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Robert D. Stephens
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Intended Audience: AES, CPE, EAS, Hughes, IGR

PURPOSE

The purpose of this research is to better understand CO emissions from vehicles during normal, on-road operation by developing instrumentation capable of remotely measuring emissions from thousands of vehicles per day.

SUMMARY

Failure of many urban areas to meet clean air standards for CO has increased pressure for stricter vehicle emission controls. To understand the impact of this strategy and/or to propose alternative, more effective control strategies, requires a better understanding of the emissions from vehicles during normal, on-road operation. This report describes instrumentation that is capable of remotely measuring the CO emissions from thousands of vehicles per day with a sensitivity of ±1% CO, which, for new vehicles, is approximately 10 grams per mile of CO. A prototype of this instrument was used in Denver, CO in January of 1989 during a study conducted in conjunction with researchers from the University of Denver, who have developed similar instrumentation. Emission measurements were made on approximately 4000 vehicles that were identified by make and model year from state vehicle registration records. The data demonstrates a clear trend of higher emission rates from older vehicles, suggesting that a lowering of emission standards for new vehicles will have little impact upon ambient urban CO levels.

Significance: This research supports GM's position that emissions from older vehicles are a major source of the urban CO problem.

INTRODUCTION

The Environmental Protection Agency has recently reported a 32% decrease in the composite national average carbon monoxide (CO) values measured between 1978 and 1987[1]. Although emission standards on vehicles have been largely responsible for this air quality improvement, approximately 54% of all CO emissions in the U.S. are still from highway vehicles[2]. Furthermore, improvements in air quality have not occurred as quickly as have been expected; in 1988, 44 urban areas continued to experience exceedances of the 8-hour air-quality standard for CO[3,4]. In the next decade, the trend toward decreasing levels of ambient CO is expected to reverse due to increases in vehicle miles traveled and problems of urban traffic congestion.

Failure of urban areas to meet CO air quality standards has increased pressure for stricter vehicle CO emission controls. However, current understanding of fleet average vehicle emission rates is not adequate to determine if reductions in automotive CO exhaust standards will significantly improve urban air quality. For example, GM in-use data show that MOBILE4 (an EPA model that predicts fleet average emission rates) overpredicts emissions from late model GM vehicles[5], yet roadside and tunnel studies have measured CO concentrations that are a factor of two higher than concentrations predicted by MOBILE4[6]. A possible explanation for these apparent descrepancies is that a few vehicles contribute an unexpectedly large fraction of urban CO. Such an explanation is supported by Stedman et al, who claim that 50% of CO emissions are generated by only 10% of all vehicles[7].

MOBILE4 predictions and GM in-use data are both based upon costly and time-consuming FTP and dynamometer tests of vehicles. With the large number of model years and technology types existing in vehicles operated on the road today, it is extremely difficult to obtain statistically valid samples of the entire fleet. This limits the ability to understand the urban CO problem. Another limitation of using the FTP test is that the driving cycles used may not be typical of the urban area under consideration.

It is possible that MOBILE4 predictions could be substantially improved with more measurements and with measurements made under conditions more typical of the urban area being considered. To obtain such measurements, we have designed and built a prototype instrument capable of remotely measuring

CO emissions from vehicles operated under normal roadway conditions. Operation of the instrument does not require driver cooperation and in no way interferes with the operation of the vehicles being measured. The instrument is capable of measuring emissions from a thousand or more vehicles per day. The sensitivity of the instrument is adequate to identify the vehicles labeled by MOBILE4 as "super emitters" (closed-loop technology vehicles that emit more than 150 grams-per-mile of CO as measured via FTP tests) and most of the vehicles in the "high emitter" category (vehicles emitting more than 10.1 to 21.6 grams-per-mile CO during FTP tests, depending upon model year and type of vehicle technology employed). An instrument capable of performing similar measurements has been previously reported by Stedman and Bishop of the University of Denver[7-9].

During January of 1989, General Motors conducted a study in Denver, CO in which the GM and University of Denver (DU) instruments were used to measure CO emissions from thousands of vehicles. For the purposes of this study, DU was contracted by GM to provide CO measurements for five days of operation of the DU instrument. During most of this time the GM and DU instruments were operated side by side. The goals of the study were twofold; to assess the accuracy of the DU and GM instruments, and also, to use the measurements to better understand real-world automotive CO emissions.

This report describes the instrument designed and built at General Motors Research Laboratories. Potential problems with the two (slightly different) techniques is discussed, and the results of the comparison of the GM and DU techniques are presented. Finally, the measurements of CO emission rates and their implications will be discussed.

EXPERIMENTAL

Instrument

The system operates by measuring the intensity of an infrared beam transmitted across a roadway. Intensity measurements are made for one second immediately before and for 1.5 seconds immediately after a vehicle passes through the beam. CO and CO_2 concentrations in the exhaust plume are determined from these transmittance measurements.

A schematic diagram of the system is shown in Figure 1. The system consists of an infrared source module, an infrared detector module interfaced

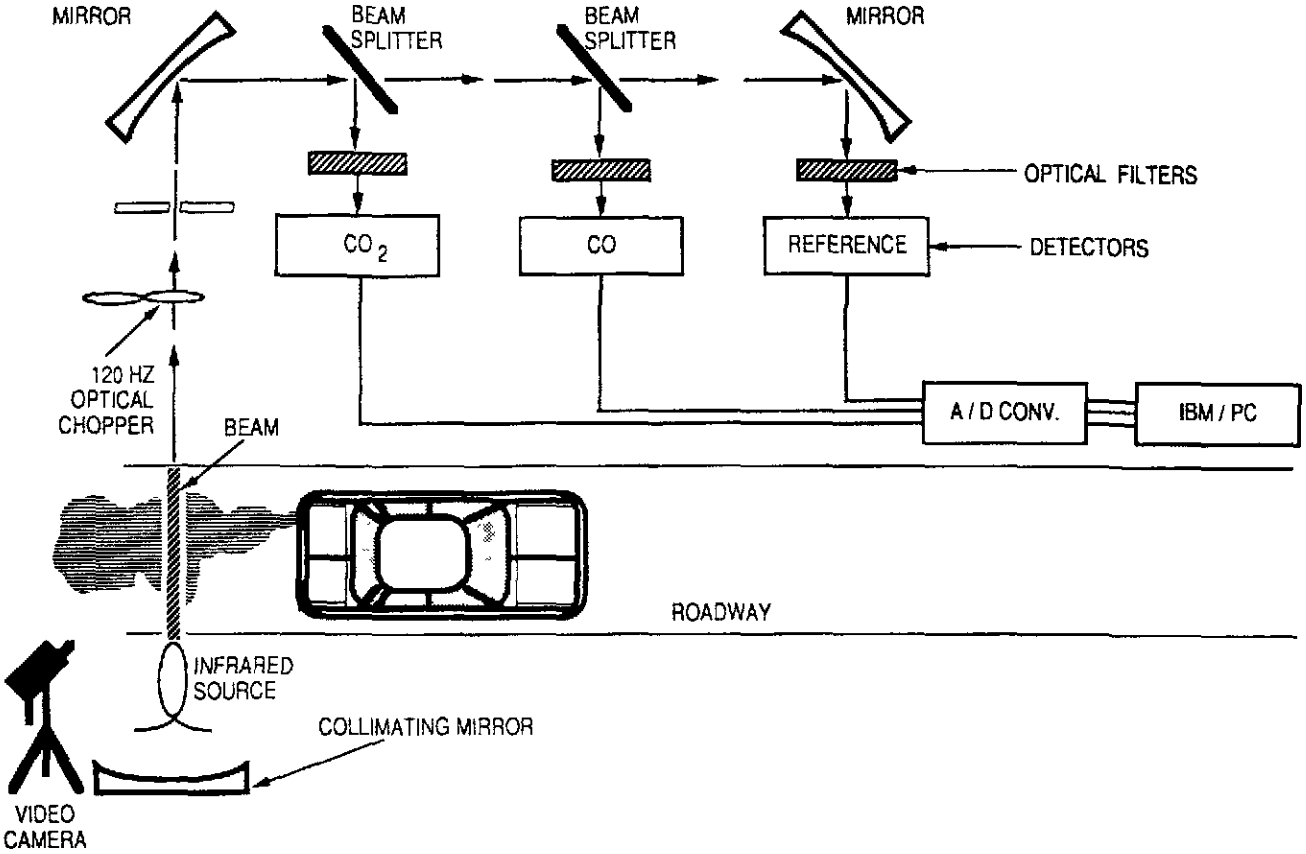

FIGURE 1. Schematic diagram of the GM instrument for CO emission measurements.

to a computerized data acquisition system and a video recording system. The infrared source and detector modules are each positioned on opposite sides of the roadway, approximately 8.6 m apart. The video camera was aimed at the area between source and detector and was used to record license plate numbers of the vehicles measured.

The source module consisted of an infrared source and a 152-mm diameter f/1 MgF overcoated aluminum mirror. The mirror and source were positioned so as to produce a collimated infrared beam that was directed across the roadway at a height of 0.28 m above the road surface. A HeNe laser was also incorporated into the source module and was used only during optical alignment of the source and detector modules.

As shown in Figure 1, the detector module consisted of an optical chopper, an aperture and a series of beamsplitters, optical filters, mirrors and detectors. The optical chopping frequency was 120 Hz, which provided an 8.3-millisecond measurement time resolution. The aperture was a variable iris, which was set at 15-mm diameter. The infrared beam was divided into three paths each going to three detectors that measured intensities of different infrared spectral regions. Path one was created by the reflection from a calcium fluoride beamsplitter and transmission through an optical filter that isolated the infrared region associated with CO_2 absorption (88.3% peak transmission and half-power points at 4.224 and 4.314 microns). Beam intensity was monitored via a 1-mm diameter active area, liquid-nitrogen cooled, indium antimonide detector. Path two was created by reflection from a germanium beamsplitter and transmission through an optical filter that isolated the infrared region associated with CO absorption (85.1% peak transmittance with half-power points at 4.532 and 4.693 microns). Beam intensity was monitored by a 10-mm diameter active area, liquid-nitrogen cooled, indium antimonide detector. Path three consisted of the infrared region transmitted by beamsplitters one and two and an optical filter that transmitted an infrared region unaffected by automobile exhaust constituents (75% peak transmittance with half-power points at 3.664 and 4.058 microns). Beam path three utilized a 1-mm diameter active area liquid-nitrogen cooled mercury-cadmium-telluride detector. This "reference" detector provided signals used to normalize the CO and CO_2 detector signals, hence correcting for measured infrared intensity fluctuations caused by source intensity fluctuations and/or the presence of exhaust particulates or road dust between the source and detector modules. Tests were conducted using wire screens placed in front of the infrared source to simulate aerosol scattering and/or source intensity fluctuations. These tests demonstrated that all channels were affected equally by beam intensity fluctuations. Signal to noise ratios were approximately 220 for the CO and CO_2 detectors and approximately 300 for the reference detector.

Data acquisition was accomplished via an IBM PC/AT based four channel digital oscilloscope (Rapid Systems R1000) with 8 bit A/D resolution. A/D conversion was performed simultaneously on all three detector signals. Conversion rates were synchronized to a 240-Hz clock signal that was generated by the 120-Hz optical chopper. This provided peak-to-peak sampling of the modulated detector signals. Data storage was triggered via detector signal level increases that occured when the infrared beam became unblocked, i.e., when a vehicle exited the area between source and detector modules. Pretriggering capability of the digital oscilloscope provided automatic storage of data measured for a predefined time period prior to and following each triggering event. Typically 240 pre-trigger data points (1 second) per detector channel and 360 post-trigger data points (1.5 seconds) per channel were recorded for each vehicle.

The video recording system consisted of a Panasonic model WV-3260/8AF color video camera and a Panasonic model AG-1950 video cassette recorder. This was used to record license plate numbers of vehicles driving past the emission measurement system. The license plate numbers were subsequently used to obtain vehicle registration information, such as vehicle age and make. This information was used to investigate the relationship between vehicle age and emissions.

The instrument was calibrated by measuring transmittance versus known concentrations of CO and CO_2 flowing through a 203-mm long gas cell. Polynomial fits were made to plots of concentration versus transmittance. Typical calibration curves obtained in this manner are shown as Figure 2. The polynomial equations were subsequently used to derive concentrations from the transmittances experimentally measured through exhaust plumes. Accuracy of the instrument is estimated to be ±1% CO.

The most notable difference between the DU and GM instruments is the use of a spinning gas filter correlation cell in the DU instrument[8]. This cell enables the use of one detector to alternately measure infrared intensity in

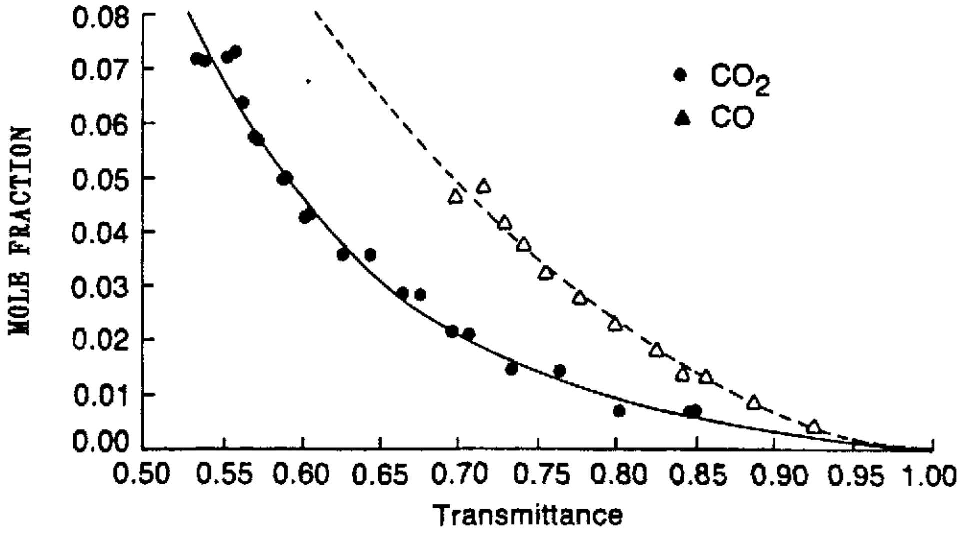

FIGURE 2. Calibration curves for 203 mm path-lengths of CO and CO_2. Solid lines represent the polynomial equations that best describe the experimental curves.

two separate portions of the infrared: in a CO absorbing part of the spectrum when the N_2 side of the cell is in the beam, and in a reference or nonabsorbing part of the spectrum when the CO side of the cell is in the beam. This system provided time resolution of 16.6 milliseconds for the CO and reference signals and 8.3 milliseconds for the CO_2 measurement. Signal to noise ratios for the DU system were approximately one-thousand to one[10].

Field Study

The instruments were used to measure emissions from vehicles at a site in Denver, CO in January of 1989. The site was located on the exit ramp of southbound I-24 to southbound Speer Blvd, a major Denver traffic artery. Our instruments were located approximately half-way around this nearly circular uphill ramp, assuring that most vehicles were modestly accelerating, although occasionally drivers slowed down to observe the instrumentation. The nearest on-ramp to this freeway was approximately two miles away, which guaranteed that all vehicles would be at operating temperature when our measurements took place. A small fraction of the measurements reported here were obtained at a second site located at the on-ramp to southbound I-25 from southbound University Blvd.

Data Analysis

Exhaust gas concentration measurements in this study were conducted in a way analogous to conventional optical transmittance studies. For example, transmittance studies typically utilize the ratio of two measurements: the optical intensity measured after transmission through a sample (i.e., sample measurement) and optical intensity measured without a sample present (i.e., background measurement). For this study, for each vehicle measured, the background intensity measurements were the average of the detector voltages from each channel (CO, CO_2 and reference) measured prior to each car entering the infrared beam (pre-car data). The sample measurements were the detector voltages measured for each channel for one second immediately after the car exited the infrared beam (post-car data).

Each post-car CO, CO_2 and reference detector voltage was converted to a transmittance value by dividing the post-car voltages by the pre-car average voltages for each respective channel. The CO and CO_2 transmittances were then normalized by dividing by the transmittance of the reference channel. This normalization corrected the CO and CO_2 signals for fluctuations that could occur due to source intensity fluctuations and/or fluctuations in signal strengths that would result from the presence of particulate matter (e.g., from either the vehicle exhaust or from the roadway) between source and detector.

Transmittances for the CO and CO_2 channels were converted to concentrations using the polynomial equations derived as best fits to the calibrations described in the Experimental section (see Figure 2). The CO and CO_2 within an exhaust plume from a vehicle will disperse at an equal rate, which means that although CO and CO_2 concentrations will vary rapidly with time, the CO/CO_2 ratio should be constant. For this reason concentrations were determined relative to a fixed pathlength (203 mm) and values of CO and CO_2 are reported as CO/CO_2 ratios. Potential interferences to the accurate measurement of this ratio are discussed in Appendix A.

Although the CO/CO_2 ratio measurements are, in themselves, good indicators of vehicle emission levels, the ratios can also be converted to percent CO levels, or also, to gram-per-mile emission rates. Stedman et al. use an engine map (a description of variations in exhaust gas concentrations as a function of engine air/fuel ratio) to convert from CO/CO_2 ratio to percent CO[8]. Gram-per-mile (gpm) emission rates are a more conventional unit because it accounts for fuel economy.

The conversion from measured CO/CO_2 to grams-per-mile (gpm) of CO required knowledge of fuel density, the fraction of fuel weight present as carbon, and the fuel economy (miles per gallon) of the vehicle during the measurement. During the time of this study, Denver was participating in the oxygenated fuel program, whereby the fuel contained 2% oxygen by weight. Average fuel density was measured as 2745.6 grams/gallon and the average fraction of fuel weight present as carbon was 0.844. Clearly the most uncertain aspect of the conversion to grams-per-mile emission rates is the fuel economy of the vehicle. To minimize the uncertainties of this conversion, the measurements were carefully sorted by vehicle type, age and make and conversions were then based on fuel economy data for each subset of vehicles. The emission rates reported in this study, then, should be viewed as average, relative rates that could have substantial errors for any one vehicle. These potential errors are discussed in Appendix B.

Sorting of vehicles involved several steps. First, emission measurements made on vehicles that yielded unreadable license plates on video tape were eliminated from the analysis. Registration information was obtained on all other vehicles. Registration information was then compared to each vehicle on video tape and vehicles were eliminated from analysis if the registration information was obviously incorrect (for example, Cadillac does not manufacture light-duty trucks). During this review of the video tapes, vehicles were also specially coded if they were pickup trucks, vans or utility vehicles. This step was undertaken since vans and utility vehicles are often registered as passenger vehicles, despite their classification as light-duty trucks. This step also served to further eliminate vehicles with incorrect state registration information. At this point, the database contained make and age information for each vehicle measured. The database was then sorted into two separate groups, passenger cars and light-duty trucks. Each of these groups was then further subdivided into two subgroups, domestic and imports.

Domestic passenger cars were sorted by model year back to 1975, pre-1975 domestic passenger cars being grouped together since these were all non-catalyst equipped vehicles. Yearly groupings were used because the average mile per gallon ratings of domestic passenger cars has changed dramatically on an annual basis over this time period. Conversions to gpm of CO were based upon the domestic fleet fuel economy ratings reported by the Motor Vehicle Manufacturers Association (MVMA)[2]. Separate mile-per-gallon ratings were used for AMC cars[2] since these (generally smaller) vehicles had fuel economy ratings significantly higher than other domestics during this time period. Miles-per-gallon ratings used for these conversions are listed in Table B-I.

Imported passenger cars were sorted by manufacturer, but not by year, since MPG ratings varied most significantly by manufacturer rather than by model year. Conversions to gpm of CO were performed separately for each foriegn manufacturer using the average of the 1978 through 1989 corporate average fuel economy ratings of each foriegn manufacturer as reported by MVMA[2]. These mile-per-gallon ratings and the standard deviation over all model years are shown in Table B-II.

Both imported and domestic light-duty trucks were sorted by model year back to 1979, pre-1979 models being grouped together due to the limited light-duty truck sample size. Conversions to gpm of CO were performed separately for imports and domestics according to the import and domestic fleet average fuel economies, respectively; again as reported by MVMA[8], except for pre-1979 vehicles where the fuel economy was estimated. Table B-III lists the mile-per-gallon ratings used for gpm conversions on all light-duty trucks.

The following equation was used in conjunction with the fuel economy ratings listed in Table B-I to convert from CO/CO_2 ratios to grams-per-mile of CO emitted:

$$CO(gpm) = 2747.9\ (g/gallon) * 0.844\ (g\text{-}C/g\text{-}fuel) * Q/(1 + 1.175Q) * 28/12\ (g\text{-}CO/g\text{-}C) \div X\ (mpg)$$

In this equation, Q represents the measured CO/CO_2 ratio. Note that the emission rate is corrected for an assumed, but unmeasured, rate of hydrocarbon emission (1.175 * Q). This and other potential uncertainties in the conversion of CO/CO_2 to CO emission rates are discussed in Appendix B.

After CO/CO_2 measurements were converted to gpm values, all passenger car groups were recombined into a single data set of passenger car measurements; likewise for light-duty truck measurements. A third data set was created by combining the passenger car and light-duty truck measurements.

RESULTS

Comparison of GM and DU Results

Although five days of measurements were obtained for both instruments, only four days of the study utilized both instruments side by side. A modification of the GM instrument was made prior to the last day of side by side operation of the two instruments. For comparison of the measurements of the two systems, only the GM results obtained by the modified instrument were used. The GM instrument measured emissions from approximately 1100 vehicles on this day of the study, whereas the DU instrument measured approximately 3100 vehicles. Because the instruments were not turned on and off at the same time and because calibrations were not conducted at the same time, only 294 direct measurement comparisons are available. A comparison of the two sets of measurements can be conducted in at least two ways. A direct comparison of the measured CO/CO_2 ratios can be made, or alternatively, a comparison of the frequency distributions of CO/CO_2 ratios can be performed.

Figure 3 shows the direct comparisons between the DU and GM measured CO/CO_2 ratios. The linear best fit to the relationship of GM measurements to

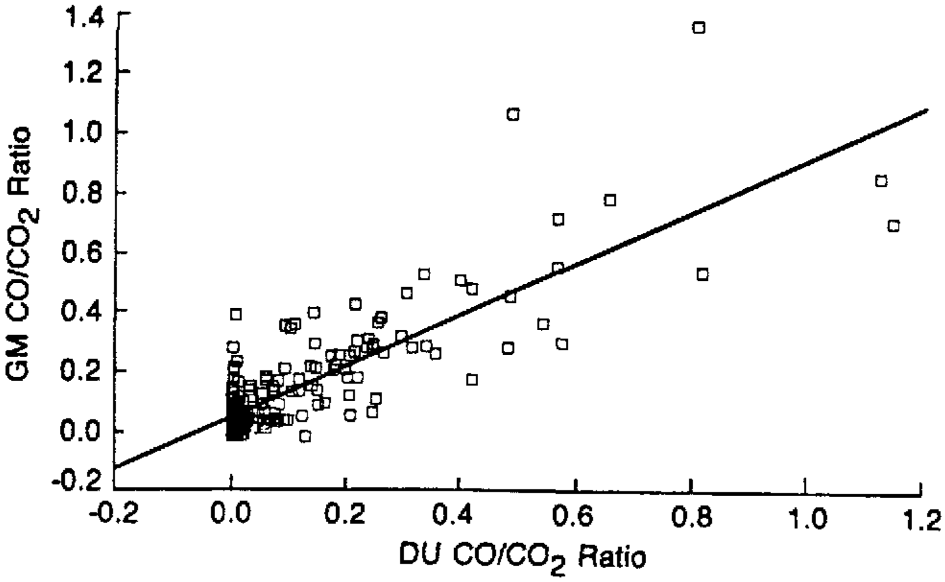

FIGURE 3. Comparison of GM And DU Measurements of CO/CO$_2$ Ratios. The solid line represents a least squares fit of the two sets of data and yields a correlation (r^2) of 0.71. The slope and intercept of the fit is 0.88 and 0.04 respectively.

DU measurements of the CO/CO_2 ratio is 0.88, with an intercept of 0.04. The r value of the fit is 0.84. Uncertainty in reported ratios (unitless) is approximately 0.07. Likely contributors of scatter in this plot are the low signal to noise ratios of the GM instrument and the susceptibility of the DU system to errors induced by the reference correction technique when particulate matter is present during measurements (see discussion in Appendix A). Figure 4 shows a comparison of the distribution of emission levels measured by the two instruments.

Vehicle Emission Measurements

During this study, emission measurements were made on a total of 3243 passenger cars and 887 light-duty trucks. Analysis of these measurements have been done on each group separately, and on the combined group of vehicles (all vehicles except heavy trucks and motorcycles). Each of these three groups of data were sorted by year and statistics calculated for each model year. Tables I, II and III show several important statistics resulting from this study; the number of vehicles measured from each model year, the mean and median gpm and percent CO for each model year, the fraction of total vehicles represented by each model year and the fraction of total CO that is contributed by each model year. The fraction of all CO emitted by each model year was calculated by multiplying the number of vehicles within each model year by the mean gram-per-mile emission rate for each model year and dividing this product by the sum of all such products. From this table it is clear that older vehicles emit a large fraction of the total CO. For example, 6.9% of the total number of passenger cars measured in this study were pre-1975 models (with a mean model year of 1970), yet they contributed 26.0% of all CO emitted by cars. Alternatively, 1987 through 1989 models contributed only 4.1% of CO from cars, but represented 23% of all cars measured. Analogous statistics have been calculated for light-duty trucks (Table II) and for all vehicles measured (Table III).

Figure 5 shows a plot of the mean grams-per-mile emission rates measured for passenger cars and light-duty trucks as a function of model year. The smaller sample sizes of light-duty trucks result in higher uncertainties in the measured mean emission rates for these vehicles. Figure 6 shows the fraction of the 3243 car measurements that are associated with each model year and also the fraction of all passenger car CO emitted by vehicles of each

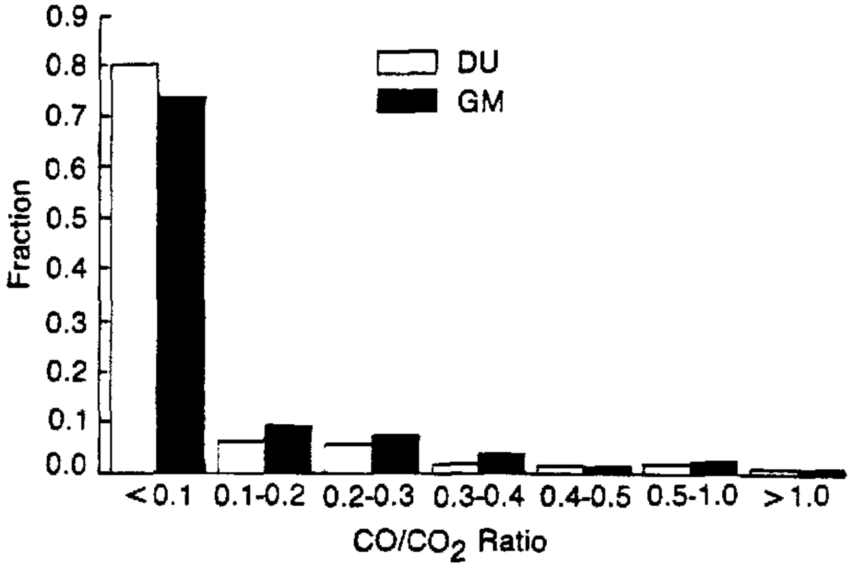

FIGURE 4. Comparison of distributions of GM and DU CO/CO_2 ratios.

Table I. Passenger Car Statistics

Year	Mean gpm	Median gpm	Mean % CO	Median % CO	No.of Cars	Car Frac.	CO Frac.
PRE-1975	54.9	37.23	2.73	2.04	224	0.069	0.260
1975	38.1	25.88	2.32	1.45	40	0.012	0.032
1976	33.5	22.61	2.07	1.43	65	0.020	0.046
1977	22.8	7.81	1.49	0.55	109	0.034	0.053
1978	28.2	18.85	1.97	1.22	152	0.047	0.091
1979	27.0	15.24	1.88	0.99	179	0.055	0.102
1980	22.9	10.47	1.74	0.80	198	0.061	0.096
1981	16.1	3.53	1.33	0.28	221	0.068	0.075
1982	8.7	2.22	0.72	0.19	203	0.063	0.037
1983	10.2	2.35	0.85	0.17	198	0.061	0.043
1984	8.6	1.54	0.73	0.12	293	0.090	0.053
1985	6.5	1.36	0.56	0.10	293	0.090	0.040
1986	4.4	1.08	0.37	0.08	321	0.099	0.030
1987	3.2	0.71	0.27	0.06	345	0.106	0.023
1988	2.1	0.53	0.19	0.04	334	0.103	0.015
1989	1.96	0.53	0.15	0.04	68	0.021	0.003
TOTALS	14.6	2.27	1.0	0.17	3243	1.000	1.000

Table II. Light-Duty Truck Statistics

Year	Mean gpm	Median gpm	Mean % CO	Median % CO	No.of Vehicles	Vehicle Frac.	CO Frac.
PRE-1975	53.33	43.17	2.29	1.77	80	0.090	0.214
1975	59.86	58.89	2.60	2.47	11	0.012	0.033
1976	56.55	51.05	2.57	2.12	13	0.015	0.037
1977	46.01	28.25	2.09	1.14	33	0.037	0.076
1978	37.30	22.58	1.64	0.91	44	0.050	0.082
1979	35.73	33.30	2.06	1.75	49	0.055	0.088
1980	47.01	45.15	2.72	2.60	39	0.044	0.092
1981	29.21	23.9	2.00	1.54	44	0.050	0.065
1982	22.76	8.48	1.40	0.54	43	0.048	0.049
1983	26.13	14.99	1.70	0.88	51	0.057	0.067
1984	15.07	3.70	0.96	0.20	84	0.095	0.064
1985	9.49	1.98	0.63	0.12	97	0.109	0.046
1986	5.22	1.05	0.33	0.07	99	0.112	0.026
1987	6.96	1.04	0.48	0.07	93	0.105	0.033
1988	3.46	0.87	0.21	0.05	92	0.104	0.016
1989	15.27	1.58	0.99	0.09	15	0.017	0.012
TOTALS	22.43	6.27	1.22	0.33	887	1.000	1.000

Table III. All Light-Duty Vehicle Statistics

Year	Mean gpm	Median gpm	Mean % CO	Median % CO	No.of Vehicles	Vehicle Frac.	CO Frac.
PRE-1975	54.49	38.14	2.61	1.96	304	0.074	0.247
1975	42.82	29.25	2.38	1.73	51	0.012	0.033
1976	37.32	30.00	2.16	1.51	78	0.019	0.043
1977	28.18	13.60	1.63	0.66	142	0.034	0.060
1978	30.22	19.53	1.90	1.16	196	0.047	0.088
1979	28.89	16.72	1.92	1.09	228	0.055	0.098
1980	26.86	14.97	1.90	1.23	237	0.057	0.099
1981	18.27	5.23	1.44	0.39	265	0.064	0.072
1982	11.17	2.61	0.84	0.21	246	0.060	0.041
1983	13.46	3.04	1.02	0.25	249	0.060	0.050
1984	10.02	1.79	0.78	0.13	377	0.091	0.056
1985	7.23	1.47	0.58	0.11	390	0.094	0.042
1986	4.57	1.07	0.36	0.08	420	0.102	0.029
1987	4.03	0.80	0.32	0.06	438	0.106	0.026
1988	2.39	0.59	0.19	0.05	426	0.103	0.015
1989	4.36	0.58	0.30	0.05	83	0.020	0.005
TOTALS	16.3	2.6	1.05	0.19	4130	1.000	1.000

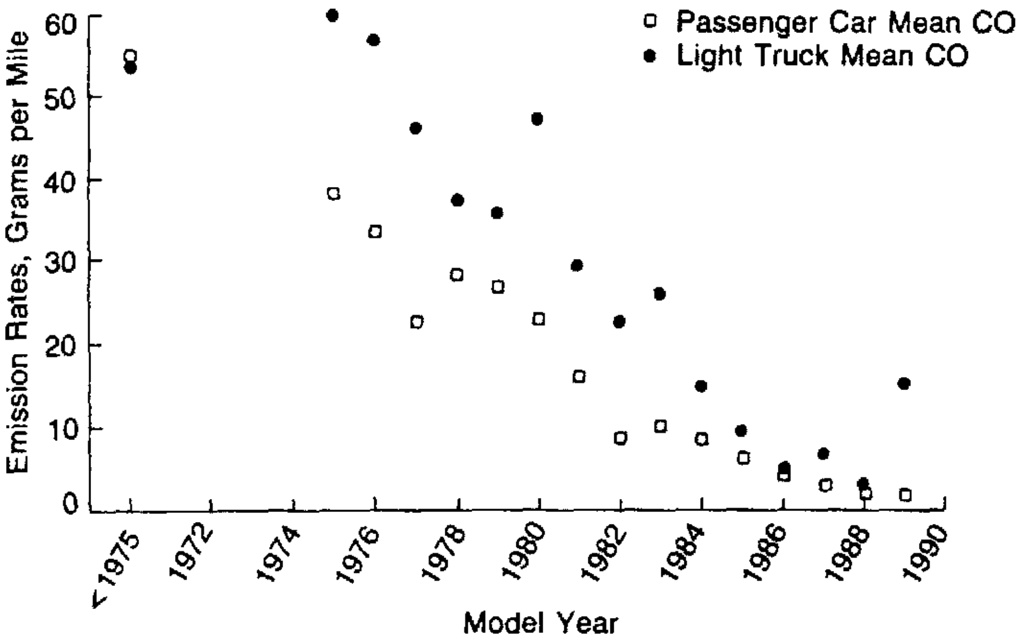

FIGURE 5. Mean gram-per-mile emission rates measured for each model year of passenger car and light duty truck.

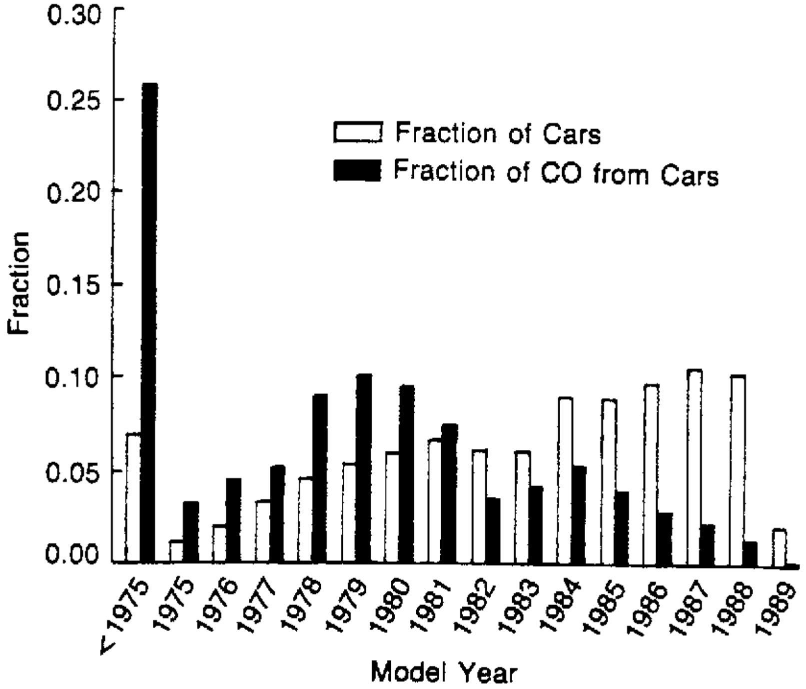

FIGURE 6. Bargraph showing the fraction of all cars in each model year and the fraction of total car CO emitted by each model year.

model year.

To better understand the emission rates of vehicles within each model year group, a frequency distribution was measured, showing the number of cars (and the fraction of all cars within the group) emitting CO at various rates. This data is included in Table B-IV and is also illustrated with Bargraphs B1-B3. For example, 19.7% of all pre-1975 passenger cars emit greater than 100 gpm of CO, whereas 94.1% of all 1989 cars emit less than 10 gpm of CO. Analogous calculations have been performed for light-duty trucks (Table B-V and Figure B3 and B4) and for all vehicles (Table B-VI).

An examination of the highest emitting passenger cars indicates that 50% of CO from cars is emitted by 8.1% of the cars. These cars, on average, were 12.3 years old and emit 90.4 gpm of CO. If all passenger cars emitted at the rate measured for 1989 cars, emission rates would be reduced by 86.5%. For the combined group of passenger cars and light-duty trucks, 50% of the CO is emitted by 8.9% of the vehicles. On average, the age of these vehicles is also 12.3 years with average emission rates of 91.7 gpm of CO.

MOBILE4 uses well-defined emission levels to define vehicles as super-emitters and high-emitters. However, using these MOBILE4 definitions to analyse our data is not entirely valid since MOBILE4 calculations include cold and hot start CO emissions. However, our data should provide a lower limit for the fraction of the fleet which meets the definitions of super-emitters and high-emitters. The MOBILE4 definition of a super-emitter is a passenger car that utilizes closed-loop emission technology and emits more than 150 gpm CO. Closed-loop control was initiated in 1981. From Table B-IV it can be seen that there were no super-emitters observed. However, 22 open-loop cars were measured as emitting more than 150 gpm CO. Of these, 21 were pre-1975 and 1 was a 1975 model. These 22 vehicles contributed 8.3% of all CO measured at our site in Denver, CO.

The MOBILE4 definition of a high-emitter is more complicated, the definition being different for different model years and different emission control technologies. For 1981 and 1982 a high-emitter is any of the following three categories of vehicle: 1) a closed-loop carbureted car that emits more than 17.4 gpm 2) a closed-loop fuel-injected car that emits more than 10.5 gpm or 3) an open-loop car that emits more than 21.6 gpm CO. For 1983 and later cars the definitions are 1) 10.4 gpm for closed-loop carbureted cars 2) 10.6 gpm for closed-loop fuel-injected cars and 3) 10.1 gpm for open-loop cars. In this study, the emission control technology that was utilized by each vehicle was not determined. For 1983 and later cars, this is not a serious problem since the definitions for high-emitters is nearly constant, i.e., 10.37 ± 0.21 gpm. For 1983 and later cars we found that 13.3% of the cars were high-emitters and that these cars contributed 74.8% of CO emitted by all cars of those model years. Since we do not know the emission technology employed by each individual 1981 and 1982 model year car that we measured, we used the MOBILE4 technology distribution to obtain a weighted mean of 18.6 gpm as the definition for high-emitters in these model years. Using this definition, we find that 22.2% of 1981 and 1982 cars were high emitters and that they emitted 78.4% of CO from all vehicles within these model years.

MOBILE4 also calculates deterioration rates, i.e., increases in emission rates with vehicle miles traveled. Separate deterioration rates are calculated for vehicles with less than 50,000 miles and for vehicles with more than 50,000 miles. We have no knowledge of the mileage of the individual vehicles measured and therefore cannot calculate deterioration rates as a function of miles traveled. We can, however, measure the increases in emission rates as a function of model year. We conducted regression analysis on passenger cars for the 1986 through 1989 model years and for the pre-1986 model years. For 1986 through 1989 model year cars, the relationship between CO emissions and model year showed a rate of increase of 1.3 gpm per year. For pre-1986 model year vehicles, the analysis showed a 2.9 gpm per year increase. The relationship for pre-1986 vehicles is very likey dominated by emission rates which have varied with emission control technology. Also, these increases can occur for a variety of reasons; deterioration of emission control systems, malfunctioning systems, misfueling, or emission control modifications (tampering). Indeed, a recent study sponsored by the California Air Resources Board and General Motors Research Laboratories found that approximately 27% of the high emitting in-use vehicles were found to be cases of tampering[12]. We expect that the combination of increasingly reliable emission control systems, increased use of on-board diagnostics, more tamper-resistant systems and the removal of lead from gasoline will make late model vehicles less prone to emission control failures.

Another example of the kind of information that can be derived from this kind of study is shown in Table 4. This table shows the mean and median

Table IV. Manufacturer Comparisons of Emission Levels

	Chevrolet			Ford			Chrysler			Toyota			Nissan		
	Mean	Med.	#	Mean	Med.	#	Mean	Med.	#	Mean	Med.	#	Mean	Med.	#
PRE-1975	65.0	50.8	44	90.6	78.4	40	84.5	85.4	22	27.5	24.8	6	15.5	12.0	13
1975-1979	31.0	11.8	74	34.5	18.7	79	36.7	30.0	48	31.2	31.1	68	14.3	7.6	41
1980	31.3	27.3	28	44.0	45.6	19	48.3	47.0	19	22.0	16.2	16	7.8	2.4	28
1981-1982	8.6	2.9	40	21.2	5.1	30	13.1	5.4	29	10.5	3.2	51	8.6	2.5	48
1983-1986	7.1	1.3	96	10.3	1.6	119	9.7	1.7	79	5.7	1.0	104	8.2	1.8	60
1987-1989	3.0	0.7	57	3.7	0.8	87	3.6	0.7	48	1.9	0.6	67	1.7	0.5	36
TOTALS	21.3	4.2	339	25.1	3.9	374	23.9	3.5	245	12.5	2.9	312	8.7	2.5	226

emission rates measured for various major automobile manufacturers for several model year groupings and the number of each make of vehicle that was measured.

DISCUSSION

The remote sensing technique described here can provide accurate measurements of CO/CO_2, with only minor interferences (see Appendix A) that can be eliminated with instrument modifications. These ratios are, in themselves, useful indications of relative CO emission rates. The ratios can be converted to values of %CO with reasonable accuracy (±1% CO). Conversions of the ratios to emission rates (gpm) requires knowledge of hydrocarbon emission rates and instantaneous fuel economy (see Appendix B). Using careful estimates of these values probably provides reasonably accurate fleet average emission rates when large numbers of vehicle measurements are available. In this study, large sample sizes were used for most vehicle categories; however, it is likely that improved accuracy of the light-truck emission distributions (reported in Table B-V) would result from a larger data base. The variability of emission rates with driving conditions can also cause uncertainty in the interpretation of individual emission measurements. Emission rates also vary with driving conditions and these factors are discussed in Appendix C.

Care must be taken with the interpretation of observed trends in CO emissions as a function of vehicle age. A trend toward decreased CO emissions from newer cars can be expected due to improved emission control technology. However, it is also expected that several factors such as deterioration of emission control systems, malfunctioning, misfueling and tampering can cause average emission rates to increase with vehicle age. A single study of the type described here, is not able to separate these factors. It would be informative to repeat these measurements over a period of several years to identify the effect of aging of late model vehicle emission control systems.

This study is also affected by other factors that cannot be assessed; for example, the effect of site selection, the Denver oxygenated-fuel program, altitude, and the effect of ambient temperature. These measurements are also not representative of other cities due to differences in vehicle fleets. All of these factors should be addressed with further measurements.

CONCLUSIONS

The data acquired during this study has provided important insight into fleet average CO emission rates at a site located in Denver, CO. To the extent that this site is typical of other urban areas within the United States, the results of this study can be useful in identifying cost-effective strategies for reducing urban CO pollution.

We have found that the majority of CO is emitted by a small minority of all vehicles. By examining the highest emitting vehicles, we find that 50% of the CO is emitted by 8.9% of all vehicles. By examining the oldest vehicles, we find that 57% of the CO is emitted by pre-1980 vehicles. In contrast, 1988 and 1989 vehicles contributed a combined total of only 2% of all CO emitted.

For CO control strategies, this data suggests that ambient CO levels can be impacted most by reducing emissions from the highest emitting vehicles rather than further reductions in emissions from new vehicles. Such a strategy obviously requires identifying the high emitters. Since the data suggests that emissions tend to increase with vehicle age, one aspect of an effective strategy might be to increase the frequency and effectiveness of emission testing (with required emission control repairs) of older vehicles. Tampered vehicles or cars which require retests to pass emission tests, should also be required to undergo more frequent tests. Alternatively, any strategy that would result in increasing the costs of operating older cars will increase the rate of obselescence of these cars, hence their replacement with newer, lower emitting vehicles. An effective I/M program, together with fleet turnover, should greatly decrease total vehicle CO emissions.

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REFERENCES

1. National Air Quality and Emissions Trends Report, 1987, EPA-450/4-89-001, March, 1989.

2. MVMA Facts and Figures '89, Motor Vehicle Manufacturer's Association, 7430 Second Ave., Detroit, MI 48202.

3. EPA Press Release, July 27, 1989, U. S. E. P. A., Office of Public Affairs (A-107), Washington, D.C. 20460.

4. MVMA Information Bulletin No. 1B-89-206-FRC.

5. Haskew, H. M. and Gumbleton, J. J., SAE Technical Paper Series, 881682, International Fuels and Lubricants Meeting and Exposition, Portland, OR, October 10-13, 1988.

6. Ingalls, M. N., Smith, L. R. and Kirksey, R. E., Project SCAQS-1 Final Report, 1989, Coordinating Research Council, Inc., 219 Perimeter Center Parkway, Atlanta, GA 30346.

7. Stedman, D. H., Env. Sci.and Tech.,23,147,1989.

8. Bishop, G. A., Starkey, J. R., Ihlenfeldt, A., Williams, W. J., and Stedman, D. H., Anal. Chem., 61,671A, 1989.

9. Bishop, G. A. and Stedman, D. H., SAE Technical Paper Series, 89116, Government/Industry Meeting and Exposition, Washington D. C., May 2-4, 1989.

10. Bishop, G. A., University of Denver, Denver, CO, Private Communication, March 16, 1990.

11. 1989 Ward's Automotive Yearbook Fifty-First Edition, Ward's Communications, Inc., 28 W. Adams, Detroit, MI 48226.

12. Groblicki, P. J., Private Communication, March 20, 1990.

13. 1986 Ward's Automotive Yearbook Forty-Eighth Edition, Wards' Communications, Inc., 28 W. Adams, Detroit, MI 48226.

APPENDIX A

CO/CO_2 MEASUREMENT INTERFERENCES

Three potential problems that might affect the accuracy of the remote measurements of CO/CO_2 ratios are: 1) Interference due to mixing of exhaust plumes from different vehicles 2) Infrared emission from hot exhaust 3) The technique by which transmittance measurements are corrected for scattering by particulate matter.

Residual Plumes The GM and DU measurements each have the potential for inaccurately measuring an exhaust plume when remnants of a previous plume of different concentration remains. This is an important consideration because measurements during the Denver study were frequently made when car separations were less than 2 seconds. For example, during one midmorning hour of measurements, the DU system measured exhaust emissions from 650 vehicles, 236 of which were measured within two seconds of the previous vehicle measurement. This is likely to be typical of the overall study because the traffic pattern was often dictated by one slow lead vehicle.

In the DU instrument, a software routine converts CO/CO_2 ratios to percent CO and CO_2 and plots each measured concentration of CO vs CO_2. Measurements are discarded if the standard deviation of the linear fit to the slope exceeds 20%[8]. Such a test is meant to detect changing CO/CO_2 ratios that would occur due to mixing of two plumes of different concentration ratios.

An attempt was made to answer three important questions concerning the potential for residual plume interferences; 1) does this effect occur 2) if so, how long does the effect persist and 3) does the nonlinearity test employed by the DU instrument prevent measurement errors.

If a residual plume effect occurs, the effect would be expected to be most pronounced when measurements are made with short time separations between vehicles that emit very different concentrations of CO. The DU instrument recorded the hour, minute and second of each vehicle measurement, making it possible to sort measurements not only by CO concentrations measured, but also by time between vehicles. We have written a short software routine that was used to tabulate all DU measurements by several parameters; measured percent CO, seconds since the last vehicle measurement, and percent CO measured for the previous vehicle. This data base was analysed several ways in an attempt to assess the potential impact that the two variables (time since previous vehicle measurement and concentration difference between two sequential vehicle measurements) have on reported CO/CO_2 measurements.

The first step in the analysis involved separating all measurements into two groups; measurements made on vehicles following behind a low CO emitting vehicle (<1%); and measurements made on vehicles following behind a high CO emitting vehicle (>5%). Next, the measurements within each of these groups were sorted according to time since the previous vehicle measurement. The distribution of measured emission levels was then determined for each time interval.

Figure A1 shows the distribution of emissions measured when the previous vehicle's plume contained more than 5% CO. This bargraph shows that measurements made on cars that are following within one second of a high emitting vehicle are, on average, different than measurements of cars that are following 4 or more seconds behind a high emitting vehicle. For example, cars that pass the instrumentation within one second of a high emitting vehicle are measured as clean (0-1% CO) only 47% of the time, whereas, if the cars are separated by four seconds, 67% are measured as clean. Also, when the car separation time is short, a higher percentage of measurements are rejected due to plume nonlinearity.

Figure A1 suggests several important points. First, the increased frequency of measurement rejections that occur with short time separations between sequential vehicles suggests that a residual plume effect does occur. Secondly, the DU nonlinearity test identifies plume nonlinearity, at least for many instances where a 0-1% CO vehicle follows closely behind a >5% CO vehicle. Third, the data suggests that the residual plume effect seems to last, on average, at least one second and possibly as long as 3-4 seconds. Fourth, the time dependence of the residual plume effect suggests that meteorology may play a role in measurement accuracy under certain conditions. For example, on windy days this problem might be minimized. Fifth, and less obvious, is that a sampling bias occurs when the residual plume effect occurs. For example, plume nonlinearity only occurs when sequential plumes are of greatly different concentrations. This means that a clean car (low CO) might not be measured if it follows closely behind a dirty car.

The effect of this sampling bias is shown in Figure A2. The median CO

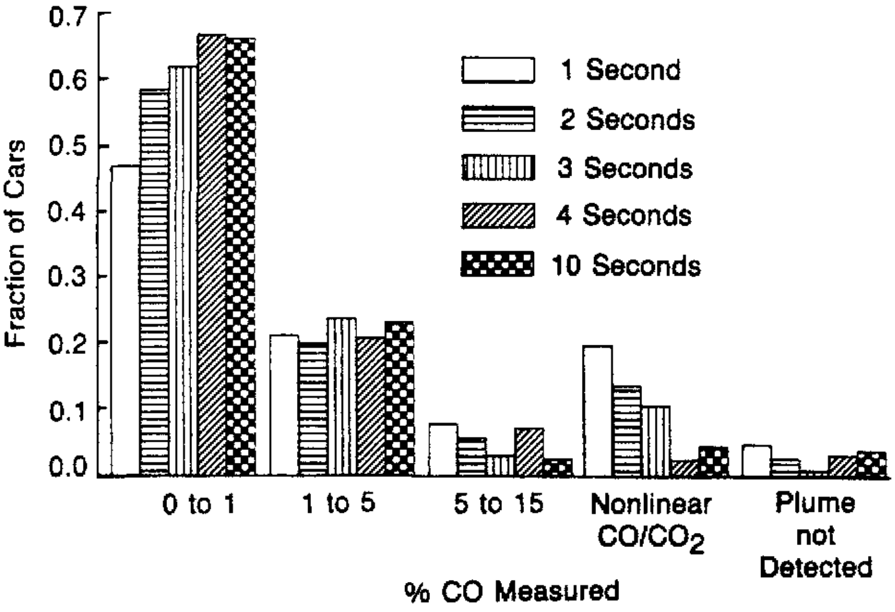

FIGURE A1. This plot shows the distribution of emission levels measured for cars that follow behind cars that emit more than 5% CO.

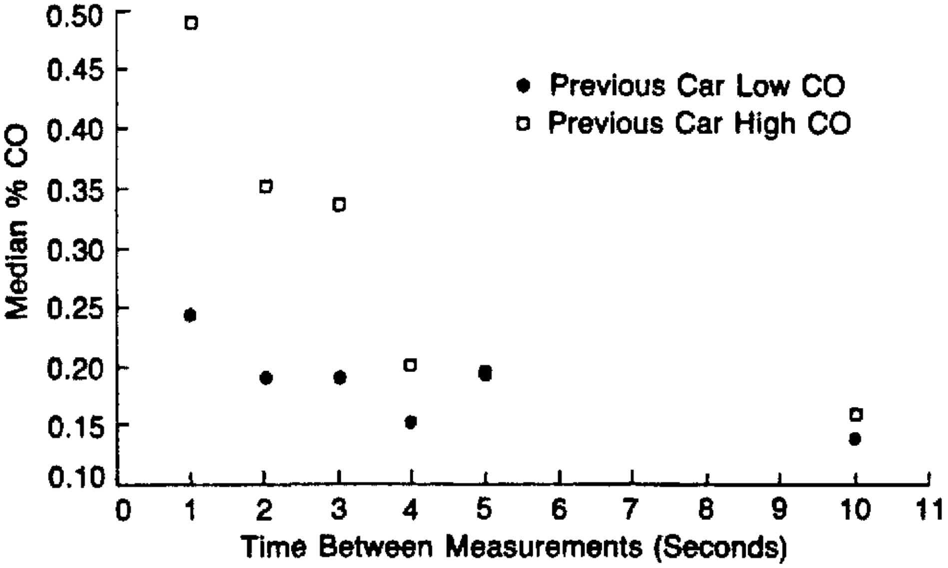

FIGURE A2. This plot shows the median percent CO measured for all cars following behind either 1) high CO emitting vehicles (more than 5% CO) or 2) low CO emitting vehicles (less than 1% CO), as a function of car separation time.

measured in an exhaust plume is higher when a residual plume of >5% CO is present. Again, the residual plume appears to effect the measurements for approximately 3-4 seconds. It is impossible to determine from this data whether this increase in median CO is due only to sampling bias or is partially due to measurement error induced by the presence of a high level of CO.

Infrared Emission from Hot Exhaust The instruments are intended to operate by measuring decreases in infrared signal strengths that would result from infrared absorption by CO and CO_2. However, the potential exists for these decreases to be offset by infrared emission from hot automobile exhaust gas and/or exhaust particulate.

The effect of detection of infrared emission from hot gases or particulate would be slightly different for the GM and DU instruments, primarily because of the differences in the reference detection techniques. However, the effect will be to induce inaccuracies in the measurement of CO and CO_2 by both systems.

The GM system was occasionally operated with no infrared source to determine if infrared emission was detectable. Emission signals were detected in 17 of 220 measurements taken in this manner. Figure A3 shows an example of emission signals measured by the GM system. Due to differences in the electronics of the instrument, emission signals are of positive polarity for the CO_2 signals and negative for the CO signals. For the 17 measurements, signals were always detected in the CO and CO_2 channels, and detected in the reference channel 13 times. The distribution of the signal intensities in the three channels followed no identifiable pattern for these 17 measurements, suggesting that blackbody emission was not the sole source of these signals. The source of the emission signal in the reference channel has not been identified, however the signals are not inconsistent with infrared emission from a mixture of hot CO, CO_2 and particulate.

Of the 17 vehicles that generated detectable infrared emission, 16 were either vans, pickup trucks or heavy duty trucks. The factor most common to these vehicles seems to be the orientation of the tail pipe. Vans and pickup trucks frequently have tail pipes that direct hot exhaust perpendicular to the direction of travel, i.e., toward the instruments used for this study. This interference can be minimized by modifications to the instrumentation.

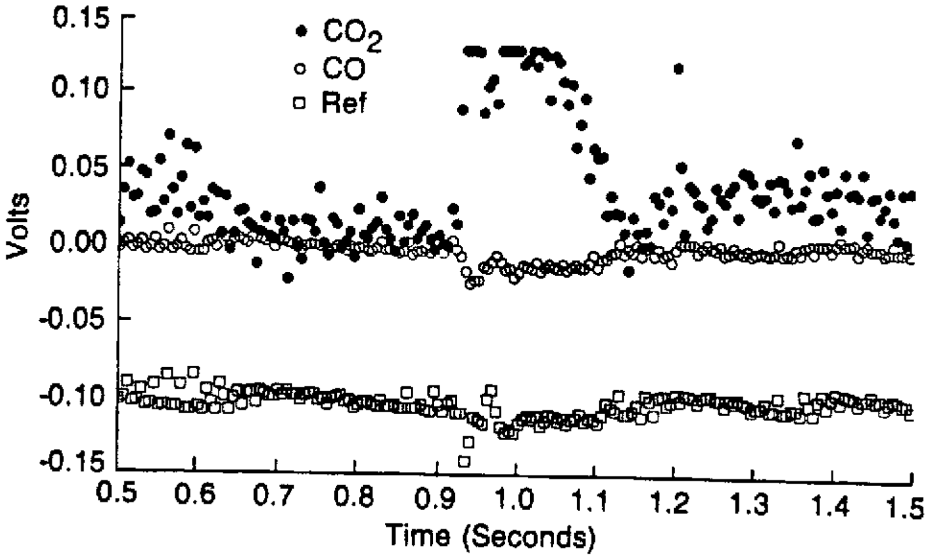

FIGURE A3. Measured detector voltages for the GM instrument when operated without an infrared source. Data collection was initiated prior to the car passing the instrument. These signals represent the detection of infrared emission from hot automobile exhaust. The reference detector voltages are offset by -0.1 volts for clarity of presentation.

Reference Correction As was briefly mentioned in the Experimental section, the DU instrument alternately measures the CO and reference signals. The GM system measures all signals simultaneously. Alternately measuring CO and reference signals, as is done in the DU system, can potentially be a problem. In effect, each CO data point and every other CO_2 data point is being corrected by a reference data point being measured 8.3 milliseconds later. The turbulence behind most vehicles causes significant plume concentration fluctuations on this time scale. Concentrations of road dust or exhaust particulate within the exhaust plume will also fluctuate at approximately this rate, hence affecting the accuracy of such measurements. Simultaneous measurements of CO, CO_2 and reference signals will provide more accurate measures of CO and CO_2 concentrations in cases where source intensity fluctuations occur or when particulate is present.

APPENDIX B

CONVERSION FROM CO/CO_2 RATIOS TO GRAM-PER-MILE EMISSION RATES

As shown in equation (1), the calculation of emission rate requires knowledge of the fuel economy and hydrocarbon emission rates of the vehicles measured. Both of these quantities were estimated for the results shown in Tables B-IV through B-VI and Figures B1-B5.

It would clearly be impossible to know the instantaneous fuel economy of the individual vehicles measured in this study. Several factors obviously affect fuel economy, including vehicle make, model, model year, speed, load and vehicle condition. In this study, care was taken to correctly identify the manufacturer and model year of each vehicle measured. However, most manufacturers produce a number of models with differing fuel economy ratings. Rarely does Colorado state registration data include model information, making it nearly impossible to adjust fuel economy estimates according to model. Speed and load conditions, which also affect the accuracy of the emission rate determinations are also unknown. The fuel economy estimates employed (Tables B-I, B-II, and B-III) provide estimated emission rates; overestimating emission rates for vehicles more fuel efficient than the fleet average and underestimating emission rates for vehicles with lower fuel efficiency. The large sample sizes utilized in this study will tend to average the errors associated with incorrect individual vehicle fuel economy estimates.

Correct determination of CO emission rates also requires knowing the fraction of carbon that is present in the form of CO in the exhaust. In these measurements, only CO and CO_2 are measured. A fraction of the carbon in automobile exhaust is also present in the form of hydrocarbons (HC). Since HC's were not measured during this study, estimates were made. Haskew and Gumbleton report emission rates for CO, HC and NO_x for hundreds of GM cars from model years 1981 through 1986[5]. These were in-use vehicles (obtained from owners and returned after testing). The average CO/HC for these vehicles was 5.73 ± 0.59. This relationship between CO and HC was used in equation (1) to adjust the CO/CO_2 ratio to the desired (but unmeasured) ratio: CO/total C. Haskew and Gumbleton also utilized a set of criteria to identify the outliers, i.e., the highest emitters of the vehicles tested; these vehicles exhibited CO/HC ratios of 6.75 ± 0.76. However, instantaneous CO/HC ratios can vary significantly from these ratios.

Table B-I. Domestic Passenger Car Mile-Per-Gallon Ratings

Model Year	---Manufacturer---	MPG	No. of Vehicles
PRE-1975	GM, FOR, CHR, AMC	12.7[1]	135
1975	GM, FOR, CHR, AMC	14.8	23
1976	GM, FOR, CHR, AMC	16.6	37
1977	GM, FOR, CHR, AMC	17.2	63
1978	GM, FOR, CHR, AMC	18.7	83
1979	GM, FOR, CHR, AMC	19.3	104
1980	GM, FOR, CHR, AMC	22.6	103
1981	GM, FOR, CHR, AMC	24.2	100
1982	GM, FOR, CHR, AMC	25.0	82
1983	GM, FOR, CHR,	24.6	74
1983	AMC	34.2	2
1984	GM, FOR, CHR,	25.6	132
1984	AMC	36.0	0
1985	GM, FOR, CHR,	26.3	139
1985	AMC	33.5	4
1986	GM, FOR, CHR,	26.6	159
1987	GM, FOR, CHR,	27.0	151
1987	AMC	33.7	1
1988	GM, FOR, CHR,	27.3	158
1989	GM, FOR, CHR,	26.9	39
TOTALS			1589

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[1] Estimated

Table B-II. Import Passenger Car Mile-Per-Gallon Ratings

Manufacturer	MPG	1 σ	No. of Vehicles
ACURA	32.82	2.1	19
ALFA-ROMEO	24.83	2.4	5
AMC HORNET	31.12	2.4	2
RANGE ROVER	25.40[1]		2
AUDI	21.68[2]		40
BMW	24.65	2.9	42
CAPRI	31.84	4.9	2
DAIHATSU	31.20[3]		2
FIAT	26.00	2.6	12
HONDA	32.82	2.1	323
HYUNDAI	34.45	1.0	62
ISUZU	34.02	4.0	7
JAGUAR	20.05	1.2	2
LANCIA	26.00	2.6	1
MAZDA	29.72	2.5	89
MERCEDES-BENZ	23.36	2.8	21
MERCURY MERKHUR	20.75[4]		2
MG	25.40	1.2	2
MITSUBISHI	31.49	1.2	20
NISSAN	30.42	2.0	226
OPEL	22.20[5]		1
PEUGOT	25.56	1.8	1
PORSCHE	20.00[6]		9
RENAULT	31.12	2.4	17
SAAB	25.16	1.7	33
SUBARU	31.39	1.6	166
TOYOTA	31.04	3.1	312
TRIUMPH	25.40[7]		1
VOLKSWAGON	30.61	2.2	140
VOLVO	24.78	2.3	91
YUGO	33.75[8]	0.1	2
TOTALS			1654

[1] 1976 import fleet average[2]
[2] City/highway average[11]
[3] 1988 import fleet average[2]
[4] City/highway average[13]
[5] 1974 import fleet average[2]
[6] City/highway average[11]
[7] 1976 import fleet average[2]
[8] 1987-1988 Yugo average[2]

Table B-III. Light-Duty Truck Mile-Per-Gallon Ratings

Model Year	MPG	No. of Domestics	MPG	No. of Imports
PRE-1979[10]	16.1	167	18.8	14
1979	17.9	39	20.9	10
1980	17.5	29	25.0	10
1981	18.6	25	28.3	19
1982	19.2	27	27.0	16
1983	19.6	33	27.1	18
1984	19.3	59	26.7	25
1985	19.9	66	27.4	31
1986	20.1	64	27.3	35
1987	20.4	51	27.5	42
1988	20.7	72	24.4	20
1989	20.4	15	23.8	0
TOTALS		647		240

[10] Estimated

Table B-IV. Distribution of Emissions in GPM for Passenger Cars

Model	--- <10---		--10-20---		--20-30---		--30-40---		--40-50---		--50-60---	
Year	Frac.	#	Frac.	#	Frac.	#	Frac.	#	Frac.	#	Frac.	#
pre-1975	0.219	49	0.121	27	0.098	22	0.098	22	0.067	15	0.094	21
1975	0.275	11	0.150	6	0.150	6	0.125	5	0.075	3	0.000	0
1976	0.431	28	0.062	4	0.062	4	0.108	7	0.077	5	0.031	2
1977	0.532	58	0.092	10	0.101	11	0.092	10	0.037	4	0.037	4
1978	0.355	54	0.171	26	0.125	19	0.092	14	0.033	5	0.072	11
1979	0.430	77	0.128	23	0.089	16	0.061	11	0.101	18	0.050	9
1980	0.490	97	0.116	23	0.086	17	0.081	16	0.071	14	0.045	9
1981	0.661	146	0.063	14	0.041	9	0.077	17	0.063	14	0.023	5
1982	0.744	151	0.103	21	0.089	18	0.030	6	0.000	0	0.005	1
1983	0.722	143	0.126	25	0.035	7	0.030	6	0.025	5	0.030	6
1984	0.781	229	0.090	27	0.027	8	0.020	6	0.034	10	0.020	6
1985	0.840	246	0.061	18	0.034	10	0.020	6	0.010	3	0.007	2
1986	0.872	280	0.060	19	0.034	11	0.025	8	0.003	1	0.003	1
1987	0.913	315	0.055	19	0.014	5	0.003	1	0.009	3	0.003	1
1988	0.952	318	0.030	10	0.009	3	0.000	0	0.005	2	0.000	0
1989	0.941	64	0.059	4	0	0	0.000	0	0.000	0	0.000	0
TOTALS		2266		276		166		135		102		78

Model	---60-70---		--70-80---		--80-90---		--90-100---		-100-150--		-->150--		Tot.	
Year	Frac.	#	Frac.	#	Frac.	#	Frac.	#	Frac.	#	Frac.	#	Frac.	
pre-1975	0.036	8	0.027	6	0.018	4	0.027	6	0.103	23	0.094	21	1	224
1975	0.025	1	0.050	2	0.000	0	0.050	2	0.075	3	0.025	1	1	40
1976	0.046	3	0.062	4	0.031	2	0.031	2	0.062	4	0.000	0	1	65
1977	0.009	1	0.037	4	0.018	2	0.018	2	0.028	3	0.000	0	1	109
1978	0.033	5	0.026	4	0.033	5	0.039	6	0.020	3	0.000	0	1	152
1979	0.039	7	0.006	1	0.045	8	0.017	3	0.034	6	0.000	0	1	179
1980	0.035	7	0.030	6	0.015	3	0.005	1	0.025	5	0.000	0	1	198
1981	0.027	6	0.014	3	0.023	5	0.009	2	0.000	0	0.000	0	1	221
1982	0.005	1	0.020	4	0.000	0	0.005	1	0.000	0	0.000	0	1	203
1983	0.020	4	0.005	1	0.000	0	0.000	0	0.000	1	0.000	0	1	198
1984	0.014	4	0.007	2	0.000	0	0.003	1	0.000	0	0.000	0	1	293
1985	0.020	6	0.000	0	0.003	1	0.003	1	0.000	0	0.000	0	1	293
1986	0.000	0	0.000	0	0.003	1	0.000	0	0.000	0	0.000	0	1	321
1987	0.003	1	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	1	345
1988	0.003	1	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	1	334
1989	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	1	68
TOTALS		55		37		31		27		48		22		3243

Table B-V. Distribution of Emissions in GPM for Light-Duty Trucks

Model	--- <10---		--10-20---		--20-30---		--30-40---		--40-50---		---50-60---	
Year	Frac.	#	Frac.	#	Frac.	#	Frac.	#	Frac.	#	Frac.	#
PRE-1975	0.200	16	0.088	7	0.088	7	0.088	7	0.063	5	0.075	6
1975	0.182	2	0.000	0	0.091	1	0.000	0	0.091	1	0.182	2
1976	0.077	1	0.000	0	0.154	2	0.231	3	0.000	0	0.231	3
1977	0.212	7	0.242	8	0.061	2	0.061	2	0.000	0	0.061	2
1978	0.273	12	0.205	9	0.114	5	0.023	1	0.091	4	0.023	1
1979	0.286	14	0.122	6	0.061	3	0.163	8	0.102	5	0.041	2
1980	0.205	8	0.051	2	0.077	3	0.128	5	0.103	4	0.077	3
1981	0.295	13	0.159	7	0.136	6	0.068	3	0.023	1	0.205	9
1982	0.558	24	0.116	5	0.023	1	0.047	2	0.070	3	0.000	0
1983	0.392	20	0.216	11	0.039	2	0.137	7	0.059	3	0.039	2
1984	0.643	54	0.119	10	0.083	7	0.024	2	0.012	1	0.036	3
1985	0.711	69	0.124	12	0.041	4	0.062	6	0.031	3	0.021	2
1986	0.848	84	0.081	8	0.010	1	0.020	2	0.030	3	0.010	1
1987	0.860	80	0.054	5	0.011	1	0.022	2	0.022	2	0.000	0
1988	0.924	85	0.033	3	0.011	1	0.022	2	0.011	1	0.000	0
1989	0.800	12	0.000	0	0.000	0	0.000	0	0.067	1	0.000	0
TOTALS		501		93		46		52		37		36

Model	---60-70---		--70-80---		--80-90---		--90-100---		-100-150--		-->150--		Tot.	
Year	Frac.	#	Frac.	#	Frac.	#	Frac.	#	Frac.	#	Frac.	#	Frac.	
PRE-1975	0.088	7	0.063	5	0.038	3	0.050	4	0.150	12	0.013	1	1	80
1975	0.000	0	0.182	2	0.091	1	0.000	0	0.182	2	0.000	0	1	11
1976	0.077	1	0.154	2	0.000	0	0.000	0	0.000	0	0.077	1	1	13
1977	0.091	3	0.030	1	0.091	3	0.000	0	0.121	4	0.030	1	1	33
1978	0.091	4	0.045	2	0.045	2	0.000	0	0.091	4	0.000	0	1	44
1979	0.020	1	0.061	3	0.082	4	0.041	2	0.020	1	0.000	0	1	49
1980	0.077	3	0.077	3	0.103	4	0.026	1	0.077	3	0.000	0	1	39
1981	0.045	2	0.068	3	0.000	0	0.000	0	0.000	0	0.000	0	1	44
1982	0.047	2	0.093	4	0.023	1	0.023	1	0.000	0	0.000	0	1	43
1983	0.020	1	0.000	0	0.059	3	0.000	0	0.039	2	0.000	0	1	51
1984	0.048	4	0.012	1	0.000	0	0.000	0	0.024	2	0.000	0	1	84
1985	0.000	0	0.000	0	0.000	0	0.000	0	0.010	1	0.000	0	1	97
1986	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	1	99
1987	0.011	1	0.011	1	0.000	0	0.000	0	0.011	1	0.000	0	1	93
1988	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	1	92
1989	0.000	0	0.067	1	0.067	1	0.000	0	0.000	0	0.000	0	1	15
TOTALS		29		28		22		8		32		3		887

Table B-VI. Distribution of Emissions in GPM for All Light-Duty Vehicles

Model	--- <10---		--10-20---		--20-30---		--30-40---		--40-50-----		-50-60---	
Year	Frac.	#	Frac.	#	Frac.	#	Frac.	#	Frac.	#	Frac.	#
PRE-1975	0.214	65	0.112	34	0.095	29	0.095	29	0.0658	20	0.089	27
1975	0.255	13	0.118	6	0.137	7	0.098	5	0.078	4	0.039	2
1976	0.372	29	0.051	4	0.077	6	0.128	10	0.064	5	0.064	5
1977	0.458	65	0.127	18	0.092	13	0.085	12	0.028	4	0.042	6
1978	0.337	66	0.179	35	0.122	24	0.077	15	0.046	9	0.061	12
1979	0.399	91	0.127	29	0.083	19	0.083	19	0.101	23	0.048	11
1980	0.443	105	0.105	25	0.084	20	0.089	21	0.076	18	0.051	12
1981	0.600	159	0.079	21	0.057	15	0.075	20	0.057	15	0.053	14
1982	0.711	175	0.106	26	0.077	19	0.033	8	0.012	3	0.004	1
1983	0.655	163	0.145	36	0.036	9	0.052	13	0.032	8	0.032	8
1984	0.751	283	0.098	37	0.040	15	0.021	8	0.029	11	0.024	9
1985	0.808	315	0.077	30	0.036	14	0.031	12	0.015	6	0.010	4
1986	0.867	364	0.064	27	0.029	12	0.024	10	0.010	4	0.005	2
1987	0.902	395	0.055	24	0.014	6	0.007	3	0.011	5	0.002	1
1988	0.946	403	0.031	13	0.009	4	0.005	2	0.007	3	0.000	0
1989	0.916	76	0.048	4	0.000	0	0.000	0	0.012	1	0.000	0
TOTALS		2767		369		212		187		139		114

Model	---60-70---		--70-80---		--80-90---		--90-100---		-100-150--		-->150--		Tot.	
Year	Frac.	#	Frac.	#	Frac.	#	Frac.	#	Frac.	#	Frac.	#	Frac.	
PRE-1975	0.049	15	0.036	11	0.023	7	0.033	10	0.115	35	0.072	22	1	304
1975	0.020	1	0.078	4	0.020	1	0.039	2	0.098	5	0.020	1	1	51
1976	0.051	4	0.077	6	0.026	2	0.026	2	0.051	4	0.013	1	1	78
1977	0.028	4	0.035	5	0.035	5	0.014	2	0.049	7	0.007	1	1	142
1978	0.046	9	0.031	6	0.036	7	0.031	6	0.036	7	0.000	0	1	196
1979	0.035	8	0.018	4	0.053	12	0.022	5	0.031	7	0.000	0	1	228
1980	0.042	10	0.038	9	0.030	7	0.008	2	0.034	8	0.000	0	1	237
1981	0.0302	8	0.027	6	0.019	5	0.008	2	0.000	0	0.000	0	1	265
1982	0.012	3	0.033	8	0.004	1	0.008	2	0.000	0	0.000	0	1	246
1983	0.020	5	0.004	1	0.012	3	0.000	0	0.012	3	0.000	0	1	249
1984	0.021	8	0.008	3	0.000	0	0.003	1	0.005	2	0.000	0	1	377
1985	0.015	6	0.000	0	0.003	1	0.003	1	0.003	1	0.000	0	1	390
1986	0.000	0	0.000	0	0.002	1	0.000	0	0.000	0	0.000	0	1	420
1987	0.005	2	0.002	1	0.000	0	0.000	0	0.002	1	0.000	0	1	438
1988	0.002	1	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	1	426
1989	0.000	0	0.012	1	0.012	1	0.000	0	0.000	0	0.000	0	1	83
TOTALS		84		65		53		35		80		25		4130

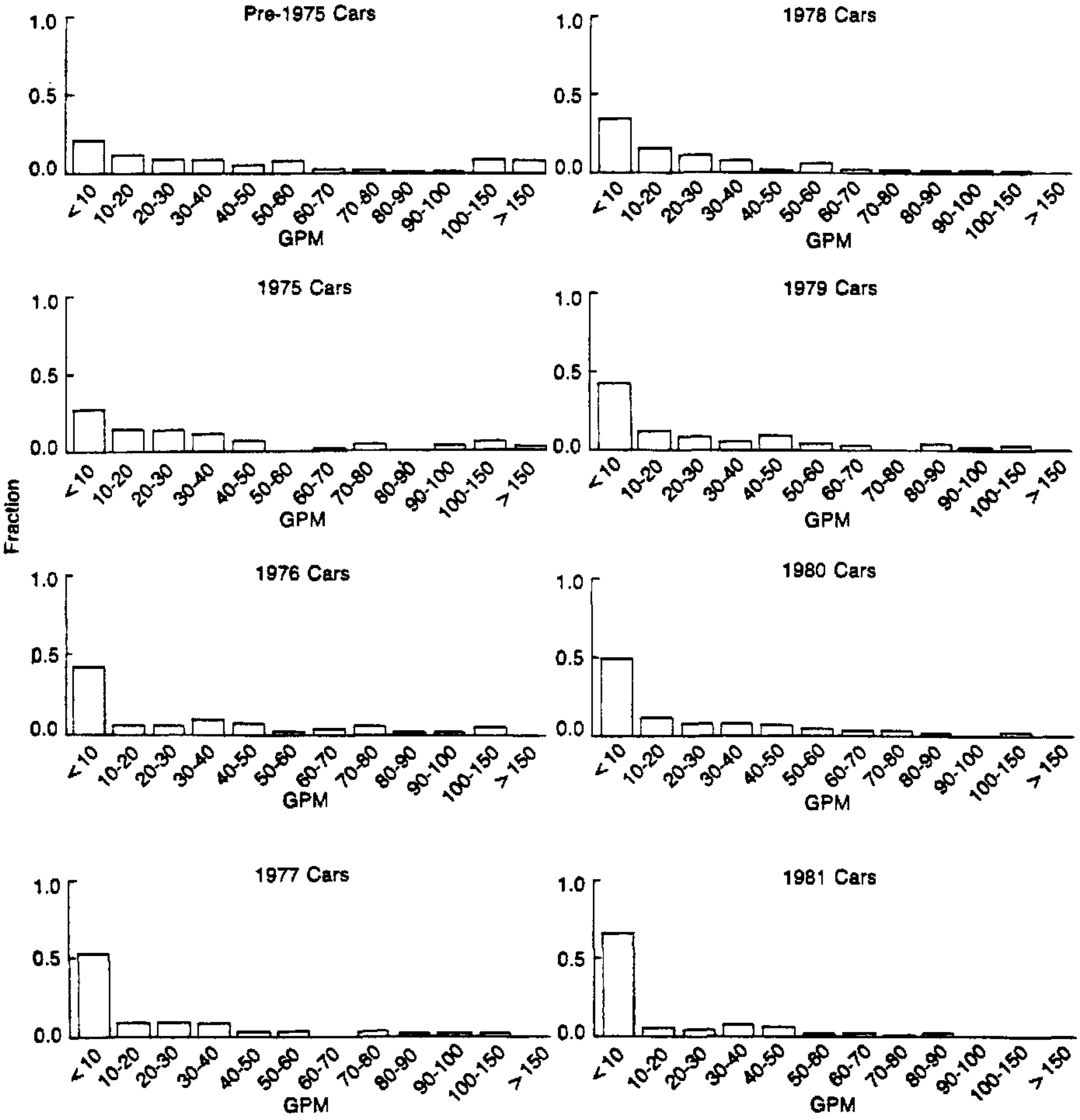


FIGURE B1. Emission rates of passenger cars within each model year.

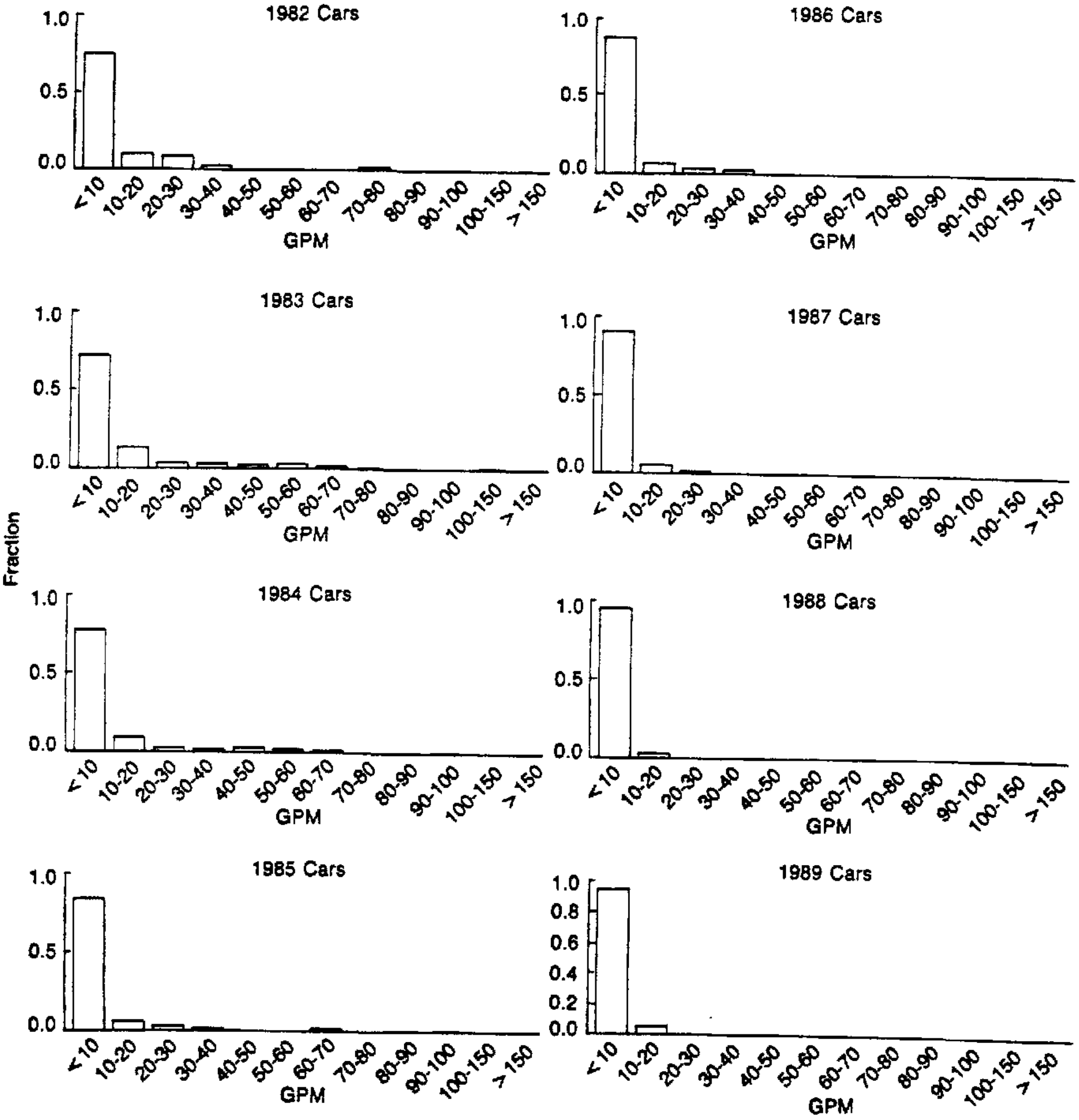


FIGURE B2. Emission rates of passenger cars within each model year.

PASSENGER CARS

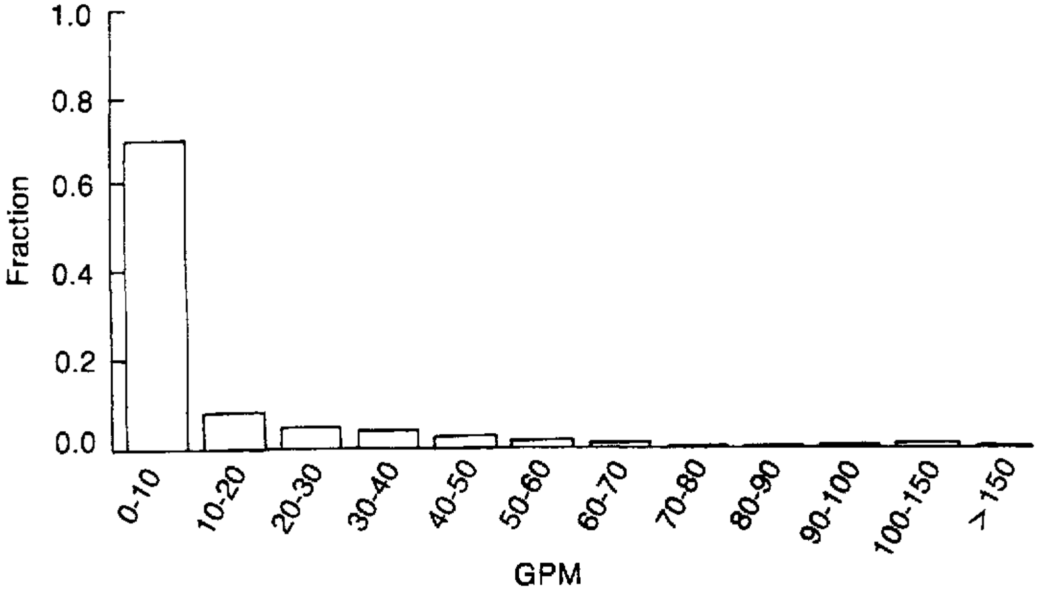
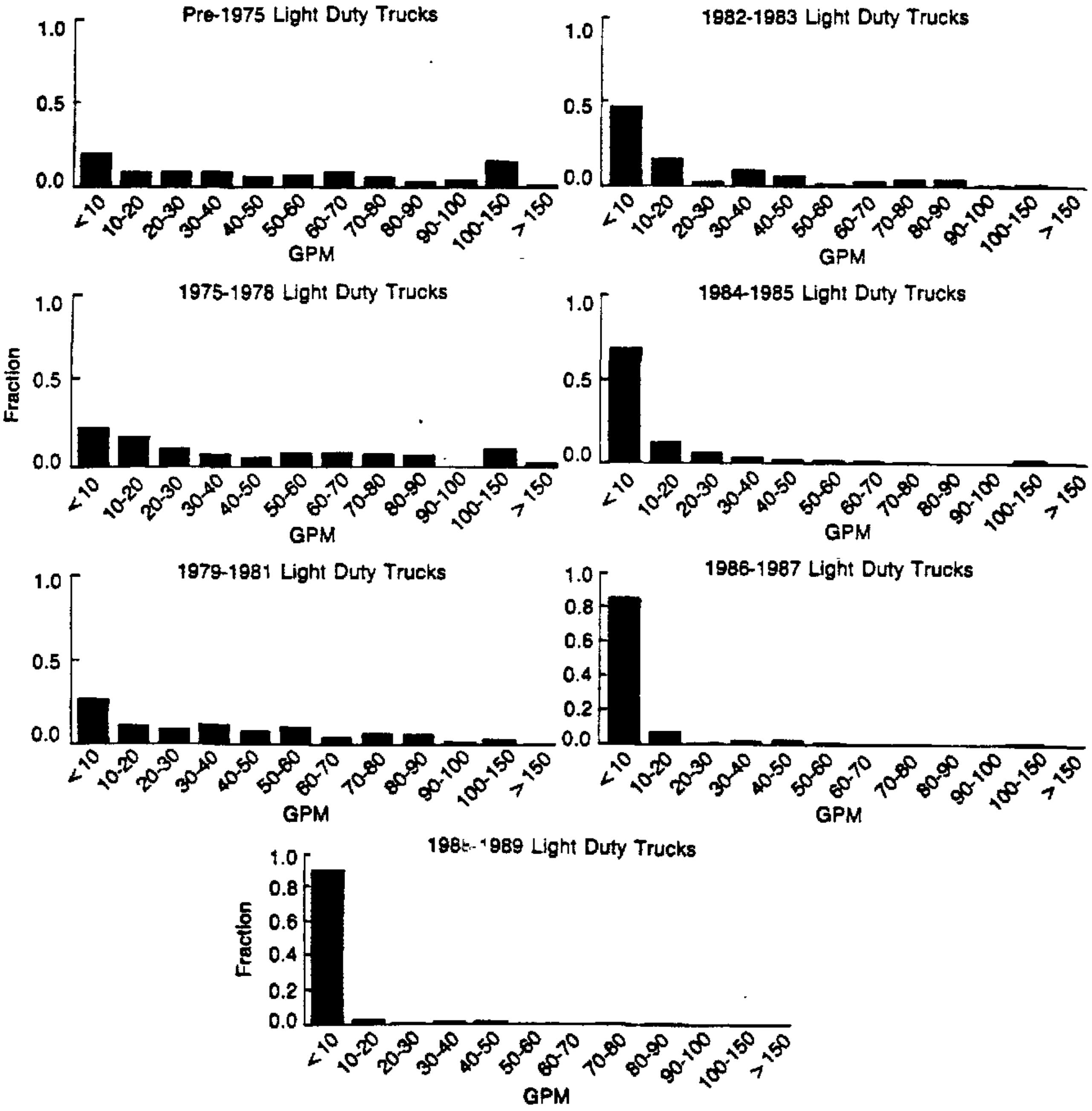


FIGURE B3. This figure shows the distribution of emission levels for all passenger cars measured.



Pre-1975 Light Duty Trucks

1982-1983 Light Duty Trucks

1975-1978 Light Duty Trucks

1984-1985 Light Duty Trucks

1979-1981 Light Duty Trucks

1986-1987 Light Duty Trucks

1988-1989 Light Duty Trucks

FIGURE B4. Emission rates of light duty trucks within each model year.

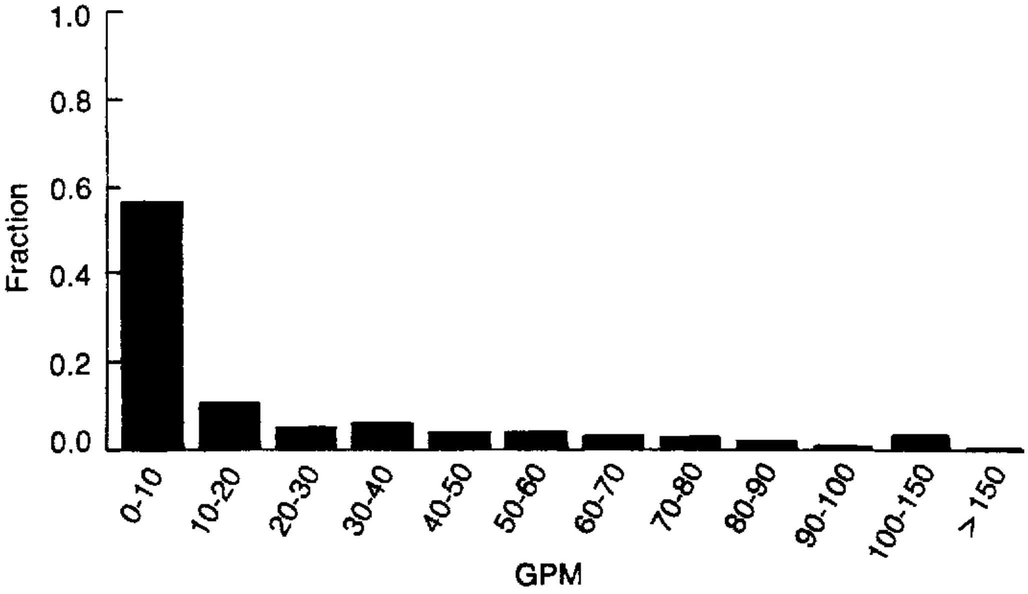


Figure B5. This figure shows the distribution of emission levels for all light duty trucks measured.

APPENDIX C

A potential problem with the interpretation of "snapshot" measurements of CO emissions results from the variability of emission rates with driving conditions. Remeasurement of the same car under a variety of driving conditions should yield a range of measured emission rates. Furthermore, the relationship between driving conditions and emission rates will depend upon the type of vehicle being measured. For example, sudden throttle decreases will cause carbureted vehicles to very briefly shift toward rich air/fuel ratios, hence higher CO emissions. Alternatively, vehicles with computer controlled fuel-injected engines are known to occasionally operate in very brief power enrichment or catalyst protection modes during periods of heavy load or acceleration. These short duration, rich operating modes cause increases in CO emissions. The frequency of these rich excursions will vary with driver, driving conditions and type of vehicle. For this study, a site was chosen (slight uphill grade on a circular freeway off-ramp) where vehicles would likely be operated with slight acceleration. However, the variability between drivers and the variability between different times for the same driver obviously cannot be eliminated. An attempt was made to assess the effect of these variables by examining repeat measurements of the same vehicle. In this study, 172 vehicles were measured at least twice. Of these 172 vehicles, 27 emitted CO in amounts that varied by more than the accuracy of the instrumentation (±1% CO). These factors suggest that caution must be used before using the measurements reported here to extrapolate to overall emissions. Our measurements reflect the emission rates during the average driving conditions at our sites. Using a large number of measurements and several measurement sites would likely provide adequate statistics to determine the average contribution from all driving modes.

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