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On-Road Hydrocarbon Remote Sensing in the Denver Area

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The University of Denver's remote sensor for on-road motor vehicle carbon monoxide (CO) and hydrocarbon (HC) emissions was used in August and October, 1991, at two different locations in the Denver area. The results of analysis for HC emissions show a similar skewed distribution for the two data sets, although the average HC emissions are very different for the two data sets because different driving modes (no-load/load) existed at the locations where the data sets were collected. There was no significant difference between HC emissions from those vehicles from counties in Colorado with and without an annual emission testing program. The fraction of high emission polluters increases with vehicle age. The evidence suggests that proper maintenance and elimination of tampering are very important even for those new vehicles which are equipped with the latest emission control technology.

Introduction

Automobile emissions originate from fuel rich-burning, misfiring, fuel evaporation, engine oil combustion, and other sources (*1*). Automobiles with an inadequate or nonfunctional emission control system can produce high emission rates for carbon monoxide (CO), hydrocarbon (HC), oxides of nitrogen (NO_x), and other toxic air pollutants. These emissions play important roles in all urban pollution inventories (*2*). In many locations, photochemical transformation of oxides of nitrogen and hydrocarbons give rise to violations of the ozone standard (*3*). Carbon monoxide standards are violated as a result of direct emission of the gas under conditions of persistent meteorological stagnation.

Recent legislation has been enacted by the federal government to require further reduction of automobile emissions to improve air quality (*4, 5*). Approaches to reducing vehicle emissions include lower new vehicle emission standards, inspection and maintenance (I/M) programs, use of oxygenated fuels (*6*), and use of improved catalysts and emission control systems. Numerous analytical techniques have been developed over the past 20 years to characterize vehicle emissions (*7*).

With initial support from the Colorado Office of Energy Conservation, the University of Denver developed a remote monitoring system for automobile exhaust emissions. The basic instrument measures the carbon monoxide to carbon dioxide ratio (CO/CO_2) and the hydrocarbon to carbon dioxide ratio (HC/CO_2) in the exhaust of any on-road vehicle passing through an infrared light beam directed across a single lane of roadway. All data are fed to a computer for analysis. Significant fuel economy improvements result if rich-burning (high CO emissions) or misfiring (high HC emissions) vehicles are tuned to a more stoichiometric and more efficient air/fuel (A/F) ratio. Therefore, the remote sensing system is named Fuel Efficiency Automobile Test (FEAT). The details of the instrument system are described elsewhere (*8, 9*). The instrument compares the air from before the vehicle passage to that after the beam is blocked to eliminate the effects of background pollutants. Error-checking routines in the FEAT computer eliminate invalid data caused by an inadequate amount of exhaust, pedestrians, bicyclists, etc. Calibration, on site, is performed at least twice daily with a cylinder containing known, certified CO, propane, and CO_2 concentration ratios.

Because the 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 in the exhaust. Using the fundamentals of combustion chemistry (*1*), many of the parameters of the vehicle emission system can be accurately determined from these ratios, including the instantaneous air/fuel ratio, grams of CO or HC emitted per gallon of gasoline, and the percentage of CO or HC which would be measured by a tailpipe probe (*8*). All of the percentages reported here are mole percent on a dry basis assuming a fuel carbon to hydrogen ratio of 2. The FEAT remote sensor is accompanied by a video system when license plate information is required. The video camera is coupled directly into the data analysis computer which writes the date, time, and calculated exhaust CO, HC, and CO_2 percentage concentrations on the video image. This information is stored on videotapes or digital storage media.

The mass emissions in grams of CO per gallon of gasoline burned can be derived from

$$\text{g of CO/gal} = 5500 \times \%\text{CO}/(\%\text{CO} + 3 \times \%\text{HC} + \%\text{CO}_2)$$

The mass emissions in grams of HC per gallon of gasoline burned can be derived from

$$\text{g of HC/gal} = 8644 \times \%\text{HC}/(\%\text{CO} + 3 \times \%\text{HC} + \%\text{CO}_2)$$

For the purpose of obtaining emissions inventories, it is likely that accurate data on gallons of gasoline sold are more easily obtainable than accurate vehicle miles traveled data. However, if emissions in g/mi are required then g/gal must be converted to g/mi by means of average gas mileage data.

The University of Denver's remote sensor (FEAT) for on-road CO and HC emissions has been used to measure the emissions of more than 600 000 vehicles in many locations over the world. It has been shown that the on-road CO readings are correct within ±5% and the HC readings are correct within ±15% by means of double-blind comparisons with vehicles of known emissions (*10*).

The purpose of this paper is to identify the statistical distributions and characteristics of the on-road HC emissions by presenting the on-road emissions measurements made by means of remote sensing in the Denver area in August and October 1991. The comparisons of the results from these two data sets and between I/M and non-I/M vehicles are also presented to provide information

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potentially useful for exploring which factors affected on-road HC emissions.

Experimental Section

In August 1991, four days of measurements were carried out at the intersection ramp between westbound 6th Avenue and westbound I-70 west of Denver. This site was chosen because it was expected to have no vehicles in a cold-start enrichment mode and a significant percentage of both I/M and non-I/M vehicles. Also, it was expected that there would be minimal influence from acceleration because the site was on a slight downhill gradient. A second set of data was collected during eight days of morning measurements at the tightly curved uphill 4% grade intersection ramp between southbound I-25 and southbound Speer Boulevard close to downtown Denver in October 1991. In this case, the vehicles were traveling uphill under load but, in view of the heavy traffic and tight curve, were not strongly accelerating. In these two studies, tailpipe hydrocarbon and carbon monoxide exhaust concentration ratios of passing vehicles were measured by using the on-road remote sensor. The license plates of passing vehicles were recorded on video tapes which were read for license plate identification. The plates which appeared to be in-state and readable were forwarded to the Department of Motor Vehicles of the state of Colorado to determine make and model year information. In view of the large data set, we chose only to analyze data for which all parameters were valid. Complete records, with valid CO and HC data and make and model year information, were obtained for 11 170 vehicles at 6th Avenue and I-70 and for 8482 vehicles at I-25 and Speer Boulevard. Analyses of the HC emissions and comparison of the two data sets are presented in this paper.

HC data are measured by NDIR absorption, essentially identical to the process used in periodic motor vehicle inspection programs. IR absorption at 3.4 μm differs for different molecules. Hexane per molecule has a measured absorption almost twice as much as propane when using the FEAT instrument. Readings of HC by NDIR are not directly comparable to readings by FID or GC-FID, and neither process gives readings directly comparable to either photochemical reactivity or potential toxicity. Calibration and reporting are as percent propane. The more commonly used "hexane equivalent" can be approximated by division of the propane percentage values by a conversion factor of 2.0.

Results and Discussion

I. Overall Results. Figure 1 shows the distribution of HC emissions (clear bars) by % HC category from the first data set of 11 170 vehicles measured in the Denver area in August 1991. The black bars show the percentage of the HC emissions from each category. The mean HC emission is 0.18 % HC or 88.6 g of HC/gal of gasoline, while the median is 0.12. More than 70% of the 11 170 vehicles emit less than 0.20 % HC. The skewed nature of the distribution is such that more than half the emissions come from only 17.9% of the vehicles with emissions greater than 0.27 % HC or 129.3 g of HC/gal of gasoline. Vehicles comprising the fraction of the fleet which caused over half the total HC emissions are referred to as "HC gross polluters". Figure 2 shows the distribution of HC emissions (clear bars) by % HC category from the second

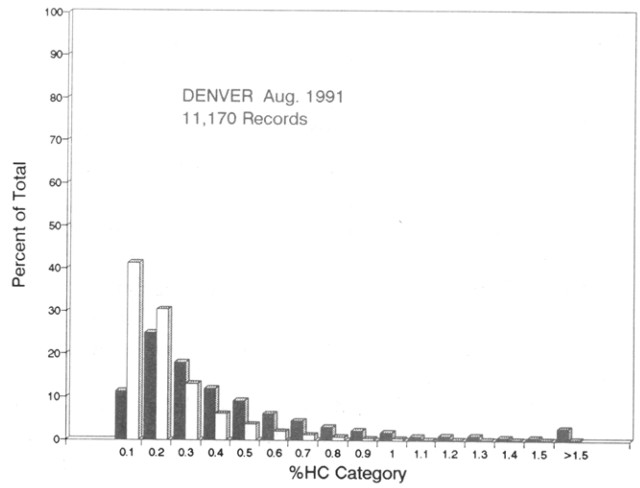

Figure 1. Normalized histogram for the 6th/I70 data showing as black bars the percentage of total emissions. Clear bars show the percentage of the fleet of vehicles with emissions within the stated % HC category.

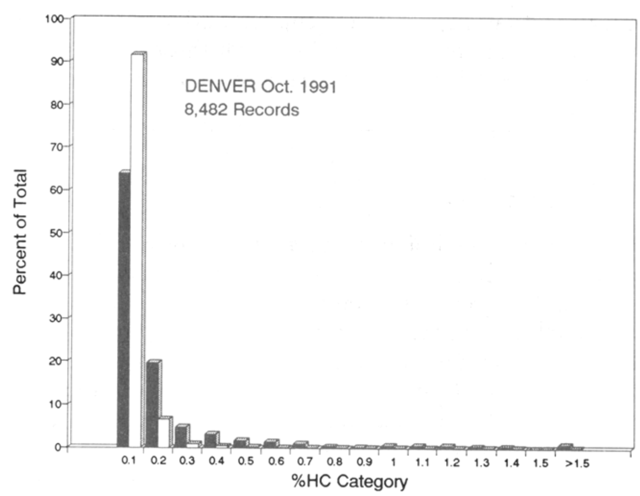

Figure 2. Normalized histogram for the Speer/I25 data showing as black bars the percentage of total emissions. Clear bars show the percentage of the fleet of vehicles with emissions within the stated % HC category.

data set of 8482 vehicles measured in the Denver area in October 1991. Again, the black bars show the percentage of the HC emissions from each category. The mean % HC is 0.04 or 22.8 g of HC/gal of gasoline, while the median is 0.03 % HC. More than 90% of the 8482 vehicles emit less than 0.10 % HC. One-half of the total emissions was generated by 1332 vehicles (which is 15.7% of the total 8482). The cutoff point for HC gross polluters in this case is 0.07 % HC or 34.8 g of HC/gal of gasoline, which is significantly lower than 0.27 % HC for the first data set. The skewed nature of the distribution of the 1991 Denver HC data shown in Figures 1 and 2 is similar to that from Chicago in 1990 (*11*). This similarity illustrates that most vehicles are very low emitters, even though the altitude (5000 ft.) in Denver and the I/M programs are different from Chicago. The I/M program in Denver was annual and decentralized. The I/M program in Illinois was annual and centralized.

For Figure 3, the measurements of each data set were sorted by HC level from the lowest to the highest and then divided into 10 equal sized groups (deciles). The clear bars represent the Speer/I25 data, while the black bars present the 6th/I70 data. Each bar corresponds to the average % HC emissions of one-tenth (a decile) of the total

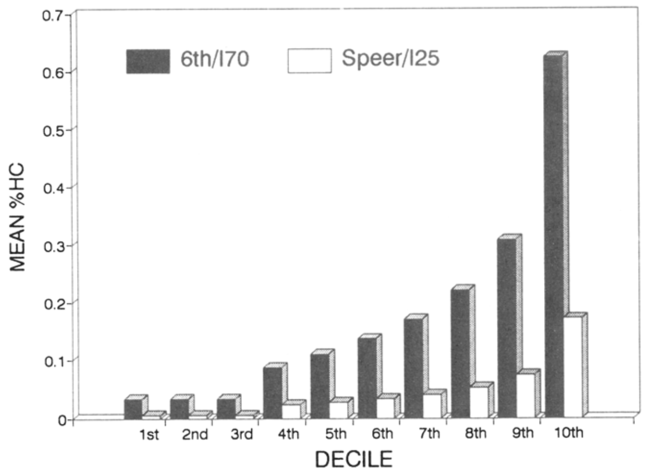

Figure 3. Mean %HC emissions organized into deciles. The cleanest three deciles are given the average of all three since the differences are negligible.

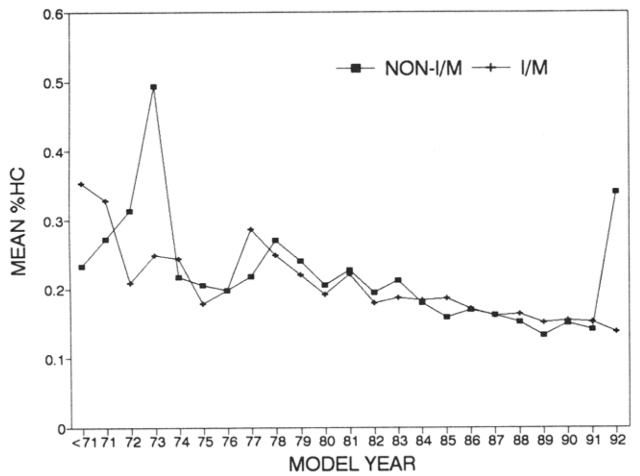

Figure 4. Mean %HC emissions in each model year for the I/M and non-I/M vehicles.

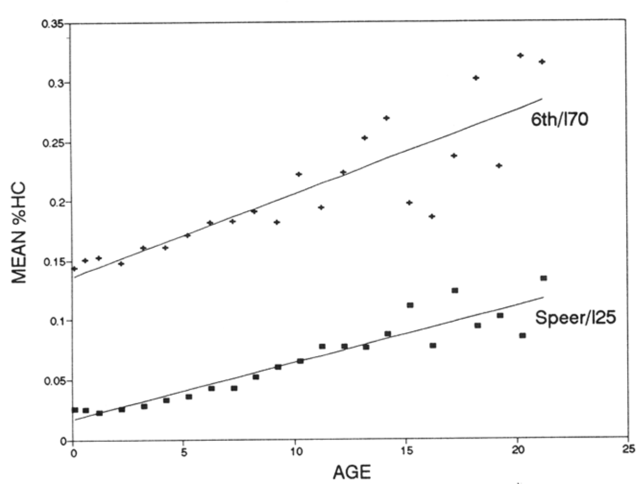

Figure 5. Average HC emissions as a function of vehicle age.

vehicles. Note that the cleanest three bars have been averaged together. This has been done because the tiny distinctions which would arise from one to the next are not significant. Figure 3 shows that half of the 11 170 vehicles for the 6th/I70 data set emit less than 0.10 %HC. In contrast, the dirtiest 10% of vehicles emit as high as 0.62 %HC. The Speer/I25 data show very similar behavior for the HC emission distribution, though each bar for each decile is significantly lower than the corresponding decile for the 6th/I70 data. A total of 60% of the 8482 vehicles emit less than 0.03 %HC, while the dirtiest 10% of the vehicles emit an average of 0.17 %HC. Comparison of HC emissions of these two data sets illustrates that the emission level of HC highly depends on the driving mode as will be discussed later, but the skewed nature of the distribution remains similar.

As illustrated by Figures 1–3, motor vehicle HC emissions are not Gaussian (normal) distributed. They turn out empirically to be distributed according to a γ distribution. The overall averages of γ distributions are controlled by the tails, and the tails contain the vehicles which we call the gross polluters. Therefore, outliers can not be estimated or eliminated based on classical (normal) statistics (i.e., ±3 SD). Robust analysis of emissions data requires large population N values since the HC emissions picture is dominated by only a small number of high emitters. This is same result as obtained for on-road CO emission distributions (*12*).

II. Comparison of I/M Vehicles with Non-I/M Vehicles. According to the vehicle registration information supplied by the Department of Motor Vehicles of Colorado State, among the 11 170 vehicles for the 6th/I70 data set, 2043 vehicles were registered in areas with no formal I/M requirements; 9313 vehicles were registered in areas with a formal I/M requirement. The data were analyzed to determine if there was a significant difference between HC emissions among the two sample sets. The mean of total %HC emissions for all vehicles in each sample set was calculated. The average %HC emissions was 0.175 for the I/M group and 0.176 for the non-I/M group.

Figure 4 presents a plot of the mean %HC emissions against model year for the I/M and non-I/M vehicles. Two peaks in the 1992 and 1973 model years appear for non-I/M vehicles. However, it should be pointed out that these peaks were caused by a few gross polluters in a small sample size.

A hypothesis test was done to determine the significance of the mean difference between I/M and non-I/M vehicles based on the paired data presented on Figure 4. A single derived variable D_i was defined as the difference between the paired values on means of non-I/M and I/M vehicles in each model year. It was found that the mean difference (D) was 0.0143. The standard deviation of the difference (S_D) was found to be 0.0781. At a significance level of 0.05, we accept the hypothesis that the mean difference is zero, since the obtained $t = 0.879$ is inside the required value of $t_{0.05} = \pm 1.717$ forming the borders of the acceptance areas for $n = 23$.

There was no statistically significant difference between the I/M and non-I/M group for %HC emissions. This result is different from the on-road CO emissions. The analysis of CO emission levels in I/M and non-I/M vehicles, already published, illustrated that the non-I/M group generally had significantly 13% higher CO emissions and a higher percentage of CO gross polluters than the I/M group (*13*). It appears that the I/M program is reducing on-road CO emissions. However, there is no evidence in the data to support the effectiveness of the current Colorado I/M program in reducing on-road HC emissions.

III. %HC Emissions vs Age. The remote sensing on-road HC emissions data were analyzed with regard to vehicle age. The average HC emissions vs vehicle age are plotted in Figure 5. A regression line of slope 0.0069 %HC per year and an intercept at 0.136 for the 6th/I70 data has

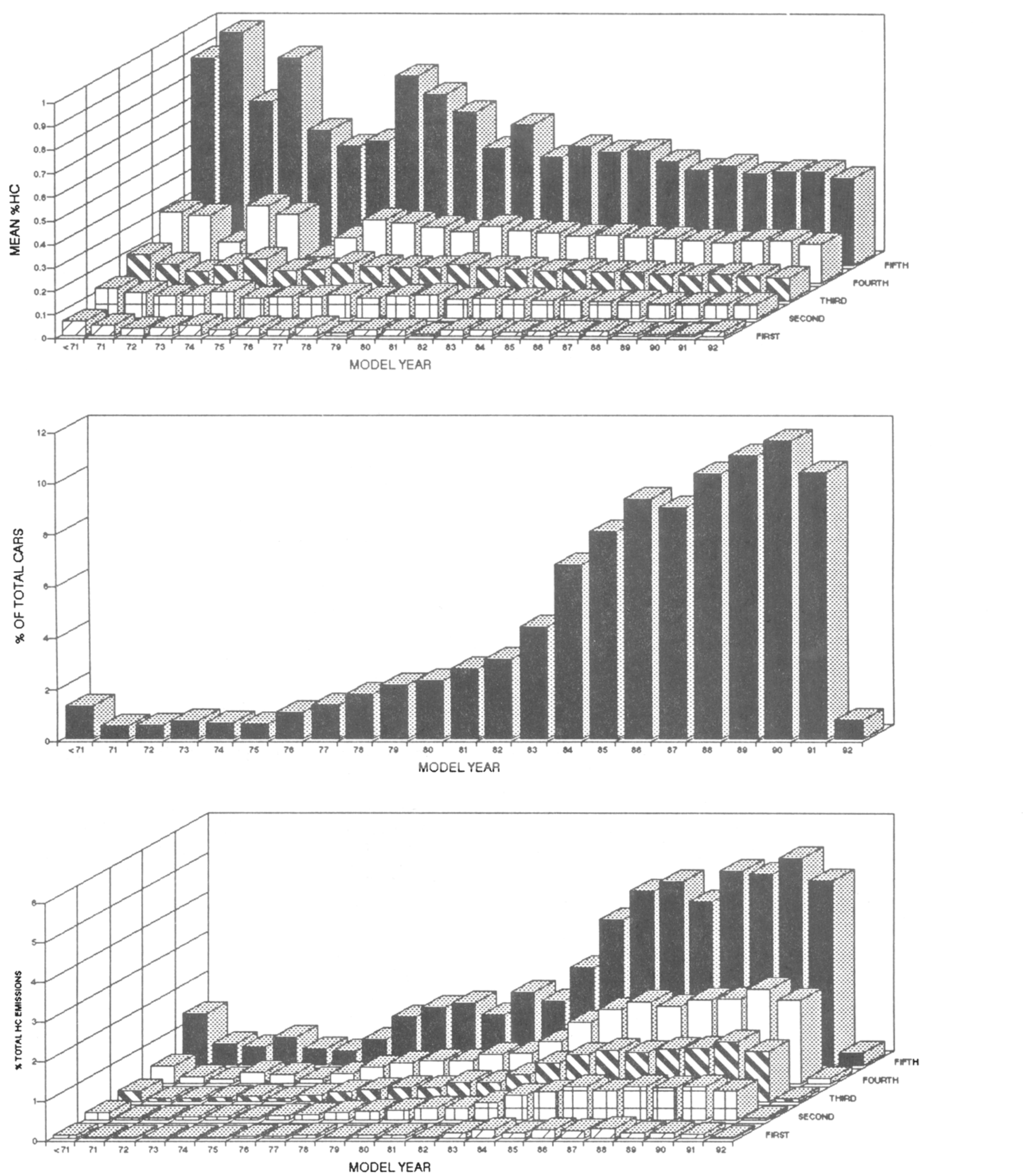

Figure 6. 6th/I70 data presented as (a, top) emission factors by model year divided into quintiles, (b, middle) fleet model year distribution, and (c, bottom) percentage of the total HC emissions for each quintile of each model year. Panel c is the product of graphs a and b.

an R^2 of 0.75. A regression line of slope 0.0047 %HC per year and an intercept at 0.017 for the Speer/I25 data has an R^2 of 0.89. Here, R is the correlation coefficient, which is a measure of the degree with which the vehicle age and mean %HC correlated. When R equals 0, there is no correlation, when R equals 1, there is perfect correlation. From the high R values in both the cases, mean %HC emission is highly correlated with vehicle age for both driving modes, although driving mode also strongly affects the mean HC emissions. Note that the remote sensing data and the video license plate data are independent from one another, i.e., if a statistically significant year-to-year smooth variation in emissions is observed that can only arise if the average data are in fact more precise than the observed year-to-year variation. The wider swings of the points around the line for vehicles older than 12 years arise because of the smaller numbers of vehicles in each of these categories.

The fleet-averaged HC emissions model derived from these data are as follows:

$$\%\mathrm{HC} = 0.0069 \times \mathrm{age} + 0.136(\mathrm{6th/I70\ data})$$

$$\%\mathrm{HC} = 0.0047 \times \mathrm{age} + 0.017(\mathrm{Speer/I25\ data})$$

where age = test year − model year (assumed to be 0.1 year for 1992 model-year vehicles measured in 1991).

The equation illustrates the age-related increase in %HC. This is attributed to poor maintenance and/or emissions system tampering increasing with age (see later). The fact that emissions system tampering increases with

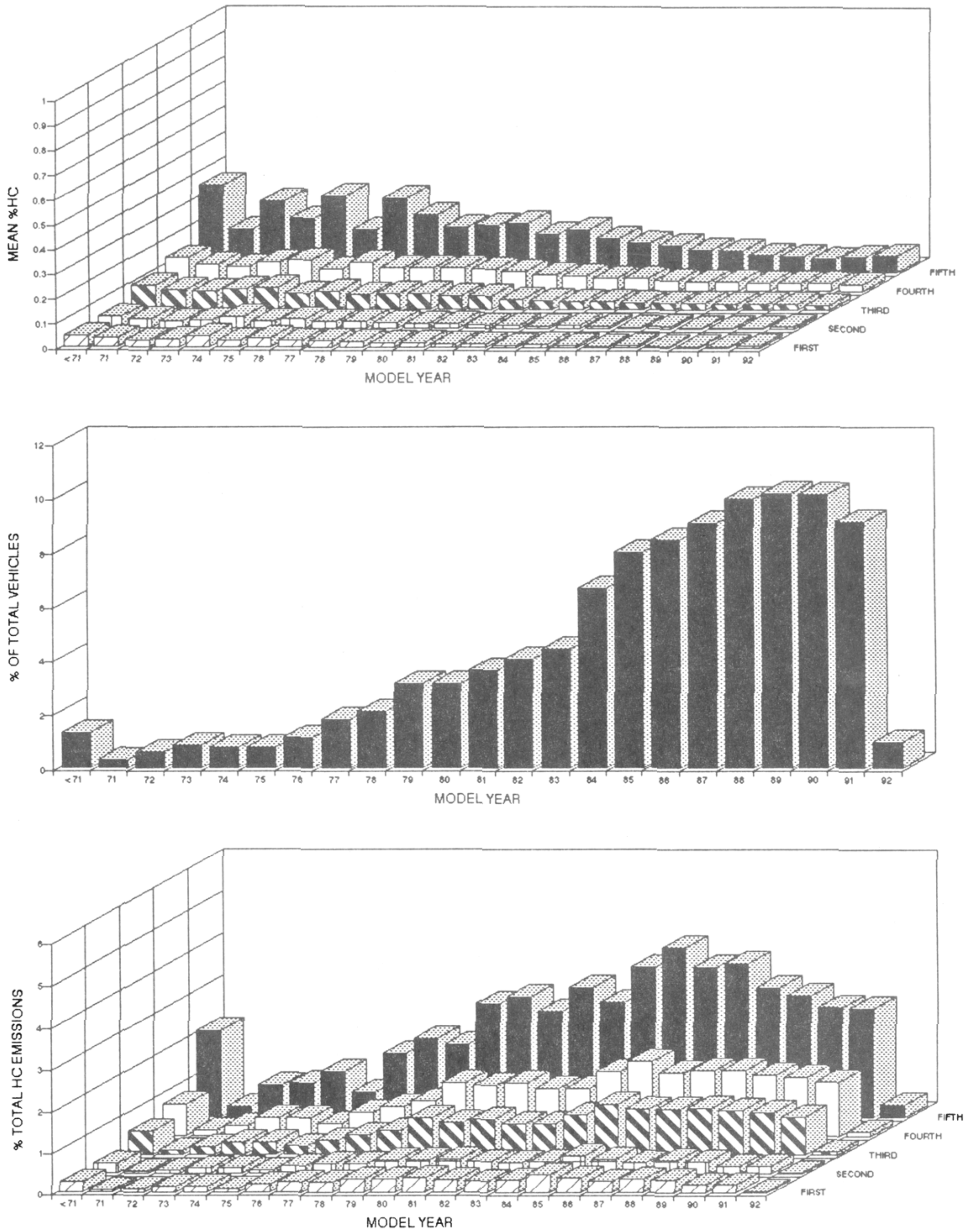

Figure 7. Speer/I25 data presented as (a, top) emission factors by model year divided into quintiles, (b, middle) fleet model year distribution and (c, bottom) percentage of the total HC emissions for each quintile of each model year. Panel c is the product of graphs a and b.

increasing age is clearly demonstrated by EPA tampering surveys *(14)*.

The dramatic differences in HC emissions at the two sites stand in contrast to the (already published refs 6 and 13) CO emissions and age distribution, which are essentially identical (the regression equations are %CO = 0.147 × age + 0.03 and %CO = 0.148 × age − 0.01 for 6th/I70 and Speer/I25 data, respectively). We attribute the larger offset in HC emissions at the 6th/I70 site to the fact that many vehicles are traveling fast (45–55 mph) with the driver's foot off the accelerator. These vehicles are likely to be emitting relatively little exhaust and yet misfiring on some cylinders to which small amounts of fuel are still being delivered. The similar CO readings indicate that the overall air/fuel ratio distributions are similar when combustion takes place. The uphill ramp at I-25 and Speer Blvd. is not a location where any misfiring behavior is expected. As one perceptive reviewer noted, at the 6th/I70 deceleration site, modern vehicles shut down the fuel injectors leading to CO_2 emissions close to zero and "HC/CO_2 may approach infinity". This effect we believe to be the reason for the large offset between the otherwise similar data sets. Note that under these conditions, the emissions in g/mi may be very low because of the large mpg attributable to vehicles coasting at 45–55 mph.

IV. Quintile Investigation. For each model year, the on-road HC emissions are divided into five groups (quintiles) in ascending order of emissions. Examination of the quintile emission factor distributions from the two data sets (Figures 6a and 7a) shows that for each model year the HC emission factors are similar except that the 6th/I70 data are uniformly higher than the Speer/I25 data. The value of the mean % HC in both fleets rises smoothly as the age increases. But the highest emitting quintile for the 6th/I70 location remains almost constant at about 0.4 % HC back to 1982. At this point it rises until it averages above 0.9 % HC. However, the highest emitting quintile for the Speer/I25 location rises only to about 0.35 % HC. The quintile plots show no sign of any sharp breaks in emission factors to coincide with those model years when emissions control technologies were changed. Notice that in Figure 7a the gross polluters from the 1985 model year and older all have emissions higher than the median (third quintile) for 1975 model year and older. Since the 1975 and older vehicles have no catalysts, those gross polluters must arise from a phenomenon other than ordinary catalyst deterioration.

The second panels, Figures 6b and 7b, show the observed age distributions of the two measured fleets. The observed age distributions depend on the combined effects of recession, rust, and riches (socioeconomic status) of the locations chosen. In this study, the observed age distributions in the two locations are almost exactly same.

When the emission factors are multiplied by the fleet age distributions, the results are the percentages of the total HC emitted for each quintile of each model year, Figures 6c and 7c. In both cases, the 40% lowest emitting vehicles, regardless of the model year, make an essentially negligible contribution to the total HC emissions. The greatest contribution is from the 20% highest emitting vehicles newer than 1983. This is due to the large number of vehicles dating from 1983 and newer combined with the relatively high emission rates of these vehicles. The dirtiest emitting 20% of the new vehicles is dirtier than the cleanest 40% of any model year, however old. From this point of view, age alone is not a good predictor of high on-road HC contributions from individual vehicles. The oldest vehicles, 20 years and older, are almost irrelevant to total fleet emissions because they are not numerous.

If we use the Speer/I25 data, which are more representative of a loaded-mode urban driving condition, then the percentages of the total HC emissions from various model year groups are 26% for 1979 and older model years, 43% for 1980–1986 model years, and 31% for 1987–1992 model years. As an exercise to show that tighter new car standards are unlikely to be an emission reduction strategy as useful as proper maintenance of current new technology, we performed the thought experiment in which all 1984 and newer model years vehicles are given the median 1991 model year HC emissions. The total fleet emission reduction is 29%.

Conclusions

The analyses of mobile source HC emissions performed in this study lead to the following conclusions. First, most vehicles are low in HC emissions as well as CO emissions. Mobile source HC emissions are dominated by small fractions of vehicles of all ages having extremely high emission rates. Second, remote sensing measurements indicated there is no significant difference in on-road HC emissions between vehicles participating in a Colorado State I/M program and those not participating in the program. Third, the fraction of HC gross polluters increases with age. This is due to increased poor maintenance and tampering with age. Last but not least, good maintenance and elimination of tampering are very important even for those new vehicles which are equipped with the latest emissions control technology. This conclusion is supported by two pieces of evidence. The quintile plots show no sign of any sharp breaks in emission factors for model years when emissions control technologies were changed. A high-emitting new vehicle is significantly worse than a low-emitting old vehicle as seen from comparing the fifth quintile of the new vehicles against the first quintile of any age. The highest emitting 20% of the vehicles between 2 and 10 years of age stand out as the vehicles in most need of improvement.

The absolute emission levels observed on-road, the large contributions from a small fraction of the vehicle population, and the significance of tampering and poor maintenance suggest that some alternative regulatory approaches may provide a better opportunity to reduce mobile source emissions with timely and cost-effective methods. The application of the remote sensing techniques discussed in this paper may have the potential to contribute to the reduction of mobile source emission inventories required in noncompliance areas (*15*).

Acknowledgments

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