1999

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

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November 1999

Prepared for:

Coordinating Research Council, Inc.
219 Perimeter Center Parkway
Atlanta, Georgia 30346
Contract No. E-23-4

EXECUTIVE SUMMARY

The University of Denver conducted a four-day remote sensing study in the Phoenix, AZ area in the fall of 1998. 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.

Four days of fieldwork (November 16-19, 1998) were conducted on the uphill exit ramp from I-10W to US 143N in Tempe, AZ. A database was compiled containing 17,759 records for which the State of Arizona provided make and model year information. All of these records contained valid measurements for at least CO and CO_2, and 11,897 contained measurements for HC and NO.

The mean percent CO, HC, and NO were determined to be 0.28%, 0.019%, and 0.036%, 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 71%, 66%, and 56% of the CO, HC, and NO emissions, respectively.

The majority of vehicles (81%) at this location were measured once. The remaining 19% 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 Phoenix area. However, because of the driving mode at this site a new location similar to the Denver, Chicago and L.A. Basin sites has been selected for 1999.

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, which spreads the light across the four infrared detectors: CO, CO_2, HC and reference.

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

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

$$\text{gm CO/gallon} = 5506\times\%\text{CO}(15 + 0.285\times\%\text{CO} + 2.87\times\%\text{HC})$$

$$\text{gm HC/gallon} = 8644\times\%\text{HC}(15 + 0.285\times\%\text{CO} + 2.87\times\%\text{HC})$$

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

Quality assurance calibrations are performed as dictated in the field by the atmospheric conditions and traffic volumes. A puff of gas containing certified amounts of CO, CO_2, propane and NO is released into the instrument's path, and the measured ratios from the instrument are then compared to those certified by the cylinder manufacturer (Praxair). These calibrations account for day-to-day variations in instrument sensitivity and variations in ambient CO_2 levels caused by atmospheric pressure and instrument path length. Since propane is used to calibrate the instrument, all hydrocarbon measurements reported by the remote sensor are as propane equivalents.

Studies sponsored by the California Air Resources Board and General Motors Research Laboratories have shown that the remote sensor is capable of CO measurements that are correct to within ±5% of the values reported by an on-board gas analyzer, and within ±15% for HC.[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, 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 Phoenix, AZ area in November 1998, under CRC contract no. E-23-4. Measurements were made for 4 consecutive weekdays, from Monday, Nov. 16 to Thursday, Nov. 19, conducted on the uphill exit ramp from I-10W to US 143N in Tempe, AZ. I-10W is mostly northbound at this point, and the exit to 143N is the two right lanes (one is exit only) and is sign posted to Sky Harbor Airport amongst other destinations. The two lanes merge into one as they pass straight down under westbound Broadway, then rise up a straight 3.7% grade towards a bridge over the exit lane from Broadway to I-10W. The measurements were made as far up the 3.7% grade as feasible before the bridge structure. The location is GPS N.33.41038°: W. 111.97415°, claimed accuracy of 88 ft (Garmin International). Measurements were generally made between the hours of 6:30 and 16:30. Monday is mostly afternoon measurements and Tuesday has no afternoon measurements because of a construction closure. This was the first year of a 5-year study to characterize motor vehicle emissions and deterioration in the Phoenix area.

RESULTS AND DISCUSSION

Following the four days of data collection in November of 1998, the videotapes were read for license plate identification. Plates which appeared to be in-state and readable were sent to the State of Arizona to be matched against registration records. The resulting database contained 17,759 records with registration information and valid measurements for at least CO and CO_2. Some of these records also contained valid measurements for HC and NO (see Table I). The complete structure of the database and the definition of terms is included in Appendix B. The temperature and humidity record from nearby Sky Harbor Airport is included in Appendix C.

Table I. Data Summary

	CO	HC	NO
Attempted Measurements	32,789		
Valid Measurements Percent of Attempts	26,261 80.1%	17,946 54.7%	17,462 53.3%
Submitted Plates Percent of Attempts Percent of Valid Measurements	18,800 57.3% 71.6%	12,812 39.1% 71.4%	12,476 38.0% 71.4%
Matched Plates Percent of Attempts Percent of Valid Measurements Percent of Submitted Plates	17,759 54.2% 67.6% 94.5%	12,215 37.3% 68.1% 95.3%	11,897 36.3% 68.1% 95.4%
Mean (%)	0.28	0.019	0.036
Median (%)	0.07	0.009	0.012
Percent of Total Emissions from Dirtiest 10% of the Fleet	70.7	65.5	56.0
Mean Model Year	1993.28		
Mean Speed (mph)	37.2		
Mean Accel (mph/sec)	-0.7		

Despite the roadway grade at this site, the majority of vehicles are traveling at high speed and low power. These are the major contributors which account for the large reductions between attempted measurements and valid measurements and between matched plates with CO and matched plates with CO, HC and or NO. This sites layout and driving modes combine to produce vehicle exhaust plumes which are very small and result in a large number of measurement attempts which are invalidated by the sensor's software. Because of this data loss we are going to change the measurement site in 1999 to a location which we hope will provide higher loads and thus higher data capture rates.

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 grey 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 70% of the fleet (for HC), and as much as 91% 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. For CO and HC the lowest seven deciles are each given the average of all seven. For NO the first six are given the average of all six, 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 a 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,[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, only the HC emissions show a tendency for the mean and median emissions of each pollutant to increase slightly for the 1999 model year[9]. There were 719 1999 model year vehicles measured compared to 2,584 1998 model year vehicles.

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.

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

$$SP = 4.364\times\sin(slope)\times v + 0.22\times v\times a + 0.0657\times v + 0.000027\times v^3$$

where SP is the vehicle specific power in kW/metric tonne, *slope* is the slope of the roadway (in degrees), *v* is vehicle speed in mph, and *a* is vehicle acceleration in mph/s. Using this equation, vehicle specific power was calculated for all measurements in the database. The emissions data were binned according to vehicle specific power,

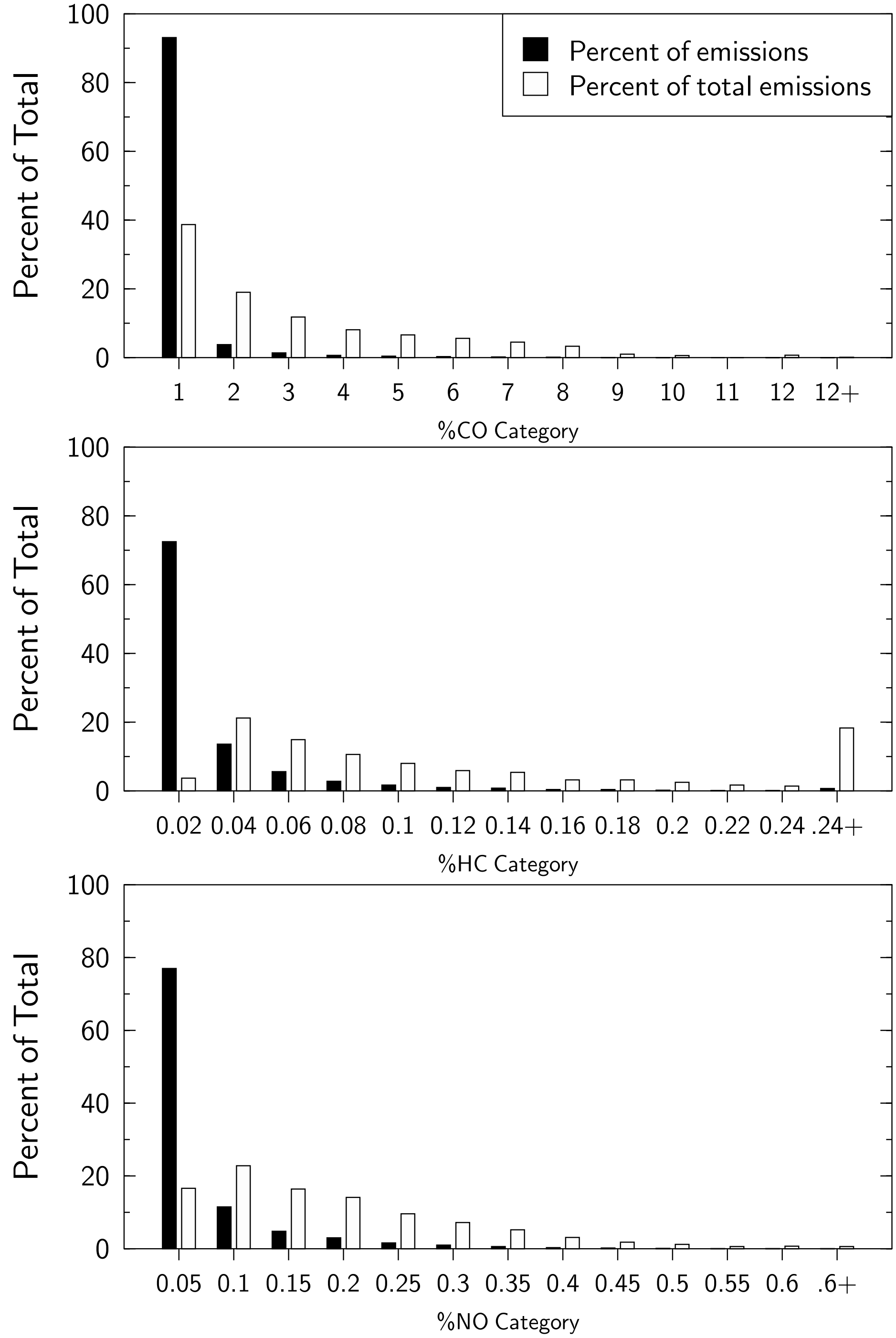

Figure 1. Emissions distributions showing the percentage of the fleet in a given emissions category (solid bars) and the percentage of the total emissions contributed (grey bars).

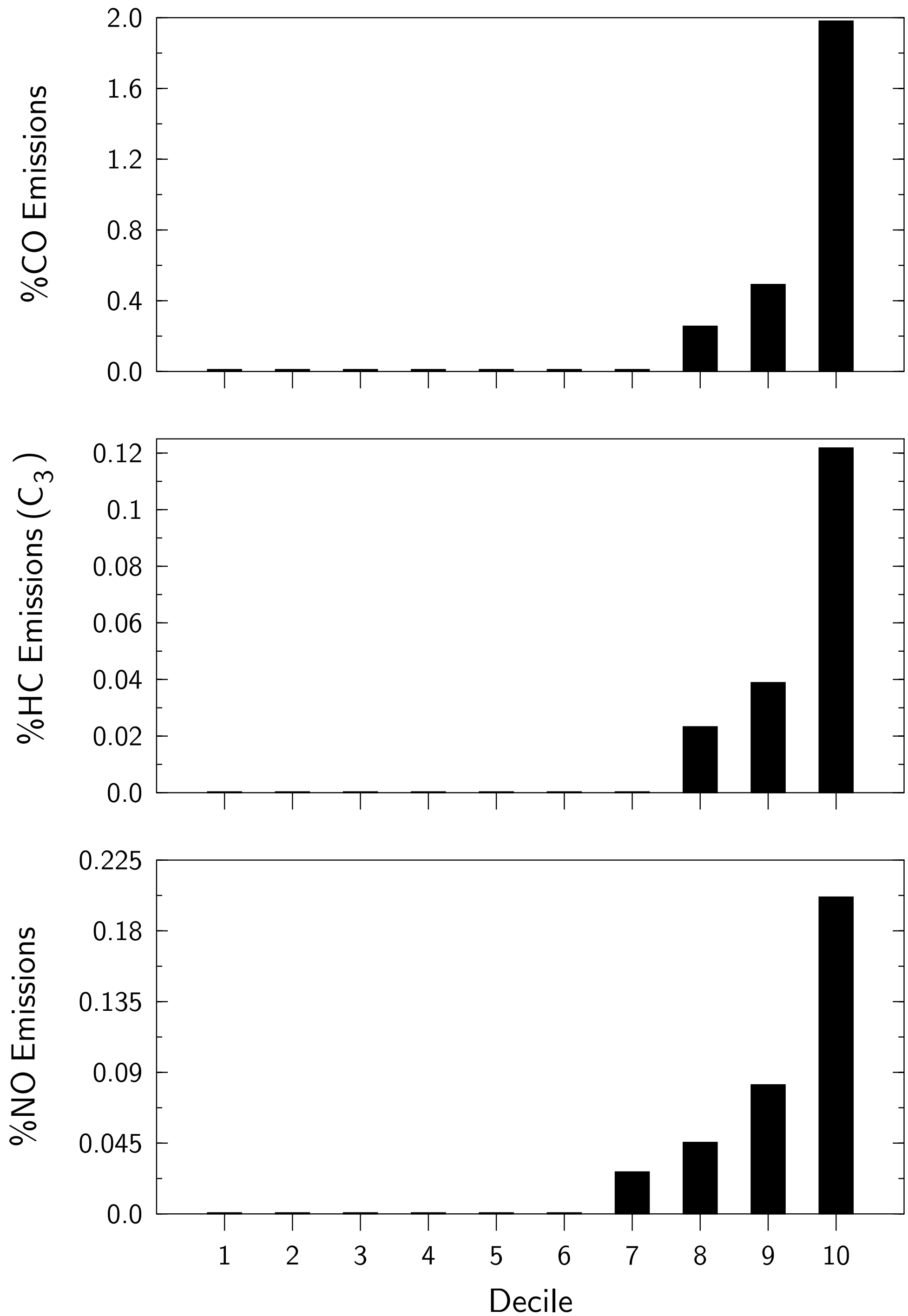

Figure 2. Fleet emissions organized into deciles. For CO and HC the lowest seven deciles and the NO the lowest six deciles are represented by the average of the group.

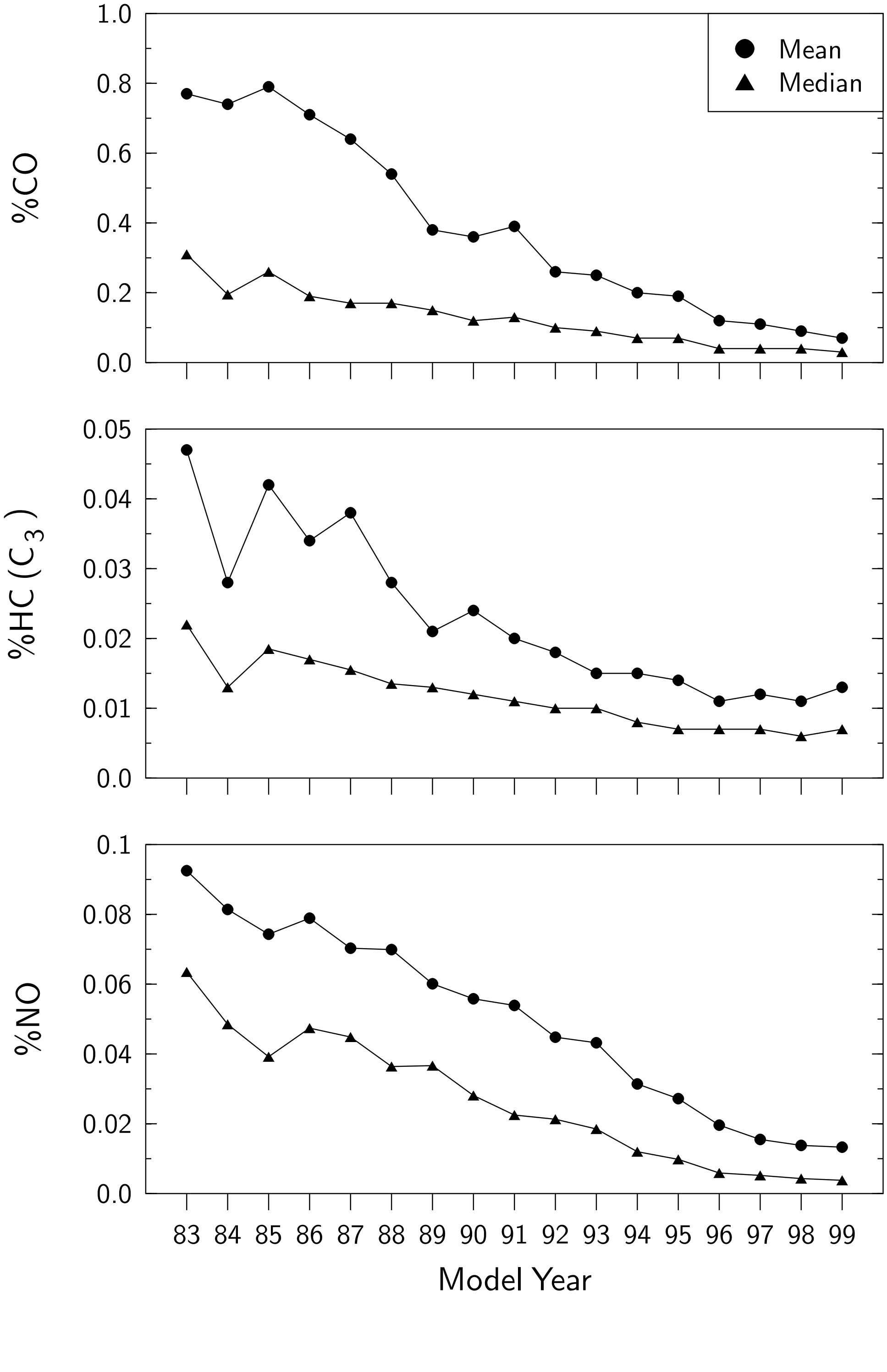

Figure 3. Mean and median emissions illustrated as a function of model year.

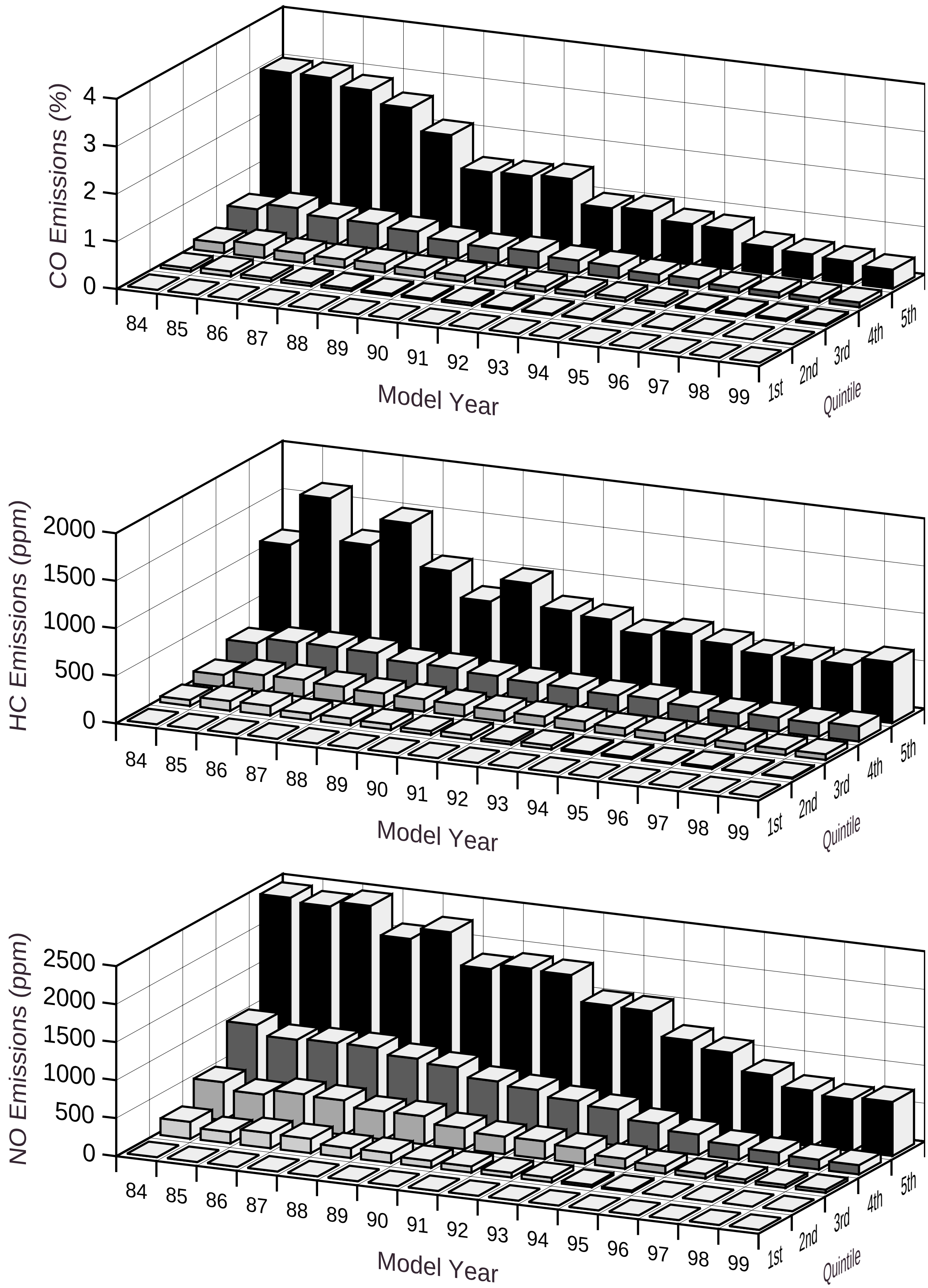

Figure 4. Vehicle emissions by model year, divided into quintiles.

and illustrated in Figure 5. The solid line in Figure 5 provides the number of measurements in each bin. As expected, NO emissions show a positive dependence on specific power while HC emissions show a negative dependence on specific power. Carbon monoxide emissions also show a slight negative dependence on specific power in this range.

Table II provides an analysis of the number of vehicles that were measured repeatedly, and the number of times they were measured. Of the 17,759 records used in this fleet analysis, 15,181 (81%) were contributed by vehicles measured once, and the remaining 2,578 (19%) records were from vehicles measured at least twice.

Table II. Number of measurements on repeat vehicles.

Number of Times Measured	Number of Vehicles
1	15,181
2	2,137
3	379
4	41
5	10
6	5
7	3
8	2
9	1

The only historical comparison we can make with the data in this report is a small data set (a few thousand measurements) collected in Phoenix in September 1992 by Remote Sensing Technologies. Their mean and median values of %CO were 1.05 and 0.154, respectively. Reporting HC as propane the mean and median of the RSTi data were 0.116% and 0.046%, respectively. One has to discount the mean readings because negative results were set to zero. There are other caveats one needs to take into account when comparing the RSTi means/median with the data in this report, however, the large reductions in CO and HC emissions as a result of fleet turnover documented by other studies is certainly reflected in the large differences observed between these two data sets.

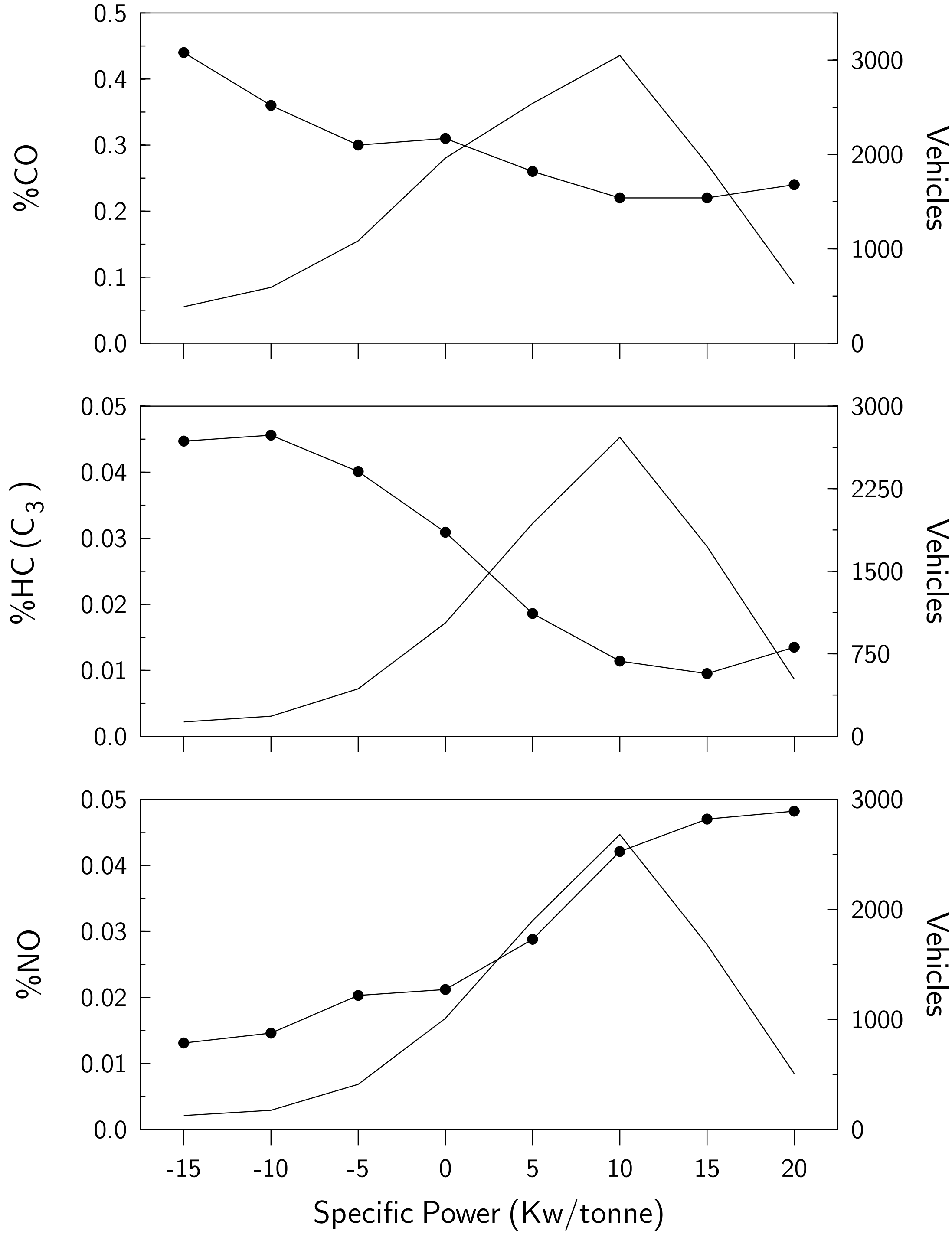

Figure 5. Vehicle specific power (filled circles) for the three measured emission species. The solid line shows the number of vehicles averaged into each vehicle specific power bin.

Comparison of Phoenix Remote Sensing Data to Denver

In the process of validating data from remote sensing devices (RSD), one could compare two cities with similar characteristics. The two cities would need to have similar socioeconomic and fleet characteristics and the same I/M program for the same amount of time. Denver and Phoenix are a pair of cities that falls into this category. Furthermore, the optimal condition would be to take readings at similar locations in the two cities so that the driving mode and load on the vehicles is the same. In the absence of this condition, however, one may group the emissions as a function of vehicle specific power (VSP) so that differing load and driving modes are accounted for.

Such a comparison was done on the RSD data sets from Denver and Phoenix in the January of 1999 and November of 1998, respectively. All measurements with valid gas emissions data, model year and VSP inputs were used. This corresponded to 16,776 records from the Denver database and 7,239 records from the Phoenix database. The data were divided into VSP and model year bins. The data indicate that Denver has consistently higher levels of CO and NO emissions but that HC emissions are noisy but higher in Denver for older vehicles and lower for newer ones. Only data points representing a significant number of vehicles were used, and the smallest bin included 23 records. Data in which acceleration was less than 14 mph/s or greater than 13 mph/s were discarded. The data are plotted in Figure 6.

Figure 6 shows the expected general trends of emissions as a function of VSP and of model year. There is a general increase in all three gas emissions with older model year vehicles. Furthermore, NO increases and HC decreases with increasing VSP, while CO remains relatively constant. It can be seen that CO and NO emissions in Phoenix (light lines) are consistently lower than those in Denver (dark lines) regardless of model year or VSP. This may indicate that the I/M program in Phoenix has been more successful than in Denver. However, other factors may be affecting the data. The fuel in Denver may differ from that in Phoenix. More vehicles registered outside the I/M program may drive by the RSD site in Denver than in Phoenix. There may even have been calibration differences in the instrumentation in the two cities, even though calibrated with the same certified cylinder.

The trend in the HC data, where emissions are higher in Denver than in Phoenix for older model years but lower for newer model years, may indicate a faster deterioration of vehicles in Denver. Alternatively, I/M may be having an impact here in that gross polluters (often older cars) are being discovered and repaired in Phoenix to a greater extent than in Denver. The differences in the emissions level in the two cities, however, are relatively small compared to the difference between model year bins in one city. The 1999 Phoenix data will be obtained at a site where driving mode more closely resembles the measurement sites in Denver, Riverside, and Chicago.

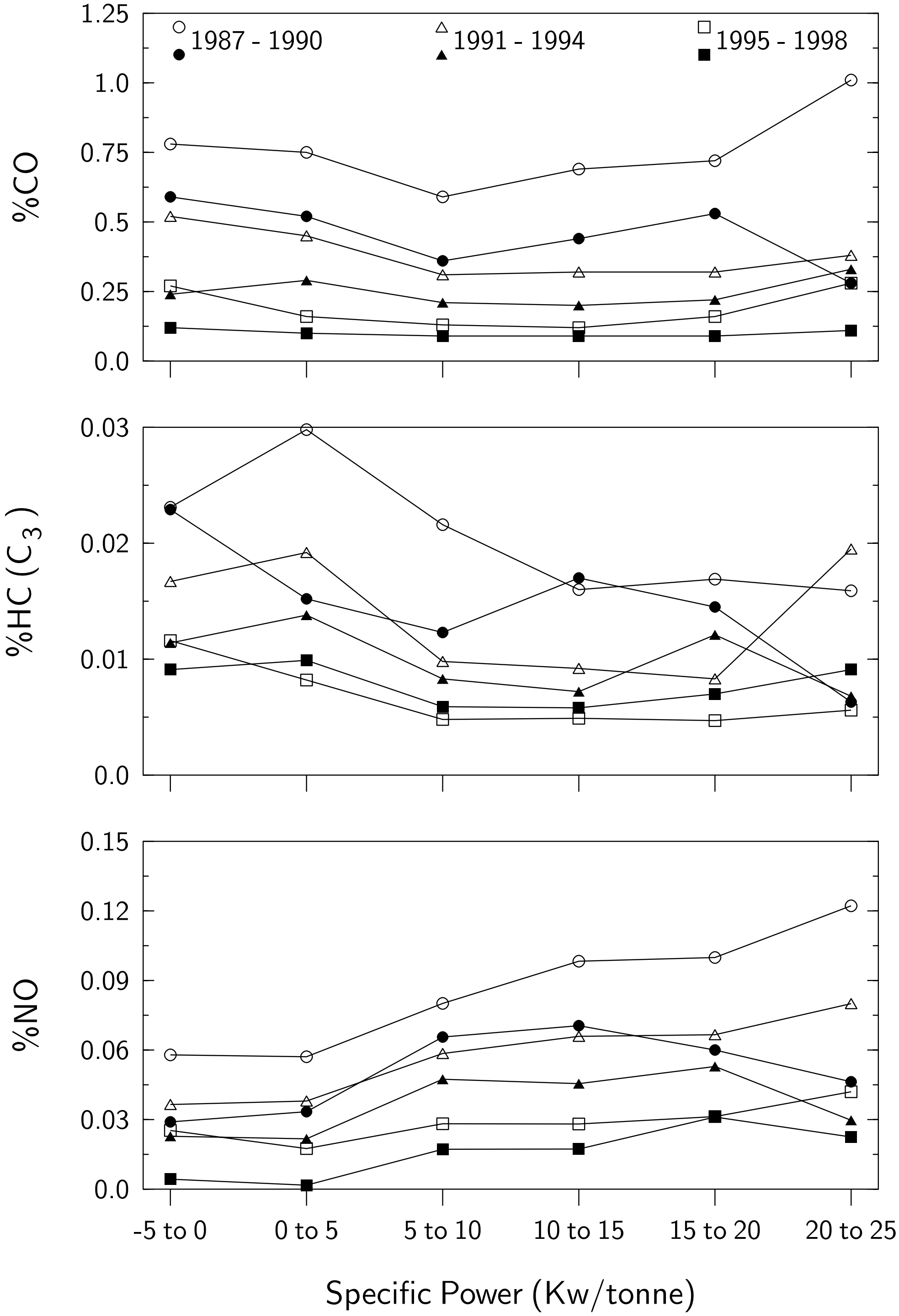

Figure 6. Vehicle specific power for the three measured emissions species in Denver (open symbols) and Phoenix (filled symbols) for three different model year groupings.

CONCLUSION

The University of Denver successfully completed the first year of a 5-year remote sensing study in Phoenix. Four days of fieldwork (November 16-19, 1998) were conducted on the uphill exit ramp from I-10W to US 143N in Tempe, AZ. A database was compiled containing 17,759 records for which the State of Arizona provided make and model year information. All of these records contained valid measurements for at least CO and CO_2, and 11,897 contained measurements for HC and NO. A database was compiled containing 17,759 records with make and model year information, and valid measurements for at least CO and CO_2.

The mean measurements for CO, HC, and NO were determined to be 0.28%, 0.019% and 0.036%, respectively with an average model year of 1993.3. As expected, the fleet emissions observed in this study exhibited a typical skewed distribution, with the dirtiest 10% of the fleet contributing 71%, 66%, and 56% of the CO, HC, and NO emissions, respectively. An analysis of emissions as a function of model year showed a typical inverse relationship. Measured emissions as a function of vehicle specific power revealed that fuel specific CO emissions occur relatively independent of vehicle specific power and that HC shows a slight negative correlation. More revealing was the relationship between NO emissions and vehicle specific power, showing a strong positive correlation when a significant number of vehicles were available. Of the 17,759 records in the database, only 19% arise from vehicles measured more than once.

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

Not measured:

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

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

Invalid :

1) insufficient plume to rear of vehicle relative to cleanest air observed in front or in the rear; at least five, 10ms averages >160ppmm CO_2. Often HD diesel trucks, bicycles.

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

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

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

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

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

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

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

APPENDIX B: Explanation of the phnx_98.dbf database.

The phnx_98.dbf is a Microsoft FoxPro database file, and can be opened by any version of MS FoxPro. The file can be read by a number of other database management programs as well, and is available on CD-ROM or FTP. The following is an explanation of the data fields found in this database:

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

Fuel	Fuel type G (gasoline), D (diesel) and N (natural gas).
Exp_date	License expiration date.
City	Registrant's mailing city.
State	Registrant's mailing state.
Zip	Registrant's mailing zip code.
Vin	Vehicle identification number.
Emiss_flag	Indicates vehicle within Arizona's I/M testing area.
County	Abbreviation of Arizona county vehicle is registered in.

APPENDIX C: Temperature and Humidity Data.

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

APPENDIX D: Instrument Intercomparison.

Intercomparison of On-Road Vehicle Emissions Measurements from Three Remote Sensing Devices

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INTRODUCTION

As remote sensing devices for on-road vehicle emissions are being developed, a useful study is to compare the various devices to each other. Such an intercomparison can be accomplished by operating the devices simultaneously at the same on-road site so that outside factors affecting the emissions are minimized. On November 19, 1998 three RSDs were set up at the same site in Phoenix, Arizona. The devices were the FEAT 3000 developed at the University of Denver, a Hughes Smog Dog operated for the Arizona Department of Environmental Quality, and an RSD3000 from RSTi Enivirotest, now Accuscan E.S.P., called Phoenix-RSD herein. A comparison of the data from the three devices shows that the correlation is very good for CO and NO but not for HC measurements.

RESULTS AND DISCUSSION

Correlation

Correlation plots were constructed for the three measured pollutants: CO, HC, and NO. The Smogdog did not measure NO, so there are not any NO comparisons with the Smogdog. The vehicles were matched on license plates. Only valid measurements were included in the analysis. Thus, only data with valid flags (V) were included from the FEAT data set. Data that did not have invalid flags (X) in the Phoenix-RSD data set were included. In the case of the Smogdog, measurement flags were not reported so readings of “0” and “9999” were discarded. A table of the number of matched and valid vehicles is below.

Table 1: Number of matched and valid vehicles in each comparison

	CO	HC	NO
FEAT to Phoenix-RSD	741	629	618
FEAT to Smogdog	774	443	N/A
Phoenix-RSD to Smogdog	764	457	N/A

As the CO correlation plots show (See Figure 1), FEAT 3000 and Phoenix-RSD CO measurements correlate almost perfectly, with the slope close to unity, an intercept close to zero, and a high r-squared value. The correlations are slightly less ideal when either of these two instruments is compared to the Smogdog measurements. One reason for this discrepancy may be that the Smogdog does not record negative values of emissions readings. As noise in the measurements can affect the data in either direction, very low emitting vehicles can be registered as having negative emissions. When the overall fleet data set is averaged, these artificially negative values cancel out other artificially positive values. Not allowing values to go below zero skews the data when the whole data set is averaged. Smogdog does appear to contribute some high CO outliers not present in the other comparisons. In all cases the slopes are close to 1.0.

The correlations, in terms of HC measurements, are not so ideal (Figure 2). The slope of the correlation is not unity. FEAT gives the highest HC readings, followed by

Phoenix-RSD, and then by the Smogdog. Although significant scatter is present, the relationships do seem to be linear. Thus, FEAT records HC concentrations as being proportionally higher than Phoenix-RSD, which in turn measures higher than the Smogdog. This variation may be the result of calibration differences or differences in analytical technique. FEAT measures C_3 when measuring HC (For comparison FEAT data have been divided by two to report as "hexane".); the other two devices may monitor different species. Furthermore, we again have the problem of the Smogdog not registering negative values and apparently adding more outliers.

The correlation in terms of %NO measurements in FEAT and Phoenix-RSD (Figure 3) is much better than that for HC but not quite as good as for CO. The slope is 15% less than unity, and there is some scatter in the plot. One reason for this may be that FEAT seems to measure more negative values than Phoenix-RSD. The cluster of points in the top left quadrant of the graph decreases the slope. When negative values are removed from both data sets, the slope improves to 0.91, the intercept goes to 0.0003, and the r-squared value is 0.90. This improvement indicates that the two data sets do correlate well in terms of NO except for the fact that FEAT registers more negative values than Phoenix-RSD, which may reflect a software difference. There was no attempt made to compare calibration cylinders so a non-unity slope may arise from cylinder differences.

Hit rate

Another comparison of the three on-road remote sensing devices is their hit rates, the number of valid readings obtained for a set of cars passing thorough the test site. Hit rates were calculated from data collected during time periods when all three devices were operating. These time periods were 10:47 – 11:19, 11:27 – 11:52, 13:43 – 14:05, and 14:24 – 15:20. Valid readings were those that fit criteria listed above for the correlation plots, with the additional values in parenthesis for Phoenix-RSD in the Table 2 corresponding to flags registering "V" instead of the broader "Not X".

Table 2: Hit rates of the three devices

	FEAT	Phoenix-RSD	Smogdog
Vehicles "seen" in time frame	2856	2269	2358
License plates read	2326	1554	1628
CO valid	2384	1850 (910)	1966
HC valid	1789	1863 (905)	1227
NO valid	1765	1869 (905)	N/A

The Phoenix-RSD reported fewer cars overall, followed by the Smogdog, and then by FEAT, which reported the most vehicles. This result indicates that FEAT is the most efficient device for counting passing vehicles, presumably because of a shorter "thinking time" between vehicles. During these time periods a number of cars somewhat larger than 2856 actually passed through the test site where all three devices were set up, and FEAT registered the greatest number as having passed through.

The percentage of valid license plates (from the group of vehicles registered as passing the test site) is greatest for FEAT. The plates are read by hand (from video tape images of the passing cars). The Phoenix-RSD was read manually from digital images.

The Smogdog device employs an automatic license plate reader. The percentage of not invalid CO measurements is similar among the three methods: 83.5%, 81.5% and 83.4% for FEAT, Phoenix-RSD and Smogdog, respectively.

Phoenix-RSD seems to do better with the percentage of valid HC (82.1% vs. 62.6% for FEAT and 52.0% for Smogdog) out of all the vehicles registered as passing by according to that particular device. The same is true for NO measurements: 82.4% on Phoenix-RSD and 61.8% on FEAT. However, these numbers are for entries in the Phoenix-RSD data set which do not have an invalid flag ("X"). This includes emissions readings which are suspect ("S") and did not have enough readings ("E"). When only entries with valid emissions flags ("V") are used, Phoenix-RSD has the lowest percentages of valid readings (see parentheses in Table 2). When correlations are carried out with the smaller number of "V" only RSD-Phoenix data points, the r^2 values go from 0.96, 0.39 and 0.86 for CO, HC and NO to 0.97, 0.48 and 0.91, respectively. Each instrument system has designed software with different validating criteria for different purposes. For the comparison given herein on an individual vehicle by individual vehicle basis, measured speed and acceleration (S/A) are not very relevant. The Phoenix-RSD software, however, gives an "S = Suspect" flag for S/A criteria outside certain window provided for the California Bureau of Automobile Repair.

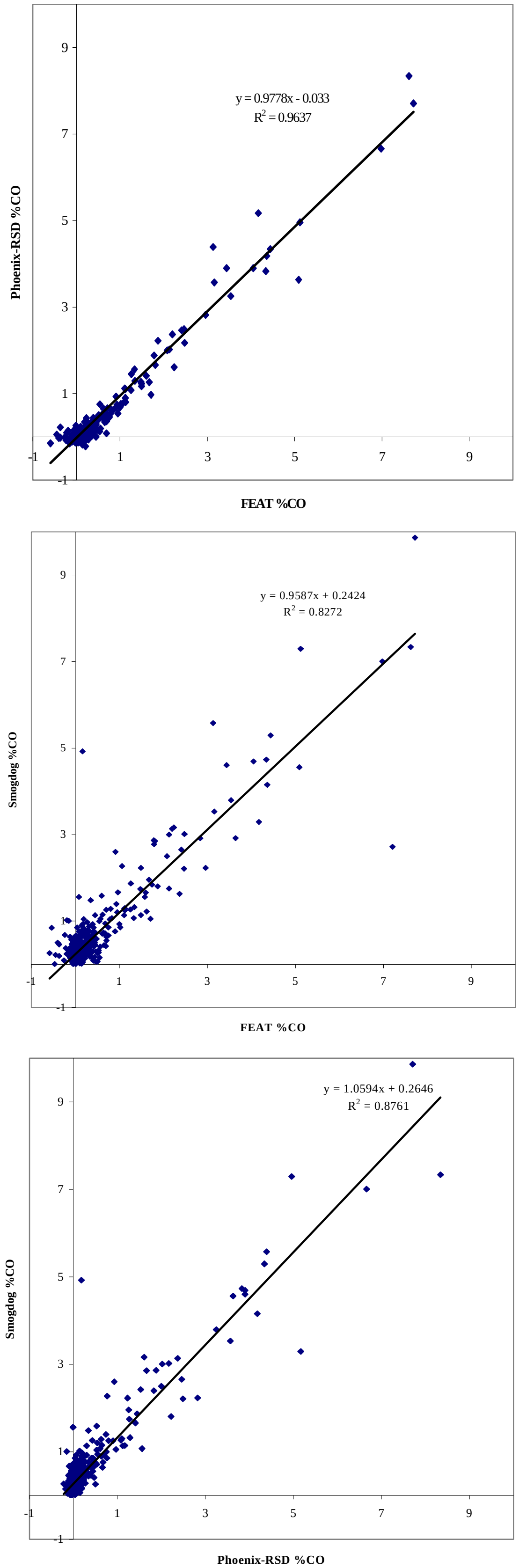

Figure 1: Correlation plots of CO emissions readings. Each point represents one vehicle that has been matched by license plate.

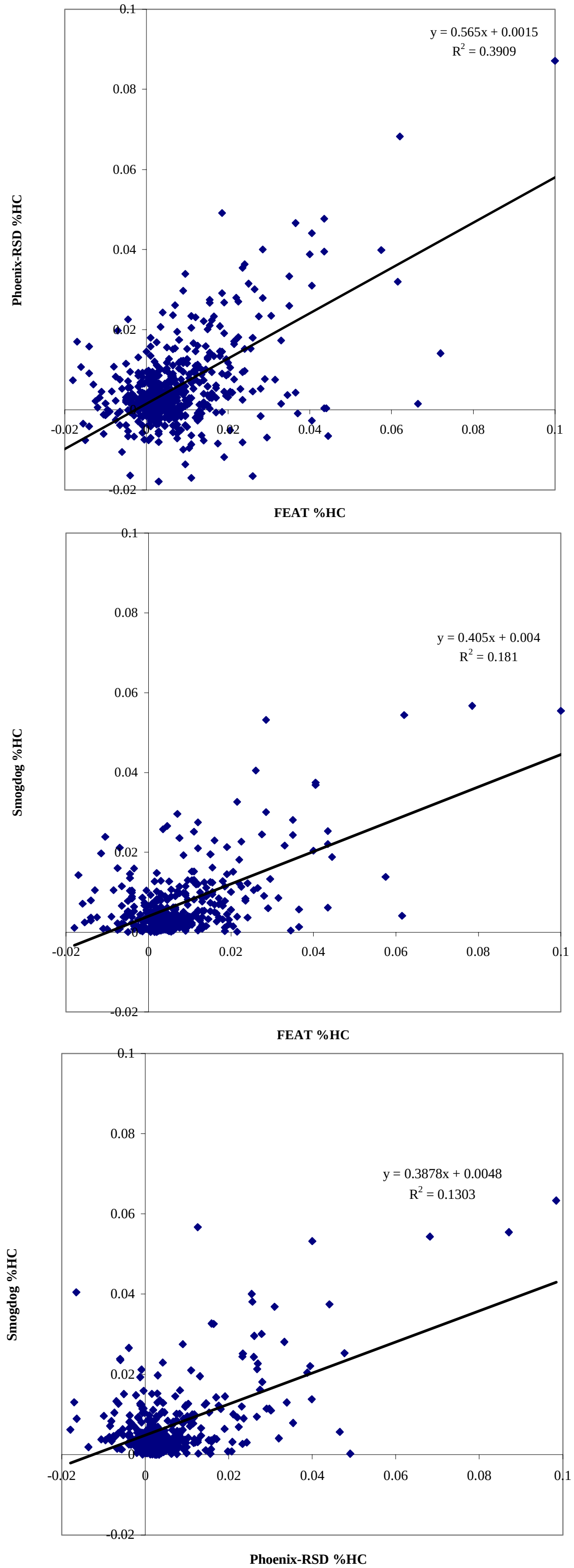

Figure 2: Correlation plots of HC emissions readings. Each point represents one vehicle matched by license plate.

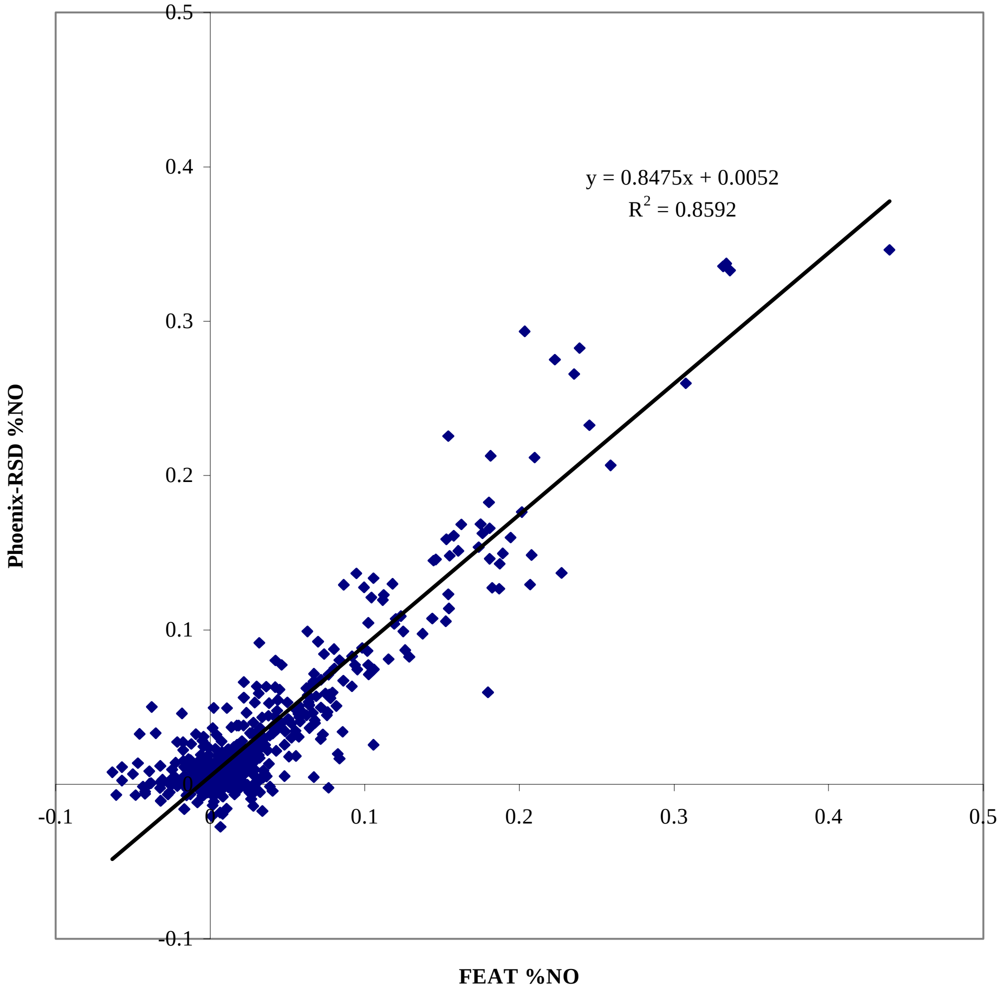

Figure 3: Correlation plot of NO emissions measurements. Each point represents one vehicle matched by license plate.

REFRENCES

Bishop, G.A.; Stedman, D.H. "*On-Road Remote Sensing of Automobile Emissions in the Phoenix Area: Year 1*." Coordinating Research Council, Inc., 1999, Draft Interim Report.