500 contained measurements for HC and NO.

The mean percent CO, HC, and NO were determined to be 0.45%, 0.021%, and 0.040%, 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. The fleet emissions measured in this study exhibit a gamma distribution, with the dirtiest 10% of the fleet responsible for 61%, 44%, and 46% of the CO, HC, and NO emissions, respectively.

Vehicle emissions as a function of acceleration revealed that fuel specific CO emissions are relatively independent of acceleration and that HC emissions show only a slight negative dependence. In contrast, the NO measurements made in this study showed a strong positive correlation on measured acceleration.

There were a considerable number of repeat measurements in the database; only 58% of the measurements resulted from vehicles measured once. The remaining 42% of the measurements were of vehicles measured at least twice. By removing all of the repeat measurements from the database and allowing each vehicle to appear only once, we have shown that these repeat measurements are not skewing the results and that the full database is statistically representative of the actual fleet at the measurement site.

This was the first year of a five-year continuing study to characterize motor vehicle emissions and deterioration in the Chicago area.

INTRODUCTION

Many cities in the United States are in violation of the air quality standards established by the Environmental Protection Agency. 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]

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

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

The remote sensor used in this study was developed at the University of Denver for measuring the pollutants in motor vehicle exhaust, and has previously been described in the literature.[4,5] The instrument consists of a non-dispersive infrared (IR) component for detecting carbon monoxide, carbon dioxide (CO_2), and hydrocarbons, and a dispersive ultraviolet (UV) spectrometer for measuring nitric oxide. The source and detector units are positioned on opposite sides of the road in a bi-static arrangement. 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 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 this reason, 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. Furthermore, a fundamental knowledge of combustion chemistry allows one to determine a number of the vehicle's emission characteristics, including the instantaneous air/fuel ratio and grams of emission per gallon of fuel burned. 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.

Quality assurance calibrations are performed twice daily in the field. 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.[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 of 25 ppm for NO, with an error measurement of ±5% of the reading at higher concentrations.

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

The purpose of this report is to describe the remote sensing measurements made in the Chicago area in the fall of 1997, under CRC contract no. E-23-4. Measurements were made for 5 consecutive weekdays, from Mon. Sept. 15 to Fri. Sept. 19, at the on-ramp from Algonquin Rd. to southbound I-290. This ramp serves both eastbound and westbound traffic on Algonquin Rd. and has an uphill grade of approximately 3%. This was the first year of a 5-year study to characterize motor vehicle emissions and deterioration in the Chicago area.

RESULTS AND DISCUSSION

Following the five days of data collection in September of 1997, the videotapes were read for license plate identification. Plates which 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 19,682 records with make and model year 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 size of the usable database had to be further reduced due to the traffic situation at the measurement site. The Algonquin Rd. to I-290 on-ramp was approximately 0.25 miles north of the off-ramp from southbound I-290 to I-90. During rush hour, we believe that construction on I-90 was causing the exit ramp 0.25 mile south of our location to back up, to the extent that it was interfering with vehicles entering I-290 from Algonquin Rd. As a result, during peak travel hours, traffic at our position on the ramp was often moving very slowly, or at a standstill. We have chosen to omit from our data analysis vehicles travelling at less than 10 mph during these peak times, because there is a significant difference between the emissions of these “slow” vehicles and the vehicles measured when traffic flow was unobstructed. The largest difference was observed in the NO measurements, with the mean percent NO during regular traffic flow being 0.040%, but dropping to 0.025% during times of obstructed traffic flow. Vehicles that were omitted

Table 1. Data summary.

	CO	HC	NO
Attempted measurements	24529		
Valid measurements	23121	22451	22408
Submitted plates	20376		
Matched plates	19682		
Valid measurements w/plates	19682	19174	19138
Records analyzed (not “S” speeds, see text)	18320	17827	17792
Mean (%)	0.45	0.021	0.040
Median (%)	0.14	0.013	0.015
Percent of total emissions from dirtiest 10% of fleet	61	44	46
Mean model year	92.73		
Mean speed (mph)	25.10		
Mean acceleration (mph/s)	0.054		

Table 2. Comparison of this study with three previous studies conducted in Chicago.

Year	Mean %CO	Mean %HC	Mean %NO	No. of records
1989 [8]	1.17	Not measured	Not measured	11,818
1990 [9]	1.10	0.139	Not measured	13,640
1992 [10]	1.04	0.088	Not measured	8,733
1997	0.45	0.021	0.040	18,320

from the data analysis were not removed from the database, but were marked with an "S" in the speed_flag field. Since there is no difference in average model year between the omitted vehicles and the remainder of the database, the exclusion of these vehicles is not expected to decrease the ability of the database to represent the vehicles travelling at this site. As a result of the slow vehicles being excluded from the data analysis, the working database contained 18,320 records.

A summary of the data analysis for the 5 days of data collection is shown in Table 1, and a comparison of this data to three previous studies conducted in the Chicago area is shown in Table 2. Compared to the three previous studies conducted in Chicago, the current fleet is considerably lower emitting. This difference is likely a result of two factors. Initially, the socio-economic status of the community in which the current study was conducted would predict a fleet of very well maintained vehicles. Secondly, it has been observed that fleet average emissions are slowly decreasing with time, for the most part as a result of advances in emissions control technology.[8]

Figure 1 shows the distribution of CO, HC, and NO emissions by percent category from the data collected in this study. The solid bars show the percentage of the fleet in a given emissions category, and the clear 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 for each of three pollutants is occupied by no less than 65% of the fleet (for HC), and as much as 89% of the fleet (for CO). The fact that the cleanest 89% of the vehicles are responsible for only 35% of the CO emissions further demonstrates how the emissions picture can be dominated by a small number of high emitting vehicles.

Figure 2 illustrates the data in a different manner. The fleet is divided into deciles, showing the mean measurement for each decile. The ten bars illustrate the emissions that a fleet of ten vehicles would have if it was statistically identical to the observed fleet. In each case, the lowest five deciles are each given the average of all five, since we do not claim that the small differences that arise from one category to the next are significant.

The inverse relationship between vehicle emissions and model year has been observed at number of locations around the world, and Figure 3 shows that the fleet reported in this study is not an exception.[4] The plot of % NO 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 1988. This has been observed previously,[12] 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. Another aspect that appeared upon data analysis was the tendency for the mean and median emissions of each pollutant to increase slightly for the 1998 model year. We suppose that this was due to the fact that the data was collected in September of 1997, but the State of Illinois did not match the license plate information until May of 1998. It is possible that some older vehicles were sold during the time period between data collection and plate matching, and replaced with 1998 vehicles. As a result, a small number of older vehicles with comparatively higher emissions appeared in the database as 1998 vehicles. This became apparent when four 1999 model year vehicles appeared in the database, which would have been impossible for a study conducted in September of 1997.

Plotting vehicle emissions by model year, with each model year divided into emission quintiles results in the plots shown in Figure 4. Very revealing is the fact that, for all three major pollutants, the cleanest 40% of the vehicles, regardless of model year, make an essentially negligible contribution to the total emissions. This observation has been previously reported by Stedman *et al.* in 1991.[13] The results shown here continue to demonstrate that broken emissions control equipment has a greater impact on fleet emissions than vehicle age, and that emissions control strategies which assume that all vehicles of a given model year have the same emissions will continue to be ineffective.

Figure 5 shows the relationship between vehicle emissions and acceleration. The data were binned according to acceleration category, and the average emissions for each bin were determined. The black line in each plot is the distribution of the vehicles according to acceleration bin, with the maximum of 3,330 vehicles occurring at 0 mph/s. The CO emissions have little dependence on measured acceleration. We might expect vehicles under hard acceleration to be in power enrichment mode and be operating with a rich air/fuel mixture, but at this location the number of vehicles in this mode is very small. In view of the traffic and site layout, there is little opportunity for a vehicle to have been in power enrichment for longer than a fraction of a second. Hydrocarbon emissions appear to be more dependant upon acceleration than the CO emissions do, showing a negative correlation. This can be attributed to the fact that a decelerating vehicle with the throttle closed generally emits very little CO_2, but may be misfiring due to small amounts of fuel still being delivered.[14] The most striking relationship between emissions and acceleration is shown by NO in the lower panel of Figure 4. The positive correlation between engine load (in this case, caused by acceleration) and NO production has previously been documented,[2,15] and it is demonstrated here as well.

Table 3 provides an analysis of the number of vehicles that were measured repeatedly, and the number of times they were measured. Of the 18,320 records used in this fleet analysis, 10,605 (58%) were contributed by vehicles measured once, and the remaining 7715 (42%) records were from vehicles measured at least twice. With 42% of the records used in this analysis coming from repeat measurements, it could be argued that the emissions data presented in this report is not truly representative of the actual fleet at the study location. To investigate the possibility of repeat measurements tainting this analysis, the decile plots shown in Figure 2 were recreated in Figure 6. The solid bars show the original data presented in Figure 2, representing the entire database, and the clear bars show a second decile analysis of the data, this time with all of the repeat vehicles represented only once (by the last time they were measured). The slight differences that arise between the complete database and the “single measurement” database appear to be insignificant and are virtually non-existent at the lower deciles. The slight negative offset of the “single measurement” emissions, indicating that repeat vehicles have slightly higher emissions, may be explained by the tendency for repeat vehicles to be driven more often, thereby suffering age-related effects sooner.

Table 3. Number of measurements on repeat vehicles.

Number of times measured	Number of vehicles
1	10605
2	1956
3	755
4	276
5	52
6	13
7	5
10	3
15	1
16	1

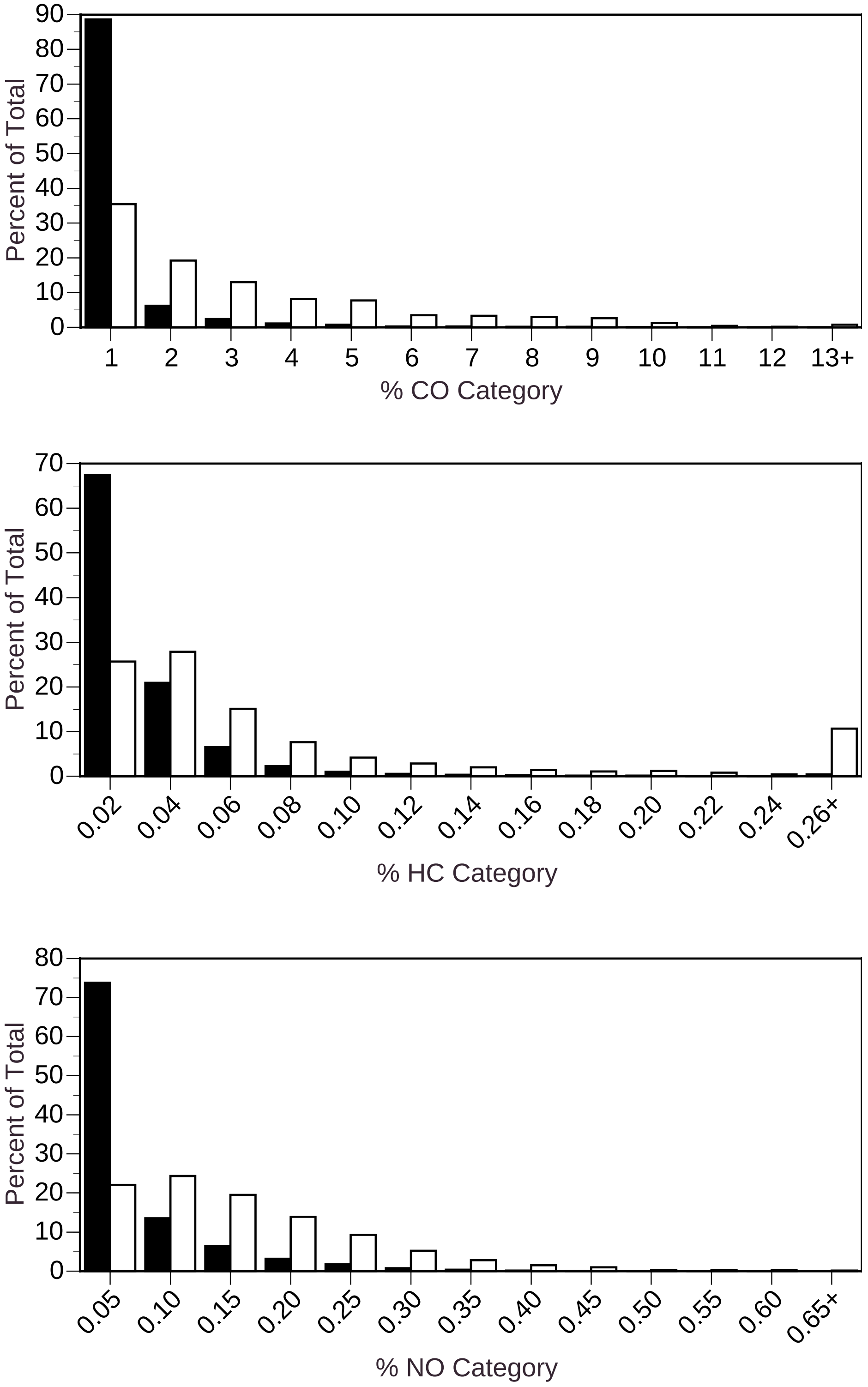

Figure 1. Emissions distributions showing the percentage of the fleet in a given emissions category (black bars) and the percentage of the total emissions contributed by the given category (clear bars).

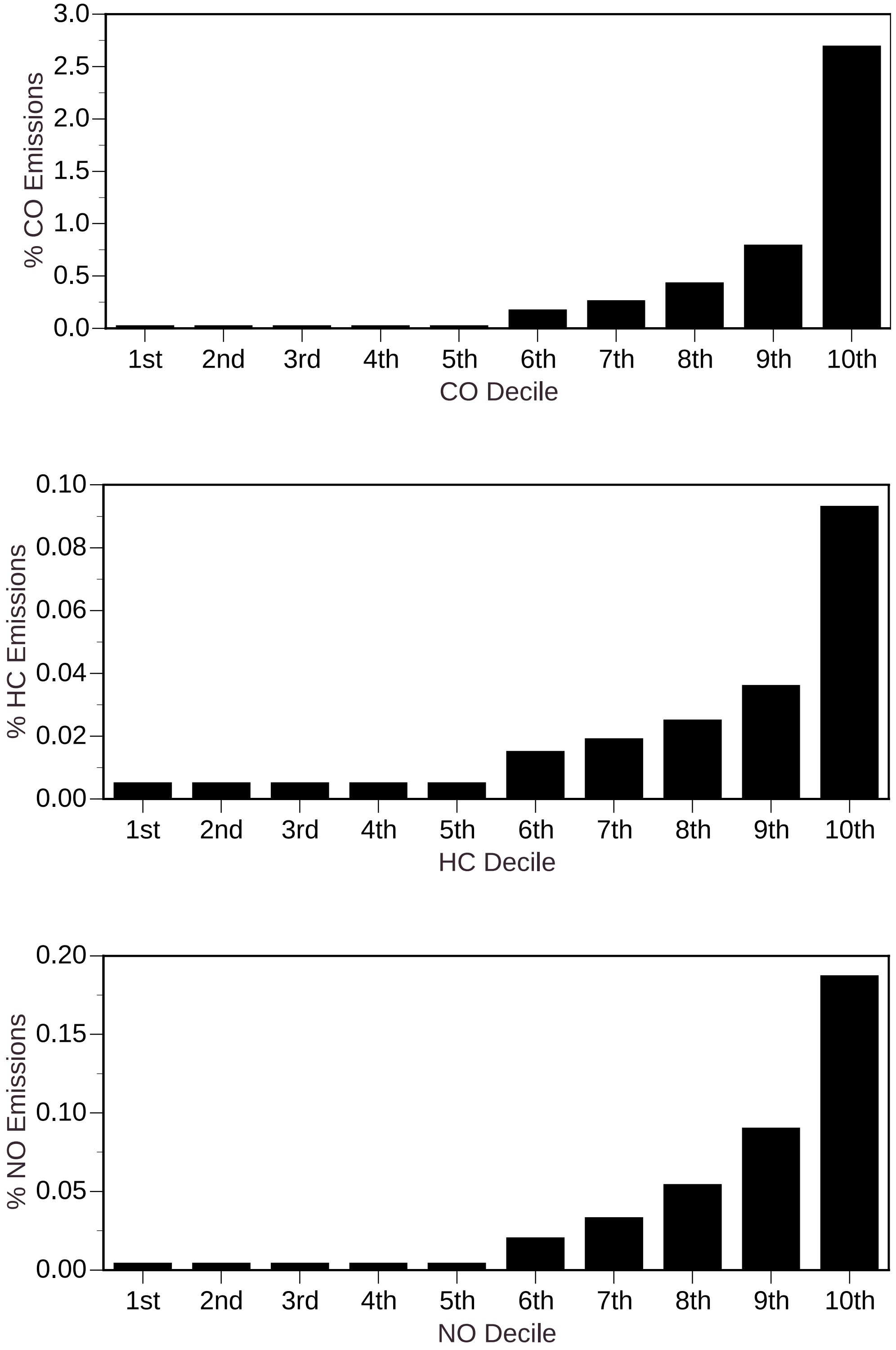

Figure 2. Fleet emissions organized into deciles. In each case, the lowest five deciles are represented by the average of all five.

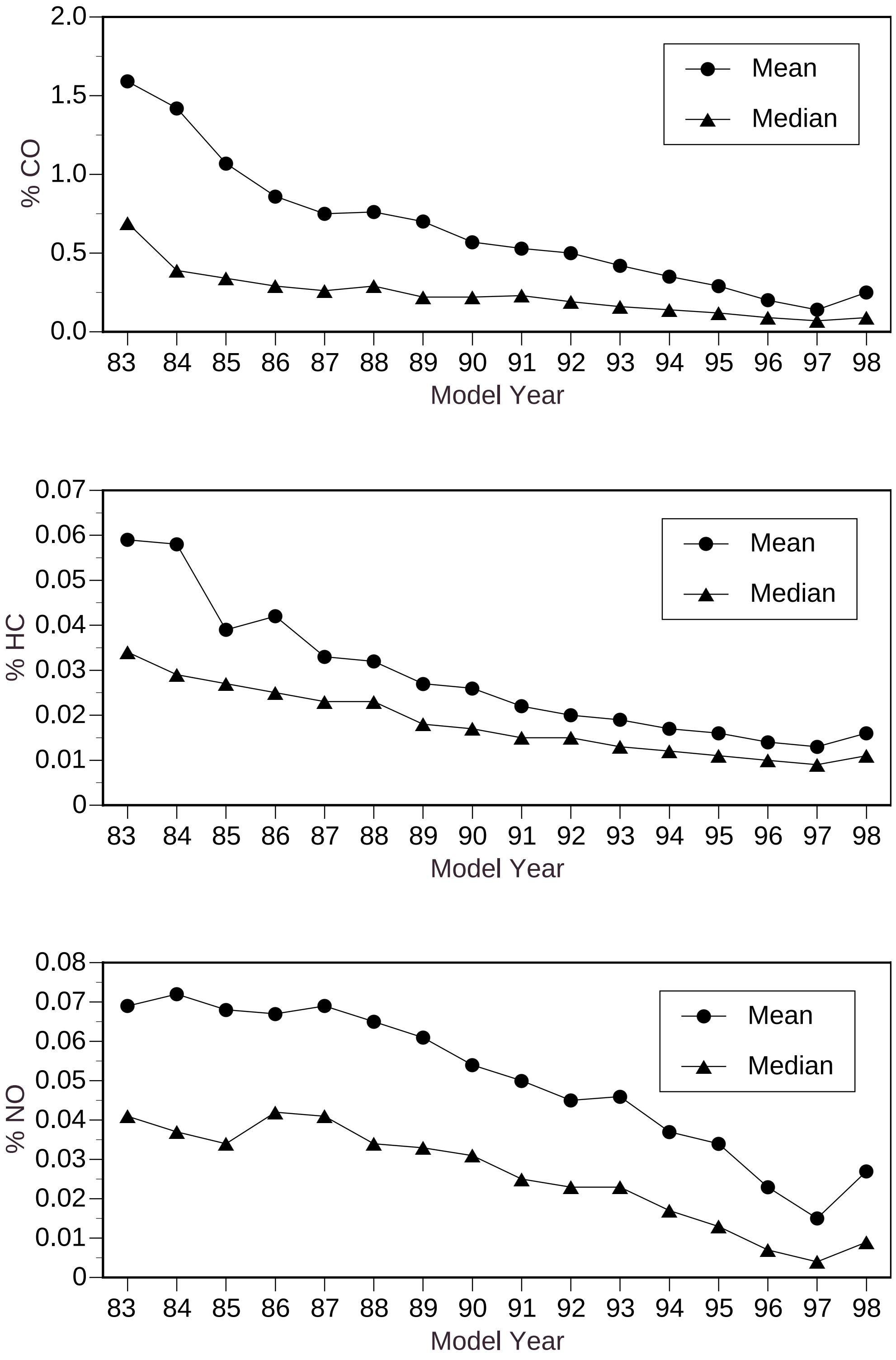

Figure 3. Mean and median emissions illustrated as a function of model year.

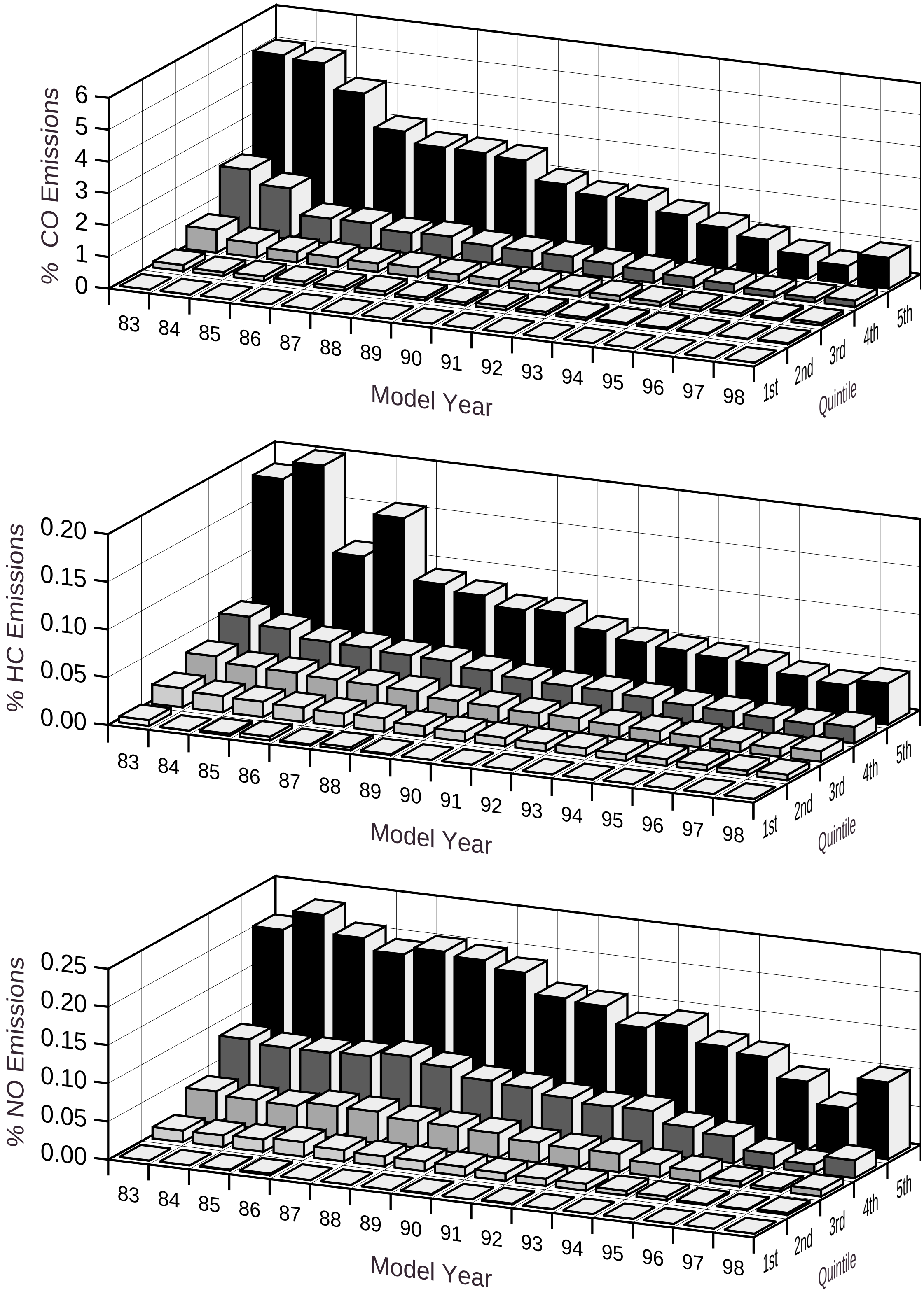

Figure 4. Vehicle emissions by model year, divided into quintiles.

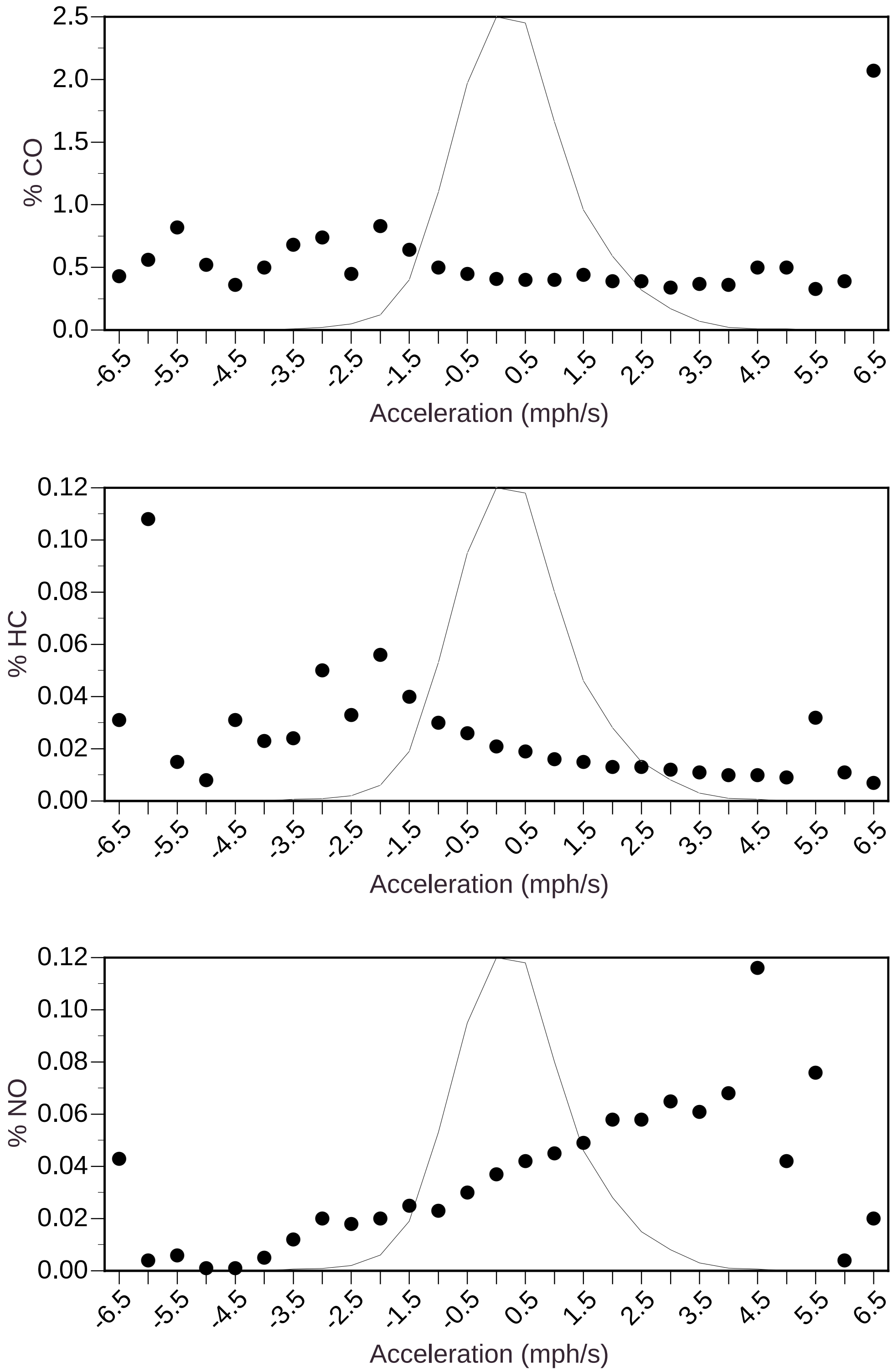

Figure 5. Fleet emissions as a function of vehicle acceleration. The black line represents a distribution by vehicle number, with the maximum of 3,330 vehicles at 0 mph/s.

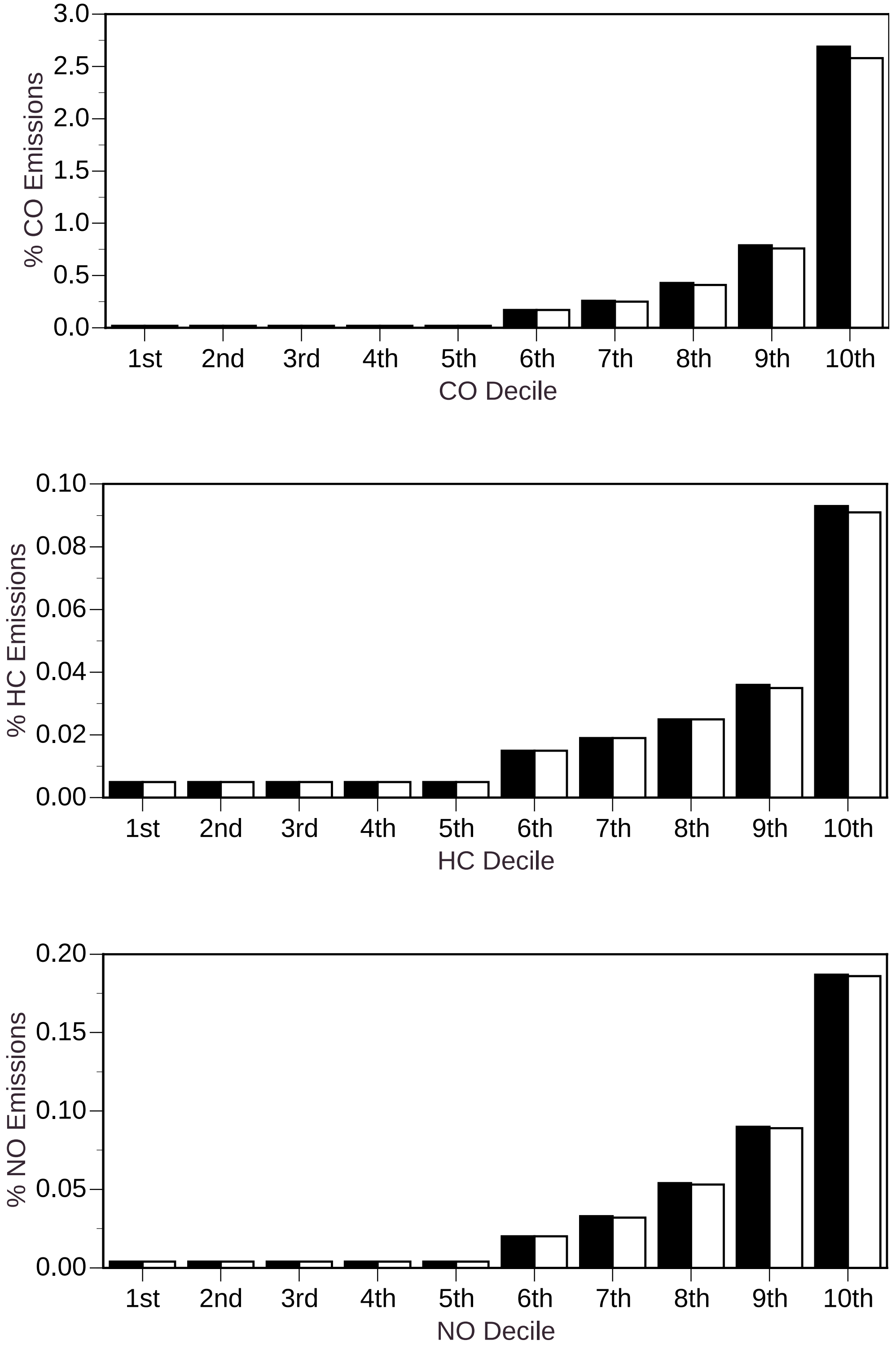

Figure 6. Fleet emissions organized into deciles, with the complete data set represented by the solid bars as in Figure 2. The clear bars represent the fleet emissions with all repeat measurements excluded (each vehicle only represented once).

CONCLUSION

The University of Denver successfully completed the first year of a 5-year remote sensing study in Chicago. The field portion of the study was conducted from September 15-19, 1997, at the on-ramp from Algonquin Rd. to southbound I-290 in west Chicago. A database was compiled containing 18,320 records with make and model year information, and valid measurements for at least CO and CO_2. This database is slightly smaller than expected, as some measurements had to be excluded from the data analysis due to vehicles travelling at extremely slow speeds. Road construction on a nearby freeway caused I-290 to back up at our location, thereby inhibiting traffic flow from Algonquin Rd. to southbound I-290.

The mean measurements for CO, HC, and NO were determined to be 0.45%, 0.021% and 0.040%, respectively. These values are amongst the lowest we have observed for a statistically significant fleet, indicating most of the vehicles at this site were relatively new and apparently very well maintained. As expected, the fleet emissions observed in this study exhibited a typical skewed distribution, with the dirtiest 10% of the fleet contributing 61%, 44%, and 46% of the CO, HC, and NO emissions, respectively.

An analysis of emissions as a function of model year showed a typical inverse relationship, but was revealing in a different respect. Both the mean and median for each of the three major pollutants exhibited a small rise for 1998 model year vehicles, as compared to the 1997 vehicles. We have proposed that a small number of older vehicles measured in this study were replaced by 1998 vehicles before the State of Illinois determined make and model year information. The new vehicles were registered with the same license plates, and as a result, some vehicles are appeared in the database with the emissions data of older vehicles but having the registration of information of 1998 vehicles. The cause of this became apparent when four 1999 model year vehicles appeared in the database. At the time the field study was conducted, in September of 1997, it would have been impossible to measure 1999 vehicles.

Vehicle emissions as a function of acceleration revealed that fuel specific CO emissions occur relatively independent of acceleration and that HC shows a slight negative correlation. More revealing was the relationship between NO emissions and acceleration, showing a strong positive correlation when a significant number of vehicles were available.

Of the 18,320 records in the database, 58% arise from vehicles measured only once, and 42% result from vehicles measured at least twice, and as many as 15 or 16 times in two cases. An analysis that involved excluding all of the repeat measurements from the database, allowing each vehicle to appear only once, revealed that the repeat measurements were not skewing the results and that the database is statistically representative of the actual fleet at the measurement location.

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APPENDIX A: Explanation of the ill_97.dbf database.

The ill_97.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. 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 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.
Lic_type	Passenger plates = 1, all other plates = 0.

Reg_month	Indicates the month the current registration expires.
Reg_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	Indicates single (1) or multiple private ownership (2,3), single (4) or multiple (6) corporate ownership, joint private/corporate ownership (5), city/local (7), state (8), or federal government (9) ownership.
Make_abrv	Abbreviated manufacturer.