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

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## EXECUTIVE SUMMARY

The University of Denver has completed the first 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 the license plate of the vehicle.

Measurements were conducted on 4 business days and one Saturday in January and early February of 1999 in Denver. The measurement site was the interchange ramp for northbound I-25 to westbound 6$^{th}$ Avenue in central Denver. A database was compiled containing 26,709 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 26,111 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 0.45%, 130 ppm and 600 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. 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. The fact that the cleanest 88% of the fleet is responsible for only 30% of CO emissions demonstrates this phenomenon. This skewed distribution was also seen in previous studies at the site. While CO emissions observed for the fleet in Denver were similar to a fleet measured in Chicago in September of 1998, the NO emissions of the fleet observed in Denver were higher while the Chicago fleet exhibited higher HC emissions. These differences are likely due to the combination of vehicles in Denver operating under higher load due to the 8% roadway grade at the measurement site and Denver using oxygenated fuels in the winter.

## 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. Engine-out 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. 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 $N_2$.

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.[3,4] 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 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. 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 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% for the values reported by an on-board gas analyzer, and within ±15% for HC.[5,6] 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.[4]

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 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 January and February of 1999, as part of CRC's E-23 program. Measurements were made on four weekdays and one Saturday in the time period from January 14 to February 1. The measurement location used in this study was the interchange from northbound I-25 to westbound 6$^{th}$ Avenue in central Denver. A map of the measurement location is shown in Figure 1. This interchange ramp has an uphill grade of 8% at the measurement location. This was the first year of a 5-year study to characterize motor vehicle emissions and deterioration in the Denver area.

## RESULTS AND DISCUSSION

Following the 5 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 have the vehicle make and model year determined. The resulting database contained 26,709 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. 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 6$^{th}$ Avenue site. These measurements were conducted in January of 1996 and 1997, respectively.

Compared to the fleets measured in 1996 and 1997, 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. In addition, it can be shown by the mean age of the 1999 fleet that it was slightly younger at the time of measurement than the fleets measured in either 1996 or 1997. 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.*[7] 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 1**: Validity summary.

| | CO | HC | NO |
|---|---|---|---|
| Attempted Measurements | 34,613 | | |
| Valid Measurements<br>Percent of Attempts | 33,600<br>97.1% | 33,084<br>95.6% | 32,757<br>94.6% |
| Submitted Plates<br>Percent of Attempts<br>Percent of Valid Measurements | 28,363<br>81.9%<br>84.4% | 27,979<br>80.8%<br>84.6% | 27,725<br>80.1%<br>84.6% |
| Matched Plates<br>Percent of Attempts<br>Percent of Valid Measurements<br>Percent of Submitted Plates | 26,709<br>77.2%<br>79.5%<br>94.2% | 26,353<br>76.1%<br>79.7%<br>94.2% | 26,111<br>75.4%<br>79.7%<br>94.2% |

**Table 2.** Data summary.

| | 1999 | 1997 | 1996 |
|---|---|---|---|
| Mean CO (%) | 0.45 | 0.51 | 0.53 |
| Percent of Total CO from Dirtiest 10% of the Fleet | 66.3 | 67.0 | 63.8 |
| Mean HC (ppm) | 130 | 260 | 250 |
| Percent of Total HC from Dirtiest 10% of the Fleet | 63.7 | 48.3 | 58.0 |
| Mean NO (ppm) | 600 | 620* | 860* |
| Percent of Total NO from Dirtiest 10% of the Fleet | 44.6 | 43.6* | 38.1* |
| Mean Model Year | 1992.4 | 1990.3 | 1989.2 |
| Mean Speed (mph) | 20.6 | 21.7 | 21.9 |
| Mean Acceleration (mph/s) | 0.21 | 0.11 | -0.21 |
| * Nitric oxide measurements in 1996 and 1997 were made using a non-dispersive ultraviolet absorption nitric oxide channel. See Zhang *et al.*[7] | | | |

Figure 2 shows the distribution of CO, HC and NO emissions by percent or ppm category from the data collected in Denver 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 50% of the fleet for NO and close to 90% of the fleet for CO. The fact that the cleanest 88% of the fleet is responsible for only 30% 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 and 1997 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 ( 200 ppm) is dominated by negative values and appears to make an almost negligible contribution to the total emissions.

An equation for determining the instantaneous power of an on-road vehicle has been proposed by Jimenez[8], which takes the form

$$SP = 4.363 \cdot \sin(slope) \cdot v + 0.22 \cdot v \cdot a + 0.0657 \cdot v + 0.000027 \cdot v^3$$

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 Denver in 1999. The emissions data were binned according to vehicle specific power and are illustrated in Figure 3. Also shown in Figure 3 are vehicle emissions binned by specific power for remote sensing measurements collected in Chicago in September of 1998.[9] As expected, CO and HC emissions show a negative dependence on vehicle specific power. The NO emissions show an overall positive dependence with the exception of unexpectedly high emissions at negative specific powers. 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.

The inverse relationship between vehicle emissions and model year is shown in Figure 4 for the emissions data collected in Denver. Shown for comparison in Figure 4 are data collected in Chicago in September of 1998.[9] While there is little difference between the CO emissions of the two fleets, the HC emissions of the Denver fleet are lower in all model years shown while the NO emissions are higher. These differences can be attributed to the fact that the vehicles at the Denver site are operating under higher load, due to the 8% grade of the interchange ramp. Furthermore, mandatory fuel oxygenation in Denver in the winter may account for some of the increased NO. We also suspect a cooling problem with the hydrocarbon detector in the Chicago 1998 data. The mean vehicle specific power, as described previously, was 9.2 kW/tonne for the vehicles measured in Denver and 8.6 kW/tonne for the vehicles measured in Chicago. Other differences in Denver include lower temperatures. Temperature data for select days of

the Denver study are shown in Appendix B. A correlation study was done with Denver RSD data versus IM240 data, including temperature corrected NO correlations. This is attached as Appendix D.

## CONCLUSIONS

The University of Denver has completed the first year of a five-year remote sensing study of motor vehicle emissions and deterioration in the Denver area. A database was compiled containing 26,709 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 26,111 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 0.45%, 130 ppm and 600 ppm, respectively. 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. 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 from the authors for the 1999 study. Appendix C defines the database format.

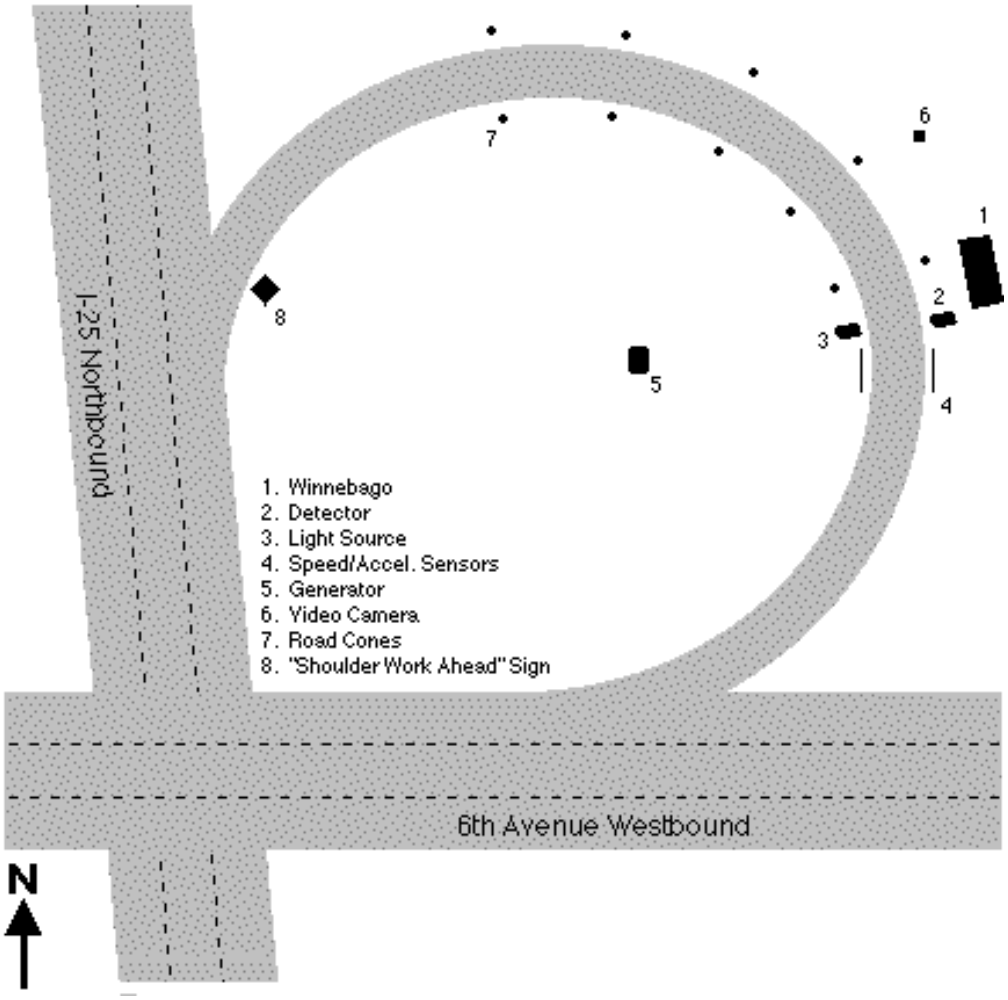


**Figure 1.** Area map of the interchange from I-25 northbound to 6th Avenue westbound in central Denver, showing remote sensor configuration and safety equipment.

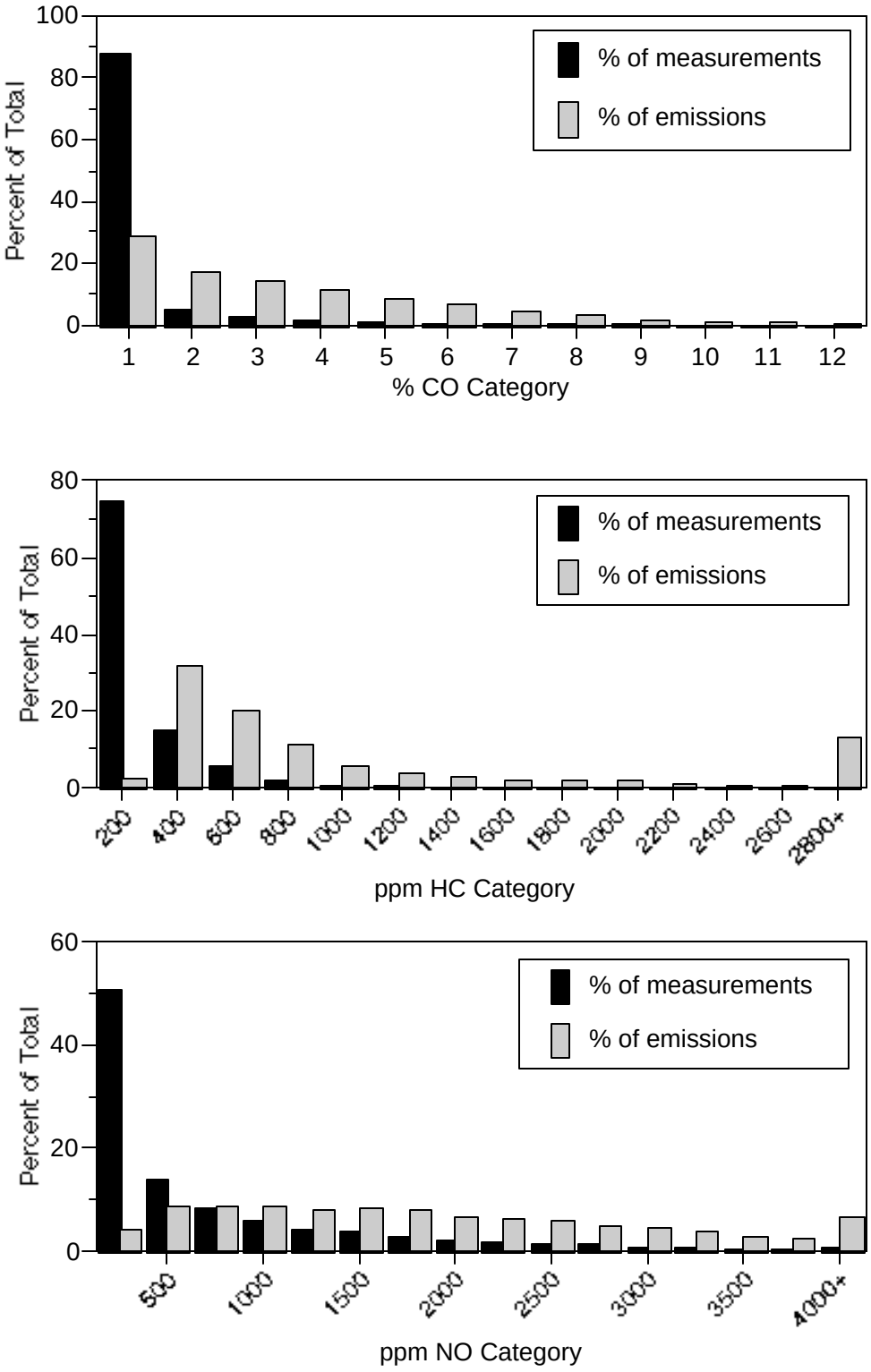


**Figure 2.** Emissions distribution showing the percentage of the fleet in a given emissions category (black bars) and the percentage of the total emissions contributed by the given category (gray bars).

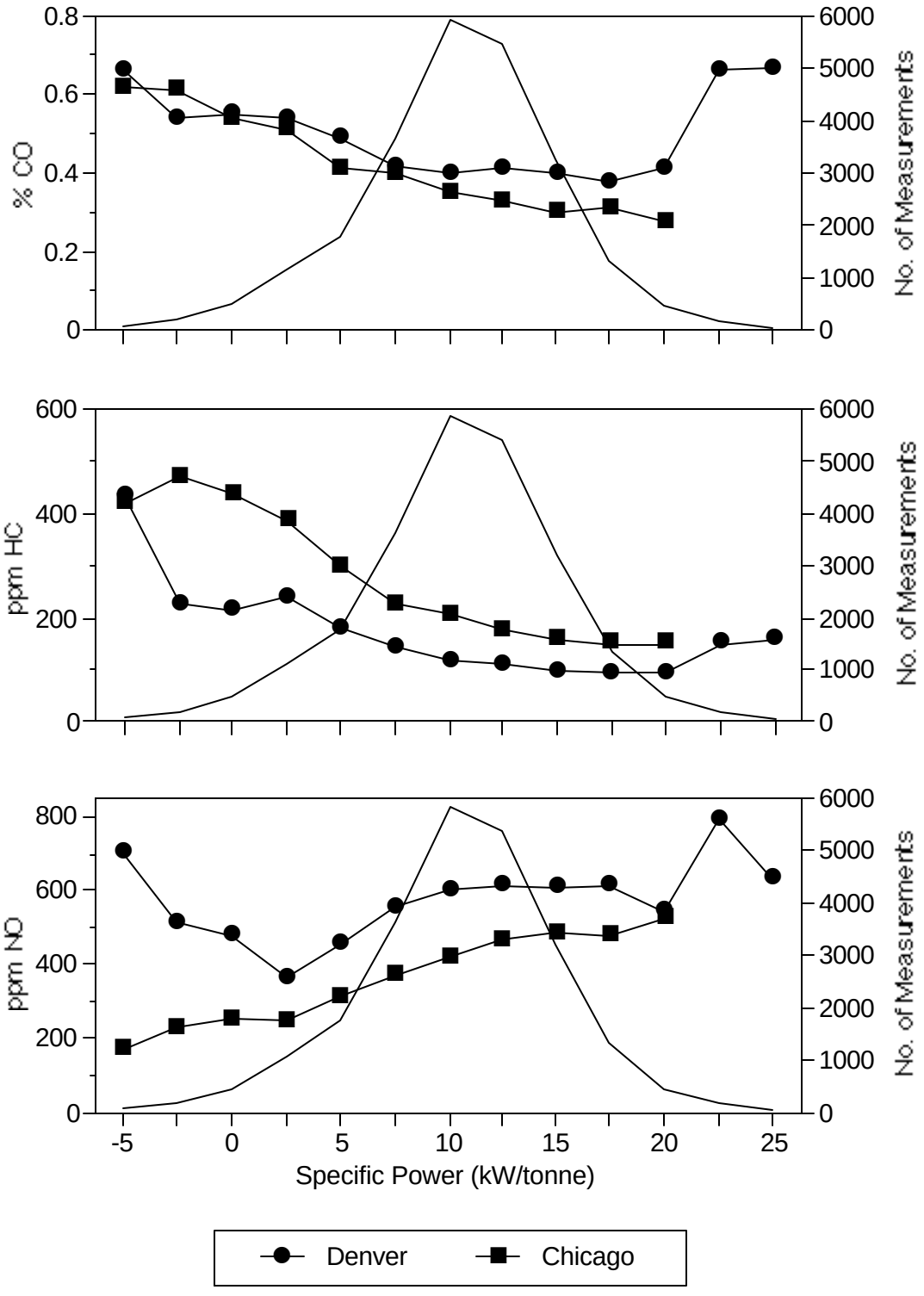


**Figure 3.** Vehicle emissions as a function of vehicle specific power. Measurement counts (for Denver only) are represented by the plain black line.

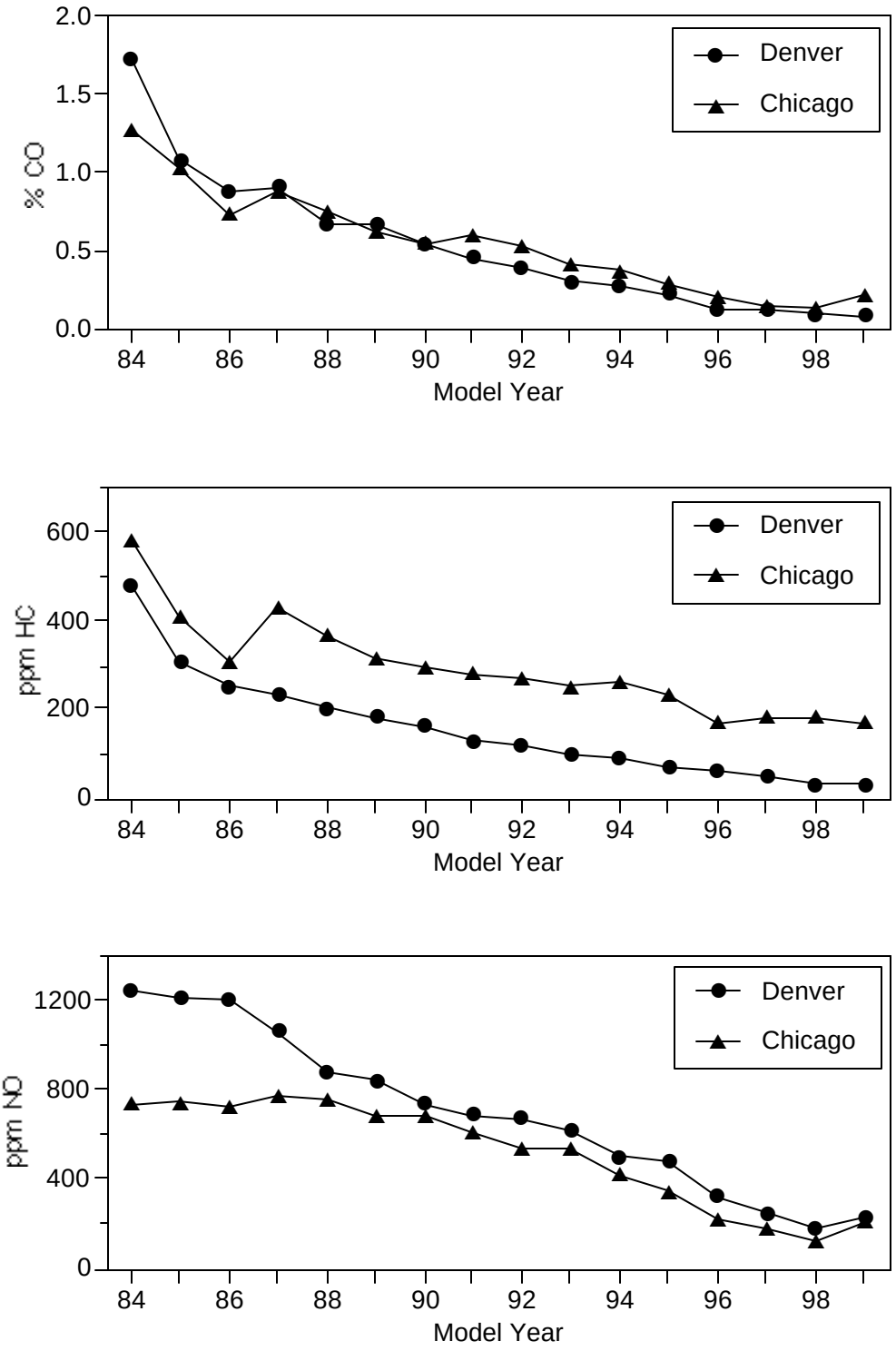


**Figure 4.** Mean vehicle emissions illustrated as a function of model year.

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9. On-Road Remote Sensing of Automobile Emissions in the Chicago Area: Year 2. A draft report to the Coordinating Research Council. University of Denver. 1999.

## 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 $CO_2$. 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.**

| Date | Time | Temperature (°F) |
|---|---|---|
| 01/14/99 | 1416 | 57 |
| | 1550 | 56 |
| 01/15/99 | 0925 | 47 |
| | 0945 | 48 |
| | 1024 | 58 |
| | 1108 | 58 |
| | 1125 | 58 |
| 01/18/99 | 0830 | 40 |
| | 0930 | 45 |
| | 1020 | 50 |
| | 1050 | 55 |
| | 1130 | 50 |
| | 1200 | 46 |
| 02/01/99 | 0800 | 26 |
| | 0833 | 30 |
| | 0911 | 33 |
| | 0929 | 33 |
| | 1000 | 40 |
| | 1025 | 46 |
| | 1107 | 54 |
| | 1156 | 55 |

## Appendix C: Explanation of the den_99.dbf database.

The den_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** | 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. |
| **Speed_flag** | Indicates a valid speed measurement by a “V”, an invali |
| **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. |
| **Body_style** | Body style of the vehicle. |
| **Legl_city** | City the vehicle resides in. |

| | |
|---|---|
| **Legl_zip** | Zip code the vehicle resides in. |
| **Bus_mo** | Unknown. |
| **Bus_yr** | Unknown. |
| **Expire_mo** | Month that current vehicle registration expires. |
| **Expire_yr** | Year that current vehicle registration expires. |

## 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 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. The figures (1-3) show 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. Furthermore, the reproducibility of the excellent correlations ($r^2$ in every case greater than 0.95) during the three separate years of study is evident.

In each of the three years of study, all of the IM240 data base, including the calculated FAST-PASS emissions, were used. Thus in each case that gave approximately 1,000,000 measurements. The remote sensing data consisted of about 25,000 measurements in 1999 and 1996 and about 35,000 in 1997.

There is a slight curvature in the NO data which may be due to temperature effects. Since all RSD data were obtained during the winter when ambient temperatures are low and oxygenated fuel is mandated in Denver, a correlation study was done with the RSD data and IM240 data from January and the first half of February. When this temperature and oxy-fuel difference is accounted for, the curvature of the NO correlation plot is diminished (Figure 4).

The CO plots show negligible intercepts. The HC and NO plots do show intercepts. 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.

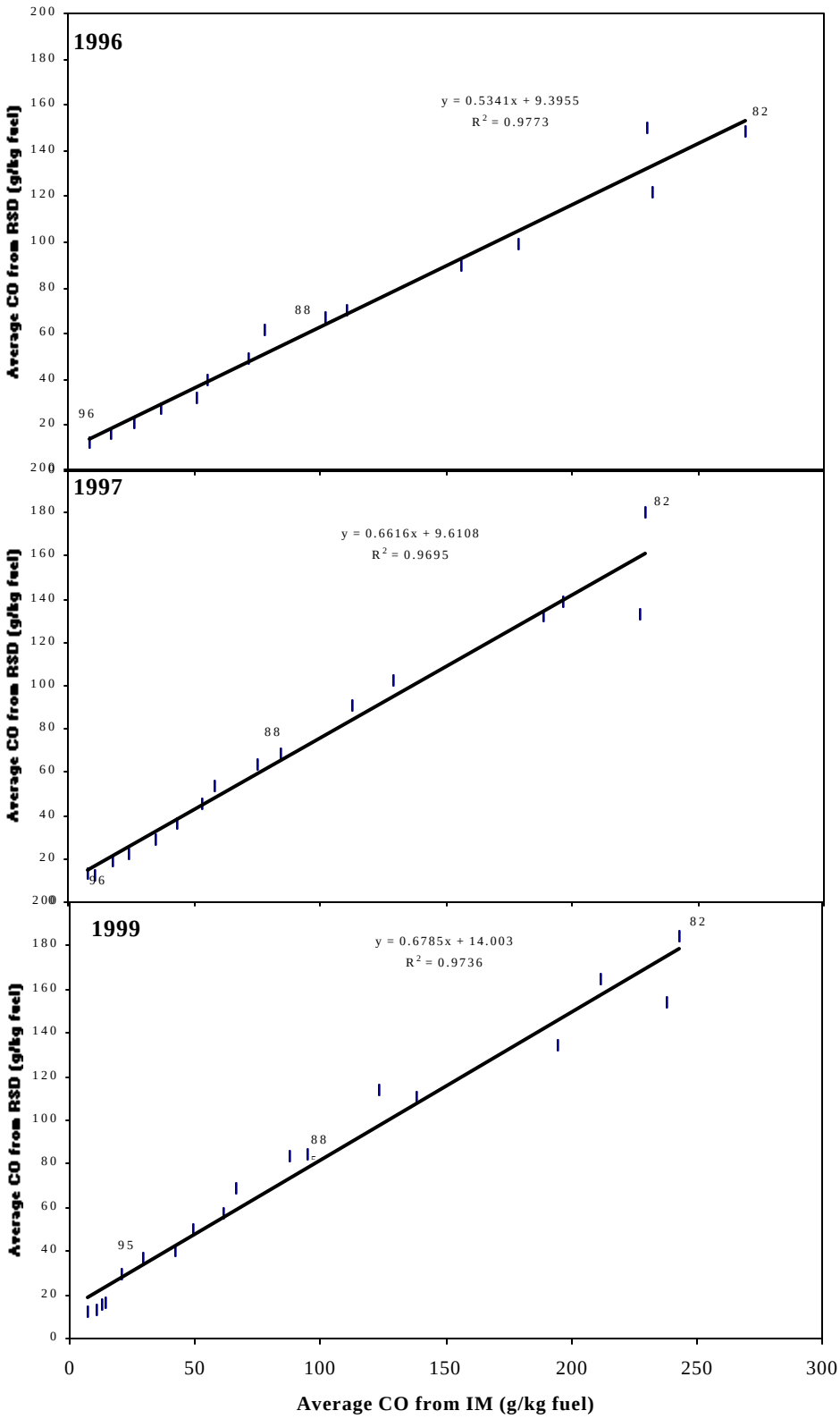


**Figure 1:** Correlation plots for CO between Denver IM240 and RSD for three separate years. The IM240 data are from a whole year of testing before the RSD data collection, which consisted of a week of measurements in the January of the year labeled on the plot. Each point represents a model year. Three model years are labeled.

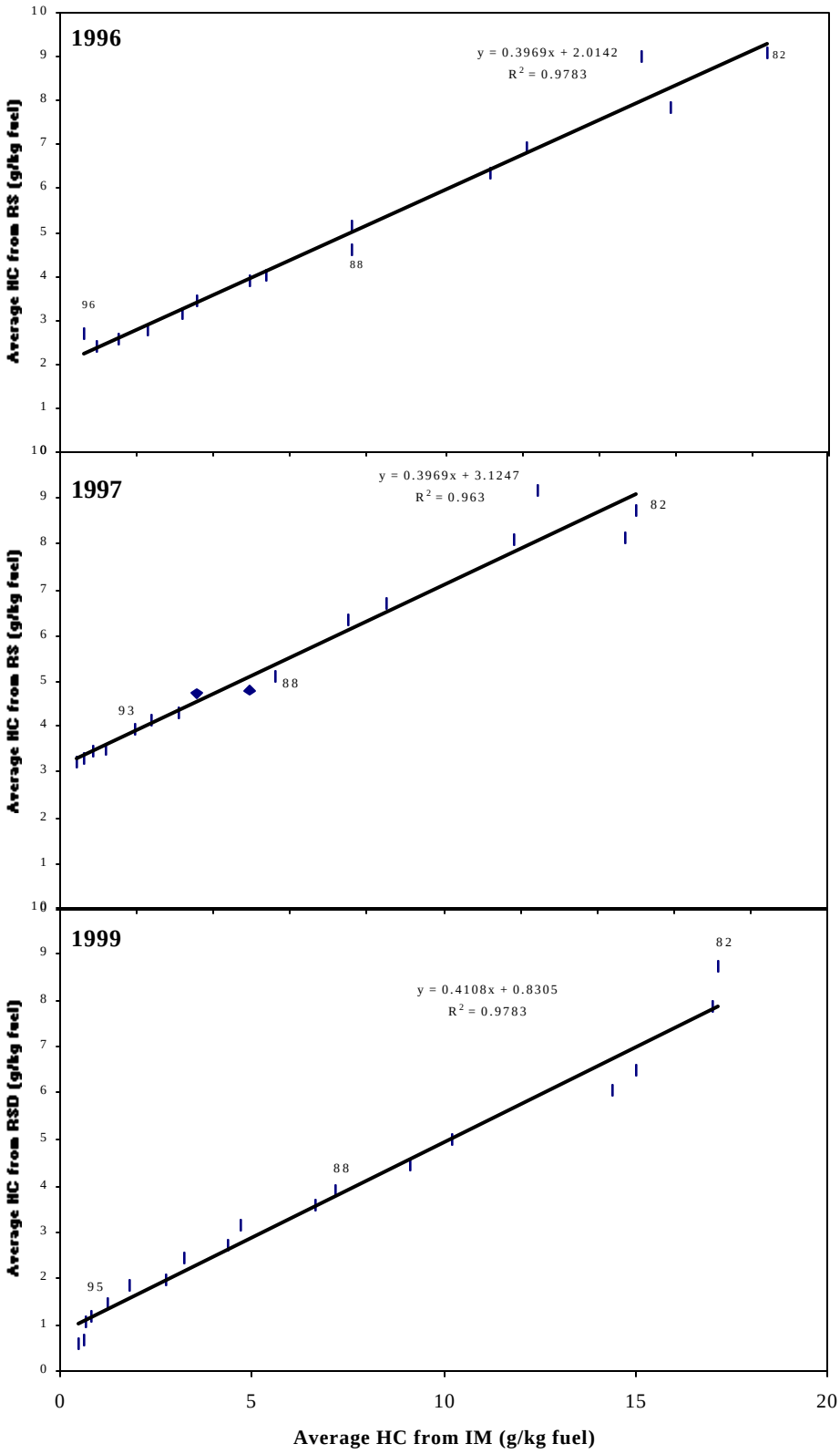


**Figure 2:** Correlation plots for HC between Denver IM240 and RSD for three separate years. The IM240 data are from a whole year of testing before the RSD data collection, which consisted of a week of measurements in the January of the year labeled on the plot. Each point represents a model year. Three model years are labeled.

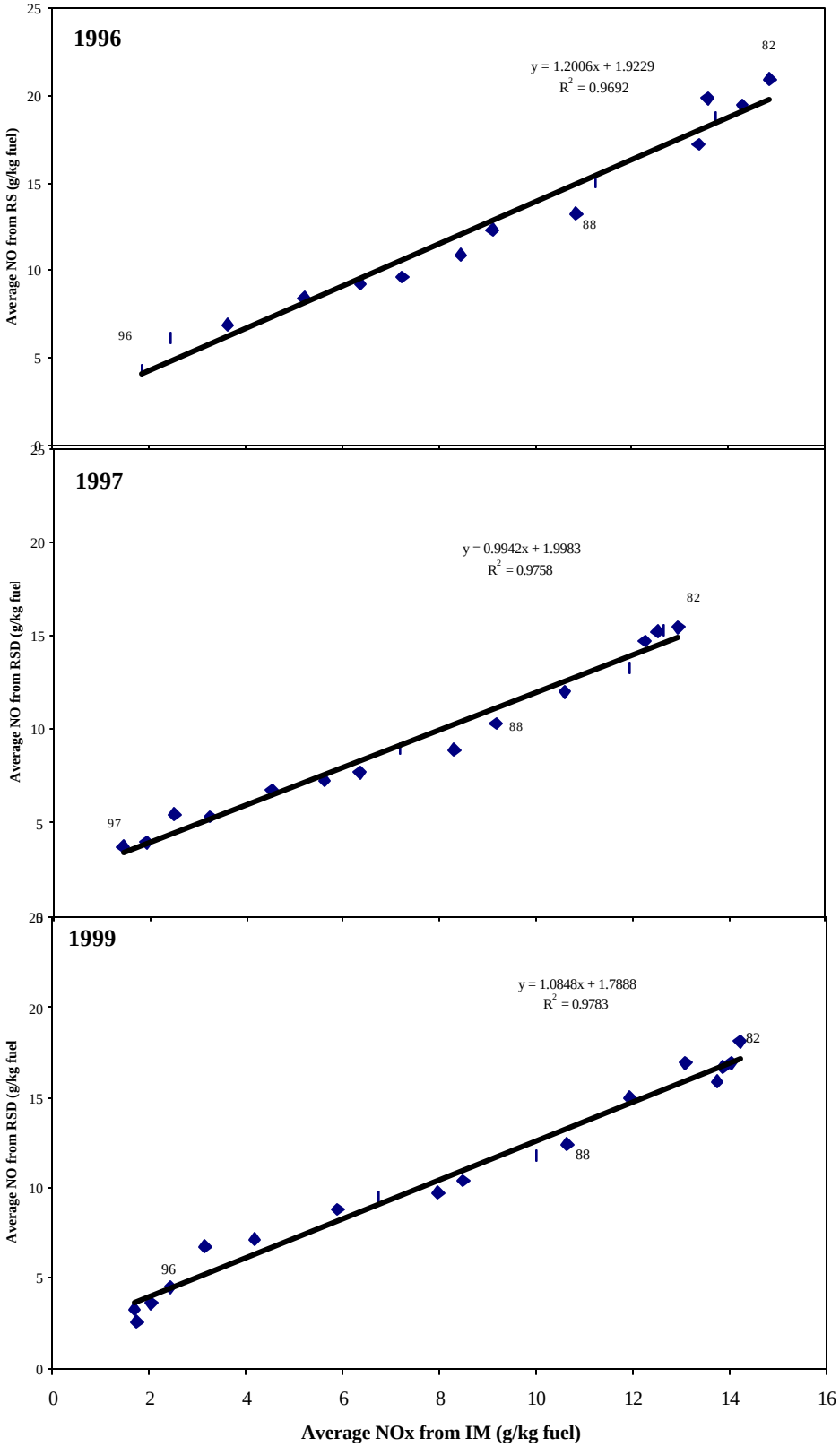


**Figure 3:** Correlation plots for NO between Denver IM240 and RSD for three separate years. The IM240 data are from a whole year of testing before the RSD data collection, which consisted of a week of measurements in the January of the year labeled on the plot. Each point represents a model year. Three model years are labeled.

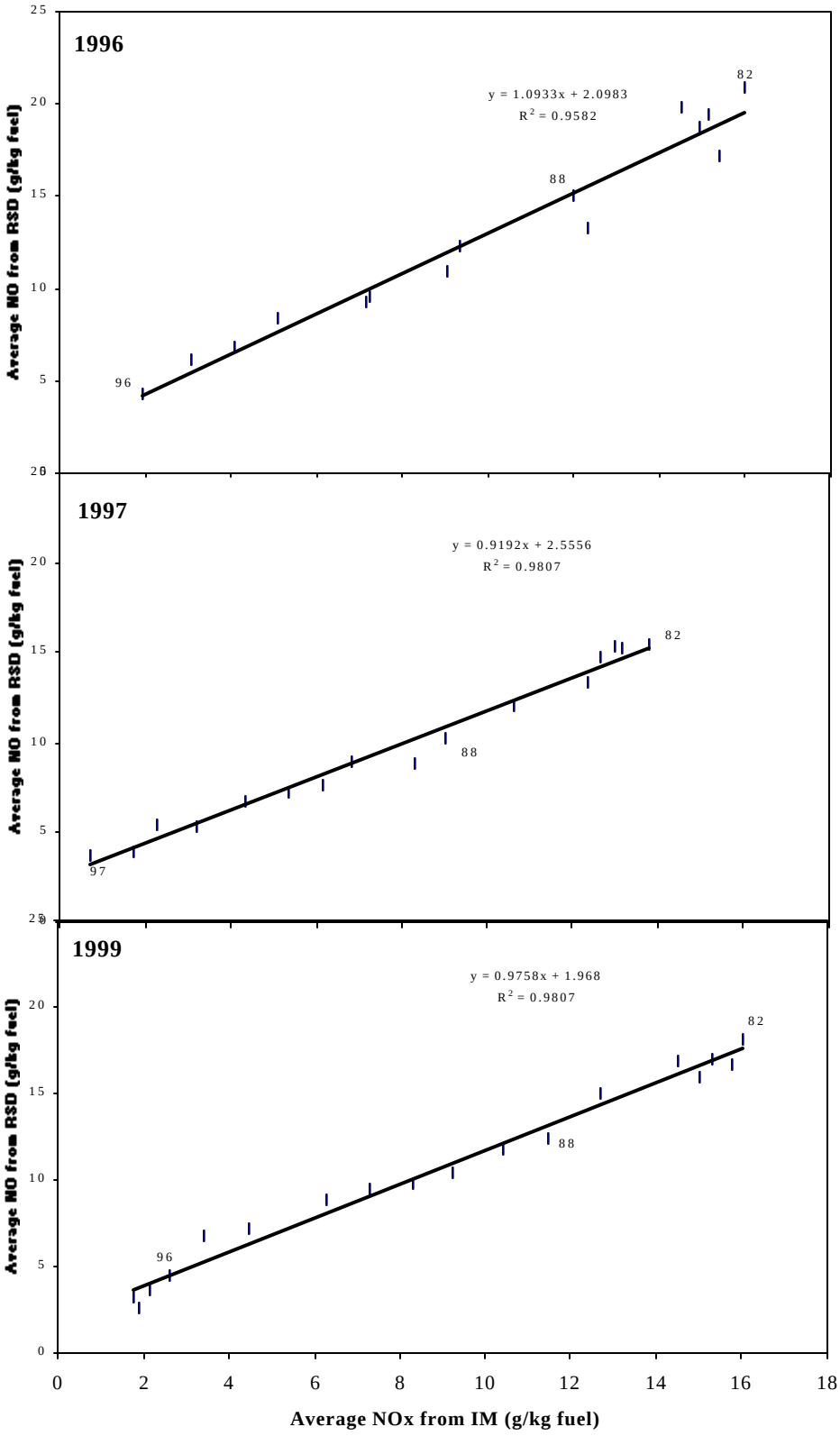


**Figure 4:** Correlation plots for NO during cold months between Denver IM240 and RSD for three separate years. The IM240 data are from January and February before the RSD data collection, which consisted of a week of measurements in the January of the year labeled on the plot. Each point represents a model year. Three model years are labeled.