On-Road Remote Sensing of Automobile Emissions in the Denver Area: Year 2

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EXECUTIVE SUMMARY

The University of Denver has completed the second year of a five-year remote sensing study in the Denver 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 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 license plates.

Measurements were conducted on 4 business days in late December of 1999 and early January of 2000 in Denver. The measurement site was the interchange ramp from northbound I-25 to westbound 6th Avenue in central Denver. A database was compiled containing 22,986 records for which the State of Colorado provided make and model year information. All of these records contained valid measurements for at least CO and CO_2, and 22,867 records contained valid measurements for HC and NO as well. The database, along with earlier databases and reports, can be found at www.feat.biochem.du.edu.

The mean CO, HC and NO emissions for the fleet measured in this study were 0.43%, 175 ppm and 511 ppm. These values are somewhat lower than the mean emissions for fleets measured by the University of Denver at the same site in the winters of 1996 and 1997, as part of a separate study, and in 1999, except for HC, which was lower in 1999. These lower emissions can be attributed to the current fleet consisting of more modern vehicles with advanced emissions control systems.

As expected, the fleet emissions observed at the site in Denver exhibited a skewed distribution, with most of the total emissions contributed by a relatively small percentage of the vehicles. For example, the cleanest 89% of the fleet is responsible for only 33% of CO emissions. This skewed distribution was also seen in previous studies at the site.

Using vehicle specific power, it was possible to adjust the emissions of the vehicle fleet measured in 2000 to match the vehicle driving patterns of the fleet measured in 1999. After doing so, the NO emissions of the 2000 fleet were lower than the emissions of the 1999 fleet. The apparent HC emissions were found to have increased probably because of an instrument noise problem, while CO remained relatively constant.

A model year adjustment was applied to a fleet of specific model year vehicles to track deterioration. Using a fleet of 1982 to 1999 model year vehicles, the deterioration of the fleet was demonstrated for CO and HC. Tracking of model year fleets through four measurements in five years (including two years of this study) showed that the rate of emissions deterioration increases significantly after the vehicle has aged several years. An analysis of high emitting vehicles showed that there is considerable overlap of CO and HC high emitters, for instance 3% of the fleet emit 27% of the total CO and 22% of the total HC.

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]

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 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. Collinear 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 that 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 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. However, 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 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 as dictated in the field by 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 given 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% for 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 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 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 Denver area in December and January of 1999/2000, as part of CRC's E-23 program. Measurements were made on four weekdays in the time period from December 30 to January 14. The measurement location used in this study was the interchange from northbound I-25 to westbound 6th Avenue in central Denver. A map of the measurement location is shown in Figure 1. This interchange ramp has an uphill grade of 8% (4.6°) at the measurement location. Measurements were generally made between the hours of 8:00 and 18:00. This was the second year of a 5-year study to characterize motor vehicle emissions and deterioration in the Denver area.

RESULTS AND DISCUSSION

Following the 4 days of data collection in Denver, the videotapes were read for license plate identification. Plates that appeared to be in-state and readable were sent to the State of Colorado to be matched against registration records. The resulting database contained 22,986 records with registration information and valid measurements for at least CO and CO_2. Most of these records also contain valid measurements for HC and NO (see Table 1). The database can be found at www.feat.biochem.du.edu. The complete structure of the database and the definition of terms are included in Appendix C. The temperature and humidity record is included in Appendix A.

Table 1: Validity summary.

	CO	HC	NO
Attempted Measurements	30,193		
Valid Measurements	29,000	28,882	28,957
Percent of Attempts	96.1%	95.7%	95.9%
Submitted Plates	24,378	24,280	24,342
Percent of Attempts	80.7%	80.4%	80.6%
Percent of Valid Measurements	84.1%	84.1%	84.1%
Matched Plates	22,986	22,899	22,952
Percent of Attempts	76.1%	75.8%	76.0%
Percent of Valid Measurements	79.3%	79.3%	79.3%
Percent of Submitted Plates	94.3%	94.3%	94.3%

The validity of the attempted measurements is summarized in Table 1. 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.

Table 2 is the data summary; included are summaries of previous remote sensing databases collected by the University of Denver at the I-25 and 6th Avenue site. The 1999 measurements were conducted in January of that year as the first of this multi-year CRC study. The measurements conducted in January of 1996 and 1997 were part of a separate study and are included here for comparison only.

Compared to the fleets measured in 1996 and 1997, the fleets measured in the last two years of the current study are considerably lower emitting. This difference is most likely due to the technological advances in the emissions control systems of the modern fleet. As with other analyses in this report, however, such effects are suggested by the data and can only be rigorously proved by further measurements.

It should also be noted that the measurements conducted in 1996 and 1997 were made with a non-dispersive ultraviolet absorption nitric oxide channel, as described by Zhang *et al.*[8] The instrument used in the current study, as in all studies conducted by the University of Denver under CRC's E-23 program, measures nitric oxide by dispersive ultraviolet absorption spectroscopy and is believed to offer a considerable improvement in measurement quality over the non-dispersive instrument.[4]

Table 2. Data summary.

	2000	1999	1997	1996
Mean CO (%) (g/kg of fuel)	0.43 (54)	0.45 (56)	0.51	0.53
Median CO (%) (g/kg of fuel)	0.11 (15)	.09 (11.7)		
Percent of Total CO from Dirtiest 10% of Fleet	65.3	66.3	67.0	63.8
Mean HC (ppm) (g/kg of fuel)	175 (3.5)	130 (2.6)	260	250
Median HC (ppm) (g/kg of fuel)	110 (2.3)	80 (1.7)		
Percent of Total HC from Dirtiest 10% of Fleet	54.6	63.7	48.3	58.0
Mean NO (ppm) (g/kg of fuel)	511 (7.2)	600 (8.4)	620*	860*
Median NO (ppm) (g/kg of fuel)	165 (2.3)	240 (3.4)		
Percent of Total NO from Dirtiest 10% of Fleet	48.4	44.6	43.6*	38.1*
Mean Model Year	1993.4	1992.4	1990.3	1989.2
Mean Speed (mph)	21.9	20.6	21.7	21.9
Mean Acceleration (mph/s)	0.08	0.21	0.11	-0.21

* Nitric oxide measurements until 1997 were made using a non-dispersive ultraviolet absorption NO channel. See Zhang *et al.*[8]

Table 3 provides an analysis of the number of vehicles that were measured repeatedly, and the number of times they were measured. Of the 22,986 records used in this fleet analysis, 17,614 (77%) were contributed by vehicles measured once, and the remaining 5372 (23%) records were from vehicles measured at least twice.

Table 3. Number of measurements on repeat vehicles.

Number of Times Measured	Number of Vehicles
1	17,614
2	2,022
3	388
4	33
5	3
5+	2
Total individual vehicles	20,062

Figure 2 shows the distribution of CO, HC and NO emissions by percent or ppm category from the data collected in this study. The solid 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 close to 90% of the fleet for CO. The fact that the cleanest 89% of the fleet is responsible for only 33% 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 1996, 1997 and 1999 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 lowest hydrocarbon emission category ($\leq$200 ppm) is dominated by negative values and appears to make an almost negligible contribution to the total emissions.

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 Denver area, both this year and in 1999, 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 1987. This has been observed previously,[5, 8] 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. Unlike data collected in Chicago, in the 2000 Denver measurements none of the three pollutants show a tendency for the mean and median emissions to increase for the newest model year.[9] In Colorado license plates can not generally be moved from one vehicle to another.

An interesting feature of the CO plot in Figure 3 is the distinctive alternation of model year averaged emissions from 1982 to 1993. Such an alternation indicates that the expected annual deterioration (which is observed on average) is reversed every other year. We believe this is a result of the biennial I/M program reducing the on-road emissions of recently tested vehicles. According to the state annual reports, 1982 through 1993 are the model years which have a significant I/M failure rate. A simple model was constructed in which a biennial I/M program causes the emissions from the year just tested to be 10% below what they would have been without that test. This was done by averaging the CO from untested years X and X+2 and then inserting in year X+1 that average multiplied by 0.9. The same was done for the 2000 data except X+1 and X+3 are the untested years. When the model was compared to the data, the size of the alterations were very similar. For each alternation except one (ten out of eleven) the positive or negative sign in the model was the same as the data. Non-parametric statistics dictates that there is only a 1/512 chance that this level of agreement is random.

A second model, which achieves the same agreement, was constructed by application of a fixed annual deterioration rate and a 10% annual I/M benefit. The conclusion drawn from this result is that our observations can be accounted for by a biennial I/M program which causes on-road emissions to be reduced about 10% from tested older MY vehicles within a year of testing, and that benefit is not carried over into the second year. From these data alone one can only detect the benefits which are not carried over from year to year. Only by comparison to a similar non-I/M fleet can one observe the benefits which are carried over for more than one year.

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 was first reported by Ashbaugh and Lawson in 1990.[10] The results shown here continue to demonstrate that broken emissions control equipment has a greater impact on fleet emissions than vehicle age; 65%, 55% and 48% of CO, HC and NO emissions, respectively, are produced by 10% of the fleet.

An equation for determining the instantaneous power of an on-road vehicle has been proposed by Jimenez[11], which takes the form

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

where SP is the vehicle specific power in kW/metric tonne, *slope* is the slope of the roadway (in degrees), v is the vehicle speed in mph, and a is the vehicle acceleration in mph/s. Using this equation, vehicle specific power was calculated for all measurements collected in the database. The emissions data were binned according to vehicle specific power and are illustrated in Figure 5. The triangles in Figure 5 provide the number of measurements in each bin. Also shown in Figure 5 are vehicle emissions binned by specific power for remote sensing measurements collected in 1999 at the same site. As expected, CO and HC emissions show a negative dependence on vehicle specific power, while NO emissions show an overall positive dependence. The error bars included in the plot are 95% confidence intervals of the mean. These uncertainties were generated for these γ-distributed data sets by applying the central limit theorem. Each day's average emission for a given VSP bin was assumed to be an independent measurement of the emissions at that VSP. Normal statistics were then applied to these daily averages. The increase of the CO and HC emissions measured in Denver at specific powers above 20 kW/tonne may be due to commanded power enrichment.

Using vehicle specific power, it is possible to reduce the influence of load and of driving behavior from the mean vehicle emissions for the 1999 and 2000 databases. Table 4 shows the mean emissions from vehicles in the 1999 and 2000 databases with specific powers between 0 and 25 kW/tonne. Note that these emissions do not vary considerably from the mean emissions for the entire 1999 and 2000 databases, as shown in Table 2. Also shown in Table 4 are the mean emissions for the 2000 measurements adjusted for specific power. This correction is accomplished by applying the mean vehicle emissions for each specific power bin in Figure 5 for 2000, to the vehicle distribution, by specific power, for each bin from 1999. A sample calculation, for the specific power adjusted mean NO emissions in Chicago in 1998, is shown in Appendix E. It can be seen from Table 4 that the mean VSP adjusted emissions in 2000 is similar for CO to the 1999 fleet average. In the cases of the other two pollutants, however, VSP adjustment does not account for the differences in average emissions. Average HC is higher in 2000 and average NO is lower. The decrease in NO may be a result of technological improvement in the fleet, but the HC effect is not explained by load and may be a result of an instrument noise problem as discussed below.

Table 4. Specific power adjusted fleet emissions (0 to 25 kW/tonne only).

	1999	2000 (measured)	2000 (adjusted)
Mean CO (%)	0.42	0.41	0.42
Mean HC (ppm)	128	174	177*
Mean NO (ppm)	576	495	488

* See text re HC "noise".

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 1999 study. Table 5 shows the mean emissions for all vehicles from model year 1982 to 1999, as measured in 1999 and 2000. Applying the vehicle distribution by model year from 1999 to the mean emissions by model year from 2000 yields the model year adjusted fleet emissions. A sample calculation, for the model year adjusted mean NO emissions in Chicago in 1998, is shown in Appendix F. Both CO and HC emissions show a noticeable deterioration effect upon model year adjustment. In the case of NO, model year adjustment seems to increase the average emission close to the 1999 level. However, there is still somewhat of a discrepancy in the opposite direction of what is expected due to deterioration. This discrepancy may arise from factors that could not be controlled between the two years of measurement, such as the ambient conditions or the proportion of diesel vehicles in the measured fleet.

Table 5. Model year adjusted fleet emissions (MY 1982-1999 only).

	1999	2000 (measured)	2000 (adjusted)
Mean CO (%)	0.39	0.38	0.42
Mean HC (ppm)	116	163	174
Mean NO (ppm)	568	500	544

In order to eliminate some of the differences in the fleet measured during the two years, an average emissions analysis was done on only those vehicles that were measured in both years. Approximately 4200 vehicles fell into this category. The average emissions of these vehicles in 1999 and in 2000 are in Table 6 below. It is apparent that CO and HC emissions for these vehicles in the two years of measurement are very similar to the fleet average. The NO measurements, on the other hand, are quite different with the 1999 average for this subset of the fleet being lower than the overall 1999 fleet average by 40 ppm and the 2000 subset being 40 ppm higher. The averages of the subsets then show that there is essentially no change in NO emissions between 1999 and 2000 for those vehicles measured in both years. This then indicates that a difference in the fleets measured during the two years is the cause of the NO discrepancy. A greater abundance of diesel vehicles in the 1999 measured fleet would cause the fleet's average NO emissions to be higher.

Table 6. Average emissions of vehicles measured in both years – unadjusted.

	1999	2000
Mean CO (%)	0.38	0.43
Mean HC (ppm)	110	180
Mean NO (ppm)	530	540

Vehicle deterioration can be illustrated by Figure 6, which shows the mean emissions of the 1982 to 2000 model year fleet as a function of vehicle age. Data from the 1996 and 1997 measurements are also included. The first point for each model year was measured in 1996, the second in 1997, the third in 1999 and the last point in 2000. Vehicle age was determined by the difference between the year of measurement and the vehicle model year. The most recent model years (up to 5 years old) show a small deterioration from one year to the next for CO emissions. The deterioration rate seems to increase in the model years that are 8 years old and older. The I/M effect on alternating model years, which was discussed above, is also apparent in this plot.

In the case of HC emissions, inclusion of the previous years' measurements yields a set of plots that is not easily deciphered. The average HC emissions from each model year fluctuates somewhat during the years of measurement. This "noise" in the yearly measurements is most likely caused by an instrument HC offset phenomenon that we have reported previously and have attempted to diagnose (Phoenix Report, Year 2 – Appendix D). The structural changes suggested to reduce noise had not been made to the instrument by the time of this study.

Even with this noise, however, we are able to see that vehicle deterioration increases dramatically after the vehicles have aged a certain number of years. The current data show a marked increase in the slope of the HC versus vehicle age plots after the vehicle has aged 9-10 years. The fluctuations in yearly measurements do mask any I/M effects as seen with the CO data, however.

The NO measurements also show a curious effect. The NO emissions of almost every model year measured in 1996 are significantly higher than in the other years of measurement. This is likely due to the fact that in 1996 and 1997 a non-dispersive method was used to measure NO. This instrument was less precise than the current instrument and most likely was measuring with an offset in 1996. Otherwise, NO emissions show a slow but steady deterioration with age.

Table 7: Percent of all vehicles that are high emitting.

Top 10% Decile	CO	HC	NO
CO	6.0%	3.0%	0.5%
HC	3.0%	5.2%	1.2%
NO	0.5%	1.2%	7.9%
All	0.5%	0.5%	0.5%

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 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 pollutant. These data are in Table 7 above; 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 fleet are high emitters only for the pollutants in the column and row headings. The values where the column and row headings are the same indicate the percentage that are high emitting in the one pollutant only. The "All" row gives the percentage of the fleet that is high emitting in all three pollutants.

Thus, the table shows that 3.0% of the fleet are in the top decile for both HC and CO but not NO; 0.5% of the of the fleet is high emitting for CO and NO but not HC; 6.0% of the fleet are high CO emitters only.

Table 8: Percent of total emissions from high emitting vehicles.

Top 10% Decile	CO	HC	NO
CO	34.1%	21.8%	2.2%
HC	26.7%	24.5%	6.0%
NO	2.1%	5.2%	38.2%
All	2.2%	2.3%	2.0%

The preceding analysis gives the percent of vehicle overlap but does not directly give emissions overlap. In order to assess the overall emissions benefit of fixing all high emitting vehicles of one or more pollutant, one must convert the Table 7 values to percent of emissions. Table 8 shows that identification of all vehicles that are high emitting for CO would identify an overall 21.8% of HC and 2.2% of NO reduction. More efficiently, identification of the 3% high CO and HC vehicles accounts for 27% of the total CO and 22% of the total on-road HC.

In the manner described in the Phoenix, Year 2 report[12], instrument noise was measured by looking at the slope of the negative portion of the log plots. Such plots were constructed for the three pollutants. Linear regression gave best fit lines whose slopes correspond to the inverse of the Laplace factor, which describes the noise present in the measurements. This factor must be viewed in relation to the average measurement for the particular pollutant to obtain a description of noise. The Laplace factors were found to be 0.065, 0.014 and 0.005 for CO, HC and NO, respectively. These values indicate minimal noise in measurements of CO and NO and a small but significant amount of noise in the HC measurements. This HC noise puts these HC measurements in the lower of the two HC noise groups reported earlier.[12]

CONCLUSIONS

The University of Denver has completed the second year of a five-year remote sensing study of motor vehicle emissions and deterioration in the Denver area. Four days of fieldwork were conducted on an uphill interchange ramp from northbound I-25 to westbound 6th Avenue in central Denver. A database was compiled containing 22,986 records for which the State of Colorado provided make, model year and I/M status information. All of these records contained valid measurements for at least CO and CO_2, and 22,867 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 0.43%, 175 ppm and 511 ppm, respectively with an average model year of 1993.4. The fleet emissions observed at the site in Denver exhibited a skewed distribution, with the dirtiest 10 % of the fleet contributing 65%, 54% and 48% of the CO, HC and NO emissions, respectively. An analysis of the emissions as a function of model year showed a typical inverse relationship. Measured emissions as a function of vehicle specific power supported the finding that HC and CO show a negative correlation while NO shows a positive one. Having collected data for two 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 CO emissions quite independent of age. An analysis of high emitting vehicles showed that there is considerable CO and HC overlap. Continuing studies at the same site should allow further insight to be gained as to the effects of deterioration on motor vehicle emissions from one year to the next. Data are available on the web at www.feat.biochem.du.edu for the 2000 and previous studies. Appendix C defines the database format.

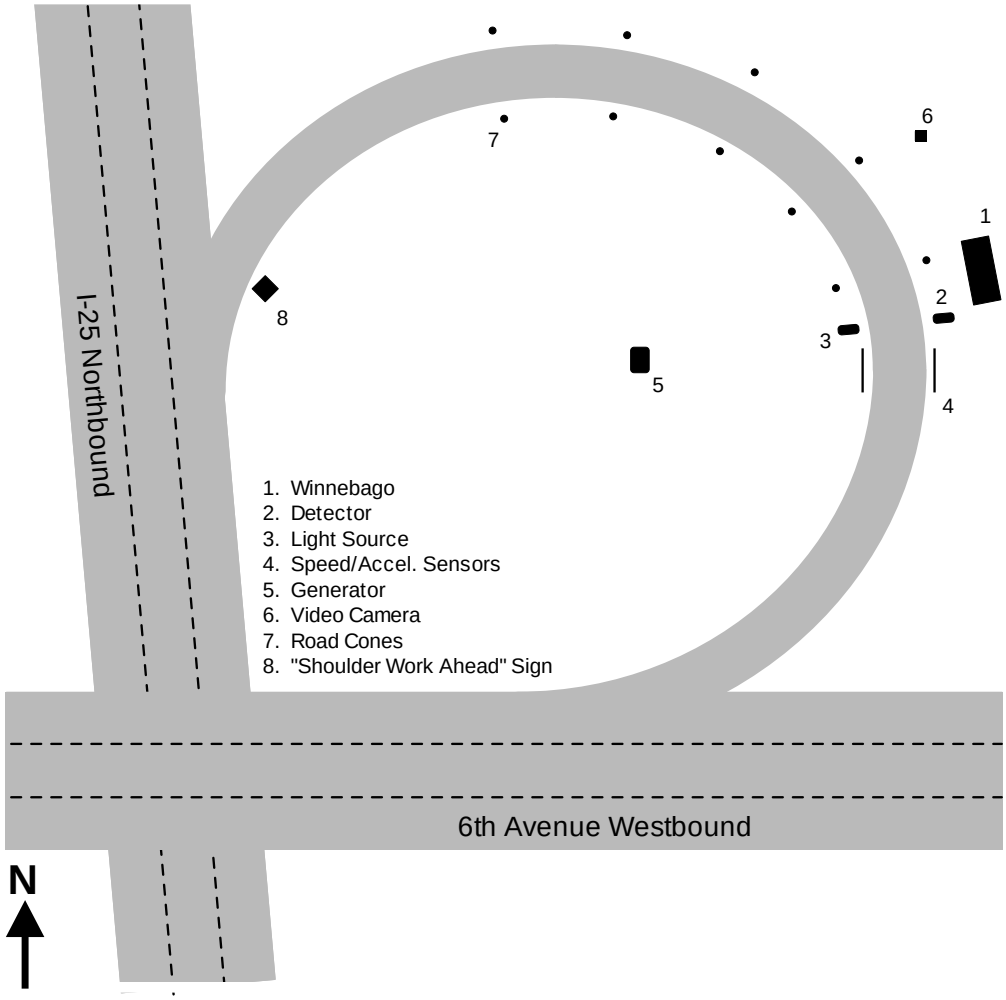
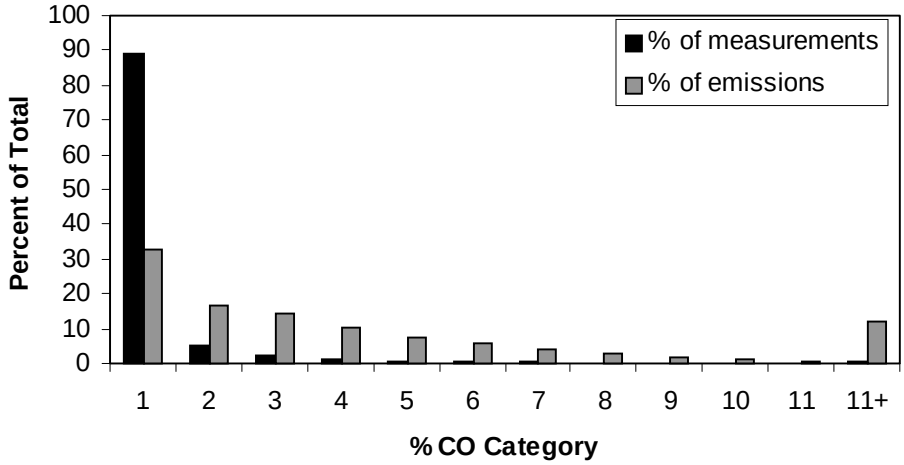
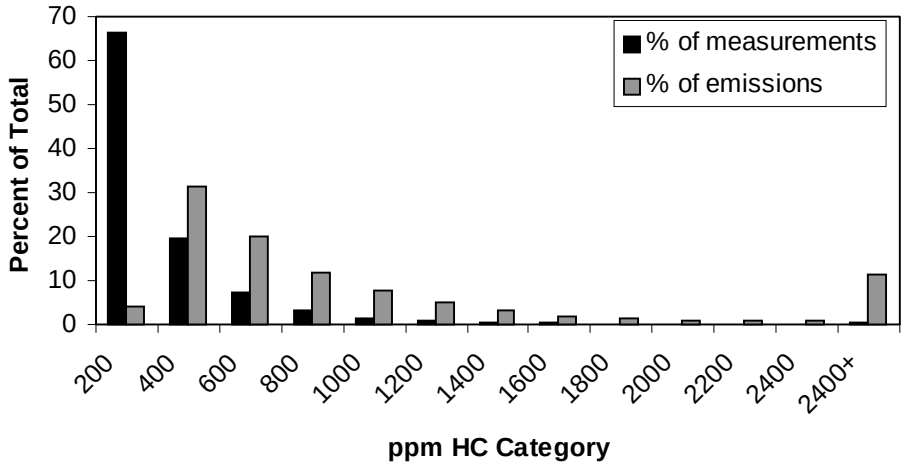


Figure 1. Area map of the interchange from I-25 northbound to 6th Avenue westbound in central Denver, showing remote sensor configuration and safety equipment.





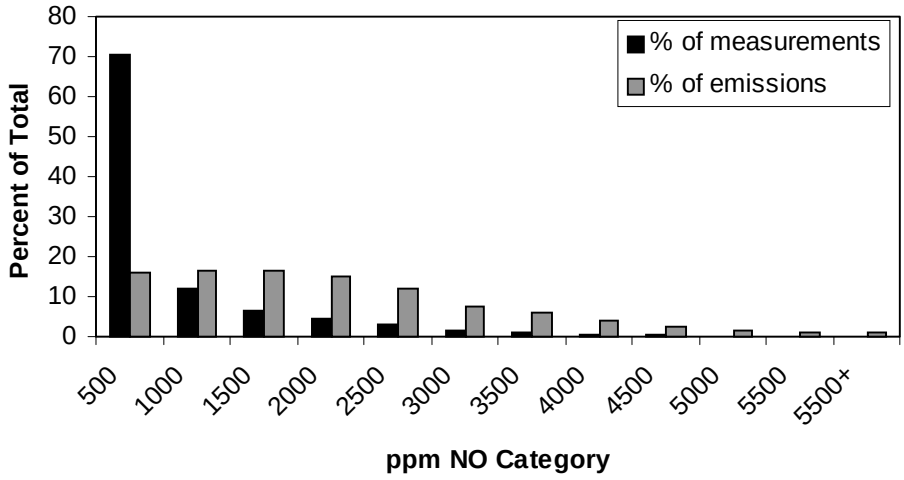


Figure 2. Emissions distribution showing the percentage of the fleet in a given emissions category (black bars) and the percentage of the total emissions contributed by the given category (gray bars).

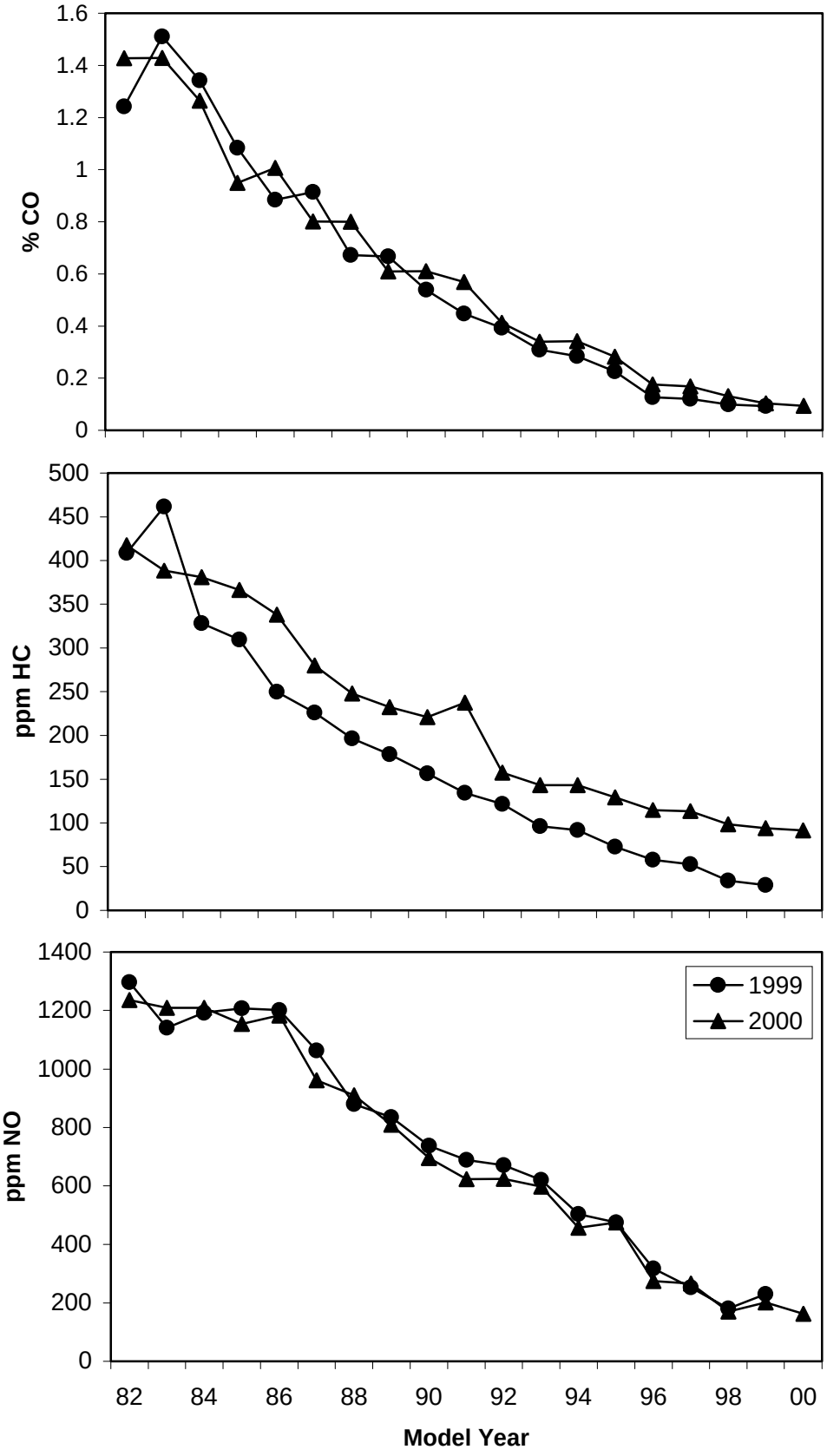


Figure 3. Mean vehicle emissions illustrated as a function of model year. Included are data from two years of measurement at this site.

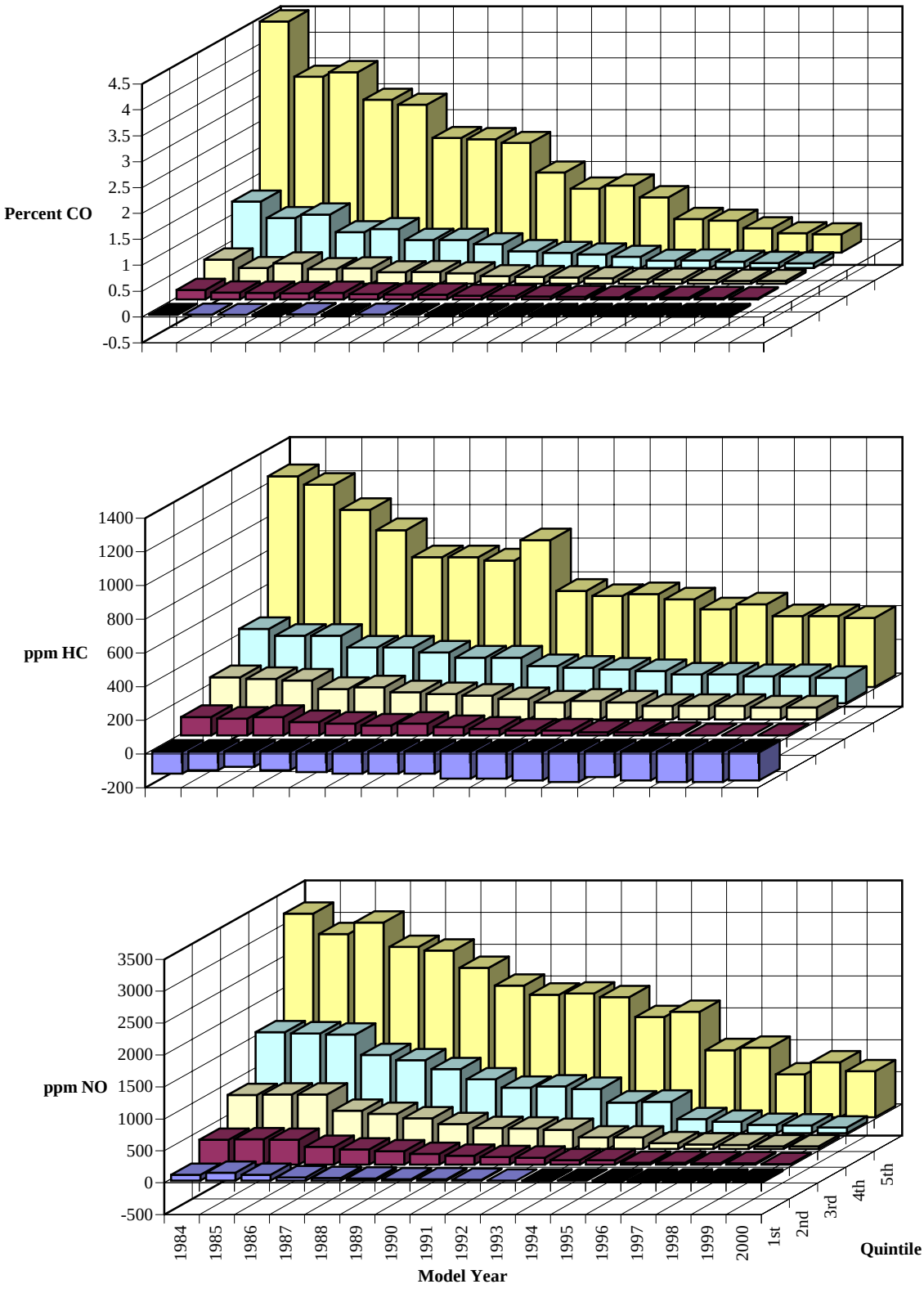


Figure 4. Vehicle emissions by model year, divided into quintiles.

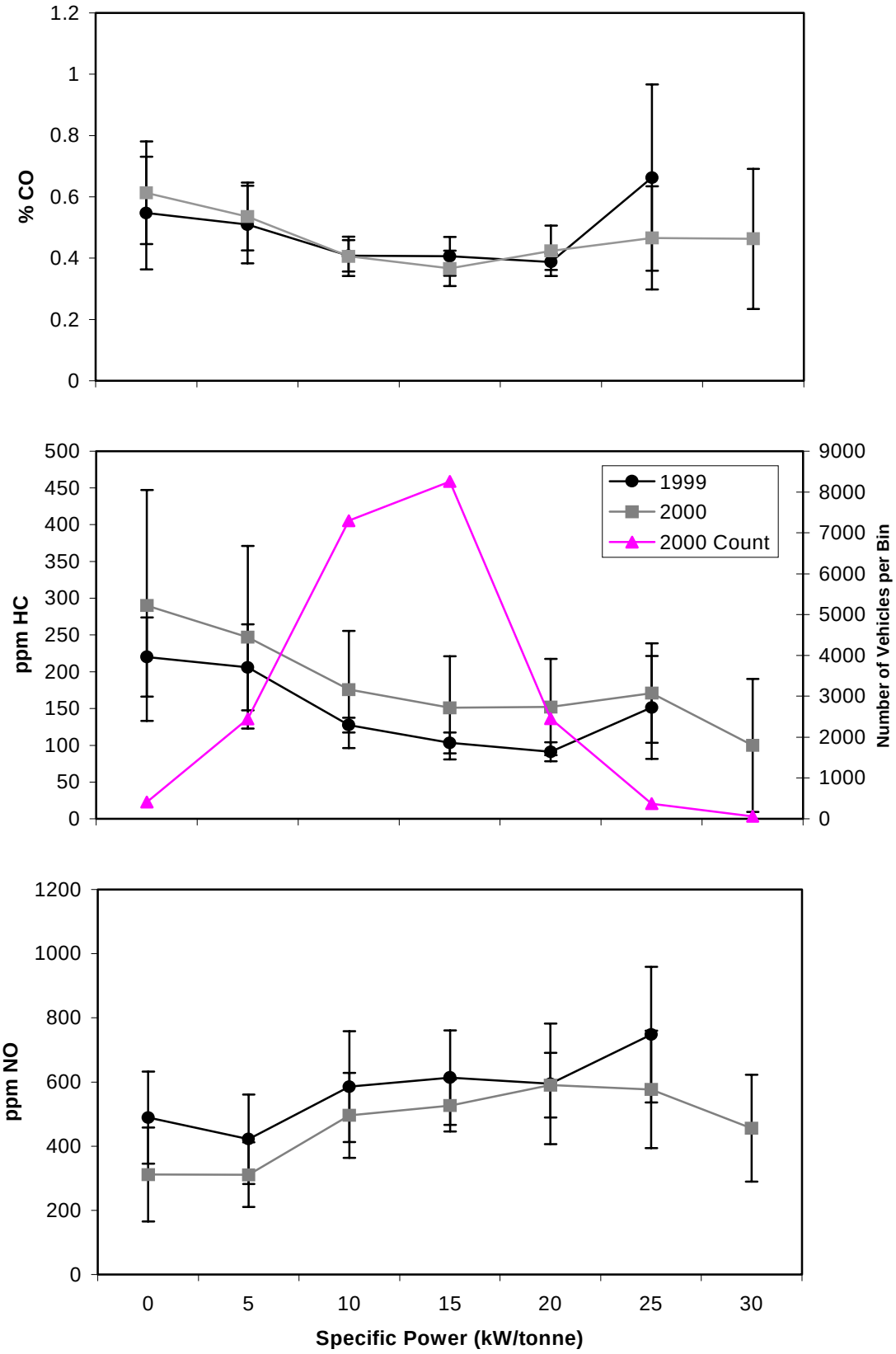


Figure 5. Vehicle emissions as a function of vehicle specific power. Data for the two years of study at this site are given, along with measurement counts for 2000 only. Error bars are 95% confidence intervals of the mean.

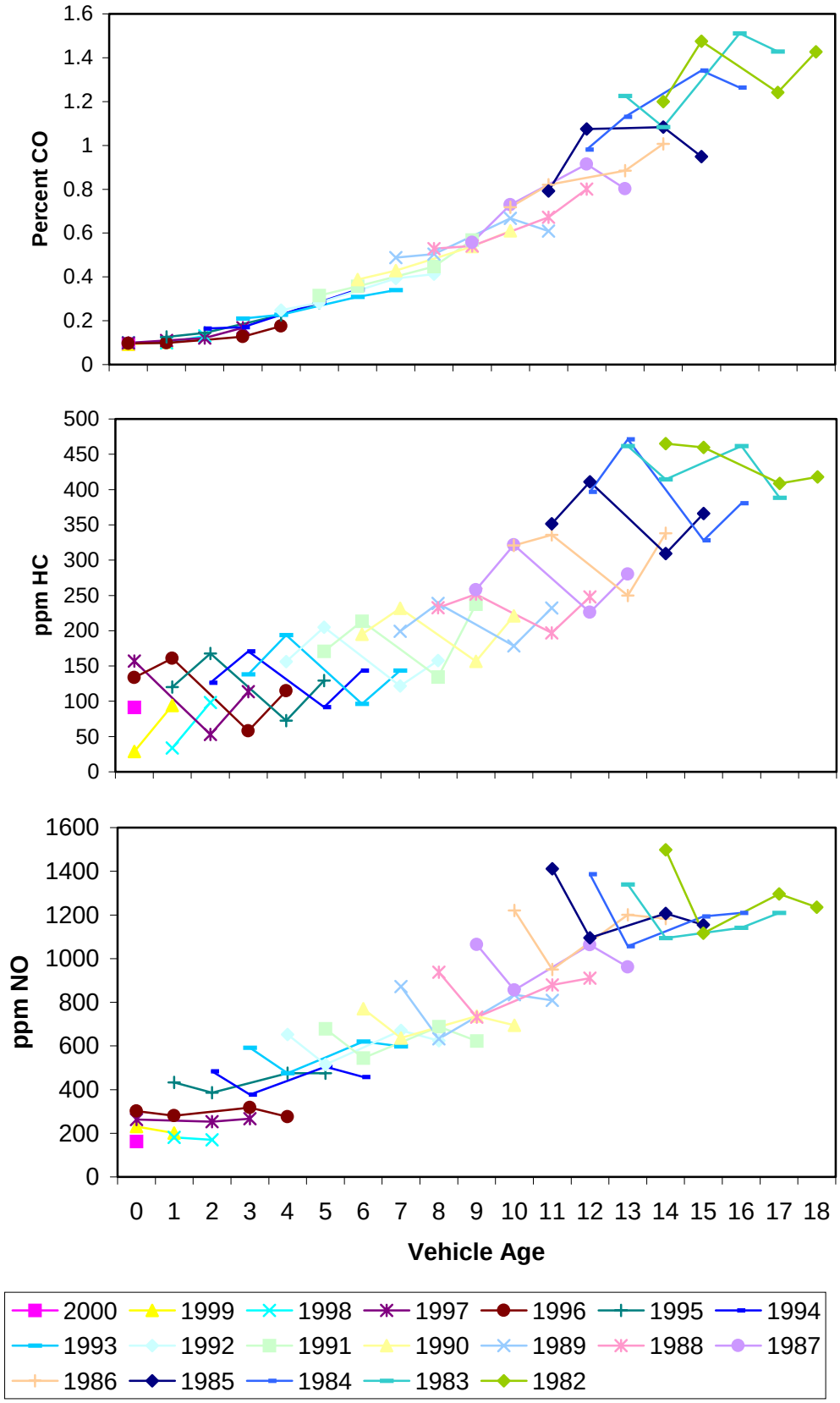


Figure 6. Mean vehicle emissions as a function of age, shown by model year.

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

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 >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 high 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 high 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 high 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: Temperature data.

1999		
Date	Time	Temperature (°F)
01/14	1416	57
	1550	56
01/15	0925	47
	0945	48
	1024	58
	1108	58
	1125	58
01/18	0830	40
	0930	45
	1020	50
	1050	55
	1130	50
	1200	46
02/01	0800	26
	0833	30
	0911	33
	0929	33
	1000	40
	1025	46
	1107	54
	1156	55

2000			
Date	Time	Temperature (°F)	Humidity (%RH)
12/30	1123	48	38
	1203	51	32
	1306	54	29
	1402	55	28
	1514	64	26
	1600	57	26
	1654	52	27
01/11	0933	54	38
	1033	54	32
	1150	55	28
	1233	52	30
	1337	49	37
	1437	50	39
	1551	49	41
	1607	48	41
01/13	0843	35	61
	0943	35	61
	1042	35	62
	1102	36	61
	1201	39	59
	1309	41	56
	1411	42	52
	1509	45	48
01/14	0753	32	69
	0842	35	65
	0953	43	50
	1115	51	36

Appendix C: Explanation of the den_00.dbf database.

The den_00.dbf is a Microsoft Foxpro database file, and can be opened by any version of MS Foxpro, regardless of platform. The following is an explanation of the data fields found in this database:

License	Colorado 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. Units are $\%CO_2$ as measured in an 8 cm cell.
Speed_flag	Indicates a valid speed measurement by a “V”, an invalid by an “X”.
Speed	Measured speed of the vehicle, in mph.
Accel	Measured acceleration of the vehicle, in mph/s.
Veh_type	Type of vehicle.
Vin	Vehicle identification number.
Year	Model year of the vehicle.
Make	Manufacturer of the vehicle.

Model	Model name of the vehicle.
Body	Body style of the vehicle.
Series	Series code of vehicle.
Fuel	Fuel type: ‘G’ indicates gasoline, ‘D’ indicates diesel
Gvw	Unknown. (Gross vehicle weight?)
Legl_city	City the vehicle resides in.
Legal_St	State the vehicle resides in.
Legl_zip5	Zip code the vehicle resides in.
Mail_City	City of owner mailing address.
Mail_St	State of owner mailing address.
Mail_zip5	Zip code of owner mailing address.
County	County code where vehicle resides.
Urbn_rl_cd	Urban or rural designation where vehicle resides. ‘R’ is rural and ‘U’ is urban.
Bus_Date	Unknown.
Expire_Date	Date that current vehicle registration expires.
Purch_Date	Date vehicle was purchased.
Msrp	Manufacturer suggested retail price in US$.
Odometer	Odometer reading during I/M inspection.
Prch_price	Price at which vehicle was purchased in US$ x 100.
Emiss_flag	I/M flag: ‘Y’, ‘N’, ‘X’.
E_Status	I/M status: ‘P’ is pass and ‘E’ is exempt.
Prog_Type	I/M type: ‘E’ is enhanced and ‘B’ is basic.
Test_date	I/M test date.
Next_insp	Due date for next inspection.

APPENDIX D: Denver RSD versus IM240 Fleet Correlations

To measure the correlation between on-road RSD data and local IM240 program data pollutant measurements from both methods were converted to common units; namely, g of pollutant per kg of fuel. IM240 data, including all "fast pass" estimates, are reported in g/mi, which is easily converted by multiplying first by the miles per gallon of the vehicle (measured during IM240) and then by the inverse of the density of gasoline (0.33295 gal/kg). Converting RSD data to g/kg 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 by 0.014 kg of fuel per mole of carbon in fuel, assuming gasoline is stoichiometrically CH_2.

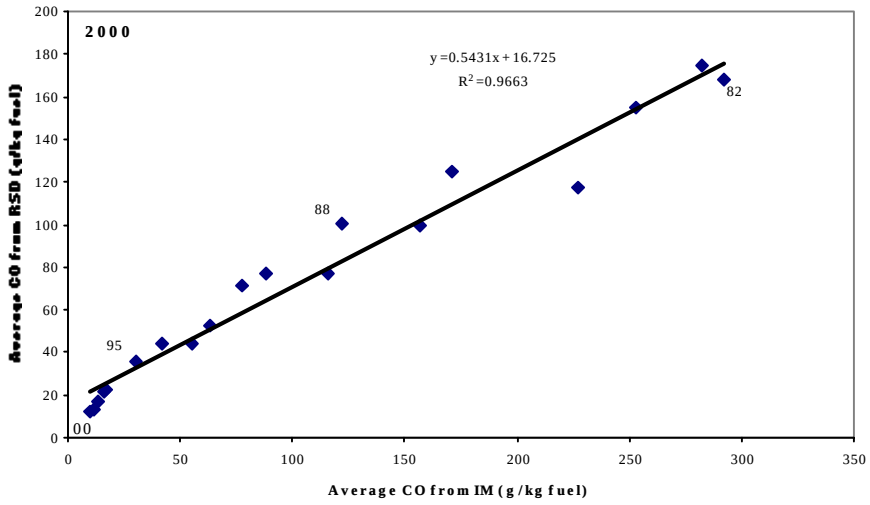
This analysis showed that fleet averaged on-road remote sensing data correlate very well versus fleet average IM240 data. We have demonstrated this previously[1] with three data sets from Denver: RSD January 1999, RSD January 1997 and RSD January 1996 correlated versus IM240 for the whole year in 1998, 1996 and 1995, respectively. For the current year's report the 2000 RSD data has been correlated to the half-year (January to June) IM database for the year 2000. The figure below shows average emissions for each measured model year. There are many more cars in the newest model years. The plots illustrate that, though the slopes of the correlations are not all one, the relationships are mostly linear as seen previously. Furthermore, the excellent correlations (r^2 in every case greater than 0.94) are repeated with the current data.

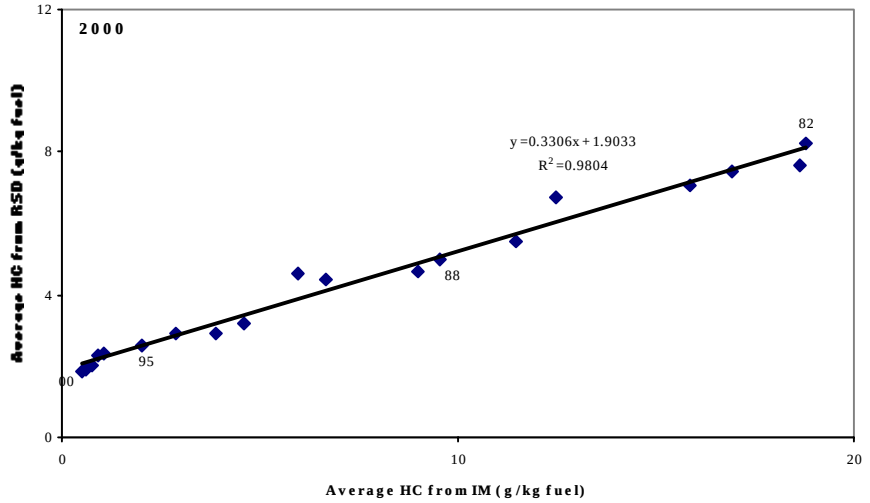
The entire IM240 database, including the calculated FAST-PASS emissions, was used, giving approximately 500,000 measurements. The IM database that we obtained included several hundred thousand other entries that did not have emission measurements. These entries were excluded, as they appeared to be duplicates generated during the data extraction process.

The CO and NO plots show negligible intercepts. As before, the HC plot does have an intercept. The intercept does not detract from the excellent correlations but does mean that the relationship needs to be treated with this intercept in mind for each species separately. The intercepts may arise from different driving modes or from a remote sensing offset, which applies to all vehicles regardless of emissions or model year.

The slopes are less than those shown in the Year 1 report probably because we have looked ahead at year 2000 (6 months) of I/M data. All earlier correlations have looked back at the previous year's data.

[1] See CRC E-23 report: "On-Road Remote Sensing in the Denver Area: Year 1," Appendix D.





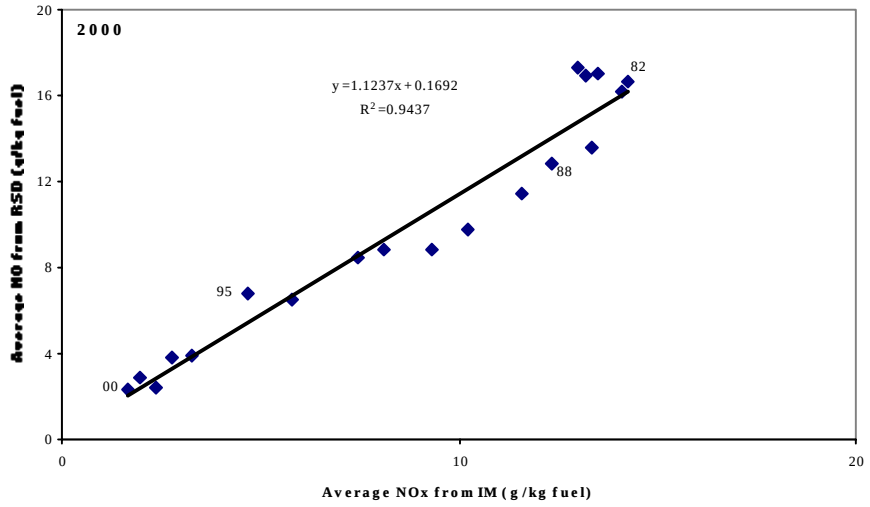


Figure: Correlation plots for three pollutants between Denver IM240 and RSD. The IM240 data are from half a year of testing after the RSD data collection, which consisted of a week of measurements in the January of the year labeled on the plot. Each point represents a model year. Four model years are labeled.

APPENDIX E: Calculation of Vehicle Specific Power Adjusted Vehicle Emissions (Chicago 1997-8 data)

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 F: Calculation of Model Year Adjusted Fleet Emissions (Chicago 1997-8 data)

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 G: Field Calibration Record.

Date	Time	CO Cal Factor	HC Cal Factor	NO Cal Factor
12/30	11:20	1.27	1.2	1.67
1/11	9:30	1.14	1.12	1.25
1/13	8:30	1.76	1.74	1.64
1/13	10:55	1.23	1.09	1.34
1/14	7:50	2.45	2.5	3.1
1/14	10:00	1.40	1.40	1.61

APPENDIX G: Discussion of a Potential Method for Using Remote Sensing Data to Diagnose which Vehicles Would Fail an IM240 Test – Transferred from LA, Year 2 draft report.

When using remote sensing to diagnose the state of a vehicle's emissions control system, it becomes imperative that criteria be set to distinguish vehicles that are "broken" from those that are simply at the high end of normal emissions. If one is to use a single emission measurement to diagnose the vehicle, a cutoff value must be set. If the measured emission of a vehicle is above this value, it is determined to be malfunctioning. Constructing receiver operating characteristic (ROC) curves (as discussed in "Better Decisions through Science," *Scientific American*, October 2000) is a robust method of determining what the most efficient cutoff value would be.

In order to construct ROC curves one must have a diagnostic measurement and also know the true status of the subject being diagnosed. In our case we are using remote sensing measurements as the diagnostic tool. What is more problematic is the knowledge of the true status of the vehicle: whether it is truly malfunctioning or not. For the current analysis we treat the I/M test result within the following six months as the indicator of the true status of the vehicle. More specifically, the result of an IM240 for a particular pollutant will be used, in this case CO. It is important to remember, however, that the IM240 result is not the true status of the vehicle but is brought about, in turn, by setting a cut-off value. Furthermore, during the six months between the remote sensing measurement and the IM240 inspection the vehicle's emissions status may change. Also, high emitting vehicles are known to show highly variable emissions upon repeated testing irrespective of the test protocol used.

The current analysis uses remote sensing data obtained under the CRC E-23 contract in Denver in December of 1999 and early January of 2000. The I/M data are from the first six months of 2000 in Denver. Thus, it is assumed that all I/M data were recorded after the RSD measurement. This distinction is significant because the diagnostic tool and the actual status must be independent of one-another. If the I/M test came before the remote sensing event, the latter might be dependent on the former, since it is believed that some vehicles are repaired after an I/M failure resulting in lowered RSD measurement.

The first step in constructing ROC curves involves mapping the distribution of diagnostic measurements for two groups of subjects. The subjects are in one group if they are negatives for the factor being diagnosed and in the other group if they are positive. Thus, one must know the true status of the subjects. In our case, the one group consists of vehicles that pass an I/M test for CO subsequent to a remote sensing measurement and the other group is comprised of those that fail. Again, remember, though, that I/M result is not actually the true status of the vehicle. The current data sets yielded 421 vehicles that were measured by RSD and went on to fail an I/M in the subsequent 6 months and 3364 that went on to pass. The distributions for the data set described above are given in Figure G1. The plots show that the peaks of the two distributions, with these rather large bins, are the same but that the distribution of vehicles that go on to fail I/M for CO has a broader tail.

These distributions are then used in the second step of the procedure, where the probabilities of true positive and false positive diagnosis at various cut-off, or threshold, values are calculated. The probabilities are found by calculating the percentage of each population that would be diagnosed positive given each threshold value. The percentage diagnosed positive from the truly positive group is the fraction of true positives, and the percentage diagnosed positive from the negative group is the fraction of false positives. In our case, a threshold of 1% CO, for example, would label 47% of the vehicles that went on to fail IM240 for CO as being "broken"; the probability of true positives at a threshold of 1% CO is then 0.47. Such a threshold would also label 11% of the IM240 passers as malfunctioning; the false positive probability is 0.11.

Such probabilities are determined for the whole range of threshold values, and a plot is constructed which graphs the true positive probabilities against the false positive probabilities for the various threshold values. This is the ROC plot and for our data is Figure G2 below. A straight line on such a plot would indicate chance accuracy, meaning that the diagnostic test has a 50/50 chance of correct diagnosis; one might as well flip a coin. The more a curve bows to the left, the more accurate the diagnostic test is. A more precise value of accuracy is defined to be the percent of the graph that lies under the curve. Our plot gives an accuracy of 73% for our diagnostic test; namely, remote sensing measurement when compared to IM240 within the subsequent 6 months.

Once the ROC curve has been constructed, it is used to decide what the most efficient threshold value should be. In choosing a threshold, one should maximize the true positive probability and minimize the false positive probability. Other factors may also come into play. If a false alarm is costly, one may want to minimize these by going to higher thresholds, but this would sacrifice the detection of some true positives as well. If, on the other hand, it is crucial that positives be detected one would use a lower threshold at the risk of triggering more false alarms.

With our automobile emissions data a threshold of 1.0% CO seems to be the most efficient value (See Figure G2). At this cut-off value, the true positive probability is 0.47, while the false positive probability is only 0.11. What does this mean? Let's take a random sample of 100 vehicles. If the 100 vehicles were all subject to IM240, 11 would fail for CO (11% overall failure rate on IM240 for CO). Alternatively, if these cars were all measured by remote sensing, 15 would be diagnosed as having malfunctioning emission control systems at the 1% threshold (15% of all vehicles have CO>1.0%). If these 15 failed vehicles of 100 measured by remote sensing were subject to IM240, 5 (47% of 11) would fail and 10 would pass. The ten that pass are the false positives (11% of 89 "unbroken" cars).

It should be noted that the current analysis most likely does not accurately describe the true efficiency of using remote sensing as the diagnostic test for broken vehicles emissions system. First, in the analysis an I/M result up to six months away is used as the true status of the vehicle due to the lack of data on the actual true status. One problem with this time lag is that motorists may repair vehicles that are suspected of being high

emitting before the I/M test. Second, we have used a limited amount of data (only approximately 4000 measurements), especially in light of the skewedness of our distribution. This resulted in the distributions not being smooth. Thus, knowledge of the true status of the vehicle and further data acquisition should more precisely determine the efficiency of using remote sensing as a diagnostic tool. It is also worth noting that we are comparing a one second test, which neither inconveniences the driver nor adds to his annual mileage, to a scheduled, centralized $24 IM240 test.

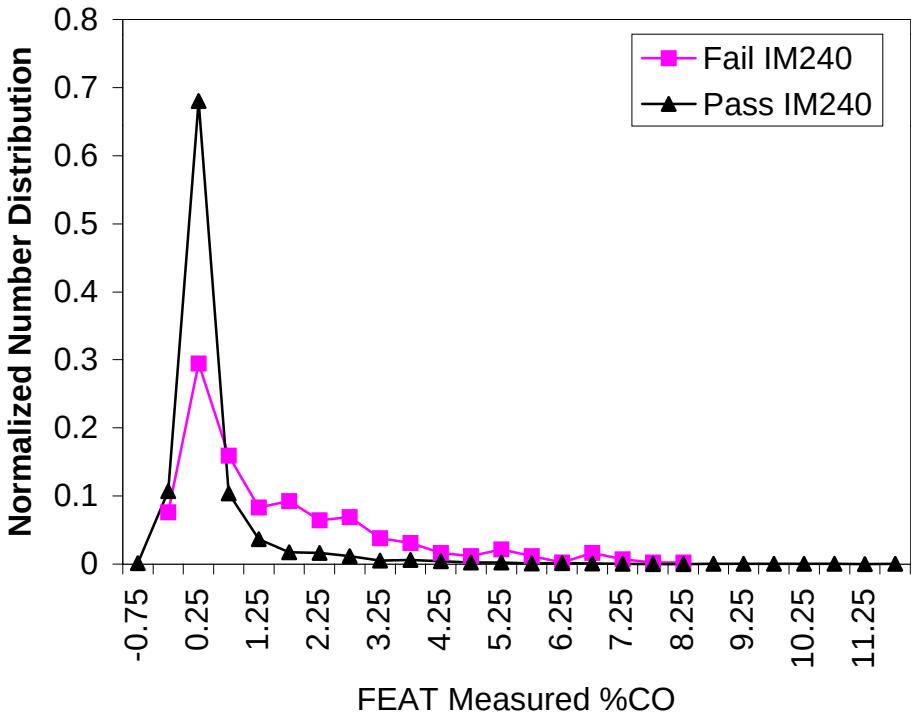


Figure G1. Distribution of subsequent IM240 passes and fails for CO only, as a function of FEAT %CO measurement category. RSD measurements are from Dec./Jan. of 1999/2000. I/M results are from the first six months of 2000.

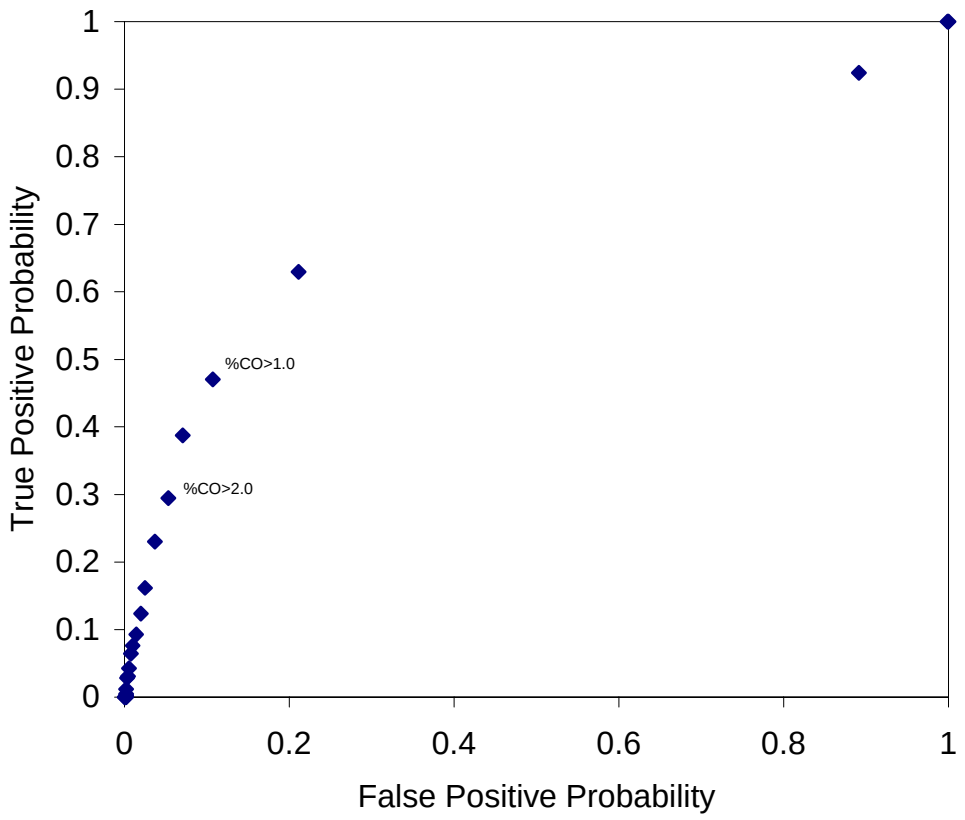


Figure G2. ROC curve for RSD CO measurements as indicators of IM240 CO result in the subsequent 6 months.