FINAL REPORT
TUCSON INTERSECTION STUDY OF AUTOMOBILE EMISSIONS

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Introduction

Automobiles emit hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NO_x), all known to be important in overall urban pollution.[1] Individual vehicle measurements have been done for some time and with many different methods.[2] One method developed at the University of Denver incorporates IR remote sensing. This technique, known as the fuel efficiency automobile test (FEAT), focuses on the exhaust of each passing vehicle giving independent emission data for large numbers of vehicles.[3,4] Since exhaust carbon comes mainly from the gasoline, a measure of the engine's combustion efficiency can be determined from the ratio of CO or HC to CO_2.[4]

Long path sensing of auto exhaust has also been done. One such study was done on an isolated stretch of Denver highway. This study was also done with an SF_6 tracer release for calculating flux measurements. The tracer was released in such a way that it simulated the emission of the pollutant cars, thereby allowing the measured ratio of pollutant to tracer concentrations at any point downwind of the highway to equal the ratio of pollutant to tracer emission rates. The results of this study gave flux measurements of CO with the average being 70 ± 15 gm/mile. Changes in CO_2 were not detected in this study. However, this was primarily done as a feasibility study and it did indeed conclude that on-road CO emission measurements can be carried out at low cost with available equipment.

Long path and on-road remote sensing were combined to study total vehicle emissions at Fort McHenry Tunnel in the Baltimore Harbor.[3] Four FEAT units were used in conjunction with a Bomem FTIR coupled to a Beckman white cell with a path length of 20 meters. Although this was not open path remote sensing, the long path idea was still incorporated. The entire FTIR assembly was enclosed in a large plastic bag to maintain stable temperature and humidity. The air from the tunnel was pumped through the white cell at 10 liters per minute. This was then analyzed for CO and CO_2. The data were compared to other gas-sampling runs conducted wherein CO_2 and CO, along with other compounds, were measured by collection into bags, canisters and sorbent traps for subsequent analysis. It was found that, in general, excellent agreement can be obtained between FTIR measured CO/CO_2 ratios and those obtained using more traditional bag integrated concentrations. The comparison, uncorrected for inlet concentrations, for CO was $\langle FTIR_{CO}/Bag_{CO} \rangle = 0.84 \pm 0.08$ and for CO_2 was $\langle FTIR_{CO2}/Bag_{CO2} \rangle = 1.00 \pm 0.03$.

The above combination of techniques for sampling automobile emissions appeared to be very effective, however were restricted to a tunnel. This is a serious limitation if different driving modes and traffic conditions are of interest. Based on these two studies we considered open path sensing with the LPIR and LPUV combined with FEAT at a busy location with appropriate meteorological conditions would prove to be more effective for correlating with FEAT. Using the same long path IR and LPUV many automobile exhaust compounds can be identified. UV would be set up to look for NO and aromatic hydrocarbons from the intersection. IR would be set up to look for the CO and CO_2 ratios as well as SF_6 for dispersion modeling with wind speed and direction.[5] The open path ratio of CO to CO_2 in relation to total emission from vehicles has not been done before in this way, combining these techniques. Another comparison that has not been done to our knowledge is a comparison of NO to CO giving a ratio thereof.

The overall program goal includes evaluation of a model of the intersection using line sources. This model calculates average vertical pollutant concentration gradients downwind of the roadway. Our primary goal was to determine the extent to which long path IR spectrometers can obtain similar results to on-road emissions monitors in terms of CO ratio to CO_2 at an intersection and to use long path spectrometers at two heights to measure pollutant gradients for comparison to the model.

Experiment

There are nine CO monitoring stations in the Tucson area, one being an intersection at 22nd and Alvernon. This was identified as an ideal site for combining the FEAT and long path technologies due to already present monitoring equipment, availability of power and space, and most importantly a high volume of traffic.

Alvernon Way runs due north and south and 22nd Street runs due east and west. Alvernon and 22nd are three lanes wide each way with a 2 foot median between each directional flow. Open path FTIR instruments were set up on site on the northwest corner for downwind measurements of auto exhaust. One LPIR was mounted on top of a 8 meter scaffolding with the source on the same approximately 30 meters away. One LPIR was installed in a van on a stable bench with specific adjustments. The long path set up between Feb 23 and Feb 27, 1994 was with the paths aligned east and west 39 meters north of 22nd Ave. The setup of the instruments was changed on March 2 to have the paths aligned north and south 16 meters west of Alvernon.

The two open path UV instruments were set up on ground level only. One instrument was calibrated for wavelengths 220 nm to 270 nm to monitor for the NO region. The second instrument was calibrated for wavelengths 270 nm to 320 nm to monitor for the aromatic hydrocarbons.

The spectrophotometers were synchronized with one computer to ensure all runs were started at the same time and averaged for the same time intervals. The computer clock was synchronized with the Tucson ambient monitoring station time. Calibrations were done for all instruments according to standard operating procedures.

Wind speeds and directions were obtained from Pima County Department of Environmental Quality and were found to be from the southeast in the morning hours generally between 1 a.m. and 11 a.m.. These were the optimum hours for sampling the intersection for our northwest position. Traffic was very low in the early morning and gradually peaked at 8 a.m. with the rush hour traffic and leveled off for the rest of the morning. The runs were conducted during these hours from Feb 23 through March 4, 1994.

Results

All LPIR data were collected as single beam spectra over a five minute time average. A reference spectrum was chosen at random from each experimental run and used to obtain an absorbance spectra from every other five minute average. With this method of obtaining a reference spectrum, both negative and positive absorbencies are reported. This process is illustrated in Figures 1 and 2. The absorbance peak areas were found by integration and then calculated for ppm-m by comparing to standard library spectra of CO and CO_2. The CO ppm-m and CO_2 ppm-m were then plotted against each other to obtain slopes, thereby giving CO/CO_2 ratios (Figure 3). The desired slopes (change in CO to change in CO_2) are independent of the absolute amount of CO or CO_2 present in the arbitrary reference spectrum. Table 1 gives dates, times, average wind speeds and directions, experimental runs, and resulting CO/CO_2 ratios with calculated errors.

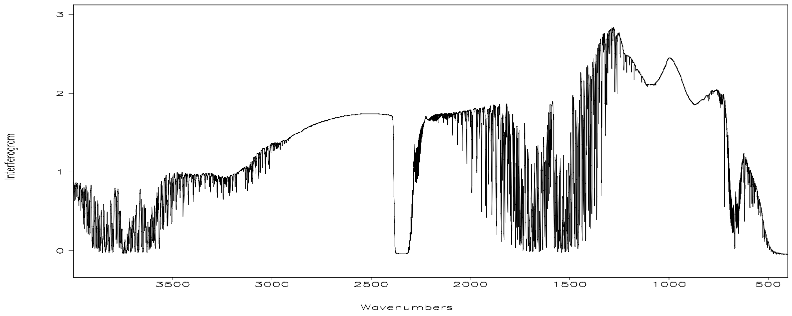

Figure 1a. Single beam reference spectrum of ambient air at the intersection of 22nd and Alvernon.

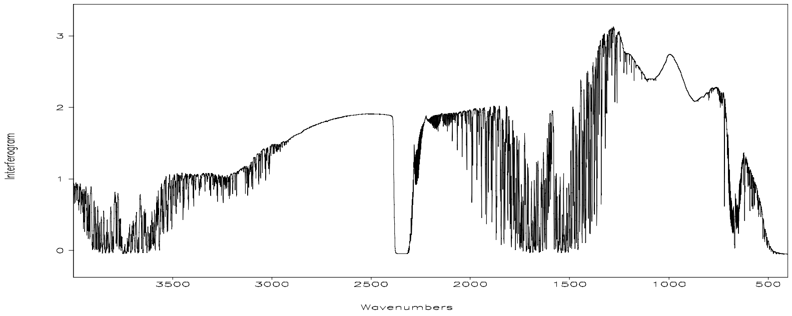

Figure 1b. Single beam sample spectrum of ambient air at the intersection of 22nd and Alvernon.

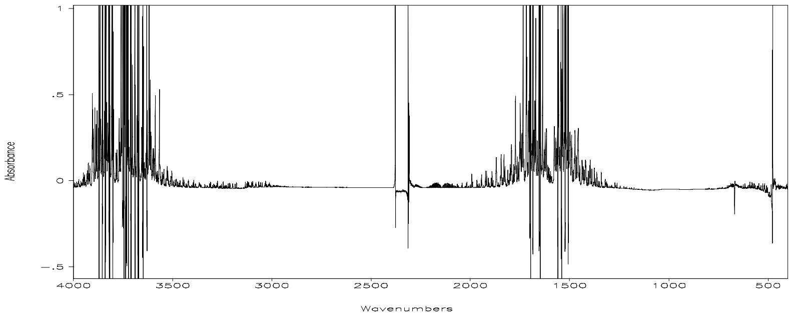

Figure 1c. Resultant absorbance spectrum of ambient air at the intersection of 22nd and Alvernon.

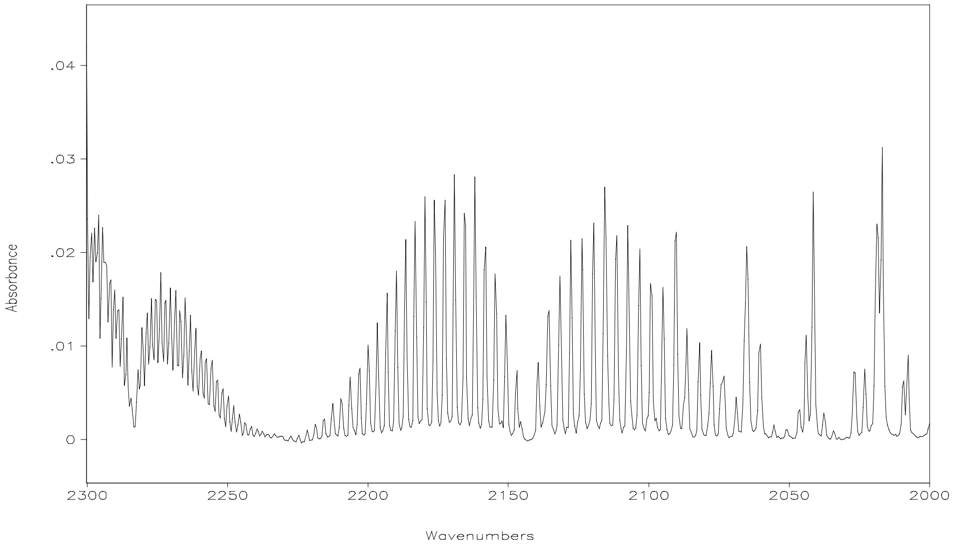

Figure 2. Magnified region of absorbance peaks of interest. For CO the area was taken from 2208 to 2145 wavenumbers and for CO_2 the area was from 2282 to 2238 wavenumbers.

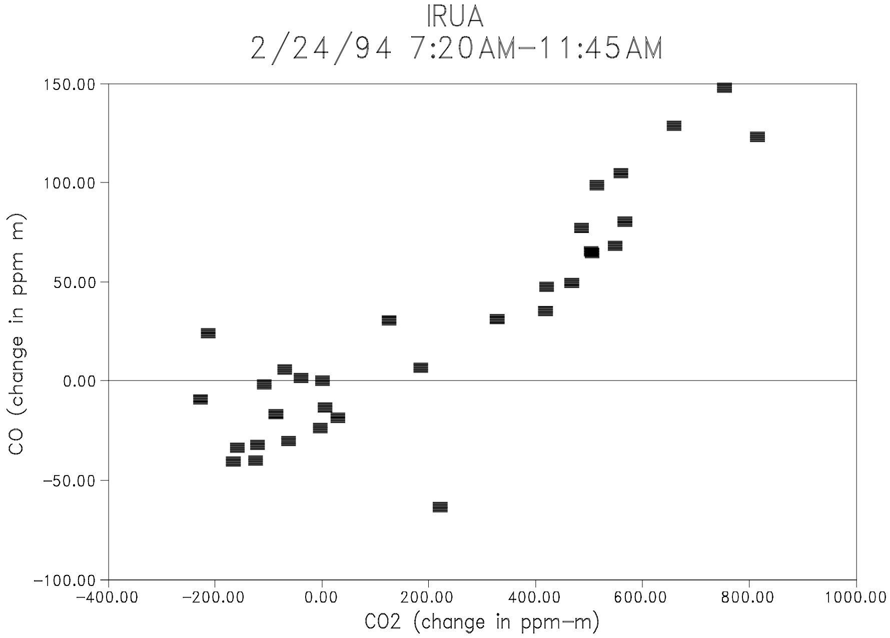

Figure 3. Correlation of changes in CO against changes in CO_2 on the morning of February 24, Run A, from 8:20 am to 11:45 am with winds from the south-southeast.

Acceptable runs were primarily determined by wind direction. The east-west path orientation from 2/24 to 2/28 determined a south-east wind as optimal. Runs 3, 4 and 6 were not from that direction and were further determined to be imprecise intersection measurements because the slope deviations were greater than the slopes. For the north-south path orientation from 3/2 through 3/4 a southeast or east wind was preferable. Run 7 with southwest winds show ratios with large deviation. Run 10 was unacceptable due to large deviations in the slopes arising from large variations in wind direction and instrument noise for the ground level instrument. The minimum detection limit for CO was 3 ppm-m.

Results from the LPUV instruments were not conclusive. The minimum detection limits (mdl) for the hydrocarbons were 5 ppm-m for benzene and toluene was 6 ppm-m. The high level of detection was due primarily to instrument noise and a sine-wave slope inherent to the detector. There were no hydrocarbons detected above the mdl. The instrument set to observe NO detected valid data for only one run on March 3, seen in Figure 4. The minimum detection limit was 0.4 ppm-m and the graph shows a rise and decline of NO over time, with a maximum of 10 ppm-m detected (Figure 5). Comparing the NO to the CO of the same run at the height of 1 meter gives a ratio of 0.05 ± 0.004 (Figure 6). This shows that with the proper meteorology, high CO and all instruments aligned and working properly, a correlation of NO and CO can be determined.

FEAT data provided by Yi Zhang are shown in Table 2. Even with data

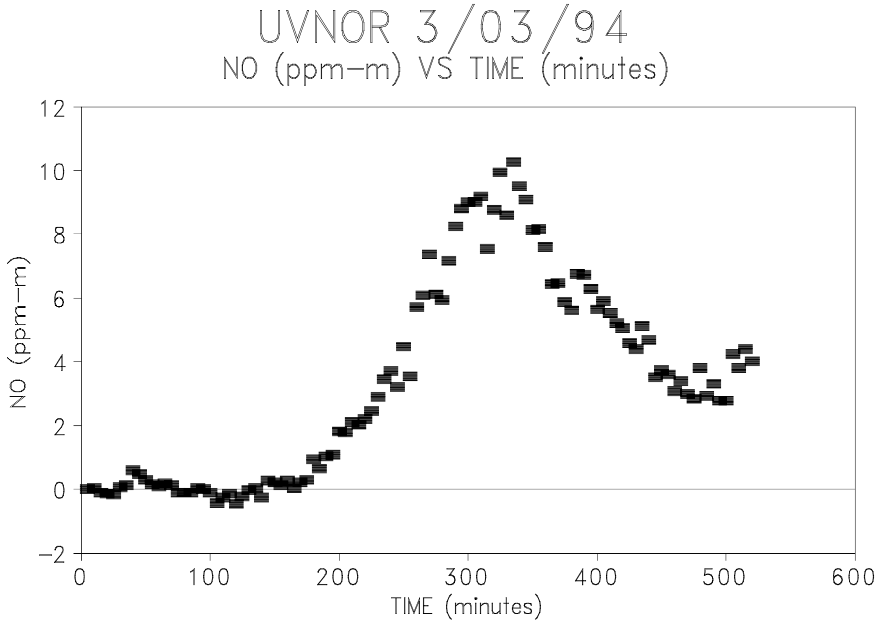

Figure 4. NO in ppm-m over time for run 9 on March 2, 1994.

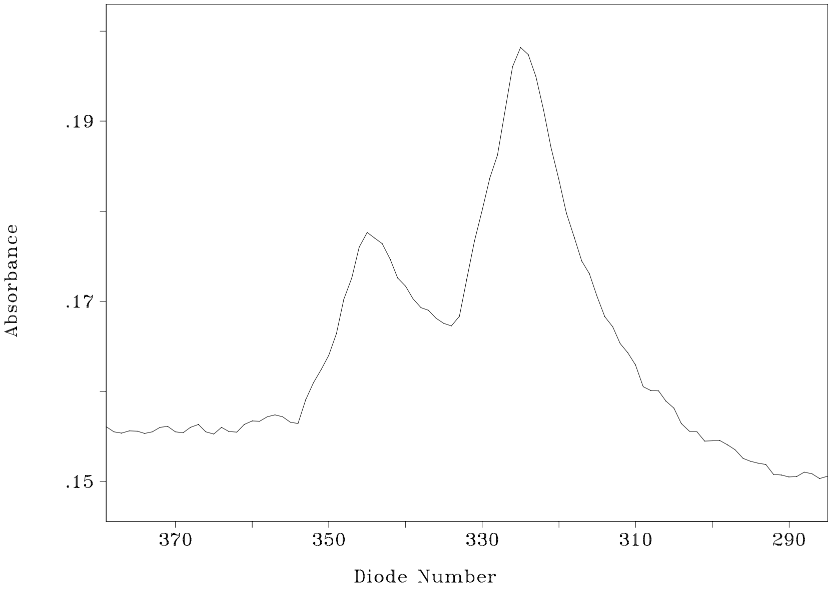

Figure 5. Spectrum of 10 ppm-m NO, the maximum amount detected in the UVNOR run.

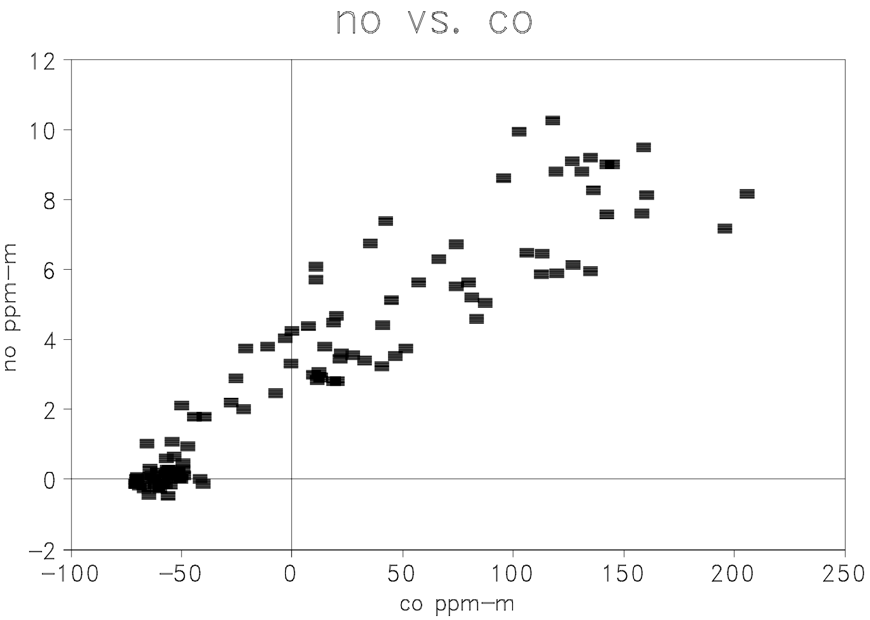

Figure 6. Graph showing NO in ppm-m to CO in ppm-m. The slope for this graph is 0.05 with a sigma error of 0.004.

we believed invalid taken out, the results show high variability for long path and on-road analysis. Using the best data the on-road FEAT and long path are similar. In view of the different methods of measurement the overall agreement is remarkable since the on-road instrument measures cars only travelling in particular lanes at different times and further from the intersection - a fraction of the fleet. Overall ratios observed by long path and FEAT are in the range of 0.05 to 0.1 which can be calculated for grams of CO to one gallon of fuel with the following equation;

$$gmCO/gal = \frac{5506 * Q}{1 + Q}$$

where Q is the observed CO/CO_2 ratio. The average grams of CO to gallon of fuel for the valid runs were found to be 303 g CO/gallon of fuel with a standard error of the mean of $\pm$ 80 g CO/gallon of fuel.

The tracer gas, SF_6, was released as a line source on one corner of the intersection. The mdl of SF_6 was 3 ppm-m due to the noise of the instruments and the short path lengths. In view of the small release rate there was no SF_6 detected.

The gradient studies were important for the computer models. The gradient correlations were carried out by comparing the CO concentrations of the 8 meter LPIR (CO_u) to the CO concentrations of the LPIR at 1 meter (CO_d) for each run (Table 3). To obtain absolute CO values the CO reference was reset to the lowest CO point of the CO to CO_2 concentration plots. This procedure does not take proper account of noise in the CO readings and will then tend to cause all absolute CO readings to be too large. It would appear that for the days on which the best data were observed, the down/up ratio varies from 1.2 to over 3.5 with the lower ratios predominating. Again the mdl for CO was 3 ppm-m. All data are available on floppy disk or from the authors.

Discussion

This is the first successful experiment for the correlation of open path CO and CO_2 to the on-road FEAT monitors. This system can be used for future total vehicle emissions studies from busy sections of road and/or intersections. Highly variable data seem to be real, as well as variable vertical gradients. This limits the potential for precise comparisons to computer models.

Recommendations for future experiments would be for longer optical paths. Flux measurements with more tracer released and with better geometry relative to the long path and the intersection would also be beneficial.

Date/Time	Average Wind Speed[A]	Average Wind Direction	Run #[B]	CO/CO$_2$ Ratio W/Error
2/24/94 AM 8:20 - 11:45	1.00 ± 0.47	S/SE	1A	0.061 ± 0.004
			1B	0.056 ± 0.021
2/25/94 AM 8:00 - 11:30	1.83 ± 0.49	SE	2A	0.036 ± 0.005
			2B	0.051 ± 0.01
2/25/94 PM 12:05 - 1:25	1.23 ± 0.62	NW/NE	3A	0.021 ± 0.062
			3B	0.0038 ± 0.0056
2/27/94 AM 4:30 - 10:25	2.19 ± 0.65	E/SE	4A	0.0012 ± 0.01
			4B	0.0002 ± 0.001
2/28/94 AM 4:15 - 6:55	1.67 ± 0.7	SE/NE	5A	0.1 ± 0.015
			5B	0.022 ± 0.0025
7:20 - 11:10	1.46 ± 0.94	NW	6A	0.1 ± 0.013
			6B	0.01 ± 0.011
3/02/94 AM 2:00 - 5:20	0.68 ± 0.49	SW	7A	0.0026 ± 0.007
			7B	0.008 ± 0.005
5:55 - 10:30	1.97 ± 0.25	SE/E	8A	0.07 ± 0.011
			8B	0.022 ± 0.0087
3/03/94 AM 2:05 - 11:00	2.17 ± 0.94	SE	9A	0.089 ± 0.018
			9B	0.148 ± 0.0079
3/04/94 AM 4:45 - 9:30	1.81 ± 0.6	SE	10A	0.0086 ± 0.023
			10B	0.017 ± 0.007

Table 1. Showing dates, times, average wind speed and directions, experimental run numbers, and calculated CO/CO$_2$ ratios with deviations. [A]Wind Speeds are given in miles per hour. [B]A refers to the instrument on the ground level and B refers to the instrument on the 8 meter scaffolding.

DATE	Daily % CO	Daily % CO_2	Daily Ratio
2/24	1.07	14.28	0.075
2/25	0.85	14.43	0.054
2/28	0.89	14.41	0.062
3/2	0.93	14.38	0.065
3/3	1.57	13.92	0.11

Table 2. Daily on-road FEAT monitor percentages for CO and CO_2 with resulting daily ratios. Data provided by Yi Zhang.

RUN #	AVG OF ALL	AVG>50 PPM	SLOPE±ERR
1	1.1 ± 0.65	1.2 ± 0.42	1.2 ± 0.062
2	4.9 ± 9.8	1.6 ± 0.26	2.2 ± 0.055
4	7.0 ± 19	N/A	3.1 ± 0.036
5	1.1 ± 0.64	1.3 ± 0.41	1.3 ± 0.082
6	1.5 ± 4.0	0.83 ± 0.26	2.5 ± 0.19
7	3.5 ± 3.7	N/A	3.7 ± 0.059
8	5.5 ± 6.8	2.8	5.0 ± 0.029
9	5.5 ± 11	1.3 ± 0.29	1.6 ± 0.033
10	2.2 ± 1.7	N/A	5.5 ± 0.053

Table 3. Three measures of observed CO_d/CO_u vertical gradients between 1 and 8 meters altitude. Column one is the average of all observed ratios; column two is all ratios with an average of CO above 50 ppm-m; column three is the slope of the regression line of CO_d versus CO_u with the reported standard deviation.

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FEAT STUDIES

Tucson Automobile Emissions Study

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Introduction

The University of Denver's remote sensor (described elsewhere[1,2]) was used for an on-road motor vehicle carbon monoxide (CO) and hydrocarbon (HC) emissions survey in Tucson, Arizona from February 18th to March 3rd, 1994. The survey sites were selected around the intersection of Alvernon Way and 22nd Street from all directions. Alvernon Way runs due north and south, and 22nd Street runs due east and west. Both are three lanes for each way with a 2 feet median between each directional flow. The intersection was level and traffic light controlled with high traffic density. The traffic flow was fairly continuous at 15-30 mph. The majorities of the vehicles were either under light acceleration or in a cruise at about 25 mph. However, a portion of vehicles under a hard acceleration regime was also observed, especially after they passed the intersection. The original data with valid CO, HC and CO_2 measurements were 29,936 records. Because the sensors were often set up across multiple lanes with a single camera aimed on only one lane, many valid emissions readings were obtained without license plates information. After eliminating those data with non-Arizona or unreadable license plates, valid data for CO, HC and CO_2 emissions with vehicle information were obtained on a total of 14,051 vehicles with an average model year of 1985.

This report presents the measurement results based on the 14,051 record data set to identify the statistical distribution and characteristics of the automobile emissions in Tucson, Arizona. Comparisons of the emissions between vehicle fleet within and without inspection and maintenance (I/M) programs and between different vehicle categories are also presented.

Overall Results

The mean CO emission of the data set was 1.03 %CO, while the median vehicle emitted 0.34 %CO. The median value more closely approximates what a typical vehicle emits while the mean value is heavily influenced by the relatively few gross polluters, referring to the part of the fleet which is responsible for half of that fleet's total emissions. In Tucson, half of the CO emissions were produced by 1,339 gross polluters (about 9.5% of the fleet) which were emitting in excess of 3.32 %CO. Figures 1 and 2 show the distributions of the Tucson emissions data in two ways. Figure 1 shows the distribution of CO emitters (black bars) by percent CO category. The clear bars show the percentage of the total CO emissions from each %CO category. It is seen that more than 70% of the 14,051 vehicles emit less than 1 %CO and are responsible for only about 16% of the total CO emissions. For figure 2, the fleet was rank ordered by CO emissions from the lowest to the highest, then divided into deciles, groups containing one tenth of the fleet. Each bar represents the contribution of each decile to the total CO emissions. The value above each bar corresponds to the average %CO emissions within each decile. Note that the cleanest seven bars have been averaged together. This has been done because the tiny differences between low emission averages of the cleanest 70% of the fleet are within the error bars of the remote sensor's measurement capability. Again it can be seen that the CO emissions of the clean 70% of the fleet are dwarfed by the overwhelming contribution of the vehicles in the tenth decile. Both figures illustrate that the mobile source CO emissions inventory is dominated by a relatively small number of high emitters.

The mean HC emission of the Tucson data set was 0.075 %HC, while the median was 0.043. Gross polluters for HC emitters are defined just as for CO emitters. Half of the HC emissions were produced by only 1,689 vehicles (about 12% of the fleet) with emissions greater than 0.146 %HC. The data for HC emissions are presented graphically in figures 3 and 4 in the same manner as that for CO emissions. The figures present a similar illustration of the significant contribution to the mobile source HC emissions inventory by a relatively small number of high polluters as seen with CO case, however, the HC data are more skewed than CO data.

Based upon a fundamental knowledge of combustion chemistry, the %CO and %HC data can be converted into mass emissions in units of grams of CO or HC per gallon of gasoline by using the following equations:

$$\text{gCO/gal} = 14880\ \%\text{CO} / (42 + 0.79\ \%\text{CO} + 8.37\ \%\text{HC})$$
$$\text{gHC/gal} = 22320\ \%\text{HC} / (42 + 0.79\ \%\text{CO} + 8.37\ \%\text{HC})$$

The overall mean emissions thus become 352.8 gCO/gal and 38.5 gHC/gal.

To determine whether the data set is still a representative sample after eliminating those data with non-readable or out-state license plates, the following analysis is performed. The mean CO emission of the original 29,936 data set was 1.02 %CO with a median value of 0.35 %CO, while the mean HC emission was 0.082 %HC with a median of 0.048 %HC. Compared with the original data set, the mean CO emissions of the final registration-matched 14,051 data set increased 0.01%, while the median CO decreased 0.01%. The mean HC decreased 0.007% for and the median HC decreased 0.005%. This result shows that the bias introduced by requiring readable plates is detectable but not significant, thus the matched fleet of 14,051 records is believed to be a representative sample of the total fleet in Tucson.

Compared to other locations, the average CO emission rate in Tucson was higher than the rate measured in Los Angeles in 1991[3], but similar as the rate measured in Chicago area in 1990[4]. The average HC emission rates were similar in Tucson, Los Angeles and Chicago.

Daily Analysis Table I gives the average %CO and %HC emissions measured at different sites for each of the days worked. No data with matched license plates is available for21 Febuary, due to the failure of video tape recording. As in seen in our previous studies, the day-to-day differences are related to the average age of the vehicles at each day. However, a closer look at the table shows that the average %HC emissions at those sites after the intersection are usually lower than the emissions for the sites before the intersection. This arises because of the fact that more vehicles were accelerating and under load after they passed the intersection, therefore lessening the HC emissions caused by misfiring behavior. The driving condition under which the engine is operated (*i.e.* speed, load and ambient temperature) is a factor which influences HC exhaust emission level, but is relatively unimportant for CO.[5]

Quintile Investigation

For each model year the on-road CO and HC emissions are divided into five groups (quintiles) in ascending order of emission levels. The 1975 and older vehicles were grouped together because our previous studies show little further deterioration beyond 15 years of vehicle age. Examination of the quintile emission factor distributions from the CO data (Figure 5a) shows that the value of the mean %CO rises smoothly as the age increases. The quintile plot shows no obvious sign of any sharp break between the model years to coincide with the changing of emissions control techniques. If the bars represent the lowest emitting twenty percent of vehicles, the best maintained, are magnified, then the expected technology breaks are observable. However, the importance of maintenance over emission control technology is apparent. The second panel, Figure 5b, shows the observed age distribution of the surveyed fleet. The observed age distribution depends on the combined effects of recession, rust and socioeconomic status of the locations chosen. In this study, the most abundant vehicles were from 1985 to 1989 model years. There was also a considerable number of pre-1975 model year vehicles also had a considerable contribution. When the emission factor is multiplied by the fleet age distribution, the result is the percentage of the total CO emitted for each quintile of each model year, Figure 5c. The lowest emitting forty percent of the vehicles, regardless of the model year, make an essentially negligible contribution to the total CO emissions. The greatest contribution is from the highest emitting twenty percent of the vehicles. The highest emitting twenty percent of the new vehicles emit higher CO than the lowest emitting forty percent vehicles of any model year.

Figure 6 shows the same investigation for hydrocarbon emissions. It shows a similar picture as CO emissions, but with different vertical scaling. Note that in both cases, the greatest contributions to the total emissions are from the high emitting 1984-1989 vehicles.

Inspection and Maintenance

Of 14,051 vehicles measured, 304 vehicles were registered to zip codes not included in the Arizona centralized inspection and maintenance program in 1994. The following analysis was undertaken to compare these to the vehicles registered in I/M required zip codes, leaving out those zip codes which are partially in the I/M program. The average exhaust concentrations for the I/M vehicles were 1.06% CO and 0.077% HC, while 0.81% CO and 0.075% HC were for the non-I/M vehicles. However, the average age of the non-I/M vehicles was two years younger than the I/M vehicles. Since this age difference could obscure differences in exhaust emissions, the non-I/M and I/M fleets were compared to age-weighted control fleets. To do this, a control fleet with the same model year distributions as the non-I/M but with exhaust concentrations (by model year) of the fleet that had been subjected to I/M, and a control fleet with the same model year distributions as the I/M but with exhaust concentrations (by model year) of the fleet that had been subjected to non-I/M, were created (procedure of Radian Corp., 1992)[6]. The average exhaust concentrations of the fleets were then calculated. The results, shown in Table II, suggest that vehicles registered in non-I/M counties had lower exhaust concentrations than equivalently aged vehicles from the I/M areas. This is the same result as from a Los Angeles survey[3]. Note, however, that the differences were not significant. The lack of significance was confirmed by a paired t-test of I/M and non-I/M vehicle emissions as a function of model year. The calculated t values are 1.59 for CO and 0.04 for HC. Since this is less than the critical value (t = 2.14), the hypothesis of MeanI/M = Meannon-I/M could not be rejected at a significance level of 0.05. The conclusion that the Arizona I/M program is without detectable effect disagrees with the US Environmental Protection Agency computer modelling, but agrees with the only other independent evaluation of which we are aware. [7]

Emissions from Different Vehicle Categories

Table III shows an analysis of the average emissions from different vehicle categories. The most abundant vehicles were passenger cars, light duty tracks and vans, and commercial vehicles. Since passenger cars were the majority of the vehicles measured, their average emissions and vehicle ages can be used to represent the fleet situation in the area. Taxis emit higher CO and HC than passenger cars and light duty vehicles even though they had a younger average age. This is expected because taxis are usually high mileage and poor maintained vehicles compare with typical personal vehicles.

Repeat Emission Measurements

Table IV provides an analysis of CO and HC emissions from 983 vehicles with two or more valid measurements successfully identified by license plates in Tucson. Of the 983, vehicles, 535 (about 55%) were consistently low emitting. They emitted less than 10% of the CO emissions and about 20% of the HC emissions. At the other extreme, the consistently high-CO emitting 36 vehicles (4%) emitted more CO than the 535 low emitting vehicles combined and were responsible for 20% of the CO, while the 25 highest HC emitters (3%) were responsible for more than 16% of the HC. About 30% of the fleet were occasionally over 1 %CO but always less than 4 %CO. They accounted for 38% of the total CO emissions. For HC, 25% of the vehicles, which were occasionally over 0.1 %HC but always less than 0.2 %HC, were responsible for about 30% of the HC. There were more than 100 "flippers" which showed variable emissions, meaning that some readings were over the gross polluter cut point established at the location and some readings were below the cut point. They constituted over 10% of the fleet but emitted more than 30% of the emissions. The variability of vehicles increased with vehicle age. It has been shown[3] that emissions variability of high emitting vehicles is a phenomenon which occurs irrespective of the emission test procedure used, including I/M 240 and FTP, with FTP results sometimes differing by as much as a order of the magnitude for the same broken vehicle using the same fuel. It has also been shown[4] that only a small fraction of the flippers can be ascribed to cold start or to off-cycle hard accelerations.

Conclusion

The pattern of the Tucson emissions data looks very much like the data we have acquired elsewhere in U.S. (e.g. Los Angeles, Chicago, Denver). That pattern consists of a very skewed distribution with most vehicles contributing very little to mobile source emissions inventories. At the other extreme lie the small number of vehicles with high emissions contributing a disproportionately high share of the total emissions. The removal or repair of those gross polluters would nearly halve the amount of total emissions. The current I/M program shows no evidence of acheiving that goal. The data file is available on a floppy disk or via e-mail from the authors.

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(6) *Performance Audit of Colorado Automobile Inspection and Readjustment Program,* Final Report to the Colorado State Auditor Legislative Services, Radian Corp., Denver, **1992.**

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Table I. Comparison of the Daily Average %CO and %HC.

Date	Site	Number of measurements	Mean %CO	Mean %HC	Average Model Year
02/18/94	North-bound before the intersection	253	1.09	0.089	85.13
02/19/94	North-bound before the intersection	383	1.21	0.084	84.86
02/22/94	North-bound before the intersection	3,059	1.10	0.065	85.11
02/23/94	West-bound after the intersection	1,559	1.12	0.057	84.99
02/24/94	West-bound after the intersection	1,599	1.04	0.062	85.25
02/25/94	South-bound before the intersection	1,877	0.92	0.113	85.02
02/28/94	East-bound after the intersection	2,016	0.86	0.050	85.24
03/01/94	North-bound after the intersection	1,660	0.96	0.079	85.41
03/02/94	South-bound before the intersection	1,240	0.87	0.111	85.47
03/03/94	West-bound after the intersection	405	1.48	0.078	84.31

Table II. Comparison of Emissions from 100% I/M fleets and non-I/M Fleets.

Fleet	Mean %CO	Mean %HC	Average Model Year	Age-Adjusted Mean %CO	Age-Adjusted Mean %HC
I/M	1.06	0.077	84.7	0.99	0.088
non-I/M	0.81	0.075	86.7	0.89	0.070

Table III. Comparison of Emissions from Different Vehicle Categories. In the case of trailers, the emissions are those of the towing vehicle whose license plate was obscured.

Code	Category	Number of Measurements	Mean %CO	Mean %HC	Average Model Year
A	Passenger Car	9,700	1.01	0.077	84.76
B	Rental Car	169	0.37	0.054	93.60
C	Commercial Vehicle	1,622	0.95	0.070	86.64
E	Taxi	76	1.30	0.091	85.62
F	Light Duty Trailer	5	0.65	0.058	85.40
G	Heavy Duty Trailer	8	1.49	0.091	82.88
I	Light Duty Track & Van	2,061	1.28	0.077	84.15
P	Government Vehicle	34	0.54	0.059	88.97
S	Heavy Duty Vehicle	362	0.53	0.053	90.48
T	Commercial Car	9	1.06	0.048	87.67
	Other	5	1.83	0.081	82.40

Table IV. An Analysis of CO and HC Emissions from 983 Vehicles with Two or More Valid Remote Sensing Measurements in the Tucson Area.

CO Data Groups	Number of Vehicles	Percent of Vehicles	Number of Records	Mean %CO	Percent of Total CO	Average Model Year
all < 1%	535	54.43	1,116	0.21	9.77	87.2
all < 4%	844	85.86	1,182	0.63	47.87	86.0
1 time ≥ 4%	103	10.48	215	3.61	32.56	80.8
2+ times ≥ 4%	4	0.41	13	4.82	2.63	78.9
all ≥ 4%	32	3.26	66	6.12	16.94	77.6
all	983	100	2,106	1.13	100	85.2

HC Data Groups	Number of Vehicles	Percent of Vehicles	Number of Records	Mean %HC	Percent of Total HC	Average Model Year
all < 0.1%	583	59.31	1,221	0.033	23.48	86.3
all < 0.2%	838	85.25	1,781	0.051	52.17	85.8
1 time ≥ 0.2%	120	12.21	266	0.207	31.82	82.2
2+ times ≥ 0.2%	4	0.41	16	0.222	2.05	82.4
all ≥ 0.2%	21	2.14	43	0.561	13.96	77.9
all	983	100	2,106	0.082	100	85.2

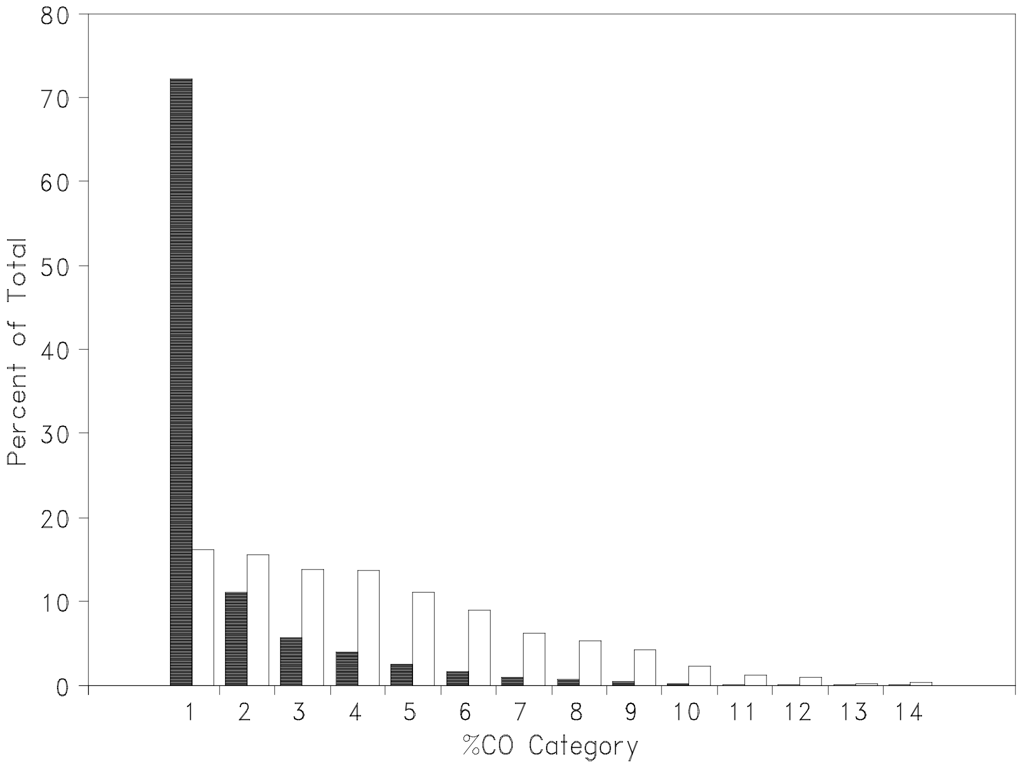


Figure 1. Normalized histogram showing as black bars the percentage of the fleet with emissions less than the stated %CO category, and as clear bars the percentage of the total CO emissions due to that catagory.

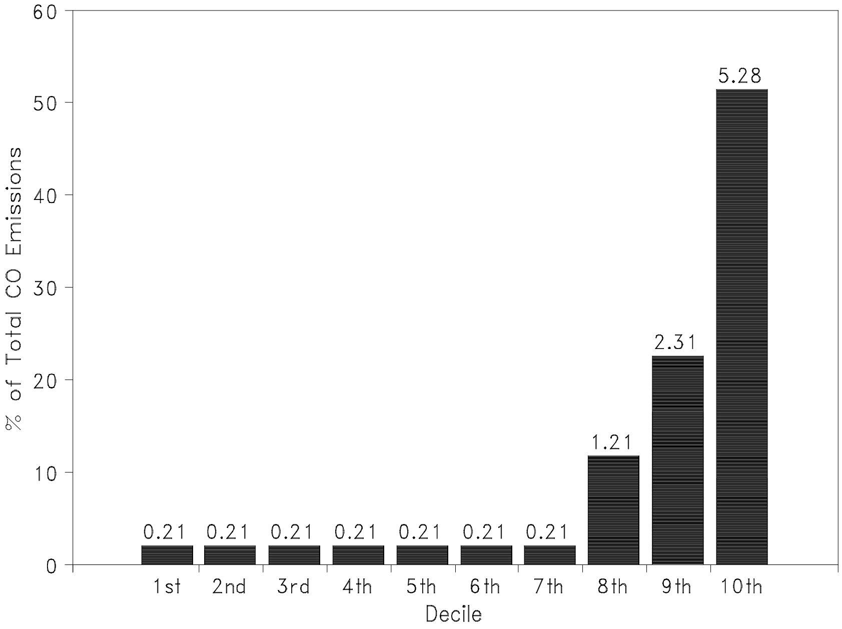


Figure 2. Mean %CO organized into deciles. The y-axis shows the contributions to total CO (summing to 100). The numbers over the bars correspond to the mean %CO in each decile. The cleanest seven deciles are give the average of all seven since the differences are within the noise limits of the sensor.

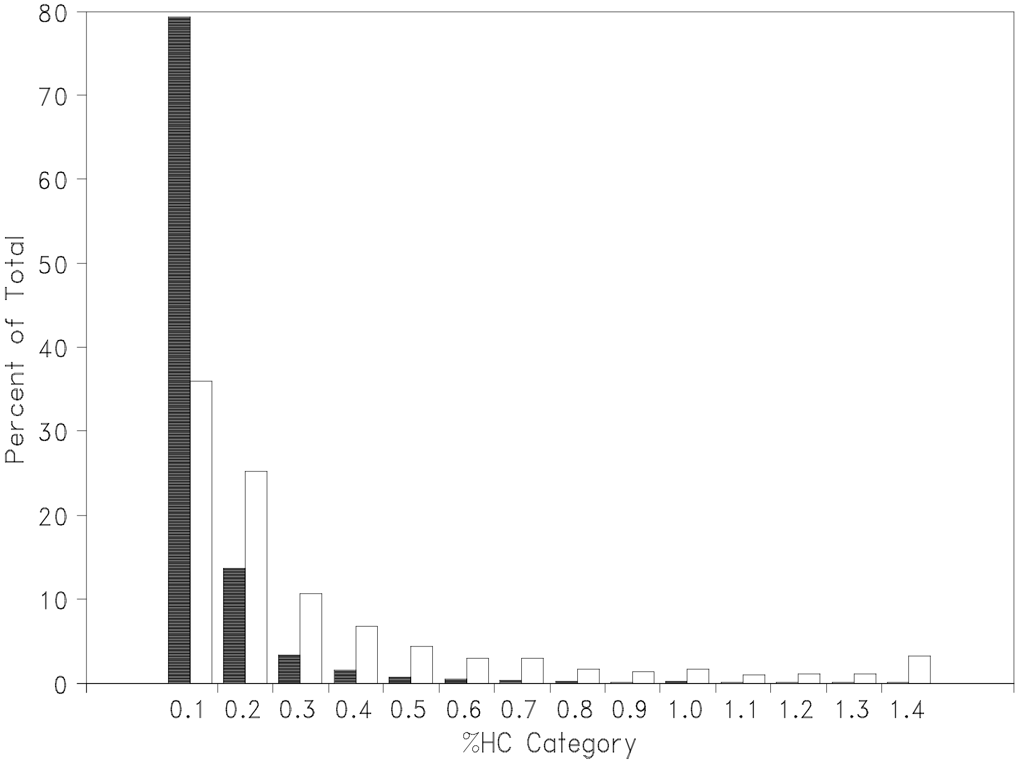


Figure 3. Normalized histogram showing as black bars the percentage of the fleet with emissions less than the stated %HC category, and as clear bars the percentage of the total HC emissions due to that catagory.

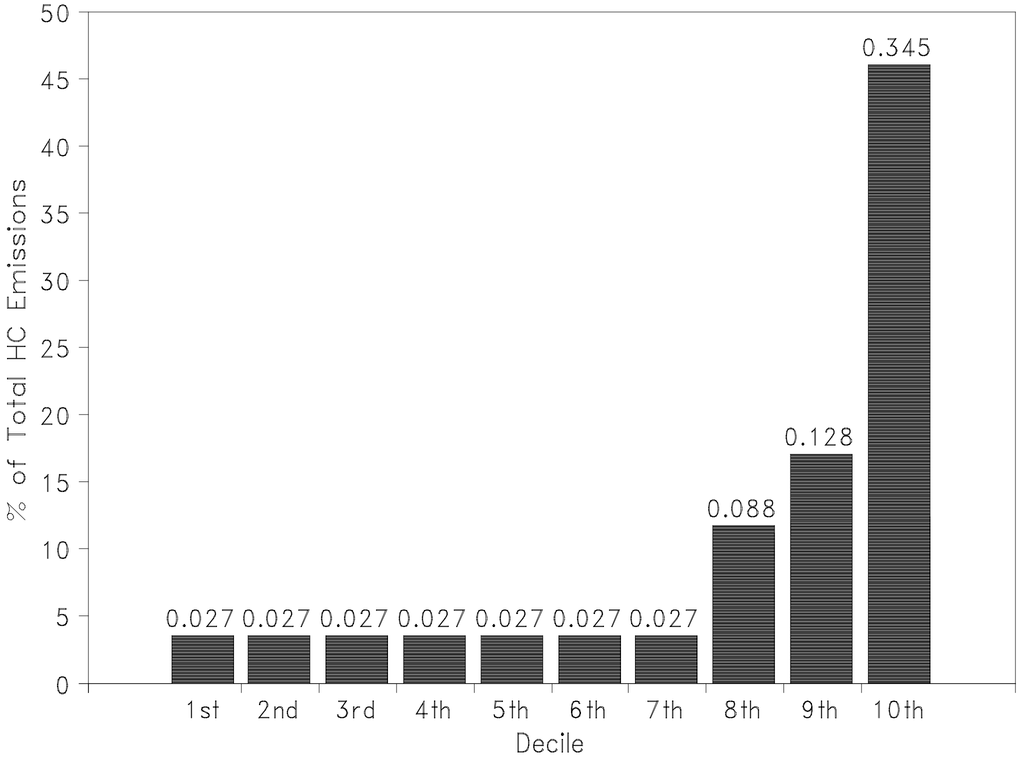


Figure 4. Mean %HC organized into deciles. The y-axis shows the contributions to total HC (summing to 100). The numbers over the bars correspond to the mean %HC in each decile. The cleanest seven deciles are given the average of all seven since the differences are within the noise limits of the sensor.

Figure Captions

Figure 5. The 1994 Tucson %CO data presented as: a) emission factors by model year divided into quintiles, b) fleet distribution and c) the percentage of the total CO emissions contributed by each quintile of each model year.

Figure 6. The 1994 Tucson %HC data presented as: a) emission factors by model year divided into quintiles, b) fleet distribution and c) the percentage of the total HC emissions contributed by each quintile of each model year.

Figure 5.

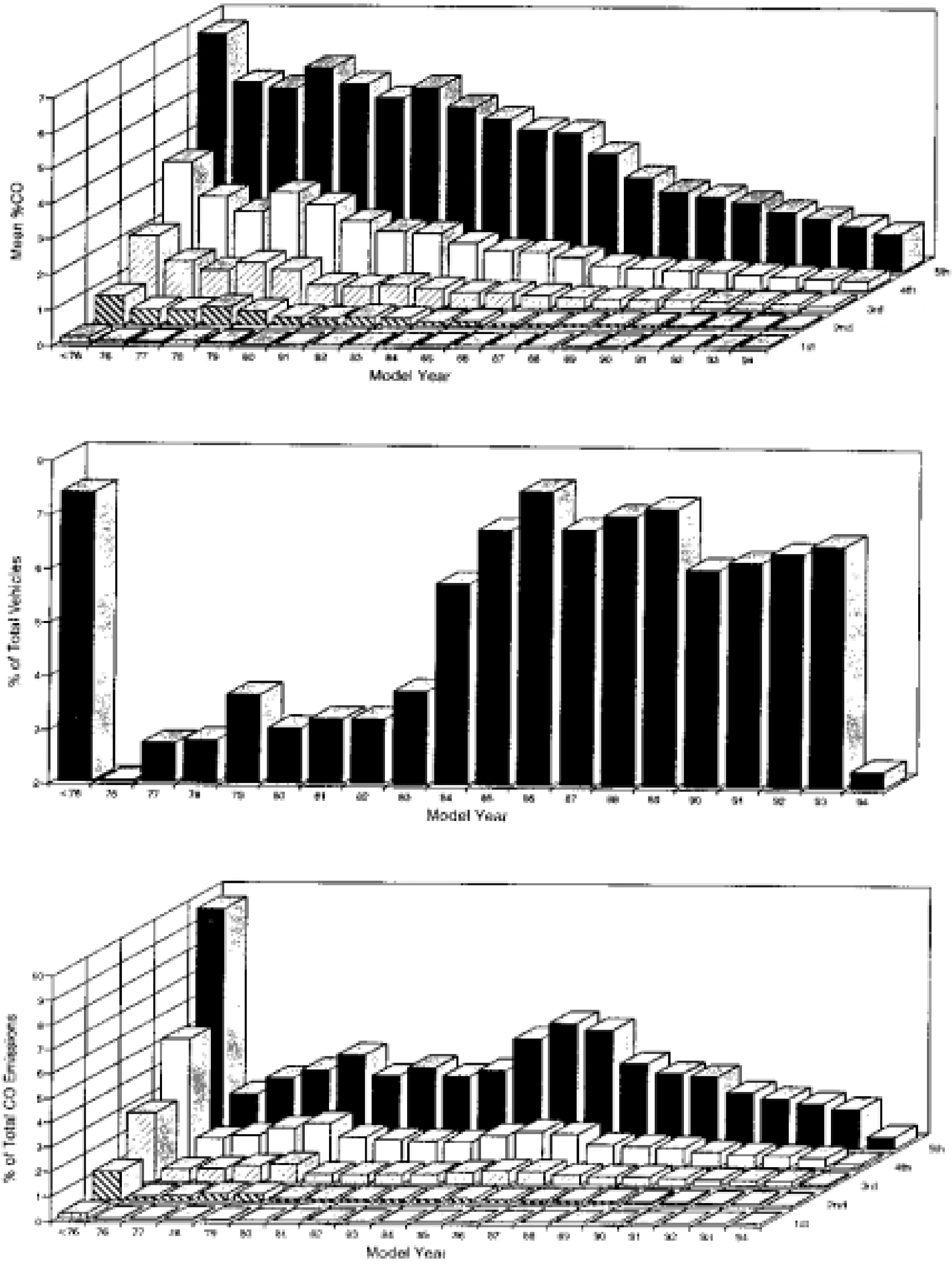
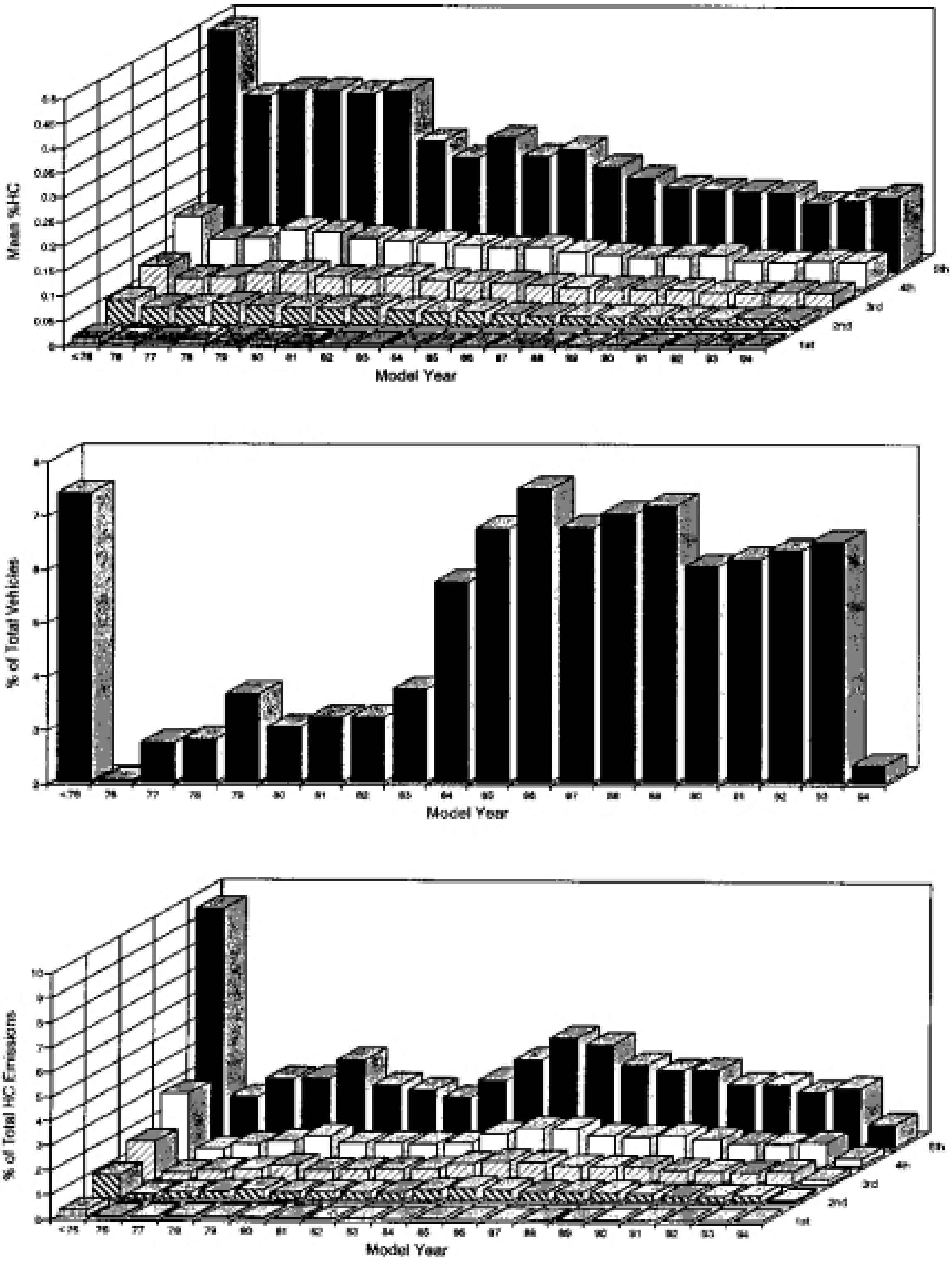

Mean %CO
0
1
2
3
4
5
6
7
<76
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
Model Year
1st
2nd
3rd
4th
5th
% of Total Vehicles
Model Year
% of Total CO Emissions
0
1
2
3
4
5
6
7
8
9
10
Model Year
1st
2nd
3rd
4th
5th

Figure 6.


Mean %HC
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
<76
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
Model Year
1st
2nd
3rd
4th
5th
% of Total Vehicles
8
7
6
5
4
3
2
<76
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
Model Year
% of Total HC Emissions
10
9
8
7
6
5
4
3
2
1
0
<76
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
Model Year
1st
2nd
3rd
4th
5th