CONTRACT NO. A932-189
FINAL REPORT
AUGUST 1991

On-Road CO Remote Sensing in the Los Angeles Basin

State of California
AIR RESOURCES BOARD
Research Division

ON-ROAD CO REMOTE SENSING IN THE LOS ANGELES BASIN

Final Report
Contract No. A932-189

Prepared for:

Research Division
California Air Resources Board
1800 15th Street
Sacramento, CA 95812

Submitted by:

University of Denver
Chemsitry Department
Denver CO, 80208

Prepared by:

Donald H. Stedman
Gary Bishop
James E. Peterson
Paul L. Guenther

August 1991

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The University of Denver remote sensor for on-road motor vehicle carbon monoxide emissions was used for eleven days in the Los Angeles Basin in December, 1989. The remote sensor has been incorporated into the 1990 Clean Air Act Amendments as "on-road emissions testing". The device measures the CO/CO_2 ratio for one-half second behind each vehicle, from which the exhaust %CO is calculated. Vehicles were measured in a mix of many driving modes and speeds ranging from deceleration coming up to a red traffic light through idling in heavy congestion up to accelerations and cruises entering a freeway ramp at highway speeds. The results have been validated by both EPA and CARB blind comparisons. The calculated %CO is analogous to that which would have been measured had the vehicle been equipped with a tailpipe probe. The mass emissions in grams CO per gallon of gasoline used can also be derived. Eight of the days monitored normal urban street driving; three monitored freeway ramps. Over 27,000 valid CO emission measurements were made. When the videotapes had been read and returned to California authorities for matching the license plates, the total number of vehicles both measured and matched with the license plate database was over 16,000. Because of the poor contrast of older California license plates and the sun angles, more plates were readable when the front of the vehicles were imaged. With this arrangement a significant number of vehicles without front plates could not be identified. The license plate matched fleet was 0.15 %CO cleaner (~3/4 of year on average newer) than the total fleet. This probably arises because older vehicles have older style plates which are both intrinsically harder to read (lower contrast), and often in poorer condition.

Overall for the driving modes and vehicles tested more than fifty percent of the CO was emitted by eleven percent of the vehicles with %CO equal to or greater than five (gross polluters). New vehicles were so clean (gross polluters were less than 1% for the 1989 and 90 model years) that their emissions were almost negligible. The percentage of gross polluters rises from 4% (328 vehicles) of the 83-90 model year vehicles through 17% for the 75-80 model year vehicles to 30% (504 vehicles) of the 1974 and older fleet. If the whole measured fleet could maintain the 1989 and 1990 measured emissions then the total on-road pollution from the 16,000 vehicles measured would decrease more than fivefold. Despite the fact that the new vehicles are on average clean, the dirtiest 20% of the one year old fleet was dirtier than the cleanest 20% of any model years regardless of age. Because old vehicles are not numerous, and most new vehicles are low emitters, most of the carbon monoxide came from emissions of the dirtiest 20% of the vehicles with model years between 1976 and 1988.

An analysis of the data indicates that a conservative upper limit of fifteen percent of the measured CO emissions arises from vehicles in either a cold start or an off-cycle acceleration mode. Forty three percent of the fleet of 77 vehicles measured four or more times were always in the clean (<1 %CO) category. These emit 4% of the total CO from all 77 vehicles. One quarter of the fleet of 77 showed emissions consistently between one and five percent CO. These vehicles emitted 18% of the CO An additional 25% of the fleet were over the five %CO cut point at least twice. These vehicles emitted 70% of the emissions. Only a small fraction (5 vehicles, 7% of the fleet of 77 vehicles) jumped into the high category only once. The emissions variability observed in this data set is similar to the emissions variability observed when vehicles are repetitively subjected to conventional I/M testing. These results imply that an inspection and maintenance program incorporating remote sensing, which targets gross polluters with multiple violations, has the potential to identify a significant fraction of the CO emissions while inconveniencing only a small fraction of the vehicle owners. Our analysis concludes that on-road remote sensing as a component of an I/M program has the advantages of being representative of the on-road emissions of the vehicle in question, being an emissions test which is almost impossible to circumvent, and incorporates a "fairness factor" such that the more a vehicle is driven, the more frequently it will be tested. When age related factors are eliminated the findings in California are essentially identical to findings from on-road CO studies of large fleets of vehicles in Denver, Chicago and Toronto.

Forty-seven vehicles out of a fleet of 387 vehicles registered as diesels show emissions greater than 2%CO. Of these vehicles, thirty-nine are 1975-84 General Motors vehicles. The vehicles are such high emitters that the only sub-fleet found to be dirtier are 1955-1970 vehicles. Three lines of evidence point to the conclusion that more than half of the vehicles listed in this category are not diesel powered and are incorrectly registered thereby avoiding the California Smog-Check program.

There were differences in average CO emissions between the sites measured, and to a lesser extent between different days at the same sites. To aid in understanding this phenomenon, all remote sensing data available at the University of Denver from a variety of US cities with altitudes lower than 7,000 ft were analyzed in terms of hourly average CO emissions compared to hourly average fleet age. From this analysis a linear model was developed which demonstrated that almost all of the observed differences could be accounted for by differences in average age. This results because of the previously shown influence of the gross polluters which increases with fleet age. Smaller, load induced average emission increases between an uphill but slow cruise-mode freeway off-ramp and a flat but high speed acceleration on-ramp were discernable after the age differences had been eliminated. The linear model predicts average %CO for all fleets measured in the USA to better than 0.5 %CO with a knowledge of only the average fleet age.

The important conclusions are that a few vehicles (gross polluters) emit most of the CO A few vehicles are always measured in the gross polluter category, a few are frequently in that category, and most are never gross polluters. The fraction of gross polluters increases from one in one hundred new vehicles up to one in three old ones. Although new vehicle standards and technology changed from the early seventies to the early eighties, no sharp breaks are observed for the transition model years. The evidence suggests that on-road CO emissions increase linearly with average age of the fleet, and that the linear increase is dominated by the steady increase in the fraction of gross polluters with age. This increase with age appears to be caused by improper (in some cases illegal) maintenance practices.

INTRODUCTION

Urban air quality does not meet the federal standards in many states. Violations of the ozone standard are believed to arise from photochemical transformation of oxides of nitrogen (NOx) and hydrocarbons (HC). Carbon monoxide (CO) standards are primarily violated as a result of direct emissions of the gas. Mobile sources are a major factor in urban emissions inventories for oxides of nitrogen, hydrocarbons and carbon monoxide.

Additional air pollution control measures beyond the Federal New Vehicle Emissions standards taken to mitigate mobile source emissions in non-attainment areas include inspection and maintenance (I/M) programs, oxygenated fuels mandates and transportation control measures. Nonetheless many areas of non-attainment remained after the 1987 deadline, and some are projected to remain in non-attainment for several more years despite the measures currently undertaken. The remote sensing techniques discussed in this report may have the potential to contribute to further control measures in non-compliance areas. The 1990 US Clean Air Act amendments require non-attainment areas to "include on-road emissions monitoring" in their post-1990 I/M programs. This amendment, the "Barton Clean Air Smog Trap Amendment" was included based on literature and demonstrations of on-road remote sensing to the US Congress by the University of Denver.

With initial support from the Colorado Office of Energy Conservation in 1987, the University of Denver (DU) developed an infra-red (IR) remote monitoring system for automobile carbon monoxide exhaust emissions. 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 University of Denver CO remote sensor is named Fuel Efficiency Automobile Test (FEAT). Figure 1 shows a schematic diagram of the basic instrument.

The basic instrument measures in under one second per vehicle the carbon monoxide to carbon dioxide ratio (CO/CO_2) in the exhaust of any vehicle passing through the IR light beam. With support from the American Petroleum Institute an additional channel to measure hydrocarbon emissions has been successfully tested and has monitored over 50,000 on-road vehicle HC emissions.

The IR source sends a horizontal beam of radiation across a single traffic lane, approximately 10 inches above the road. This radiation is picked up by the detector on the opposite side and split into three wavelength channels, CO, CO_2, and reference. Data from all channels are fed to a computer for analysis. The calibration gases (mixtures of CO and CO_2 in nitrogen) are used as a daily quality assurance (Q/A) check on the system.

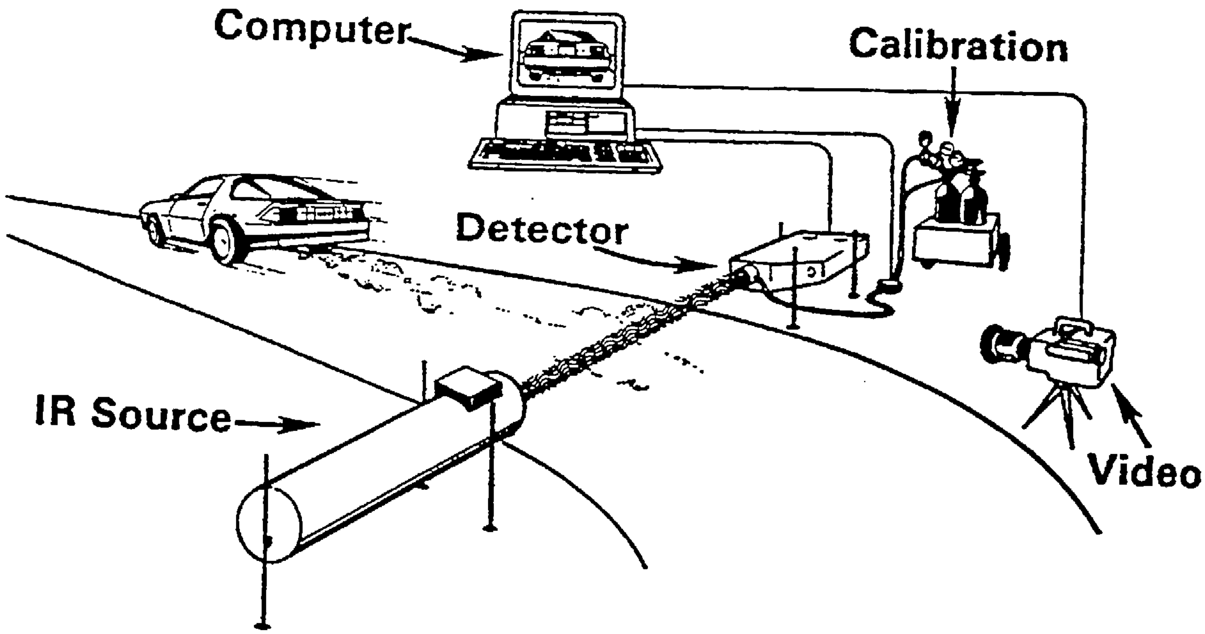

Figure 1. A schematic diagram of the University of Denver on-road emissions monitor. It is capable of monitoring emissions at vehicle speeds between 2.5 and 65 mph in under one second per vehicle.

The determination of the CO/CO_2 ratio is itself a useful parameter to describe the emission status of a combustion system. Most vehicles show ratios close to zero (low emitters). When CO/CO_2 ratios greater than zero are observed the engine must be operating with a fuel rich air/fuel ratio, and the emissions control system must not be fully operational. Emissions systems are not fully operational when the system is missing or has been tampered with. They are also not fully operational when the catalyst is cold (as in cold start operation), or under conditions of extreme acceleration when the manufacturers intentionally allow the vehicle to operate at a much higher emission level than under normal driving conditions. These so called "off cycle" emissions have been described in detail by Austin et al. of Sierra Research (1988).

With a fundamental knowledge of combustion chemistry, many parameters of the vehicle and its emissions system can be determined, including the instantaneous air/fuel ratio, grams of CO emitted per gallon of gasoline and the percentage of CO which would be measured by a tailpipe probe. The mechanism by which FEAT measures a ratio is explained in Bishop et al. (1989). The ratios can be determined by remote sensing, independent of wind, temperature, and turbulence in 0.8 seconds per passing vehicle. Other peer-reviewed publications describing remote sensing are listed in the References.

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 so that the image of each passing vehicle is frozen onto the video screen. The computer writes the date, time and the CO and CO_2 concentrations at the bottom of the image. These images are then stored on videotape.

FEAT can measure the CO emissions in all vehicles, including gasoline and diesel-powered vehicles, as long as the exhaust plume exits the vehicle within a few feet of the ground. Due to the height of the sensing beam, FEAT will not register emissions from exhausts which exit from the top of vehicles such as heavy duty diesel vehicles in the USA. Carbon monoxide and hydrocarbon emissions from diesel vehicles are in any case usually negligible. FEAT is effective across traffic lanes of up to 40 feet in width. However, if one wishes to positively identify and video each vehicle with its exhaust it can only be used across a single lane of traffic. FEAT operates most effectively on dry pavement. Rain, snow, and vehicle spray from very wet pavement cause interferences with the IR beam. These interferences cause the frequency of invalid readings to increase, ultimately to the point that all data are rejected as being contaminated by too much "noise". At suitable locations exhaust can be monitored from over one thousand vehicles per hour. FEAT has been used to measure the emissions of more than 450,000 vehicles in Denver, Chicago, the Los Angeles Basin, Toronto, the United Kingdom, and Mexico City.

FEAT has been shown to give accurate readings for CO by means of double-blind studies of vehicles both on the road and on dynamometers (Lawson et al.. 1990; Stedman and Bishop, 1990a). EPA has shown that the readings are closely comparable to laboratory readings from a vehicle on a dynamometer (Stedman and Bishop, 1990a). Lawson et al., 1990 used a vehicle with variable emissions under passenger control to show the correctness of the on-road readings. Figure 2 shows the comparison obtained, and described in more detail by Lawson et al.. There are studies underway to attempt to correlate the remote sensing measurements with other tests, particularly the Federal Test Procedure (FTP). Bishop et al., 1989, and unpublished data from EPA Ann Arbor (E. Glover presentation to CARB Mobile Source Division, March 1991) both show that remote sensing measurements are better correlated to the FTP than are the idle/no-load emissions used for I/M testing.

It is most important to point out that on-road emissions (both evaporative and tailpipe) are the parameter which all mobile source control agencies are constituted to control. The fact that a remote sensor can be used to directly measure the tailpipe component is of considerable advantage over other tests, particularly if there are ways that individuals or manufacturers can circumvent the other tests, thus rendering the results unrepresentative of the on-road fleet. When an NO channel becomes available then on-road CO, HC and NO emissions will be simultaneously measurable.

The purpose of this report is to present the carbon monoxide measurements made by means of remote sensing in the Los Angeles basin in December of 1989 and compare the results with those from other locations. Throughout this report we use the term

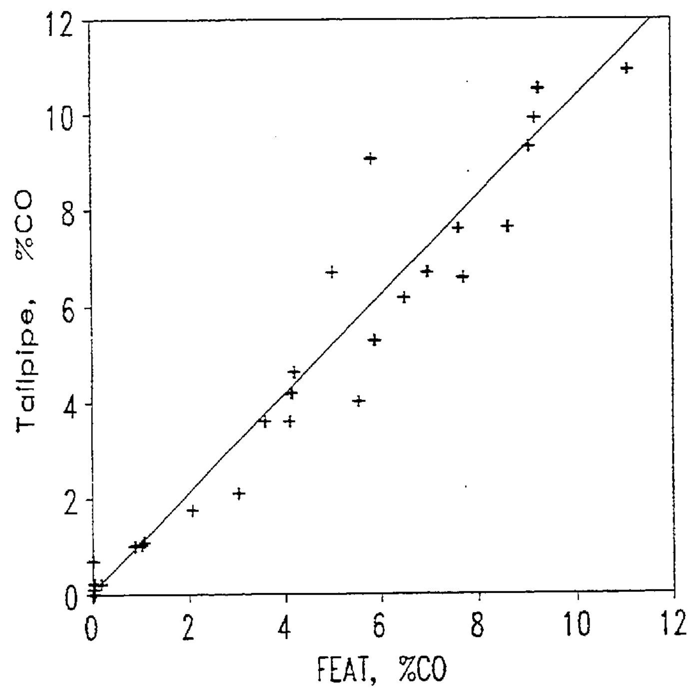

Figure 2. Comparison of tailpipe %CO measured by an on-board analyzer and by remote sensing. Data collected 12/8/89, 12/11/89 and 12/13/89 (n = 34). The equation of the regression line is [Tail pipe %CO] = 1.03[FEAT %CO] + 0.08, with r = 0.97.

"on-road CO emissions" to describe the measurements obtained by the remote sensor, and in the sense of "on-road" intended by the US congress in the 1990 Clean Air Act Amendments. The term "fleet", unless otherwise stated is used to mean those vehicles monitored by on-road remote sensing. When fleet data are analyzed as a whole we find that half the CO is emitted by a small fraction of the vehicles. These vehicles are termed "gross polluters" throughout this text. The cut point for the gross polluter category varies somewhat from fleet to fleet depending mainly on the average age of the vehicles. We also use as a working definition a "clean car" to refer to a vehicle whose on-road CO reading is less than 1 %CO.

Each measurement is a snapshot of the on-road CO emissions at the instant the vehicle passed the FEAT beam, and monitors whatever stable or transient mode the vehicle was in at the time of measurement. In this study vehicles were monitored in a mix of all operating modes. At the freeway on-ramps fast cruise and acceleration were common. At the off ramp the vehicles were travelling uphill, but sometimes the road congested to a point at which very low speed accelerations and decelerations were observed as well as cruise mode driving. On the urban streets all modes of driving common to urban streets were observed including low speed cruise, idle emissions as vehicles moved by in congested traffic, decelerations and accelerations associated with traffic control signals at the end of the block on which the measurements were made.

RESULTS AND DISCUSSION

The FEAT instrument described by Bishop et al., 1989 was set up at several sites in the Los Angeles basin in December, 1989 and three scientific programs were carried out. The three programs were a blind comparison of the FEAT data to emissions from a vehicle of known emissions in order to validate the measurements, a short pilot program in which the FEAT readings were used in real time to direct vehicles to a roadside emissions monitoring test, and a major study of the on-road emissions of a large number of vehicles at several locations chosen by scientists from the California Air Resources Board. The first two programs were very successful and the results have been published (Lawson et al.. 1990). A copy is included as Appendix 1. This report describes the third and final aspect of the study.

Measurements were carried out for eleven days at the six sites listed below. The total number of beam blocks was 33,618. Each beam block starts a search for vehicle exhaust. Error checking routines in the FEAT computer eliminate invalid data caused by pedestrians, bicyclists, etc. The number of measurements with valid emissions data was 27,766. The video tapes were read for license plate identification and the plates which appeared to be in-state and readable were forwarded to the ARB to insert make and model year information. Of the 18,836 emissions readings with readable plates, the ARB returned information on 16,511 from 15,953 unique vehicles. Unless otherwise stated the data analysis uses the data base with 16,511 entries.

Measurement locations

Data on disk will be made available upon publication of this report through Dr. Lowell l. Ashbaugh of the ARB Research Division, P.O. Box 2815, Sacramento CA, 95812, phone (916) 323-1507. The file structure of the data contains headers indicating the site locations. The text below for each site lists the file headers and describes the site in more detail. Figure 3 is a schematic map of the Los Angeles area showing the approximate locations of the sites each indicated by their file header designations.

LONGB06 / Long Beach Boulevard - Dec. 6, 1989

> The first site was used for monitoring vehicles southbound on Long Beach Boulevard in Lynwood one block north of the junction of Long Beach Boulevard and Norton on a typical straight and level city block. Although the Boulevard has two lanes southbound, the left lane was already blocked by gas company operations. The FEAT system was set up within the lane blocked off by the gas company, and the source set up half on the sidewalk and half in the gutter.

Except during the last hour of operation the traffic signals did not block the traffic as far back as the monitoring site. At other times the speeds averaged between 10 and 25 mph.

IMPER07 / Imperial Highway - Dec. 7, 1989

The second site was used for monitoring the right lane of westbound Imperial Highway about 100m west of the junction with Long Beach Boulevard in Lynwood. Both westbound lanes were open, a row of cones and a "pass either side" sign allowed traffic to flow in both lanes around a small island created to shield the FEAT light source and generator. The detector and support vehicle occupied the parking lane. This site was also straight and level driving but since the junction was traffic light controlled the speeds and traffic density depended on the timing of the signal lights. The maximum speeds were 30 mph with mild acceleration when the first few vehicles from the front of the packs came through.

LONGB08 / Long Beach Boulevard - Dec. 8, 1989

This site was approximately 75m south of the first site on the same road, and made use of the same gas company lane closure. This site was nearer to the traffic signals and the traffic regularly backed up to a stop in front of the FEAT beam.

LONGB11 / Long Beach Boulevard - Dec. 11, 1989
LONGB12 / Long Beach Boulevard - Dec. 12, 1989
LONGB15 / Long Beach Boulevard - Dec. 15, 1989

These sites were approximately 100m north of the site LONGB08. The additional move was an attempt to decrease the time that the traffic was backed up in front of the machine by the traffic light at Norton. This was not a complete success, but it was an improvement.

IMPER13 / Imperial Highway - Dec. 13, 1989

This site was used for monitoring vehicles at the south end of the single lane on-ramp from Imperial Highway to Southbound I-710. The same ramp carries through traffic on I-710 which was travelling in the exit lane but chose to carry on under the bridge without taking the optional exit. The lane was flat and the vehicles accelerating and fast moving.

IMPER14 / Imperial Highway - Dec. 14, 1989

This site was pictured on the front cover of the Journal of the Air and Waste Management Association issue of August 1990 in a photograph taken by Dr. Gary Bishop. The measurements were taken near the top of the tightly curved, single lane, uphill ramp from northbound I-710 to westbound Imperial Highway. The vehicles were travelling up a 3% grade in a direction about 45° away from their final westerly direction on Imperial Highway. This was the lone site in which vehicles were not measured on a level grade and was also subject to frequent backups.

WILLO16 / Willow/Katella - Dec. 16, 1989

The on-ramp from Willow/Katella to south bound I-605 freeway was monitored for one day on Saturday December 16th. This location, chosen for a socioeconomic contrast to the Lynwood sites, observed the newest (and cleanest) fleet in this study.

LACN18 / La Cienega - Dec. 18, 1989
LACN19 / La Cienega - Dec. 19, 1989

The La Cienega site monitored the left lane only of southbound La Cienega Blvd. about 600 yds north of the intersection with 120th. Traffic was divided as before (IMPER07) with a "pass either side" island for the light source. This location is also described by Lawson et al.. 1990.

Overall results

Figure 4a shows the distribution of CO emissions (solid bars) by percent CO category from the set of 16,511 vehicles measured at all locations in the Los Angeles area in 1989. The open bars show the overall CO emissions for each category. Not only are more than 10,000 (63%) out of 16,511 vehicles very low emitters, the skewed nature of the distribution is such that more than half the emissions come from only the 10.6 percent of the vehicles with emissions equal to or greater than 4.98% CO or 2,000 gm CO per gallon of gasoline. Very similar rsults have been published by Ashbaugh et el. based on I/M pullover studies. We use the term "gross polluters" for those vehicles identified in this category. Figure 4b and 4c show that the Los Angeles data have a very similar distribution to that from Denver (4,909 vehicles) and Chicago (11,818 vehicles). The overall results from three major studies with fleets matched to license plates are listed in Table I.

Figure 4 is not indicative of a normal (Gaussian) statistical distribution with vehicle numbers spread equally about the mean, and the mean and median equal. Motor vehicle emissions turn out empirically to be distributed according to a gamma

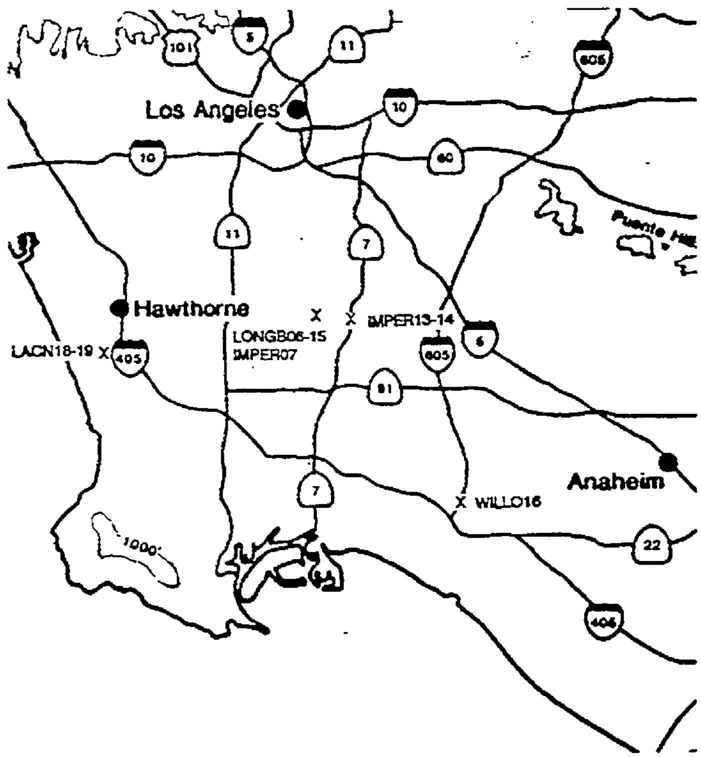

Figure 3. Map of the Los Angeles Basin indicating the approximate locations of the sampling sites.

Table I. Summary of relevant statistics for the three major US cities in which FEAT data have been collected.

Location / Year	Mean %CO	Median %CO	Mean Model Year
Los Angeles / 1989	1.56 ± 0.04	0.37	81.8
Denver / 1989	1.03 ± 0.03	0.15	83.1
Chicago / 1989	1.17 ± 0.05	0.22	83.5

distribution, which is quite different from the more familiar normal or bell shaped distribution. An additional example of this type of distribution is the age distribution of a population with a constant birth rate and an exponentially increasing death rate (for example the human population). Two consequences of gamma distributions are, 1) "outliers" cannot be estimated or eliminated based on classical statistics (i.e. ± 3 standard deviations) and 2) robust analysis of emissions data requires large N

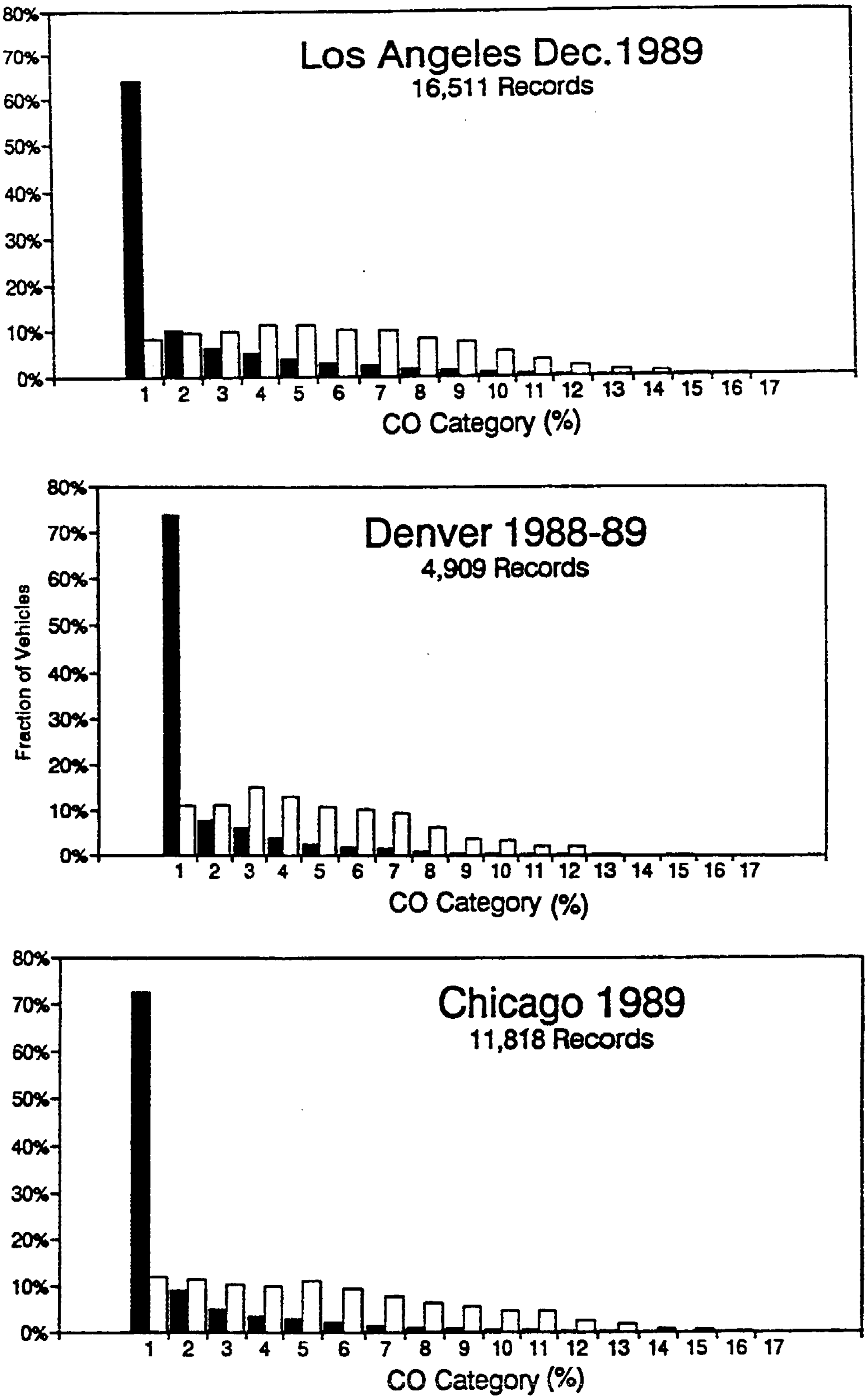

Figure 4. Normalized histogram showing as black bars the percentage of the fleet of vehicles with emissions less than the stated %CO category. Clear bars show the percentage of the emissions. a) Los Angeles data b) Denver c) Chicago.

(population) values since the emissions picture is dominated by a few high emitters (i.e. the tail really does wag the dog).

The ten bars shown in Figure 5 illustrate in deciles the emissions of a fleet of ten vehicles matching the observed total emissions and statistics of the observed data (Figure 4). Each bar corresponds to the emissions of one tenth (a decile) of the total fleet. 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 seventy percent of the fleet are within the error bars of the FEAT measurement capability. These decile plots illustrate that Denver, Los Angeles and Illinois have very similar CO emission distributions, and that most vehicles are very low emitters. The lower panels again show that the Los Angeles fleet emissions are very similar to those from other locations, even though the altitude (5,000 ft.) in Denver and the I/M programs are different. The I/M programs in Denver and Los Angeles are decentralized, annual in Denver, biennial in Los Angeles. The I/M program in Illinois was annual and centralized at the time these studies were undertaken.

As a part of this analysis we were asked by the ARB Research Division to answer several questions. Each question is given below in bold type followed by the answer.

Representativeness of the fleet

1. Is the distribution of emissions in the final data set the same as the distribution in the entire data set? That is, after eliminating measurements for which we could not obtain Department of Motor Vehicle (DMV) information, is the remaining data set a representative sample?

Of 27,766 valid CO emissions readings 16,511 (60%) were successfully matched to DMV records. The matched fleet is believed to be a representative sample of the total fleet observed with unreadable plates accounting for the majority of the difference. These were most often the result of a vehicle's position in the roadway, such that the license plate was not within the camera's field of view. This process will eliminate vehicles randomly. In California, older plates showed far less contrast and were harder to read. This effect removes older and therefore on average higher polluting vehicles. The third principal cause of unreadable plates was missing, dirty or obscured plates.

Overall, there is a cumulative effect of preferential removal of older or dirtier vehicles. This is apparent in the percentile plot of raw FEAT data versus DMV matched data shown in Figure 6. Although the difference is visible, it is also apparent that the difference is small. The small difference which accumulates through the high polluting tail of the population shows up as a noticeable difference in the means of the two data sets. The final DMV matched data set at 1.56%CO is lower than the adjusted (raw data base with only invalid records removed) FEAT mean %CO of 1.70. This effect would be observed if the total fleet were on average 3/4 model year older.

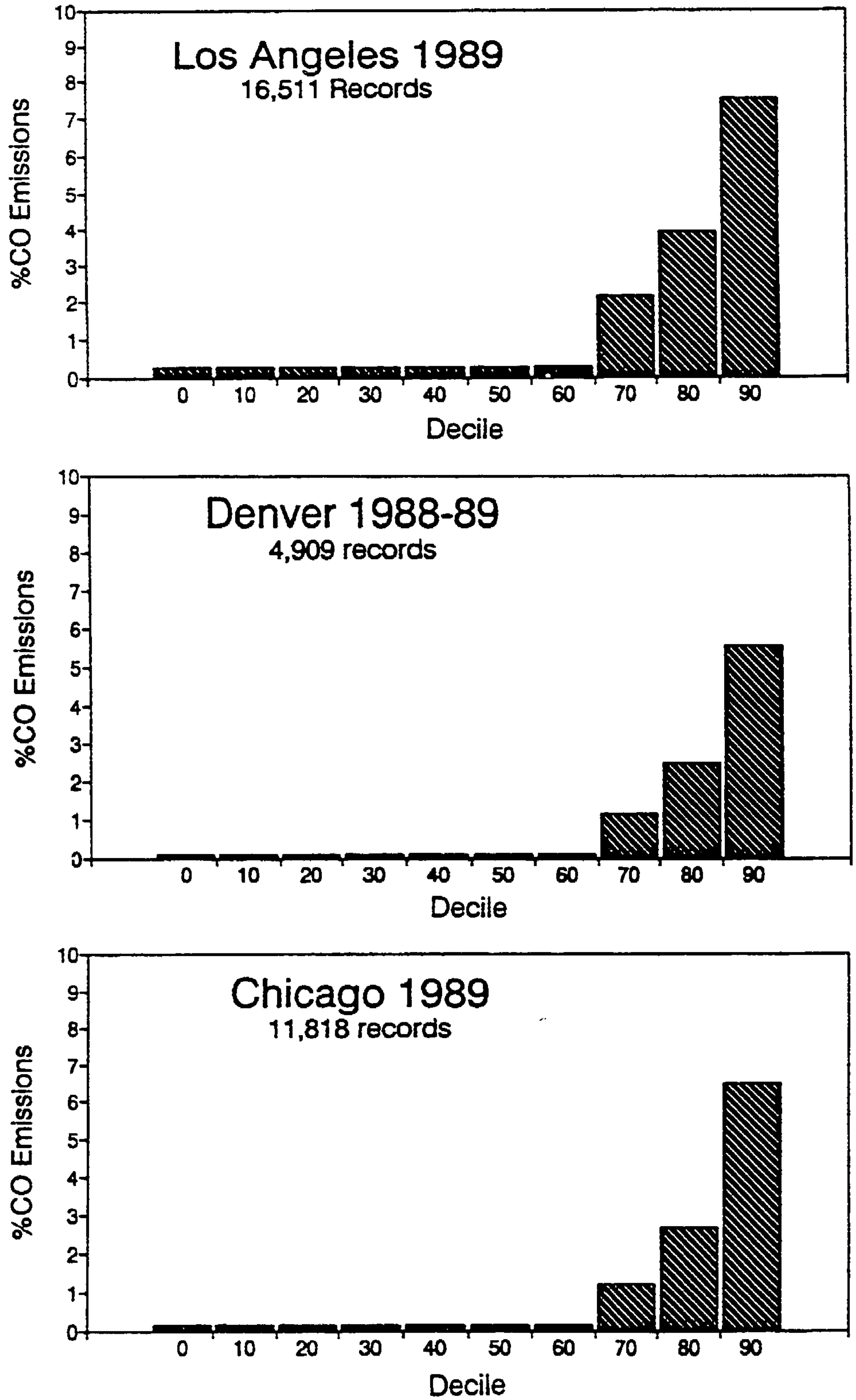

Figure 5. A fleet representation divided into ten vehicles whose %CO emissions match the observed fleet. a) LA, b) Denver, c) Chicago. Because of such small differences the cleanest seven deciles are given the average of all.

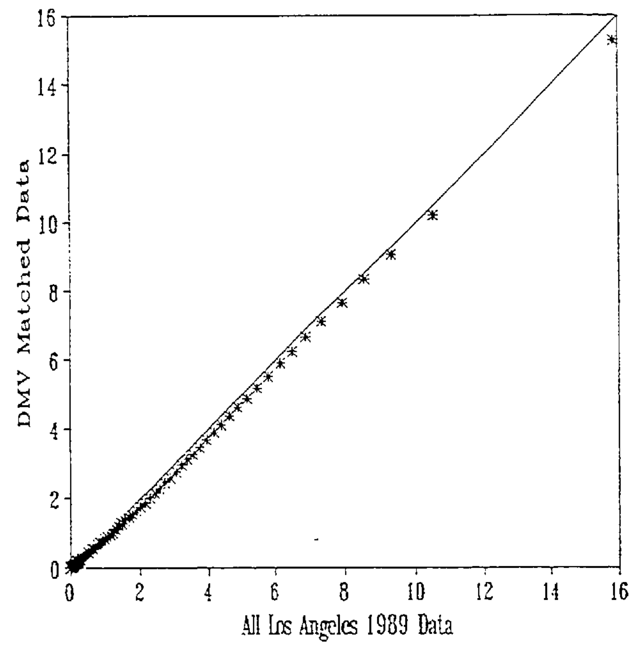

Figure 6. Each percentile of the DMV matched data by %CO plotted against each percentile of the total data set on the same scale. The solid line is where the data would fall if the two distributions where identical.

The study plan did not attempt to obtain a representative fleet, only to observe the wide variability possible in the Los Angeles area with a particular emphasis to the fleet in the Lynwood area. In view of the relatively small number of locations at which monitoring was carried out we would make no claims as to the representativeness of our data to the total fleet in the Los Angeles basin were it not for the fact that all fleets measured in the US and Canada seem to fall in a common population to be discussed herein.

Factors affecting differences between locations

2. Examine the difference in mean %CO at the different sites. Are the differences between Lynwood and the other areas caused by a different distribution of vehicles or a different distribution of emissions? Or is there another explanation?

Figure 7a shows %CO versus age correlation for all DMV matched data sets available to the University of Denver as of March 1, 1991 divided into one hour collection times. Using only the data collected below 7,000 feet altitude and for those sets containing at least 100 records, a correlation was determined of mean %CO vs hourly average age.

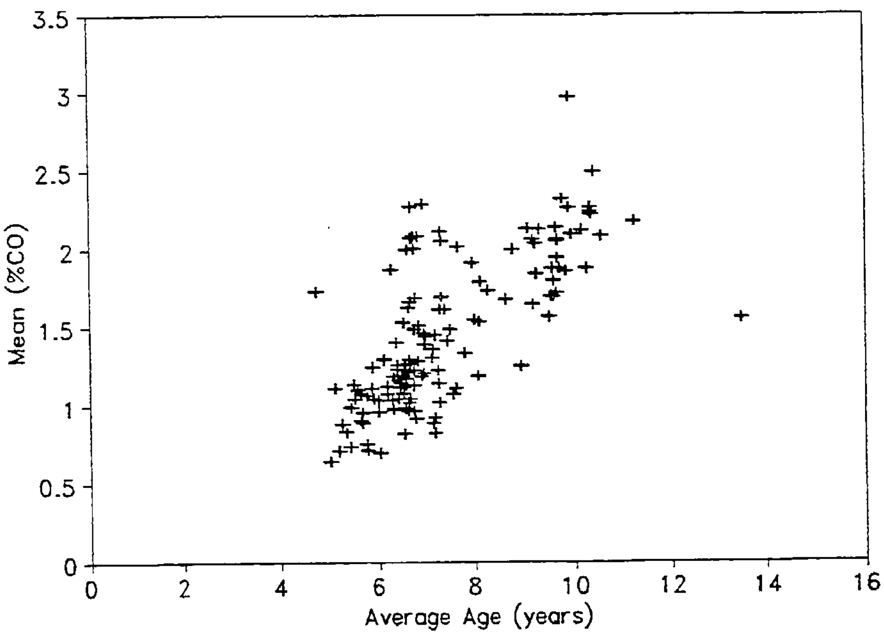

Figure 7a. Hourly measured %CO emissions plotted against hourly average age for all of the available data from US sites.

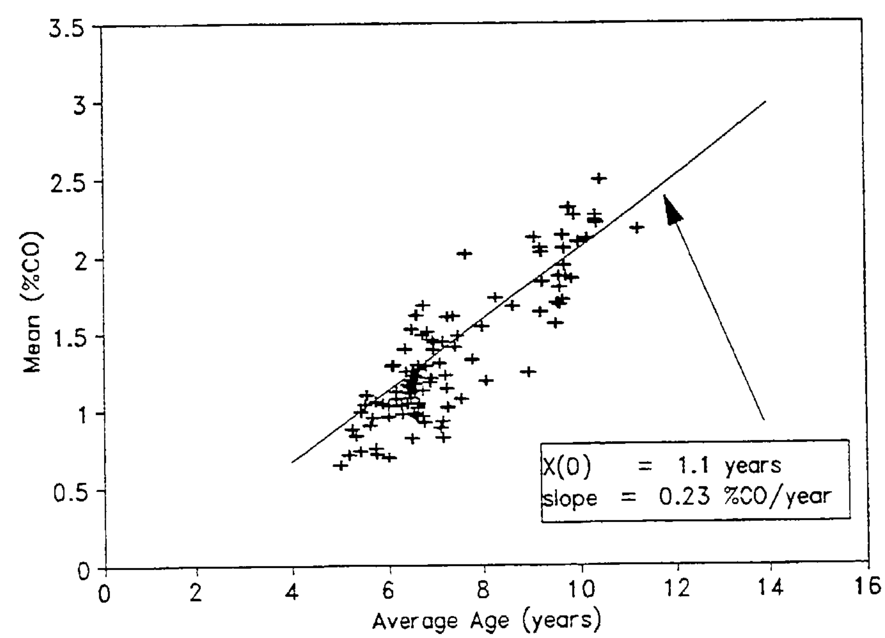

Figure 7b. A subset of Figure 7a, where only hourly averages which contain more than 100 vehicles and were collected below 7000 ft. in altitude remain. The regression line is weighted according to the number of vehicles in each point.

These selected data are shown in Figure 7b. A weighted regression line of slope 0.23 %CO per year and an X intercept at 1.1 years has a highly significant R^2 of 0.78 with 107 degrees of freedom. Figure 7a which shows all data irrespective of altitude, load and number of vehicles measured in the given hour, not surprisingly evidences more scatter, but the underlying correlation is still clear. The scatter observed when hourly fleets of less than 100 vehicles are included reinforces the conclusion about the need for large N values to obtain statistically valid data.

The fleet-averaged CO emissions model derived from these data is as follows:

$$\%CO = 0.23 * (AGE - 1.1) \qquad (1)$$

where

$$AGE = Test\ year - Model\ year \qquad (2)$$

From %CO the mass emissions in grams CO per gallon of gasoline used can also be derived (Stedman and Bishop, 1990a)

$$\frac{grams\ of\ CO}{gallon} = 15{,}800 * \frac{\%CO}{42 + 2.07 * \%CO} \qquad (3)$$

As an example the average %CO for the 16,511 vehicle fleet is 1.56%. This translates into 545 gmsCO/gallon. If for some reason mass emissions in gmsCO/mile are required then gmsCO/gallon must be converted to gmsCO/mile by means of gas mileage data. For the purposes of illustration, assuming an average gas mileage of 17mpg, then the average emissions of 1.56%CO corresponds to an average gm/mile of 32. For the purposes of obtaining emissions inventories it is likely that accurate data for gallons sold in an area are more easily obtainable than accurate vehicle miles travelled (VMT) data. According to Wolcott and Kahlbaum (1990), in many cases VMT for use with MOBILE4 are actually estimated from fuel tax data.

Figures 7c through h illustrate the same data, but with various subsets highlighted. It is important to note that the Chicago, Denver and Los Angeles data are clearly members of the same set. The only data set which lies distinctly off the line is the Ute Pass study which measured vehicles at an altitude of 7,500 ft under a heavy uphill load at high speed.

The dominant variable responsible for variation in hourly average fleet %CO emissions is hourly average fleet age. Even though the age effect dominates, more subtle effects of vehicle speed/load are observable beneath the underlying data scatter. Figure 7d shows that the on-ramp emissions are significantly greater than the off-ramp emissions for fleet of similar age. This illustrates not only that different operating modes were monitored, but that when age factors are taken into account the effect of driving mode differences can be distinguished.

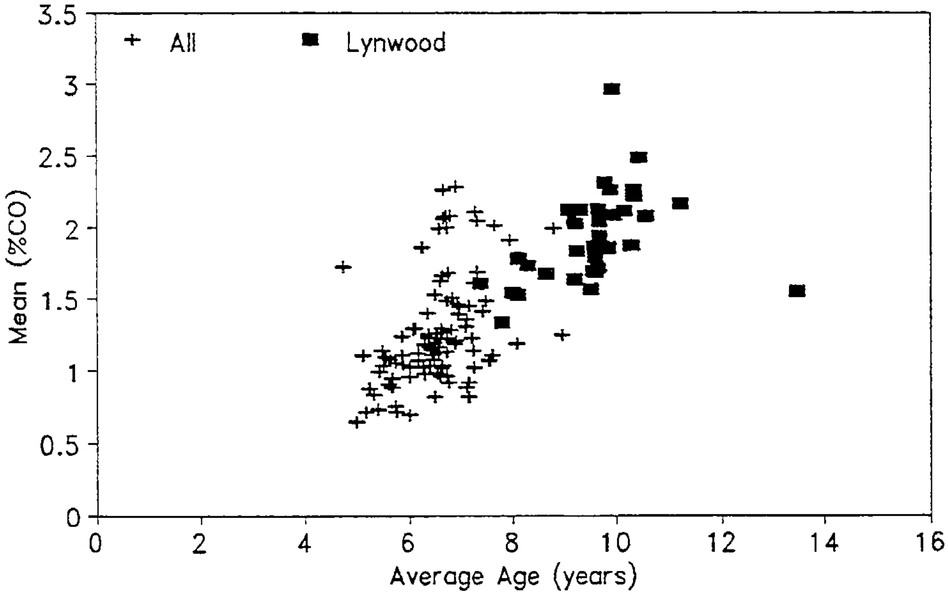

Figure 7c. Figure 7a with the hourly average data collected in Lynwood, CA highlighted as squares.

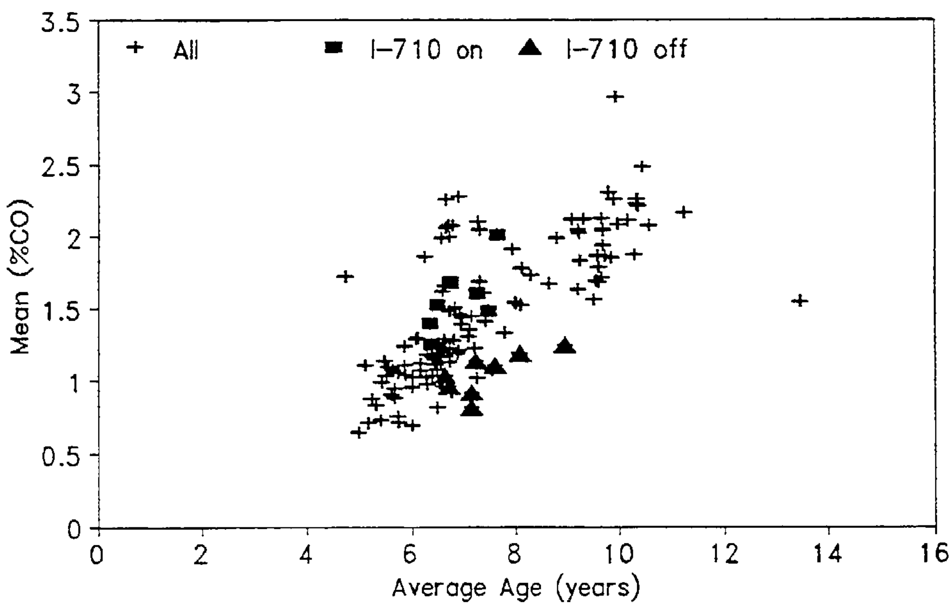

Figure 7d. Figure 7a with the hourly average data collected in Los Angeles at the I-710 on-ramp highlighted as squares and the I-710 off-ramp highlighted as triangles.

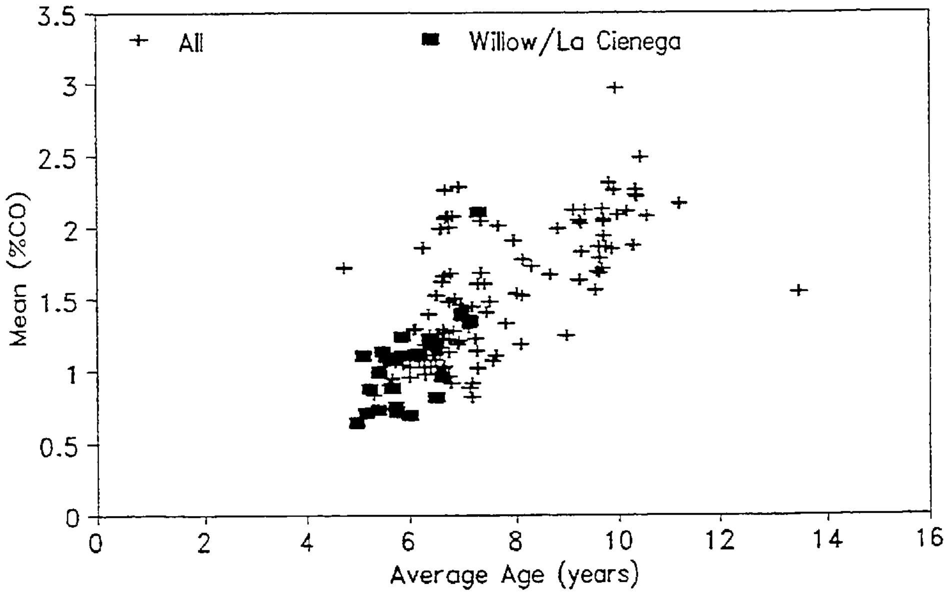

Figure 7e. Figure 7a with the hourly average data collected at the Willow/Katella and La Cienega sites in Los Angeles highlighted as squares.

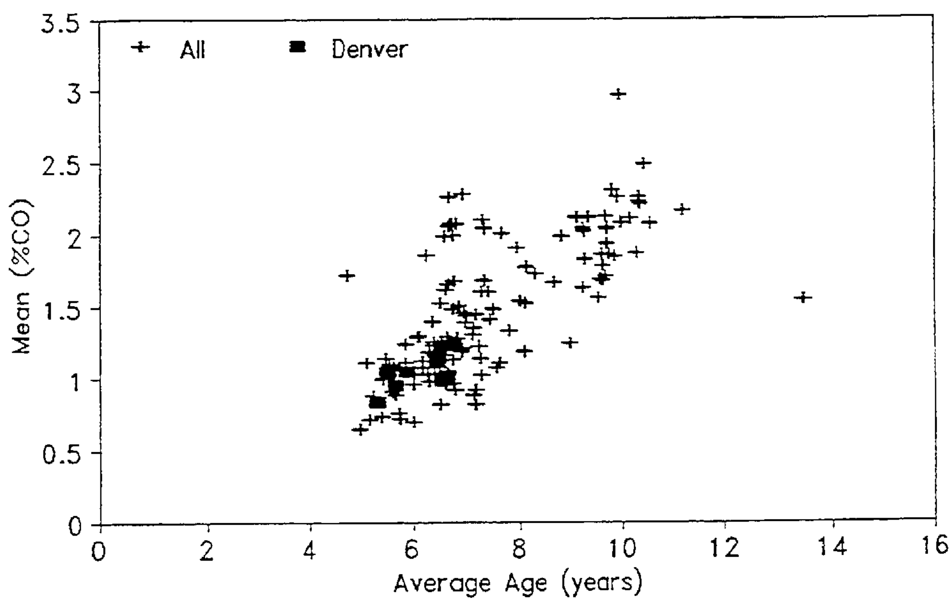

Figure 7f. Figure 7a with the hourly average data collected in Denver, CO highlighted as squares.

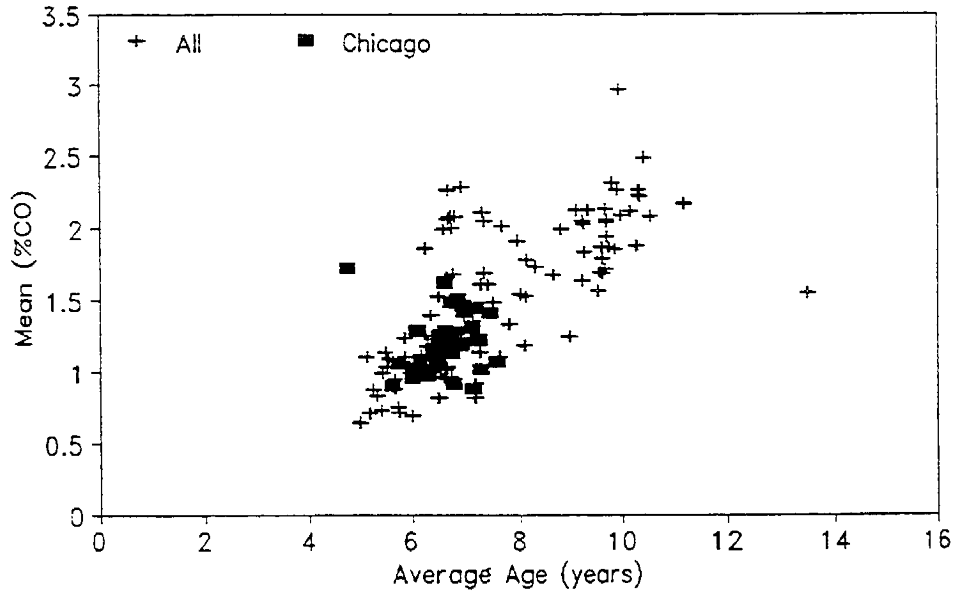

Figure 7g. Figure 7a with the hourly average data collected in Chicago, IL highlighted as squares.

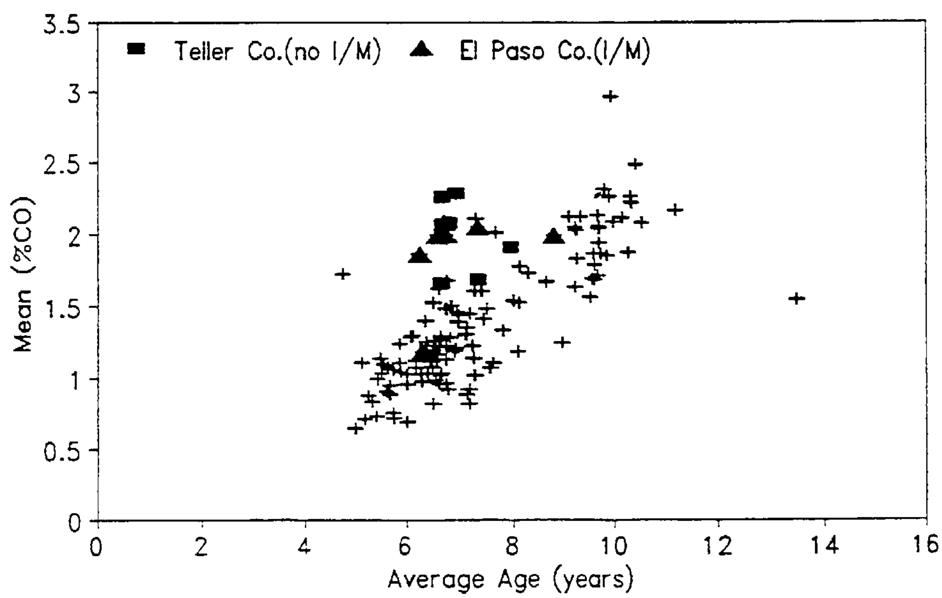

Figure 7h. Figure 7a with the hourly average data collected at Ute Pass (7,500 ft. located in Bust, CO). The data are segregated according to county of registration which distinguishes I/M program status.

Table II. Data from Los Angeles and Chicago containing a minimum of 100 vehicles.

SITE	DATE	MEAN AGE	MEAN %CO
Long Beach Blvd.	12/06/89	8.31	1.94
Long Beach Blvd.	12/08/89	8.86	1.71
Long Beach Blvd.	12/11/89	8.91	2.13
Long Beach Blvd.	12/12/89	8.91	2.01
Long Beach Blvd.	12/15/89	9.14	2.24
Imperial Highway	12/07/89	7.71	1.67
Cumulative Site Averages		8.73	1.95
Standard Deviations			0.207
I-710 [on]	12/13/89	6.09	1.57
I-710 [off]	12/14/89	6.63	1.09
Cumulative Site Averages		6.39	1.33
Standard Deviations			0.24
La Cienega	12/18/89	5.73	1.16
La Cienega	12/19/89	5.66	1.04
Willow/Katella	12/16/89	4.86	0.76
Cumulative Site Averages		5.31	0.99
Standard Deviations			0.168
Chicago	12/07/88	5.48	1.16
Chicago	12/08/88	5.59	1.20
Chicago	12/09/88	5.57	1.14
Chicago	12/10/88	5.49	1.11
Chicago	12/11/88	5.61	1.21
Cumulative Site Averages		5.53	1.164
Standard Deviations			0.037
REGRESSION ANALYSIS			
Slope 0.23% CO/year ± 0.01			
Y Intercept -0.3% CO ± 0.2			

Table II lists the measured emissions from each site in the Los Angeles basin, together with the five days of data from Chicago. Average %CO varies from 1.95 in Lynwood to 0.99 at the Willow and La Cienega sites. The variance of the four site averages is 0.175. When all data are adjusted by means of the slope of equation 1 to the average age of approximately six years the extremes are then 1.24 %CO for I-710 and 1.32 %CO for the Lynwood sites. The variance of the four site averages about their mean is reduced from 0.175 to 0.004. Most of the variation in fleet means between various locations in Los Angeles, and between Los Angeles and other locations is attributable to the changes in average fleet age. The Lynwood area fleet is considerably older than any other site, and the CO emissions reflect that age difference. The only average emission factors which vary between similar age locations are those from the on and off-ramps to I-710 in which the accelerating on-ramp is significantly higher in emissions than the tightly curled uphill off-ramp, even though both data sets fall within the overall spread of the total data set. There is no evidence of significantly different average emission factors between Los Angeles, Denver or Chicago when age is taken into account.

Factors affecting variations at the same site

3. Examine the variability within sites. In particular, mean %CO at the Long Beach Blvd. site ranged from 1.7 to 2.2 on different days. Why did this occur? Is it variability in the remote sensor, the vehicle fleet characteristics, operating conditions or some other cause?

The daily mean emissions from similar sites in Lynwood vary from 1.71 to 2.24 %CO The first set of numbers in Table II shows these means grouped together with the one measurement from Imperial Highway in the same area. Some of the observed variation in the means can be explained because the average age of the observed fleet was not constant. Since the values under discussion are means not individual measurements it is valid to use normal (Gaussian) descriptive statistical parameters. When adjusted for the different average age observed from each site at Lynwood the variance (sigma squared) is reduced from 0.044 to 0.023 (from Table II). There is still residual variance after the age factor is taken into account. This may possibly arise from the differences in the observed driving modes at the various locations. The only site which was measured more than once was Long Beach Blvd. on the 11th, 12th and 15th, which are in good agreement.

The daily means from the Imperial/I-710 on-ramp and off-ramp show a difference which increases when age adjusted. This reinforces our previous suggestion that the difference results from the effect of the higher speed/load operating condition at the on-ramp site.

In Chicago the data were collected at a single site. Notice that even before age correction the Chicago site, which was intentionally at exactly the same spot every day, shows a much smaller standard deviation than the Lynwood sites for which identical locations were not a criterion. A later starting time or an early quitting time for the on-road measurements can change the average age of the sampled fleet even when no change in the site has taken place. This age difference correspondingly alters the mean emissions, age adjustments even for the small age differences observed in Chicago reduce the observed variance from 1.4 to 0.8 (x 10^{-3}).

Comparison of data to other locations

4. Examine the variability between Los Angeles, Denver, and Chicago. What differences exist in the fleet characteristics and how does this relate to emissions?

Among the three cities, as among the different days in Los Angeles, adjusting the mean to an equal age of six years eliminates most of the variation. Examination of the quintile emission factor distributions from the three cities (Figures 8a, 9a, 10a) shows that for each model year the emission factors are similar. The value of the mean %CO in all three fleets rises smoothly back to 1980 when the fifth quintile mean reaches about 6 %CO At this point the dirtiest quintiles for Chicago and Denver stop rising. The Los Angeles dirtiest quintile continues to rise until it averages above 7 %CO The overall averages of gamma distributions are controlled by the tails, and the tails contain the vehicles which we call the gross polluters. Table III shows that the rise in the fifth quintile for the Los Angeles data set corresponds to an increase in the percent of gross polluting vehicles and not to an increase in the emissions for the "average" vehicle in the model year. The table is organized to represent the basic divisions in emissions control technology, i.e. 83-90 are closed-loop, 3-way catalyst equipped, 81-82 are a transition between 83-90 and 75-80 technologies, 75-80 are vehicles with oxidation catalyst and 74 & older are the pre-catalyst vehicles. Table III also points out how strikingly clean most new cars are. The 1989-90 model year contains more total vehicles than the 1981-82 classification, yet a factor of 13 less gross polluting vehicles. This increase from almost no gross polluters to a 20-30% minority has also been observed in Denver and Chicago (Bishop and Stedman, 1990, Stedman and Bishop, 1990b) and attributed to increasingly poor maintenance and tampering (EPA, 1990) with age. This conclusion is supported by three lines of evidence. The quintile plots show no sign of any breaks in emission factors for model years when emissions technology or emissions standards were changed. The comparison between Denver, Chicago and Los Angeles show no large differences despite the fact that California CO new vehicle standards have been a factor of two less stringent (seven g/ml) than those in the other locations. A dirty new vehicle is significantly dirtier than a clean old vehicle as seen from comparing the fifth quintile of the new vehicles against the first quintile of any age.

The second panels, Figures 8b, 9b and 10b show the observed age distributions of the three measured fleets. The combined effects of recessions, rust and riches (socioeconomic status) of the locations chosen cause significant differences in the observed age distributions. When the emissions factors are multiplied by the age distributions the lowest panels Figures 8c, 9c, 10c are obtained. These show the emissions contributions to the urban areas by the measured fleets. In all cases the

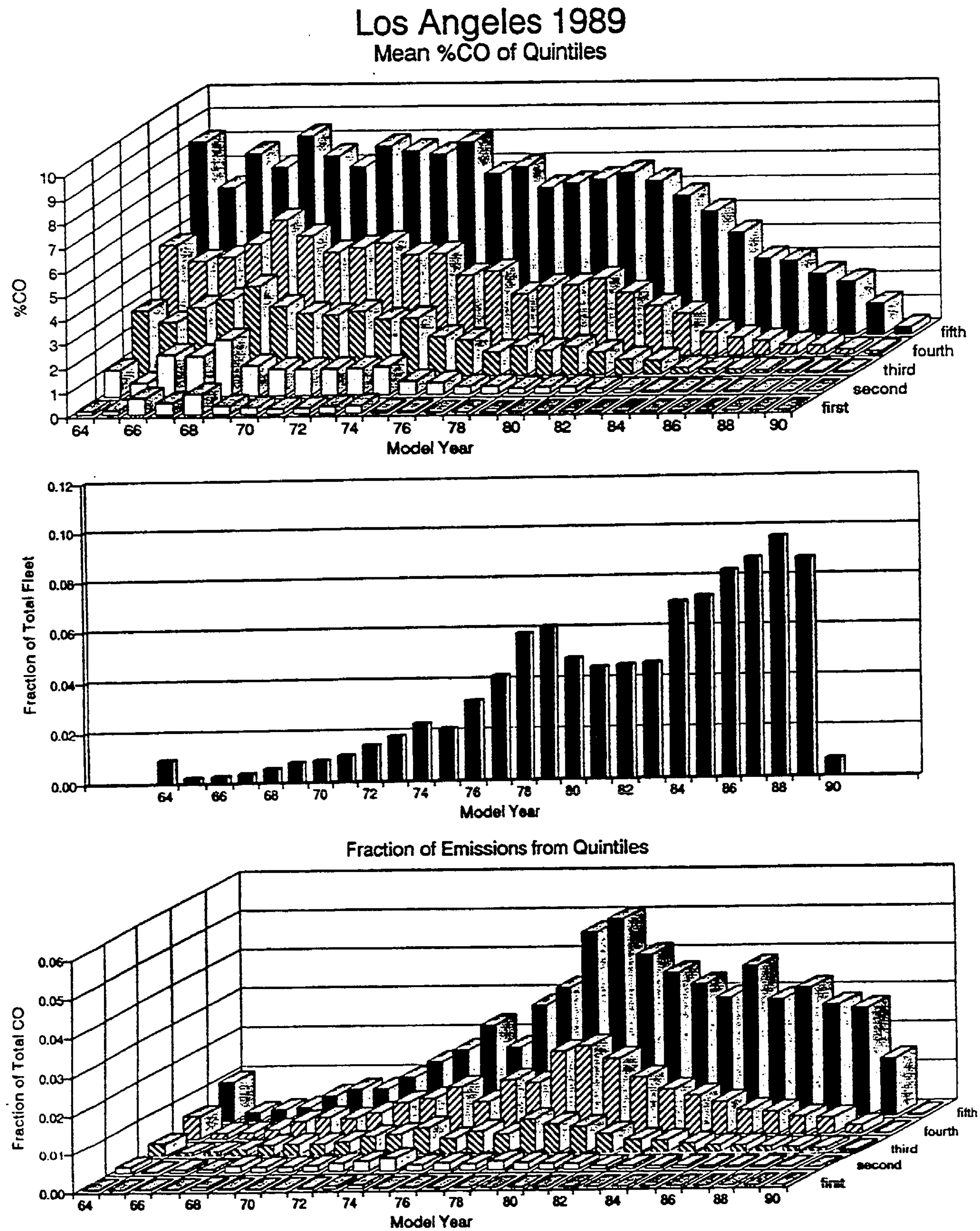

Figure 8. The Los Angeles data presented as, a) Emission factors by model year divided into quintiles, b) Fleet model year distribution and c) The product of graphs a and b. Note that the dirtiest 20% of 1976 models and newer dominates the total.

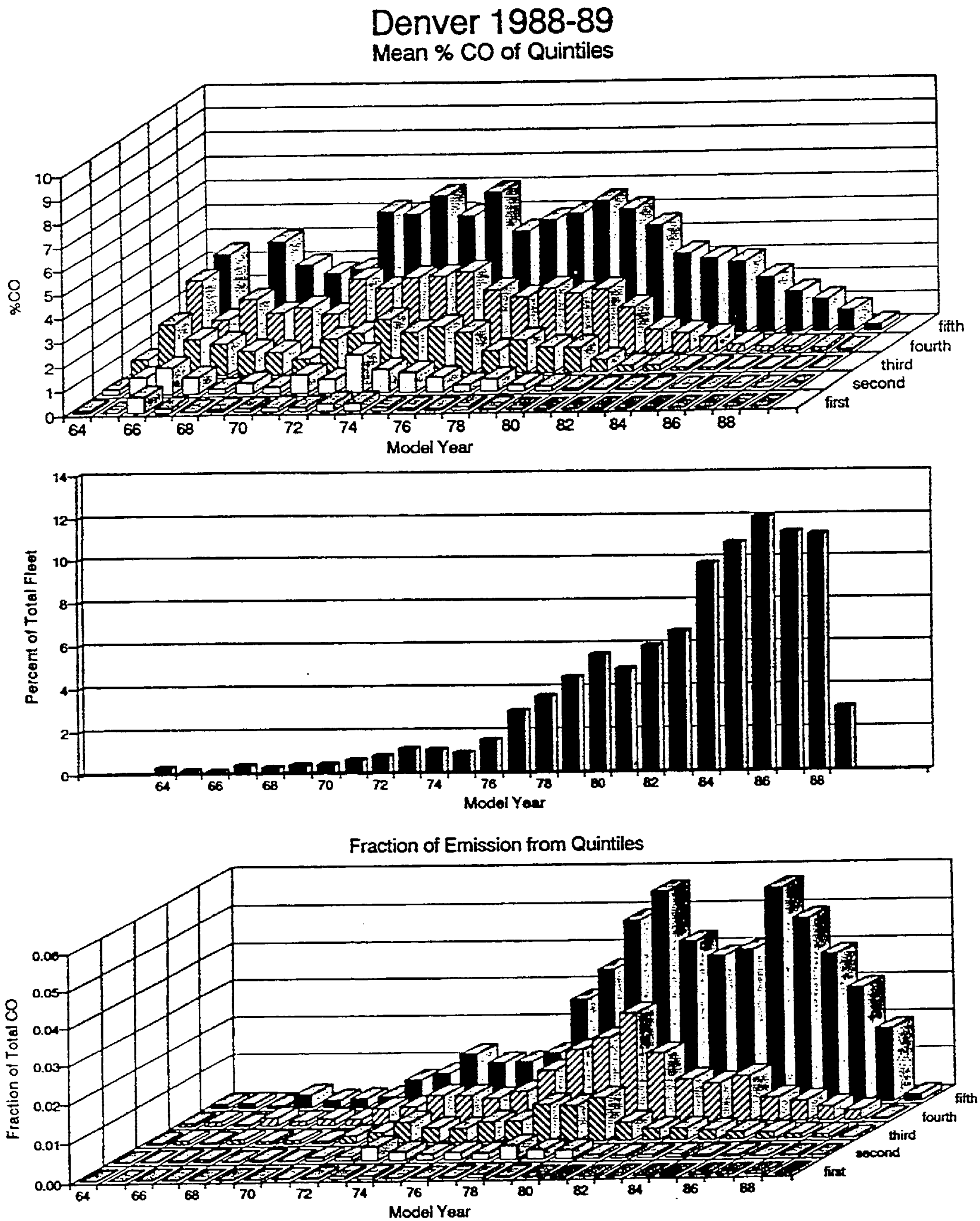

Figure 9. The same organization of plots shown in Figure 8 but for the Denver, CO data.

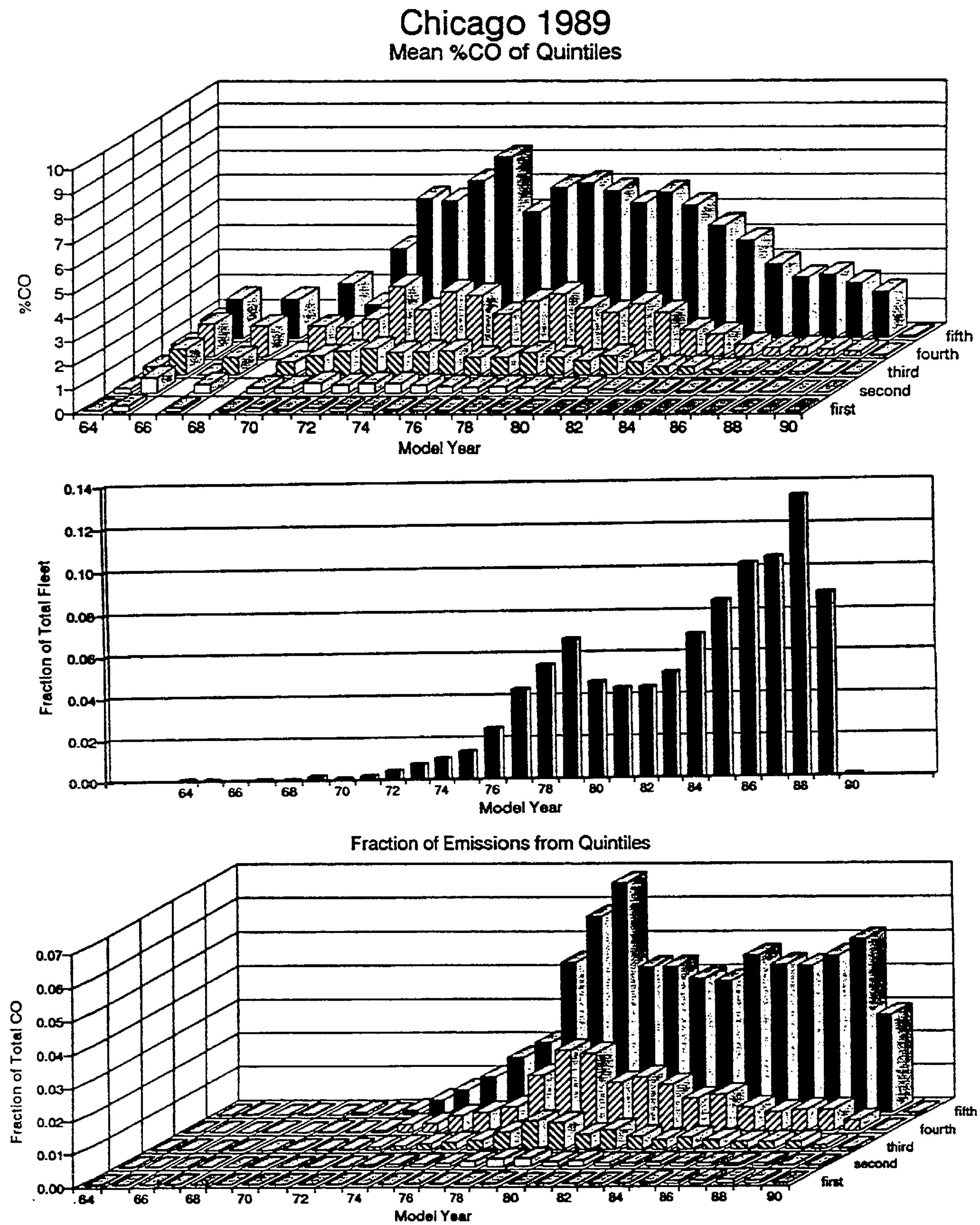

Figure 10. The same organization of plots shown in Figure 8 but for the Chicago, IL data.

Table III. Gross polluters (4.98 %CO and above) by approximate emissions control categories in Los Angeles, 1989.

MODEL YEAR CATEGORY	NUMBER OF GROSS POLLUTERS	NUMBER OF VEHICLES	PERCENT OF VEHICLES
89 - 90	15	1549	1
83 - 90	328	9004	4
81 - 82	196	1472	13
75 - 80	718	4277	17
74 & Older	504	1758	29

oldest vehicles are almost irrelevant to total fleet emissions because they are not numerous, and most new vehicles are irrelevant because they are low emitters. In all three cases the dirtiest 20% of the vehicles between two and twelve years of age stand out as the vehicles in most need of improvement. The quintiles show that even for the oldest vehicles the median emissions (almost equal to the third quintile illustrated) are quite a lot smaller than the emissions of the dirtiest quintile. On-road remote sensing can identify the gross polluting vehicles of any age or technology category which have emissions much greater than most other vehicles, even those of the same age or technology category.

There are very few vehicles in the Chicago fleet older than model year 1975. Thus the data become noisy and differences between fleets can not be resolved from the noise. Quintiles were not calculated for model years 1966 and 1968 where the total number of measured vehicles is less than five. The three fleets are very similar when compared in terms of the emissions of each model year. Denver is more variable but the sample size is smaller (4,909 total vehicles). Among the older vehicles, Los Angeles emissions are greater than Chicago or Denver.

The Chicago fleet shows the dirtiest quintiles of the 1-4 year old vehicles, noticeably higher than the same data from Denver or Los Angeles. That effect has been attributed to the fact that the single site used in Chicago is a straight uphill on-ramp, and is a location in which some vehicles will evidence "off cycle" or "power enrichment" emissions. Even at this site the contribution to the total fleet emissions from new vehicles in a power enrichment mode seems to be less than ten percent (R. Stephens General Motors, Private Communication March 1991). Note that the on-ramp emissions in Los Angeles discussed earlier when age corrected were noticeably larger then the corresponding off-ramp.

In summary, the major source of high CO in all three fleets is the dirtiest quintile of model years 1976 to 1988 vehicles. The observed differences both internal to the Los Angeles database and between Los Angeles and the other locations tested is the average age distribution of the tested fleet (Figures 7a - 7h). Driving mode and possibly altitude of the measurements when above 7,000 ft. show lesser effects. A linear model (equation 1) of CO emissions depending only on fleet average age has been derived which appears to predict fleet CO emissions from all measured US fleets except that at 7,500 ft to within ±0.5% CO The fraction of gross polluters rises from 1% of the 1989 and 1990 model year vehicles to 30% of the oldest vehicles. Most old vehicles (>70%) are not found in the gross polluting category. Note however that although the emission factors are similar for all three locations measured (Figures 8a, 9a and 10a), the older fleet in Los Angeles leads to a higher average %CO and a higher gross polluter cut point (five percent CO) than found in Chicago or Denver.

Repeat measurements of the same vehicle

5. Examine repeated measurements of the same vehicle at different times. What fraction of the vehicles are always clean, always dirty, or flip back and forth?

Only 77 vehicles were measured four or more times in the Los Angeles study when the GM test vehicles (Lawson et al. 1990) were removed from the analysis. These vehicles and their CO emissions are summarized in Table IV and listed in Appendix 2. The %CO readings are listed in order from the lowest on the left to the highest on the right. The vehicles are placed in three groups in order of decreasing variance of the %CO readings. The groups are defined as; lowest %CO reading greater than three (very dirty vehicles): lowest %CO reading greater than one (intermediate vehicles) and lowest %CO less than one (clean vehicles which might be new vehicles subject to power enrichment {off cycle emissions} at the instant of measurement). If the list is scanned for new vehicles in the last category two stand out, namely the 89 GMC and the 88 HOND. Peak power for many engines occurs at the air to fuel ratio corresponding to about 5%CO. The two vehicles identified show 6.2 and 3.6 %CO respectively as their highest readings. Some older vehicles appear to go much richer in their power enrichment mode. The 79 MAZD, 75 PONT and 82 FORD go to 11, 9 and 8 %CO respectively. Whether this high a reading is actually the peak power point for these vehicles or whether the power enrichment mechanism actually needs adjustment can not be determined.

At the University of Denver we define the term "gross polluter" to mean those vehicles that contribute half of the total measured CO emissions. In Chicago all measurements were at the same location. The gross polluter cut point (4.48 %CO) is site specific. For Los Angeles the gross polluter cut point (4.98 %CO) is a fleet average but dominated by the older fleet from six days in Lynwood. We also have a working definition of a clean vehicle as one measured with exhaust CO less than one percent (63% of the measured Los Angeles fleet). If one were to attempt a control program based on

Table IV. Vehicles which were measured four or more times at the various locations in Los Angeles 1989. (n=77)

CATEGORY	NUMBER OF VEHICLES	PERCENT OF 77	PERCENT OF EMISSIONS
Always clean <1%	33	43	4
>1% sometimes but never > 4.98%	20	26	18
> 4.98% only once	5	6	9
> 4.98% at least twice*	19	25	69
Totals	77	100	100
*Always > 4.98%	1	1.3	6.6

identifying those vehicles with emissions greater than the gross polluter cut point twice or more, then the newest vehicle which would be identified would be the 83 FORD for which the lowest CO emissions were 2.87 %CO.

Of these 77 vehicles 33 were consistently clean (<1%CO). These constitute 43% of the fleet and emit only 4% of the CO. At the other extreme one vehicle from among the "Gross at least twice" category was always in the gross polluting category. This vehicle emitted more CO than the 34 clean vehicles put together and was responsible for 6.3% of the total CO emissions. Twenty vehicles were occasionally over 1% but always less than 4.98 %CO. They constitute 26% of the fleet and emit 18% of the CO. Twenty four vehicles showed more variable emissions. Of these vehicles 19 were over the gross polluter cut point at least twice. This 25% of the fleet emitted 69% of the CO. Because the fleet of Los Angeles repeat vehicles is so small (< 100 vehicles) it is worth illustrating their similarity to the statistics of vehicles from Chicago. Table V summarizes a similar study in the Chicago area which was carried out at a single site only, and monitored a larger fleet of repeat vehicles.

As in Los Angeles, of the multiply-measured vehicles about half are always clean (less than 1 %CO whenever measured). These clean vehicles generate less than 10% of the total emissions. Vehicles measured as gross polluters at least twice are responsible for approximately half of the total CO emissions.

Table V. Vehicles measured four or more times in Chicago in 1989. (n=671)

CATEGORY	NUMBER OF VEHICLES	PERCENT OF 671	PERCENT OF EMISSIONS
Always clean <1%	425	63	9
>1% sometimes but never > 4.48%	113	17	18
> 4.48% only once	75	11	25
> 4.48% at least twice*	58	9	48
Totals	671	100	100
*Always > 4.48%	12	1.8	13

As will be discussed later, it can be shown that only a small fraction of the total observed emissions can be ascribed to cold start or to off-cycle hard accelerations which can lead to intentional fuel enrichment.

Video tape reading errors

There are several ways to check on the accuracy with which the video tapes have been read, and the accuracy with which the DMV records reflect the on-road fleet. A previous study in Colorado in which the video tapes were reviewed for positive identification showed that the proportion of misread tags and DMV errors was less than 1%. One way to flag potential plate reading or DMV errors is to look at vehicles whose emissions readings or whose registration status are not possible if the laws of California are being adhered to. There is a category of "dismantled" in the DMV records. Of the 50 vehicles (out of 18,836 submitted) reported in this category, all but one turn out to be misread plates, or plates with the alphanumerics correctly read, but not registered in California. The remaining vehicle's license was correctly identified.

Appendix 3 lists the vehicles identified as diesel in order of their CO emissions. This listing was utilized to provide a further check on the accuracy of the license plate transcription process. Since diesel vehicles are clearly a minority compared to their gasoline counterparts, their random interspersion would provide an excellent check for the entire database. One hundred of the diesel vehicles were searched for and located in the collection of video tapes and the license plate was checked for accuracy and the make/model of the car was compared against the DMV records. Only four vehicles were found to have been misidentified. Three were incorrectly typed in license plates from cars with difficult to read tags. The last vehicle's tag appeared to have been correctly read, however the DMV make was a Mercedes while the vehicle was obviously a Ford.

Inspection and maintenance

Only 32 vehicles were identified as registered in counties without an I/M program at the time of measurement. In view of the skewed statistics of vehicle emissions it is not possible to use so small a fleet to draw meaningful conclusions when comparing I/M to non-I/M fleets. When a similar study was carried out in Colorado there was much less difference between I/M and non-I/M fleets than predicted by the EPA computer models (Stedman et al., 1991).

It has been suggested (Austin et al., 1990) that the ten percent of the fleet which we observe to be gross polluters are in actual fact clean vehicles (as measured for instance by the FTP) which we find accidentally to be either in a cold start mode or engaging in an off-cycle acceleration and associated fuel enrichment. While these are valid criticisms, this and our previous data show conclusively that cold start and off-cycle emissions are small contributors to the total emissions. Figure 11 summarizes the results illustrated in more detail in Figure 8a. From Figure 11 it is apparent that the average emissions of new vehicles measured when new is small, and the median emissions from vehicles up to four years old are negligible. It is reasonable to assume that cold start and off cycle (power enrichment) emissions are just as likely to afflict new as old vehicles. It is therefore possible to determine a very conservative upper limit for the contribution of these two modes to the total emissions by assuming that **ALL** the emissions from the 1990 model year vehicles are a result of cold start and off cycle emissions. The average total fleet emissions for the Los Angeles database is 1.56 %CO The average 1990 fleet %CO is 0.232. This provides an upper limit of 14.9 percent of the total emissions which could possibly arise from off cycle or cold start operation. Similar results are obtained from Denver and Chicago.

This conclusion is based on a logical argument based on three assumptions:

1) It must be an overestimate to assume that ALL 1990 vehicle emissions arise from cold start and off cycle emissions.

2) It is reasonable to assume that cold start and off cycle emissions do not vary with model year.

3) If all model years are assigned the 1990 vehicle emissions this will be an overestimate of the total emissions arising from cold start and off cycle operating conditions.

There is no doubt that emissions vary with operating mode (Austin et al., 1988), but concentration (%CO or gmsCO/gallon) emissions are less variable than emissions per

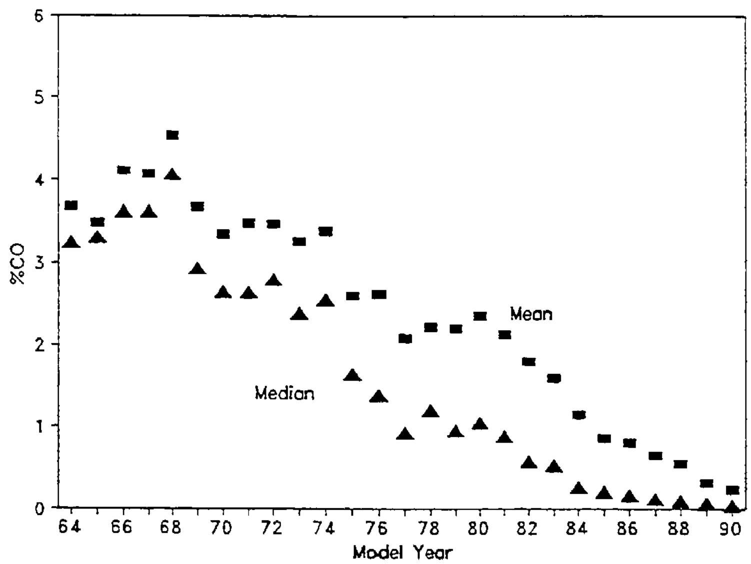

Figure 11. Mean (upper points) and Median (lower points) %CO emissions by model year from the Los Angeles database.

mile since they do not depend on the transmission selection, only on the engine air to fuel ratio and the emissions system status. Vehicles with variable emissions as measured by the remote sensor do contribute to the emissions picture, but if only those few vehicles which are frequently observed as gross polluters are required to undertake further testing and appropriate repair, then a large fraction (more than half of the current fleet emissions, see Tables IV and V) could be controlled. In view of the fact that most vehicles are measured consistently as clean, we believe that many of the variable emitters will be found to have some emissions related problem. The pilot study (Lawson et al., 1990) indicated when the remote sensor was used with a four percent CO cut point, the fleet identified thereby consisted of vehicles with almost a fifty percent tampering rate and a 91% I/M test failure rate. This result is all the more remarkable since Smith, (1988) has shown that I/M test scores of properly maintained vehicles are highly variable.

The emissions variability observed in this data set is similar to the emissions variability observed when vehicles are repetitively subjected to conventional I/M testing (Smith, 1988). These results imply that an inspection and maintenance program incorporating remote sensing, which targets gross polluters with multiple violations, has the potential to identify a significant fraction of the CO emissions while inconveniencing only a small fraction of the vehicle owners. Our analysis concludes that on-road remote sensing as a **component** of an I/M program has the advantages of being representative of the on-road emissions of the vehicle in question, being an emissions test which is almost impossible to circumvent, and incorporates a "fairness factor" such that the more a vehicle is driven, the more frequently it will be tested. On road remote sensing can be carried out at a per-test cost and at a vehicle throughput at least ten times more advantageous than any other type of I/M program.

Emissions characteristics segregated by vehicle make

Altogether the remote sensing data for CO available to the University of Denver amounts to over 35,000 records collected from Los Angeles, Denver and Chicago. With a database this size it becomes possible to analyze the emissions from various segments of the fleet without losing statistical significance. The first analysis of this type considers the effect on CO emissions of the continent of origin of the vehicle fleet. In this analysis the continent of origin is derived strictly from the maker's name. No attempt has been made to separate vehicles made in the USA by manufacturers outside the USA, thus all Renault and Volkswagen are classified as European, all Honda, Toyota and Subaru as Asian, all Ford, GM or Chrysler are treated as US wherever manufactured. Figure 12 shows the results of this analysis. The line labelled "ALL" is the overall weighted regression discussed earlier. The points are the fleet averages labelled by the location of measurement (L, D, C) and the origin of make (A, U, E). For all three fleets the same pattern emerges. In each case the Asian manufactured fleet is newer and for that reason lower in average %CO than the US fleet from the same location. In each case the European manufactured fleet stands out as falling below the regression line (i.e. cleaner) than the US fleet even though there is no consistent trend as to whether the European fleets are on average older (Denver) or newer (Chicago) than the US fleets.

The Los Angeles fleet has been further segregated in order to investigate the cause of the relationships shown in Figure 12. Figure 13 shows the data coded by the same symbols (A, U, E) as a function of model year of registration. As discussed earlier, the new vehicles are on average quite clean. Furthermore, there is no evidence of significant differences in the emissions of the new fleet depending on their continent of origin. For vehicles from one to six years old the Asian manufactured fleet appear systematically as the dirtiest on this graph. It is important to note that the gas mileage of the Asian fleet is higher on average than the US fleet, thus higher emissions in %CO or in the equivalent gm/gallon units may not in every case correspond to a higher fleet average in gm/mile units (Stephens and Cadle, 1990). For vehicles registered as 1974 and older the data lose significance because the total numbers of vehicles in the database are too small to make meaningful distinctions. For the fleet manufactured between 1975 and 1983 the US manufactured vehicles stand out as having the highest emissions in %CO or gm/gallon units. In per-mile units they would stand out even further, particularly in the 1980 to 1982 model years. For all model years from 1975 to 1989 the European manufactured fleet is the cleanest.

ORIGIN OF MAKE
All Record Regression

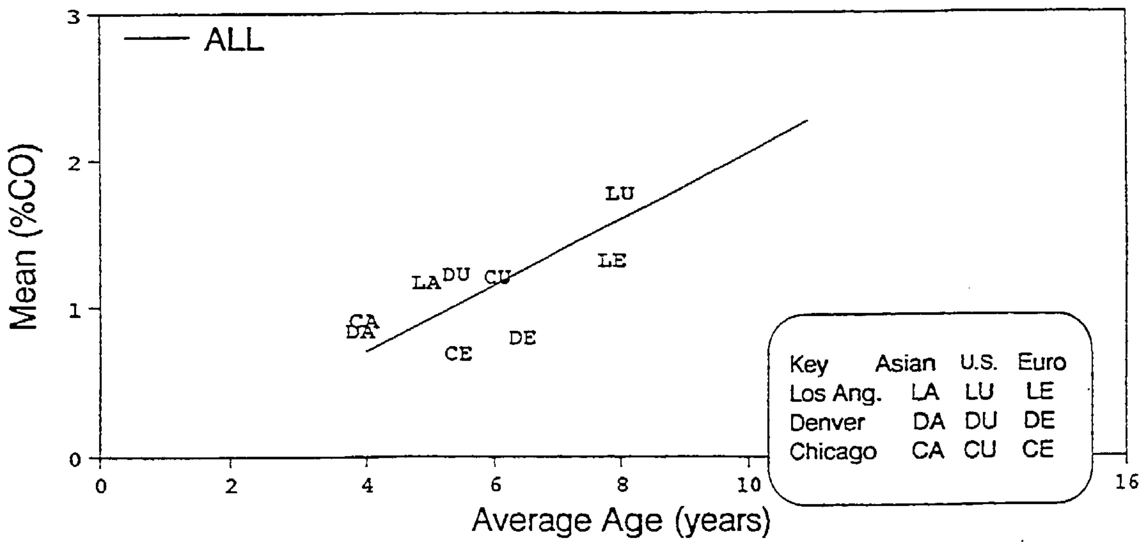

Figure 12. A plot of Mean %CO versus average fleet age based on origin of production, Asian, US, or European. The regression line drawn was previously determined in Figure 7b.

Since the 1990 fleets from different origins all have the same low emissions, and since the average emissions of all fleets is dominated by a small percentage of dirty vehicles, we believe that the differences over time are caused by maintenance factors. There are two factors affecting maintenance, the owner's willingness to pay for required maintenance, and the manufacturer's ability to provide a vehicle which either requires little maintenance, or can be easily maintained when maintenance is required.

One further analysis attempts to differentiate between these factors. The entire US database has been searched for vehicles with the maker's names Ford (>4,000), Chevrolet (>6,000) and Cadillac (>1,000 vehicles). All vehicles with these names are included regardless of whether the vehicles are listed as pickups or as passenger vehicles. Figure 14 shows this analysis again as a function of model year. In the Los Angeles data the model years 1980-1982 stood out as showing the US fleet to be particularly high emitters. For two of those years the Ford fleet appears to be significantly higher emitting than the Chevrolet fleet. For other model years the differences are not as important, although Ford CO emissions are most often larger than Chevrolet. What does stand out from this graph is that average Cadillac emissions are almost always the lowest, often less than half the Ford/Chevrolet group. Since the new vehicle average %CO emissions are both small and similar for all fleets the inclusion of pickups in the Ford and Chevrolet fleets would not appear to be the cause of the large differences in the 1980-1986 time frame. Since the average emissions are again dominated by the number of gross polluters, we ascribe the differences again to

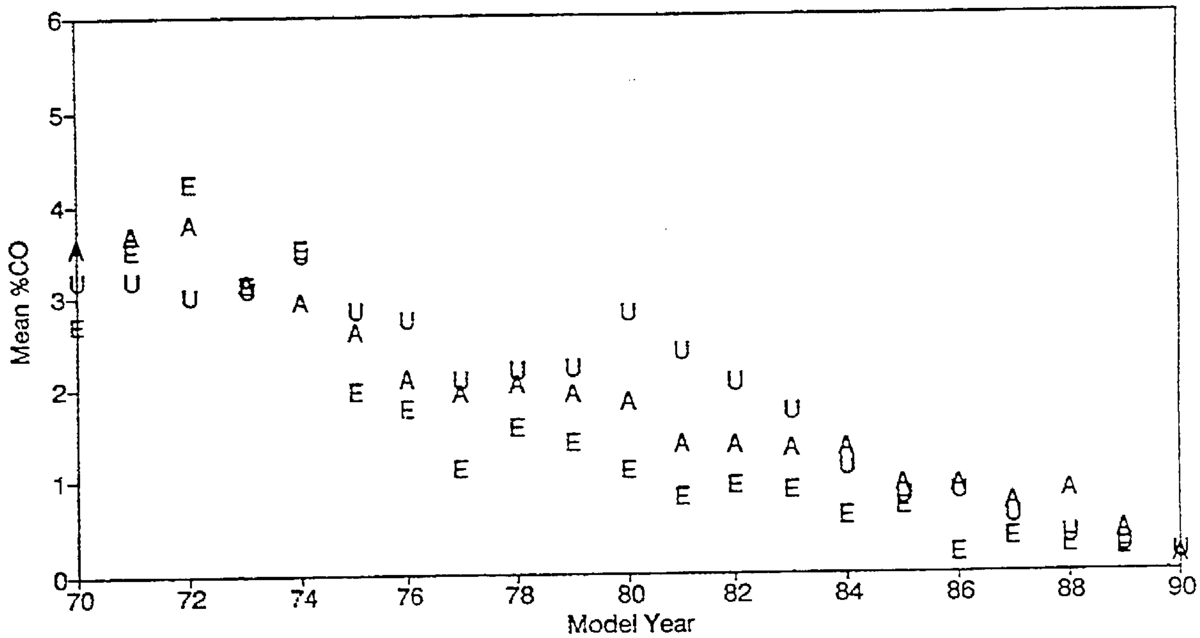

Figure 13. A plot of Mean %CO versus Model year for the Los Angeles data segregated according to origin of production. Asian (A), US (U) and European (E).

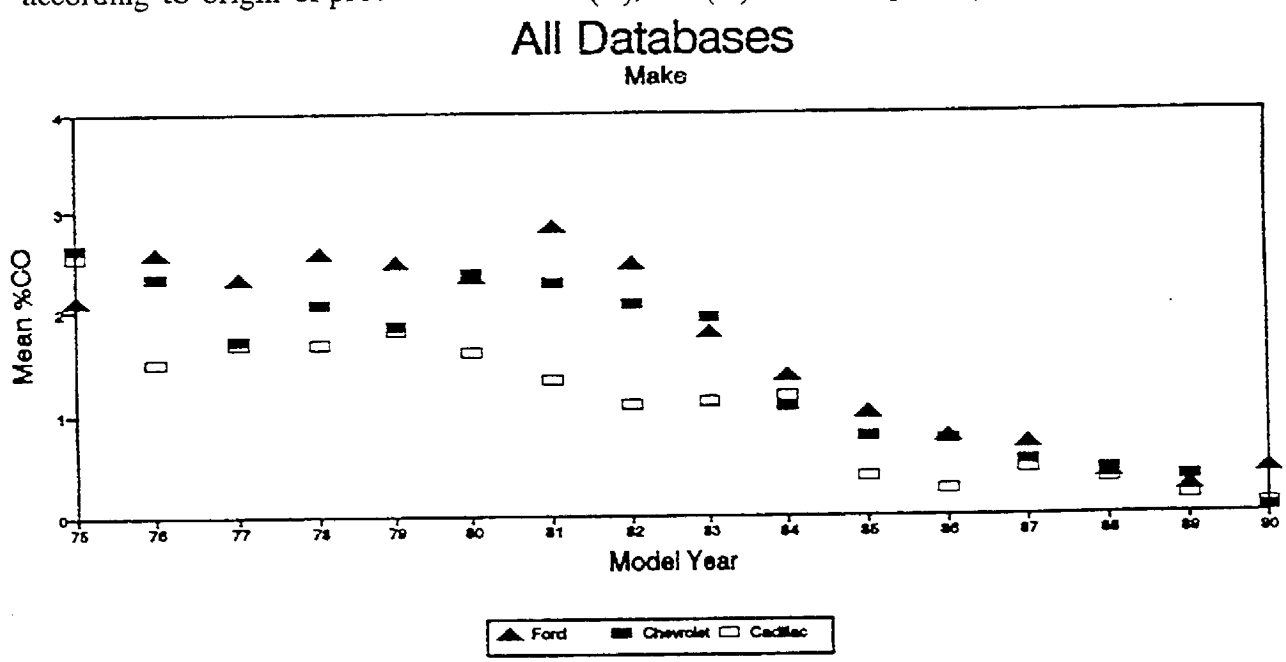

Figure 14. A plot of Mean %CO versus Model year for Fords (triangles), Chevrolets (squares), and Cadillacs (open squares) obtained from all of the US data sets.

maintenance. We believe that owners who have spent more money initially to purchase a vehicle are more likely to spend the money required to maintain the vehicle, hence

Cadillacs with fewer gross polluters than Chevrolets. This is observable despite the diesel to gas engine switching discussed below, which affects Cadillacs but not Chevrolets. To the extent that many of the European manufactured vehicles are also in the higher price range when new, their lower average emissions may also be ascribable to the fact that their owners are willing to spend the money necessary for proper maintenance.

We have analyzed the Los Angeles data base to compare 87-89 model Ford, Chevrolet, Toyota, Honda and Nissan with Hyundai. In this comparison the average %CO emissions for all but Hyundai are less than 0.55% while the Hyundai's average is more than 1.6 %CO. Although most 1987-89 Hyundais were measured at less than 1 %CO, a larger than expected fraction are observed with higher emissions. It is possible that this problem is not maintenance related, and represents a problem caused by the manufacturer.

Based on on-road emission studies in London, Toronto and Mexico City, there can be no doubt that Federal New Vehicle Emission Standards have caused a dramatic reduction in fleet emissions. This reduction is the reason that all new and most older vehicles in the US and Canadian fleet are consistently very low emitters regardless of make or country of origin. In view of the fact that high CO emissions are dominated by a few badly maintained gross polluters, and that there is no evidence that the fleet average on-road emissions show any evidence of major breaks due to changes in technology or changes in new vehicle emission standards, we believe that further analysis based on maker or technology classification is not warranted. If these analyses are correct there is still considerable room for improvement in average on-road CO emissions of the current USA fleets as measured by on-road remote sensing, provided that the required maintenance is correctly performed and illegal emissions system tampering eliminated.

Vehicles registered as diesel powered

Appendix 3 gives a tabular listing of all of the vehicles which the Department of Motor Vehicles has registered as diesel powered. As can be seen a number of these vehicles are high emitters. With the exception of some trucks which display a diesel logo on their front grills it is impossible from the video tapes to positively identify whether a vehicle is gasoline or diesel powered. One of these vehicles is the 1984 GMC pickup which was measured on La Cienega Blvd. at 8.09 %CO and was positively identified to have switched its engine to a gasoline powered engine (Lawson et al., 1990). Considering the probabilities of finding such a vehicle in only two days of testing, it can be concluded that this type of vehicle (GM diesel switched to gas) exists in sizable numbers in the Los Angeles basin. With this in mind all of the diesel vehicles which registered readings above 2% CO were organized according to make. Out of 47 vehicles, 39 or ~80% were General Motors products, mostly 79 - 82 model year

Oldsmobiles, Buicks and Cadillacs. These are vehicles for which it is very easy to insert a gasoline engine to replace the originally installed diesel. The California diesel exemption from the Smog Check program provides an incentive not to report the engine switch.

An examination of those vehicles registered as FUEL = "D" show values that are inconsistent with the known emissions from dynamometer measured diesel engines. The high compression, excess air and operating temperatures in diesel engines minimize the emission of CO in the exhaust. The question arises as to the probability that the anomalous 1979-1982 GM manufactured "diesel" fleet contains some vehicles whose engines have been exchanged and the DMV has not been notified of the engine switch.

In order to address a formal statistical answer to this question we defined the 1979-82 GM diesel fleet (GMD) as all 65 vehicles regardless of CO emissions which were identified as manufactured by GMC and powered by diesel engines. The first test is to determine whether this fleet is statistically different from the other vehicles registered as having diesel engines. The Cumulative Distribution Function (CDF) for the GMD fleet was compared with the CDF of other assumed pure diesel fleets using the Kolmogorov-Smirnov (K-S) Q-statistic (Press et. al., 1989 and von Mises, 1964). This analysis yields a probability that the two subsets could be random subsets of a single parent population. Figure 15 shows a plot of the CDF of all the above diesel subfleets and the CDF of the total LA90 fleet. There is 0% probability that the GMD fleet has a common parent population with any diesel subfleet that does not contain the vehicles in question. The GMD fleet is not only higher emitting than the other diesel labeled fleets but is obviously much dirtier than the LA90 fleet as a whole.

What fraction of the 65 GM diesel vehicles have probably had an engine exchange? To answer this question we make the following assumptions.

1. The GMD fleet contains some diesel powered vehicles.
2. These diesel vehicles resemble the fleet of all non-GM diesels in emissions.
3. The GMD fleet contains some gasoline powered vehicles.

The final assumption revolves around the question as to the emission distribution of gasoline powered subset to be merged with the diesel vehicles to match the GMD emission distribution. There is no incentive to add emission controls as long as the engine switch is not reported to the DMV and since there is a cost incentive not to install pollution controls it is therefore assumed that the exchanged engines have no emission controls. Since the diesel fleet has lower emissions than the GMD fleet, the gasoline fleet must be dirtier than the GMD fleet. Several sub-fleets were compared to the GMD fleet to find one suitable for mixing with a diesel fleet. The fleet of all Volkswagens older than 1982 is cleaner than the GMD fleet and therefore not usable. The fleet of all cars with model year from 1965 to 1975 is very similar to the GMD fleet and therefore still not usable. The fleet of cars with model years from 1955 to 1970 is

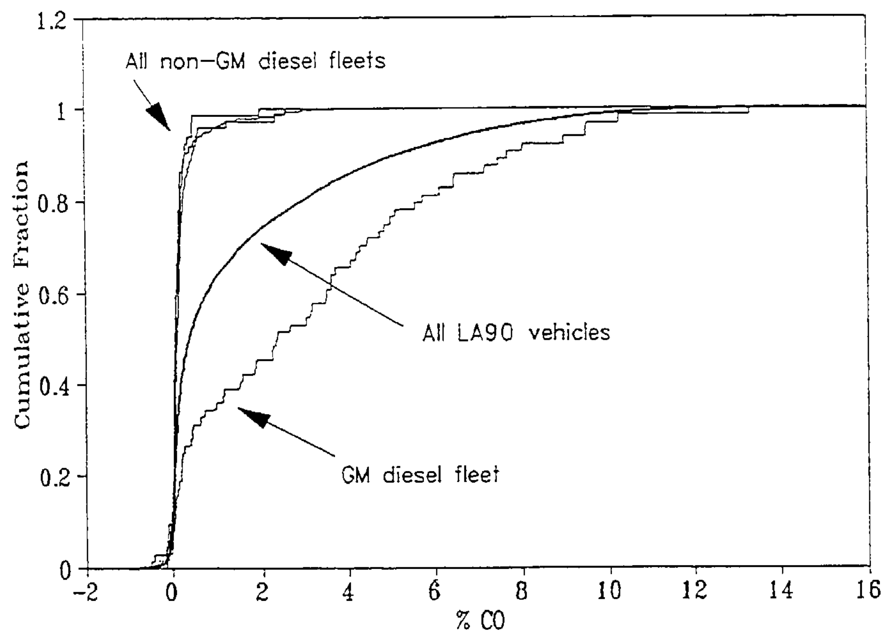

Figure 15. A plot of the CDF for the total LA90 fleet and various sub-fleets showing the relationship of the 1979-1982 GM diesel fleet. The All non-GM diesel fleet includes sub-fleets such as Ford, Mercedes Benz and all medium duty diesels.

suitable for mixing. These vehicles have no emission control devices and there are few incentives for extraordinary maintenance on these old vehicles. Our final assumption is then:

4. The "engine switched" vehicles resemble the fleet of 1955-1970 cars.

A model fleet was derived using X percent 55-70 cars and (100 - X) percentage from the non-GM diesel fleet. X represents the percentage of vehicles with engines exchanged. Again using the K-S statistic, X was adjusted to maximize the K-S probability that the model fleet and the GMD fleet came from the same parent population. A mixture of 77 percent 55-70 cars with only 23 percent diesels gave a model fleet with >99% probability of single parent population (Figure 16). All non-GM diesel fleets include fleets from Chicago and Toronto. Many heavy duty diesel powered vehicles have elevated exhaust systems and are thus infrequently observed by the current FEAT system. For this reason the observed diesel fleets at all locations are mostly the light and medium duty vehicles with exhaust pipes emitting at a level comparable to the FEAT light beam.

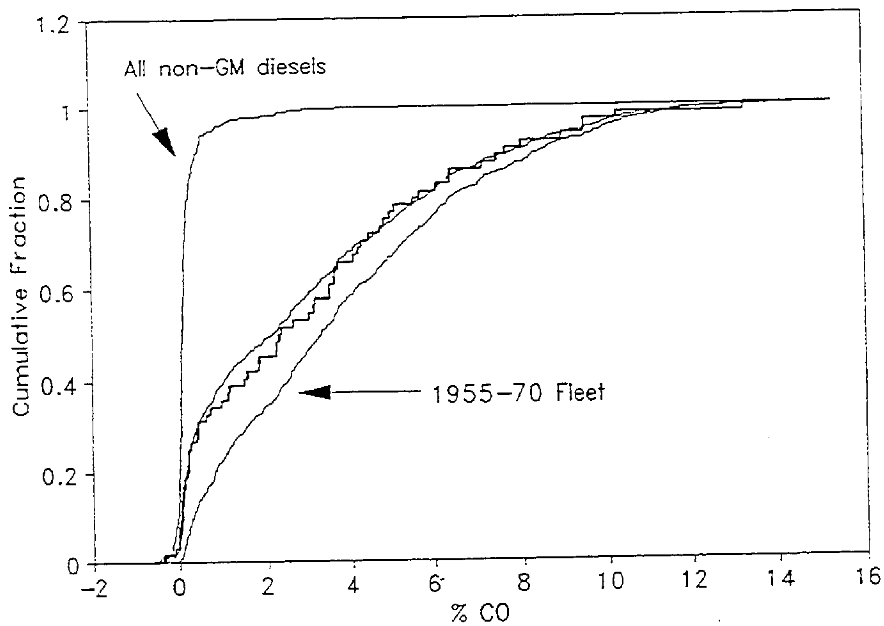

Figure 16. The two parent populations bracketing the model fleet (thin line) showing it similarities to the GMD fleet (thick line). Max P(K-S) > 99.5% for N(gas)=500, n(GMD)=65; Fraction(gas)=0.773.

This statistical analysis implies that 77% of the cars identified as GMD are not diesels. For this percentage to be lower, a dirtier gas fleet must be used for modeling. An unmentioned reason for choosing 1955-70 cars is that they are the dirtiest subfleet found. To imply that the percentage of engine exchange is less than 77% means that those cars that have had engine exchanges are dirtier as a group than any other identifiable sub fleet in the LA90 database. On the other hand, if the exchanged vehicles are cleaner than the 1955-70 fleet, the percentage of engine exchanged vehicles will increase. A 60 - 80% "engine switch" rate would be a statistically justifiable estimate within a 95% confidence. Even though the 1979-1982 GMD fleet only contains 65 vehicles, we believe that this analysis implies that over half of all vehicles registered in this category in LA county are likely to have switched their engines and neither installed emission controls nor informed the proper authorities.

REFERENCES

Lowell L. Ashbaugh, Bart E. Croes, Eric M. Fujita, Douglas. R. Lawson. "Emission Characteristics of California's 1989 Random Roadside Survey", Presented at the North American Motor Vehicle Emission Control Conference, Tampa Florida, December, 1990.

Thomas C. Austin, H. Anthony Ashby, and Thomas R. Carlson. "An Evaluation of Loaded Mode I/M Testing at Service Stations", Sierra Research Report #SR88-12-02, 1988.

Thomas C. Austin, Thomas R. Carlson, and Kathryn A. Gianolini. "An Evaluation of 'Remote Sensing' For The Measurement of Vehicle Emissions", Sierra Research Report #SR90-08-02, 1990.

Gary A. Bishop, John R. Starkey, Anne Ihlenfeldt, Walter J. Williams, and Donald H. Stedman. "IR Long-Path Photometry, A Remote Sensing Tool For Automobile Emissions", Anal. Chem.,**61**, 671A-677A, 1989.

Gary A. Bishop and Donald H. Stedman. "Oxygenated Fuels, A Remote Sensing Evaluation", Society for Automotive Engineers, Technical Paper, Series #891116, 1989.

Gary A. Bishop and Donald H. Stedman. "On-Road Carbon Monoxide Emission Measurement Comparisons for the 1988-1989 Colorado Oxy-Fuels Program", Env. Sci. & Tech., **24**, 843-847, 1990.

EPA Field Operations and Support Division. "Motor Vehicle Tampering Survey 1989" EPA Office of Air and Radiation, May 1990.

Douglas R. Lawson, Peter J. Groblicki, Donald H. Stedman, Gary A. Bishop and Paul L. Guenther. "Emissions from In-use Motor Vehicles in Los Angeles: A Pilot Study of Remote Sensing and the Inspection and Maintenance Program", J. Air Waste Manage. Assoc., **40**, 8, 1990.

Richard von Mises. "Mathematical Theory of Probability and Statistics", Academic Press, NY., 1964.

Ronald L. Ostop and Lester T. Ryder. "Ute Pass Carbon Monoxide Emissions Study", Final Report to the City of Colorado Springs, CO, 1989.

William H. Press, Brian P. Flannery, Saul A. Teukolsky and William T. Vetterling. "Numerical Recipes in Pascal", Cambridge University Press, NY., 1989.

Lawrence R. Smith. "Variability of I/M Test Scores Over Time", Final Report EPA 460/3-88-008, 1988.

Donald H. Stedman. "Automobile Carbon Monoxide Emission", Env. Sci. Tech., **23**, 147-149, 1989.

Donald H. Stedman and Gary A. Bishop. "Remote Sensing for Mobile Source CO Emission Reduction", Final Report EPA 600/4-90/032, 1991a.

Donald H. Stedman and Gary A. Bishop. "An Analysis of On-Road Remote Sensing as a Tool for Automobile Emissions Control", Final Report Illinois Department of Energy and Natural Resources ILENR/RE-AQ-90/05, 1990b.

Donald H. Stedman, Gary A. Bishop and James E. Peterson. "On-Road Remote Sensing and Motor Vehicle Inspection and Maintenance Programs", In press, 1991.

Robert D. Stephens and Steven H. Cadle. "Remote Sensing of Carbon Monoxide Emissions", J. Air Waste Manage. Assoc., **41**, 39-46, 1991.

Mark A. Wolcott and Dennis F. Kahlbaum, "Control of Air Pollution form New Motor Vehicles and New Motor Vehicle Engines. Interim Regulations for Cold Temperature Carbon Monoxide Emissions from Light Duty Vehicles and Light Duty Trucks. Notice of Proposed Rule making. Air Quality Analysis", August 17, 1990.

ACKNOWLEDGEMENTS

This project would not have been possible without the support, encouragement and participation of many individuals from the California Air Resources Board, local traffic control officials, and several other organizations and individuals who assisted us with the on-road arrangements and the license plate analysis.

APPENDIX 1

Emissions from In-use Motor Vehicles in Los Angeles: A Pilot Study of Remote Sensing and the Inspection and Maintenance Program

Douglas R. Lawson
California Air Resources Board
Sacramento, California

Peter J. Groblicki
General Motors Research Laboratories
Warren, Michigan

Donald H. Stedman, Gary A. Bishop and Paul L. Guenther
University of Denver
Denver, Colorado

As part of a major field study to understand the causes of persistent, elevated carbon monoxide pollution episodes in Los Angeles, we performed a project to understand the emissions of vehicles in use. In this experiment, we assessed the accuracy of a remote sensing instrument designed to measure CO concentrations from vehicles as they were driven on the road. The remote sensor was shown to be accurate within ten percent of the directly measured tailpipe value. We performed a roadside inspection on 60 vehicles and demonstrated that the remote sensor could be used as an effective surveillance tool to identify high CO-emitting vehicles. We also compared the roadside data set to the biennial Smog Check (I/M) tests for the same vehicles, and observed that carbon monoxide and exhaust hydrocarbons from high emitters were much higher than when the vehicles received their routine inspection. Furthermore, for the high-emitting vehicles in this data set, the length of time since the biennial Smog Check had little influence on the cars' emissions in the roadside inspection.

California's air pollution control program has been a dynamic one, serving as a pioneer for both Federal and state regulations. It began with the passage of the Stewart Act in 1947, which allowed counties in the State to create air pollution control districts. In 1967, the Mulford-Carrell Air Resources Act, which was signed into law by Governor Ronald Reagan, created the California Air Resources Board (ARB). As required by law, the ARB has been given the responsibility for the control of emissions from mobile sources.[1] Because of the severity of the air pollution problem in California, the ARB received waivers from the Federal government to establish its own emission standards for motor vehicles, and through the years, has established new car standards and assembly line test procedures for vehicles to be sold in the State. As a result of these regulations, air quality in California has improved in many areas, despite the pressures of growth in population and vehicle miles traveled.

Emission inventories show that mobile sources are responsible for 54, 76 and 97 percent of the reactive hydrocarbons, nitrogen oxides and carbon monoxide, respectively, in the Los Angeles Basin, as compared with 45, 72 and 68 percent for the Statewide inventory.[2] In order to assure the proper maintenance of motor vehicle emission control systems, California inspects pollution control systems on cars through its inspection and maintenance (I/M) program, called Smog Check. The Smog Check program, which began in 1984, is required in most of California's nonattainment areas and is administered and enforced by the State Bureau of Automotive Repair (BAR). The California Smog Check is required every two years, is performed at private garages, and consists of a three-part test: a visual, under-hood examination; a functional check of certain emission control systems; and a computerized tailpipe emissions measurement of exhaust hydrocarbons (HC) and carbon monoxide (CO). If the vehicle passes the Smog Check, the owner is issued a Smog Check certificate, which is required for vehicle registration. If the vehicle fails the inspection, repairs are required as long as costs do not exceed specified limits. Through 1989, the cost limit for all vehicles in California was $50. California's revised Smog Check program, which began January, 1990, increases the repair cost limits in amounts up to $300 depending upon model year. Among other things, the revised program includes new emissions analyzers and improved training and qualification criteria for Smog Check mechanics.

In December, 1989, a major field study sponsored by the ARB, the South Coast Air Quality Management District (SCAQMD), and the General Motors Research Laboratories (GMRL) investigated the reasons for persistent carbon

Reprinted from Journal of the Air & Waste Management Association, Vol. 40, No. 8, August 1990

monoxide pollution episodes in the Lynwood area of Los Angeles. As part of this study, we used remote sensing measurements of vehicle tailpipe CO concentrations and roadside inspection surveys to assess the emissions of vehicles in use under "real world" conditions. We were interested in testing the ability of remote sensing to quantify CO emissions from vehicles and to evaluate remote sensing as a possible tool for identifying vehicles with high CO emissions. We also compared the roadside inspection results with previous measurements made on the same vehicle during the required Smog Check program in order to provide additional information about emissions from the highest emitting vehicles.

A simple calculation shows that, for a hypothetical case, a vehicle that continuously emits seven percent CO and averages 10 mpg would emit about 300 g/mi of CO. Under the same conditions, a 0.5 percent CO vehicle averaging 30 mpg would emit about six g/mi. Therefore, using the conditions specified in this calculation, the CO emissions from one seven percent vehicle equal those from about 50 low-emitting 0.5 percent vehicles under the same operating conditions. For this reason, we were particularly interested in studying the characteristics of high CO-emitting vehicles, because previous studies showed that the highest emitting vehicles (about ten percent) accounted for about half of the CO emissions.[3–5]

Experimental

The Remote Sensing System

In this experiment we used an infrared, remote monitoring system to measure tailpipe CO emissions. This system, called the FEAT, for Fuel Efficiency Automobile Test, was developed at the University of Denver[6] with initial support from the Colorado Office of Energy Conservation. The system derives its name from the fact that fuel economy improves if rich-burning (high CO) vehicles are tuned to a stoichiometric (and efficient) air/fuel ratio. The FEAT measures the CO/CO_2 ratio in the exhaust of vehicles passing through an infrared light beam transmitted across a single lane of traffic. The emissions of a single car can be measured in less than one second at vehicle speeds as high as 60 mph.

The infrared source emits a beam of radiation 10 inches above road level, which is split in the receiver into three channels having wavelength-specific detectors for CO, CO_2 and a reference signal. Data from all three channels are fed to a computer, which converts the radiation absorbed by CO and CO_2 into the CO/CO_2 ratio (Q). A lean or stoichiometrically operating engine and emission control system will have a Q near zero, whereas Q greater than zero indicates operation on the fuel-rich side of stoichiometry. By using our knowledge of combustion chemistry, we can determine many parameters of the engine/emissions control system, including the instantaneous air/fuel ratio, grams of CO emitted per gallon of gasoline burned and the volume percent CO which would be read by a tailpipe probe (if the probe readings are corrected for the presence of water and excess air in the emissions). CO concentrations measured by the FEAT are most frequently reported as volume percent CO, since vehicle owners and mechanics are familiar with the tailpipe probe readings carried out in conventional I/M programs.

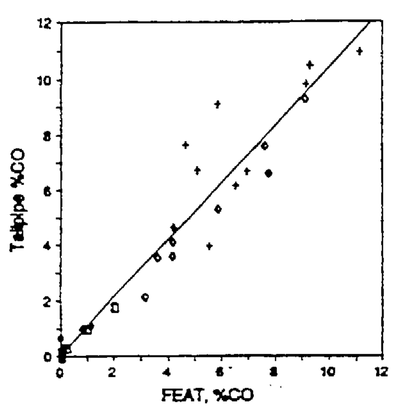

Figure 1. Comparison of tailpipe CO concentrations measured by an on-board analyzer and by remote sensing. □: data of 12/8/89 (n = 6); +: data of 12/11/89 (n = 14); ◇: data of 12/13/89 (n = 14). The equation of the regression line is [Tailpipe %CO] = 1.03[FEAT %CO] + 0.08, with r = 0.97.

We performed quality assurance calibrations each day with three certified $CO/CO_2/N_2$ gas mixtures (Linde, Denver, Colorado and Scientific Gas Products, Longmont, Colorado), with CO/CO_2 ratios of 1:12.1, 1:1, and 4.96:1. These values correspond to a low CO-emitting car (~1.3 percent CO), a high-emitting car (8.5 percent CO), and a super-emitting car (17 percent CO). The FEAT responses were fitted to a straight line, the slope of which was used to correct the vehicle exhaust measurements. The correction applied to observed CO/CO_2 ratios was less than ten percent each day.

We recorded images of the front license plates of all the vehicles using a freeze-frame video system incorporated into the FEAT. We used the license plate information to determine make and model year of the vehicles in later analyses and verified the data by visual inspection of the video tape vehicle images.

Vehicle Instrumentation

In order to assess the accuracy of the FEAT, we used a production model 1989 Pontiac SSE equipped with a 3.8 L "3800" engine with sequential, multiport fuel injection and a three-way catalyst. The Pontiac had been driven about 17,000 miles at the time of the study. We operated the vehicle on unleaded regular gasoline, purchased at local retail outlets.

As part of a larger system designed to measure CO, CO_2, and HC emissions while driving, we equipped the car with a nondispersive infrared (NDIR) analyzer (Horiba MEXA) that measured the CO concentration in the exhaust gas leaving the tailpipe. An Acro-400 datalogger from ACROSYSTEMS Corporation digitized the signal from the NDIR. The datalogger was connected via an RS232 interface to a Toshiba 3200 laptop computer, located on the front passenger seat of the vehicle. A battery bank and inverter, located in the trunk of the car, provided power for the instrumentation.

Recently manufactured GM vehicles are equipped with an "Assembly Line Diagnostic Link" (ALDL) over which vehicle operating parameters can be obtained from the engine control computer. Parameters such as vehicle speed and engine rpm were obtained from the engine control computer over the ALDL and fed into a second serial port of the laptop computer. A program written in Quickbasic controlled the merging of data from the datalogger and the engine control computer. Tables of data were displayed in real time as well as stored on the internal hard disk of the laptop computer.

The ALDL on the Pontiac was a bidirectional link, allowing messages from the laptop computer to change a limited number of parameters in the engine control computer algorithm. Of special usefulness to this study was the capability to cause the engine to run in an open-loop mode at a modified air/fuel ratio. By pressing special function keys on the laptop computer keyboard, we could change the air/fuel ratio and hence the concentration of CO in the exhaust gas of the Pontiac.

We calibrated the on-board NDIR analyzer daily by using CO-free nitrogen and known concentrations of CO in nitrogen. The ARB Mobile Source Division provided quality assurance analysis of the CO standards, and found that the gas concentrations were within 2.3 percent of the nominal cylinder values. We verified the linearity of the CO analyzer by multipoint calibration using a gas divider (Standard Technology, Inc., SGD-78) to dilute the standard gas. In order to compensate for small misadjustments of the on-board CO analyzer, we multiplied the indicated CO reading by the ratio of the expected response of the analyzer to the actual response of the analyzer to the standard gas. Because we used an ice trap to remove most of the water from the exhaust gas sample stream before analysis by the NDIR, the readings of the on-board CO analyzer were expected to correspond directly to the values measured by the FEAT, which are corrected for water in the exhaust.

Comparison of Remote Sensing and On-Board CO Measurements

In order to investigate the accuracy of the FEAT, we drove the Pontiac through the cross-roadway infrared beam on a surface street in the Lynwood area in Los Angeles on December 8 and 11, 1989. An in-car observer from ARB recorded the tailpipe CO concentration measured by the on-board CO analyzer as the car crossed the FEAT infrared beam.[a] The observer then would choose an air/fuel ratio for the next pass while the car was driven back to the starting point for the next pass. Neither the driver nor the FEAT operator knew beforehand what the tailpipe concentrations would be in this double-blind experiment. At the end of the six runs on December 8 and the 14 runs on December 11, the observer obtained the CO concentrations measured by the FEAT for comparison. On December 13 we obtained our most stable operating conditions: the vehicle was operated with cruise control in 14 runs on a freeway on-ramp in the Lynwood area. The December 13th runs were not performed in a strict double-blind mode, since the in-car observer was from the University of Denver research group. Vehicle speeds on the three days ranged from ~15 to 50 mph in these comparisons.

We corrected the FEAT and tailpipe results for each day's calibration factors, and show the values in Figure 1. By regressing the percent tailpipe CO aainst the FEAT percent CO, we obtained the equation:

$$[\text{Tailpipe \%CO}] = 1.03[\text{FEAT \%CO}] + 0.08$$

with a correlation coefficient equal to 0.97 for the sample of 34 data points. This correlation is demonstrated for CO values that ranged from zero to twelve percent on three separate days, illustrating the reproducibility and stability of the two measurement systems. The ratio of means ($\overline{\text{Tailpipe}}/\overline{\text{FEAT}}$) for all 34 values is 1.05; the ratio of means for values greater than one percent is 1.03 ($n = 22$). This data set confirms the accuracy of the FEAT in measuring instantaneous CO tailpipe values at different vehicle speeds.

Comparison of FEAT Measurements to Roadside Inspection Data

The ARB Mobile Source Division has the authority and equipment to conduct roadside inspections of in-use vehicle emission control systems. In these inspections, which are equivalent to the I/M test, tailpipe CO and HC and engine rpm measurements are made at slow and fast idle speeds and compared to pass/fail standards which vary depending upon the age and type of vehicle. A visual inspection is also performed to check for obvious tampering with the engine and emission control equipment.

[a] A problem arises because of unavoidable lags in the sample handling system and analyzer and the every two-second sampling rate of the data acquisition system. Constant speed, steady state conditions are desirable so that there is no possibility of ambiguity in matching the gas analyzed by the remote sensing beam with that analyzed on board. Much of the scatter in the data is due to the problem of choosing the right time at which to record the on-board measurement when concentrations are changing rapidly due to non-steady state engine operation. In order to compensate for the lags in the analytical system, the observer would read the concentration of CO in the exhaust from the computer display several seconds after the driver had signaled that the car had crossed the measuring beam.

We combined the ability of the FEAT to provide real-time CO measuremens with the roadside inspection to ask: 1) If the FEAT shows a car to be a low CO emitter, is that finding confirmed by the roadside inspection? 2) If the FEAT shows a car to be a high CO emitter, can the inspection give the reason (e.g., malfunction, deterioration, tampering, misfueling, cold start operation, etc.)?

The Measurement Site

With these questions in mind, we used the FEAT to identify a group of low and high CO-emitting vehicles on La Cienega Boulevard between Pacific Concourse and 120th Street in the Hawthorne area of Los Angeles on December 18 and 19, 1989. La Cienega Blvd. is a divided four-lane, north-south street. We installed the FEAT to monitor the inside lane of southbound La Cienega Blvd. Both southbound lanes remained open during the measurements. Los Angeles County personnel constructed a lane divider to create a small island (about one m wide) between the lanes of traffic within which the infrared source and a small generator could be safely located. We set up the detector unit, video camera, and the FEAT support vehicle within the center median. The site was on a flat section of highway, about 100 m north of a traffic light-controlled intersection. Because of this configuration, deceleration and light cruise were the most often-observed driving modes, with approximate speeds of 20 mph.

Fleet Characteristics at the Measurement Site

Traffic was relatively light during much of the day with 1587 FEAT measurements made between 0920 and 1725 hrs on December 18 and 1184 measurements made between 0830 and 1525 hrs on December 19. Of the total fleet passing by the FEAT on December 18 and 19, the emissions of 79 percent were measured. Twenty-one percent were not counted because they did not meet quality assurance criteria established for the FEAT measurements.[3] The overall mean FEAT percent CO values and standard error of the means were 1.42 ± 0.06 for the 18th and 1.13 ± 0.06 for the 19th. On the 19th, FEAT measurements showed that half the CO in on-road operation was emitted by the 7.8 percent of the vehicles with CO emissions greater than 4.6 percent, averaged on a gm CO per gallon of fuel burned basis. We show the distribution for the CO emissions in Figure 2a, combined for both days.

ARB Roadside Inspection

When a car passed the FEAT, we decided, based upon the CO reading, whether we wanted a roadside test performed on the vehicle. When we observed a candidate vehicle, we radioed the California Highway Patrol, who stopped that vehicle for an inspection. We obtained both a small sample of low CO-emitting cars (ten vehicles with a FEAT measurement of less than two percent CO) and a larger sample of higher CO-emitting vehicles (50 cars with a FEAT value greater than two percent CO, for better characterization of this portion of the vehicle fleet), as shown in Figure 2b. We obtained these samples to study the false positive and false negative rates of low/high FEAT measurements as predictors of passing/failing the roadside inspection. The prediction is a false positive if the FEAT value is high and the vehicle passes the test; it is a false negative if the FEAT value is low and the vehicle fails the test.

Because vehicles operating in a cold start mode could appear high to the FEAT, but normal in the roadside test, the ARB Mobile Source Division staff asked each driver how long and how many miles the vehicle was driven prior to the roadside check. We selected the 60 vehicles without regard to make and model year; the criteria for selection were the CO value measured by the FEAT and the readiness of the roadside inspection group to begin testing another vehicle. Twenty vehicles were sampled on December 18 and 40 vehicles were checked on December 19. These vehicles were not randomly chosen; therefore this small sample of vehicles is not representative of the vehicles passing the sampling point or any larger population of vehicles. Although the 60-car sample does not represent the entire fleet, the sample size is large enough for the purposes of this pilot study.

The 60-Vehicle Roadside Data Set

Table I summarizes the data obtained in the 60 vehicle set. We list the vehicles by model year, separated into three general classes according to emission control technologies. The 1980 and later model year vehicles are primarily three-way catalyst and oxygen sensor-equipped vehicles with closed loop control; the 1975–1979 model years are mostly oxidation catalyst equipped open-loop vehicles; and pre-1975 model years are pre-catalyst vehicles. In this small, non-random data set of 60 vehicles, 45 failed the ARB roadside inspection, with twelve of those 45 having emissions control systems that had been tampered with. The extreme case was a 1984 GMC pickup with a FEAT reading of 8.1 percent, which originally was a diesel vehicle. Its engine had been changed to a 350 CID gasoline engine with no emission components. Because the California Department of Motor Vehicle (DMV) records classify the GMC as a diesel vehicle, it was not subjected to the Smog Check. Another five vehicles' systems were diagnosed as nonconforming, which indicated a system problem which could not be confirmed as deliberately tampered with.

Ten vehicles were inspected which had FEAT CO levels of less than two percent, as shown in Figure 3. Eight of those cars passed the roadside inspection. Of the two vehicles that did not pass, one passed both the CO and HC tests, but failed

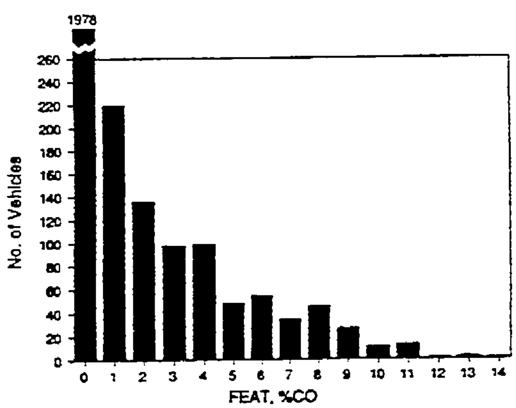

Figure 2a. Distribution of CO concentrations for 2771 vehicles measured with the FEAT on La Cienega Boulevard on December 18–19, 1989. Values in the 0% bar correspond to FEAT readings of 0 to 0.99%; the 1% bar corresponds to FEAT readings of 1.00 to 1.99%, etc.

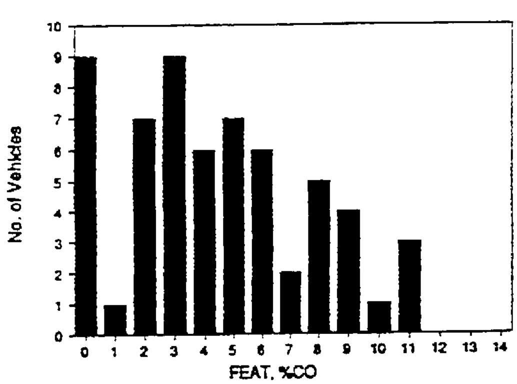

Figure 2b. Distribution of CO concentrations for only the 60 vehicles subjected to the roadside inspection.

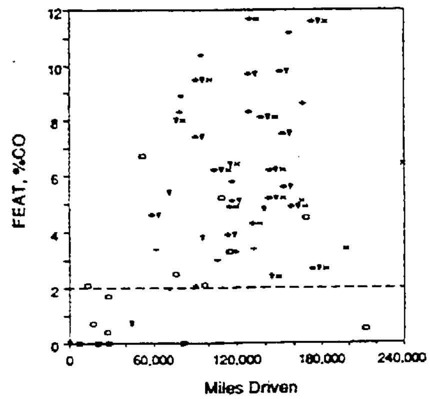

Figure 3. Comparison of the reasons for failure in the roadside inspection to the CO concentration measured by the FEAT, plotted against odometer readings. The coding for the points is: □: Pass; +: Fail, idle only; ◇: Fail, CO; ▽: Fail, HC; and X: Fail, tampering. the dashed line at 2% CO shows that below 2%, the majority of the vehicles pass the test, whereas above 2% and 80,000 miles driven, the majority fail.

the idle speed requirement (1099 rpm measured vs. 1000 rpm standard). The other vehicle failed the idle HC test (147 ppm vs. 100 ppm standard). Its CO levels were about one-fourth the standard. The FEAT CO measurement with an arbitrary two percent cutoff point had an 80% success rate at predicting pass/fail performance on the complete roadside inspection and a 100 percent success rate at predicting performance on the CO portion of the test. CO readings from the FEAT resulted in no false negatives for the CO portion of the Smog Check. Because of differing control technologies and more lenient standards for older vehicles, it is more difficult to assess the false positive rates for the FEAT CO measurements.

Fifty vehicles were inspected which had FEAT CO measurements greater than two percent. The 50 car subset with FEAT CO greater than two percent is roughly a ten percent sample of the highest emitting vehicles on the two sampling days. Forty-three of those vehicles failed the roadside test. Of the seven vehicles expected to have higher emissions, but which passed the test, it was likely that two were operating in a cold-start mode (two and three minutes' driving time) when the FEAT measurement was made. For an additional two vehicles, responses to the cold start survey questions were not obtained. It also is possible that momentary high CO emissions were present when the vehicles passed through the FEAT beam due to transient engine operating conditions. Every vehicle that had been tampered with had FEAT CO levels above two percent. The FEAT had an 86 percent success rate in identifying vehicles that failed the roadside inspection test.[b]

Having shown that the FEAT provides an accurate measure of CO concentrations being emitted by the vehicles, and also having shown that FEAT measurements with a criterion of two percent CO have a high success rate of predicting pass/fail performance on the roadside inspection, we now investigate the quantitative relationship between CO concentrations measured by the FEAT and by the roadside test. Our expectation is that real-world driving (cold start, accelerations and decelerations) would cause FEAT CO measurements to be higher than those measured on the roadside test. We illustrate the relationship between the CO concentration measured by the FEAT and the higher CO concentration measured in the low or high idle test in Figure 4. By comparing the spread of the data with the 1:1 correspondence line,

[b] Passing the Smog Check does not necessarily mean the vehicle is a low emitter. It only means the vehicle is performing as well as could be expected for its age and emission control system. For older vehicles, up to seven percent CO at idle is passing.

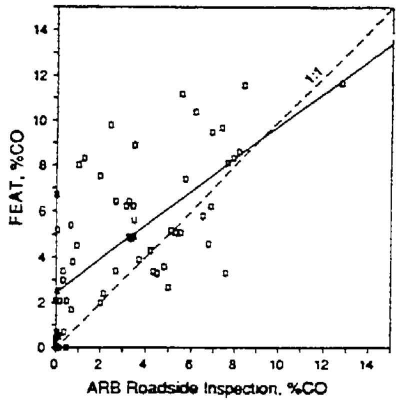

Figure 4. Comparison of the CO concentration from the moving car measured by the FEAT with the CO measured at idle during the roadside Smog Check. Most FEAT measurements are greater than the no-load idle measurements. The regression line corresponds to: [FEAT %CO] = 0.73[Roadside Idle %CO] + 2.51, with r = 0.67.

we see that the majority of the FEAT measurements are higher than the idle measurement, whereas very few are less. Figure 4 also includes the regression line:

$$[\text{FEAT \%CO}] = 0.73[\text{Roadside Idle \%CO}] + 2.51,$$

with the correlation coefficient r equal to 0.67. The regression model, which explains about 48 percent of the variance, is highly significant. Although the FEAT and idle test measurements were made with vehicles in different operating modes, the regression model indicates that, in general, cars that tend to be high emitters in the idle test are also high emitters in use. From Figure 4, we observe that there are several zero or near-zero roadside inspection values which correspond to high values from the FEAT. Apparently the FEAT is sampling emissions from higher-emitting operating modes than the no-load low idle test.

We also calculated the Spearman rank correlation coefficient r_s, which is a nonparametric measure of the association between two separate rankings—in this case, the rankings of the FEAT data and the ARB roadside inspection data. This correlation coefficient is less sensitive to outliers than the Pearson correlation coeficient r. Statistical inference for the Spearman correlation coefficient is not based on any distributional assumptions, whereas inference for the Pearson correlation coefficient is based on a commonly violated assumption that the two variables have a bivariate normal distribution. Testing the Spearman coefficient allows us to determine if, in general, higher FEAT values are significantly associated with higher ranking ARB roadside inspection values. The value of r_s is 0.66. If the null hypothesis of no association between the two rankings were true, a correlation this large would occur in less than 0.01 percent of the samples. We conclude that the hypothesis of no association between the rankings of FEAT data and Smog Check data is extremely improbable.

Factors Affecting CO Emissions

In previous studies[3–5] using remote sensing, statistical data on the tailpipe CO levels were obtained, but there was no opportunity to inquire as to potential causes of the high CO emissions. The availability of the roadside inspection data allows us to study the effect of mileage accumulation and vehicle age on CO emissions. We show four different approaches to examining the CO data in Figure 5. Figures 5a–d identify the vehicles that had been tampered with; many of the highest emitters are tampered with, but a number of those vehicles meet the standard. In Figure 5a we present the maximum CO measured on the low or high idle test (for 1980 and later model years, and the low idle value only for pre-1980 model years) as a function of odometer mileage. Apparently, CO emissions increase with mileage, as would be expected from a fleet in which the highest mileage vehicles have the least sophisticated emission controls. Figure 5b is an attempt to remove the effect of different types of emission control systems, thereby isolating the effects of mileage accumulation. The idle standard varies with the age and sophistication of the vehicle's emission control system. In Figure 5b, we show the maximum ratio of either the low or high idle CO measurement to the corresponding idle standard as a function of mileage. Based on this limited data set which is biased toward high emitters, in the 80,000 to 100,000 mi range, we see a transition from most vehicles meeting the standard to an increasing fraction of the vehicles exceeding the standard.

We present another view of these data in Figure 5c, where percent CO is plotted against model year, and in Figure 5d, where we plot the ratio of the measured CO to the CO standard against model year. Figure 5d shows that most of the cars newer than 1982 meet the idle I/M standards (see Table I for values), and that increasing numbers of older vehicles approach or slightly exceed the standard. This figure also shows a group of not-obviously tampered with vehicles in the 1978 to 1983 model years which exceed the standards by two to six times. Even though these vehicles exceed the idle standard by such a large factor, their absolute CO emissions are no higher than those from vehicles meeting the CO idle standard for 1975 and earlier model years. It is unknown whether these vehicles are high because of malfunction or undetected tampering. However, the majority of these vehicles are models likely to be driven by car enthusiasts (Camaro, Mustang, Cutlass, etc.).

Comparison of Roadside Inspection Data with Smog Check I/M Data

We used the license plate numbers of the 60 vehicles to gain access to the BAR Smog Check records to retrieve the results of the last Smog Check on each vehicle. We also obtained the vehicles' registration status from the DMV data base. This search showed that seven of the vehicles (twelve percent) were not currently registered, as compared with about six percent unregistered vehicles in an informal survey we conducted in the area.

With considerable assistance from DMV and BAR personnel, we were able to retrieve Smog Check data for 34 of the 60 vehicles in the set. These data are included in Table IIB, along with comments from the ARB roadside visual inspection conducted during this test (Table IA). Eight of the 60 vehicles were too new to have required an I/M check, and five vehicles (pre-1968 model years) were too old and exempt from the Smog Check program. Two other vehicles, the 1977 Ford 800 (a heavy duty gasoline vehicle) and the 1984 GMC, were also exempt from the I/M program. Therefore, we were able to obtain data on 34 out of 45 vehicles (76 percent) eligible for the I/M program. For five of the vehicles, we could find only data indicating that they had failed the Smog Check. However, because all of those five were current in their registration, they had received their Smog Check within the past two years. Only one of the 45 eligible vehicles (1980 Chevy Caprice) received an "FR" exemption, given when the repair cost limit was exceeded and emission standards were still violated. Although seven of the cars were not currently registered, two had passed the Smog Check. DMV records showed that the checks written for registration of those two cars apparently had bounced. At least 41 vehicles had passed the Smog Check within the last two years because they were currently registered or had received a Smog Check certificate.

We now compare the ARB roadside data with the most recent data for the 34 cars from the BAR Smog Check data set in Figure 6. This figure compares the low idle CO from

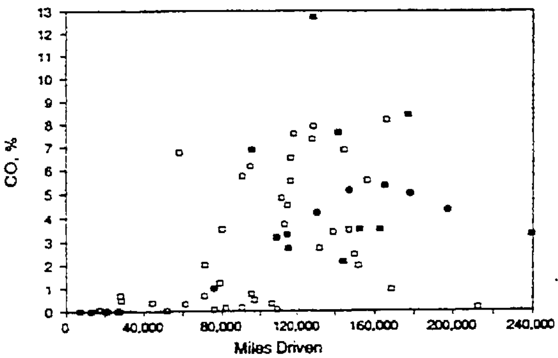

Figure 5a. The effect of mileage accumulation on idle CO concentration measured in the roadside inspection. Open squares represent vehicles that passed the visual inspection. Solid squares denote cars having emission control systems that had been tampered with; solid circles indicate nonconforming control systems (see text for explanation).

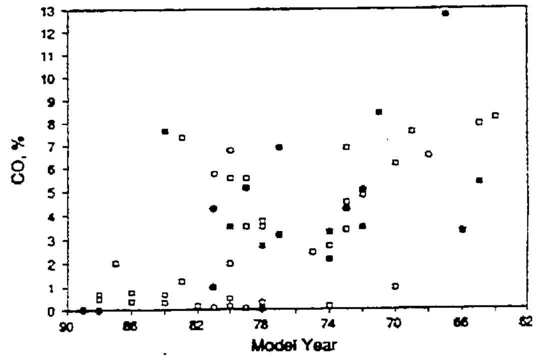

Figure 5c. The effect of model year on idle CO concentration measured in the roadside inspection.

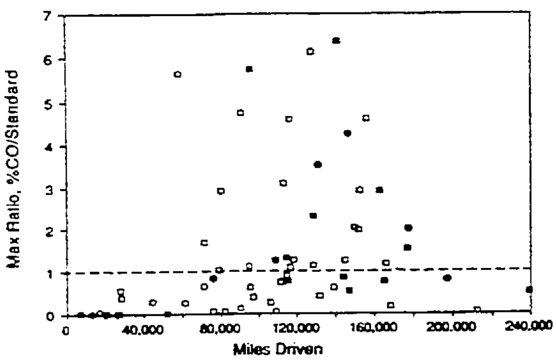

Figure 5b. The effect of mileage accumulation on the maximum ratio of the CO concentration measured in either the low idle or fast idle test to the CO standard for each vehicle.

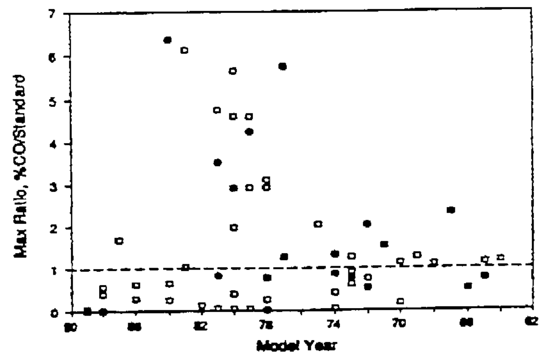

Figure 5d. The effect of model year on the maximum ratio of the CO concentration measured in either the low idle or fast idle test to the CO standard for each vehicle.

the two tests, and shows that for vehicles exceeding one percent (the low idle standard for many 1980 and later model years), 20 out of 23 vehicles showed higher current CO emissions than they had in the required, biennial I/M program. Moreover, as the figure shows, the number of months since the Smog Check was performed had little influence on how the cars performed on the roadside inspection. In fact, eight of the thirteen cars which received a Smog Check less than eleven months prior to the roadside check failed the emissions portion of the test. Five of nine cars failed the roadside inspection within six months after their regularly scheduled Smog Check. We also have labelled only the data points for which the vehicle was driven five minutes or less before ARB carried out the roadside inspection. Because the majority of these twenty cars had been driven five minutes or longer, they were not in a cold-start mode.

We carried out a similar comparison for the 34 vehicles on the low idle HC emissions. As shown in Figure 7, for the 24 vehicles exceeding the 150 ppm value (a typical low idle HC standard for early 1980 model years), 21 vehicles showed higher HC emissions in the roadside inspection than in the required Smog Check. Cars which had received the Smog Check in the six months before the roadside inspection did not seem to be any cleaner than those inspected earlier.

This comparison indicates that high CO-emitting cars identified by the FEAT are significantly higher emitters of CO and HC when measured on the road than when measured during the previously scheduled Smog Check. Possible reasons incude mechanical adjustments, illegal or improper Smog Checks, tampering with emissions control equipment and deterioration of the vehicles after the regularly scheduled Smog Check. The presence of so many cars that had been tampered with in our set of 60 vehicles suggests that either the required I/M test is not identifying tampering properly or that an appreciable fraction of the high CO-emitting cars have been tampered with after passing the Smog Check. According to studies in Arizona[6] a common practice is mechanical adjustment of vehicles to "pass the test" followed by immediate mechanical return to the normal operating mode.

Conclusions

By providing independent quality assurance and by utilizing on-board exhaust CO measurements from a specially equipped vehicle, we have show in blind and double-blind tests that remote sensing by the FEAT can measure on-road CO emissions with an accuracy of ±10 percent. We also have demonstrated that the FEAT can be used as an effective surveillance tool to identify high CO-emitting vehicles.

Our data show that for the 2771 vehicles measured by remote sensing on La Cienega Blvd., ten percent of the fleet (FEAT CO values greater than four percent) was responsible for about 55 percent of the total CO emissions, averaged on a gm CO per gallon of fuel burned basis (Figure 2a). The CO measurements made by the FEAT at this location show that the fleet characteristics are similar to those from other parts of the country.

In this pilot study, where we examined a small and intentionally biased set of 60 vehicles, we observed that for the high CO-emitting vehicles (by either the instantaneous FEAT measurement or the low or high idle value), nearly all of the eligible vehicles had passed the required biennial I/M test. However, most of the vehicles having FEAT CO readings greater than two percent failed the roadside inspection. For the cars emitting greater than one percent CO on the

Table I. Description of the vehicles in the 60 car data set, the remote-sensing CO values, and the ARB roadside inspection results. An underscored value denotes an exceedance of the standard in the roadside inspection.

Model Year	Make	Model	Odometer (miles)	Travel time	Distance traveled (miles)	University of Denver FEAT % CO	Visual inspection	ARB Roadside Inspection (measurement/standard) RPM	Low idle CO (%)	Low idle HC (ppm)	High idle CO (%)	High idle HC (ppm)	Pass/fail
89	Honda	Civic	27,216	15 min	10	0.4	Pass	/1000	0.01/1.0	20/100	—	—	P
89	Plymouth	Reliant	16,983	5 min		0.7	Pass	858/1000	0.05/1.0	2/100	0.04/1.2	1/220	P
89	Toyota	Camry	7,121	30 min	20	0.0	Pass	689/1000	0.01/1.0	11/100	0/1.2	10/220	P
89	Toyota	Corolla	12,942	5 min	2	2.1	Pass	805/1000	0/1.0	15/100	0/1.2	10/220	P
88	Honda	Accord	26,381	5 min	3	0.1	Pass	1099/1000	0/1.0	16/100	0/1.2	21/220	F
88	Honda	Civic	28,215	8 min	2	0.0	Pass	794/1000	0.01/1.0	5/100	0.47/1.2	29/220	P
88	Honda	Civic	27,726	20 min		1.7	Pass	780/1000	0.02/1.0	0/100	0.68/1.2	6/220	P
88	Mazda	626	20,677	3 min	2 blks	0.0	Pass	789/1000	0/1.0	19/100	0.01/1.2	16/220	P
87	Hyundai	Excel	71,039	4 hr	>20	2.0	?	/1000	0.03/1.0	5/100	2.01/1.2	45/220	F
86	Chevrolet	Sprint	95,350	25 min		3.8	Pass	1233/1000	0.04/1.0	38/100	0.75/1.2	340/220	F
86	Toyota	MR-2	44,210	5 min		0.7	Pass	936/1000	0.28/1.0	147/100	0.35/1.2	82/220	F
84	GMC	1500	141,565	8 min		8.1	Tamp	930/1000	6.98/2.5	864/150	7.64/1.2	396/220	F
84	Renault	Alliance	70,954	10 min	10	5.4	Pass	808/1000	0.65/1.0	260/100	0.60/1.2	184/220	F
84	Toyota	Pickup	61,211	5 min	1	3.4	Pass	1002/1000	0.03/1.0	28/100	0.31/1.2	43/220	F
83	Chevrolet	Camaro	127,934			9.7	Pass	719/1000	2.43/1.0	202/100	7.35/1.2	233/220	F
83	Dodge	Ram 50	78,780	all day		8.3	Pass	789/1000	0.02/1.0	27/100	1.23/1.2	62/220	F
82	Nissan	200SX	90,175	2 min	4 blks	2.1	Pass	1033/1000	0.13/1.0	57/100	0.15/1.2	37/220	F
81	Buick	Regal	130,963	30 min	6	4.3	Non	1408/1000	0.72/1.5	9/100	4.22/1.2	166/220	F
81	Chevrolet	Camaro	90,348	10 min	2	7.4	Pass	877/1000	2.64/1.0	386/100	5.71/1.2	108/220	F
81	Chevrolet	Malibu	75,956	6 min	2	2.5	Pass	689/1000	0.01/1.0	46/100	0.07/1.2	8/220	P
81	Dodge	Omni	76,306	3 min	3 blks	8.0	Non	890/1000	0.04/1.2	439/150	0.99/1.2	96/220	F
80	Chevrolet	Caprice	162,509	20 min	3	4.9	Tamp	/1000	0.30/2.5	72/150	3.50/1.2	274/220	F
80	Chevrolet	Monza	96,923			2.1	Pass	879/1000	0.07/1.2	78/150	0.47/1.2	75/220	P
80	Datsun	510	156,222			11.2	Pass	1267/1000	0.08/2.5	44/150	5.53/1.2	118/220	F
80	Dodge	200 Van	81,865	25 min		0.0	Pass	778/1000	0.13/2.5	0/150	0.02/1.2	1/220	P
80	Mercury	Capri	58,182	5 min	1	4.6	Pass	1112/1000	5.64/1.2	314/150	6.77/1.2	192/220	F
80	Olds	Cutlass	151,565	7 min	2	7.5	Pass	994/1000	1.97/1.0	103/100	1.78/1.2	47/220	F
79	Buick	Century Wgn	147,087	20 min	8	5.2	Non	931/1100	5.12/1.2	1918/150	0.40	1386	F
79	Ford	Mustang	109,105	10 min	5	5.2	Pass	997/1100	0.06/1.2	109/150	0.95	235	P
79	Ford	Mustang	116,458	5 min	2	5.1	Pass	971/1100	5.52/1.2	217/150	6.22	197	F
79	Olds	Cutlass	79,945	15 min	4	8.9	Pass	1255/1100	3.51/1.2	89/150	2.23	51	F
78	Chevrolet	Malibu	152,195			5.6	Pass	1170/1100	3.51/1.2	1017/150	1.23	333	F
78	Dodge	Omni	106,245	15 min	2	3.0	Pass	2286/1100	0.31/1.2	34/150			F
78	Ford	Mustang	113,205	15 min	5	3.9	Pass	1098/1100	3.72/1.2	155/150	4.13	206	F
78	Ford	T-Bird	51,916			6.7	Pass	818/1100	0.02/1.2	149/150	0.10	634	P
78	Olds	Omega	115,294	35 min	12	6.4	Tamp	779/1100	2.71/3.5	1733/250	0.22	676	F
77	AMC	Hornet	95,416	25 min	10	9.5	Tamp	601/1100	6.89/1.2	641/150	4.05	234	F
76	Ford	800	108,900	15 min	5	6.2	Tamp	1063/1100	3.73/2.5	284/220	1.54	26	F
	(Dual exhaust)							1065/1100	2.59/2.5	1244/220	0.66	42	
75	Chevrolet	10	149,497	3 min	1	9.8	Pass	557/1100	2.44/1.2	455/150	0.06	23	F
74	Chevrolet	Malibu	212,275	8 min	2	0.5	Pass	1021/1100	0.13/2.5	53/300	0.09	14	P
74	Chevrolet	Nova	143,816	20 min	8	2.4	Tamp	766/1100	2.27/2.5	1378/300	0.49	>2000	F
	(Dual exhaust)								2.04/2.5	96/300	0.20	126	
74	Ford	Mustang	114,611	5 min	1	4.9	Tamp	943/1100	3.29/2.5	172/300	1.07	85	F
74	Honda	Civic	131,720	5 min	1	3.4	Pass	1263/1100	2.71/6.5	193/350	0.52	73	F
73	Chevrolet	Nova	197,781	2 min	1	3.4	Non	911/1100	4.34/5.5	219/400	5.45	408	F
73	Ford	Courier	114,728	5 hr		3.3	Pass	987/1100	4.51/5.0	314/350	3.93	175	P
73	Olds	Cutlass	144,423	10 min	5	6.2	Pass	543/1100	6.87/5.5	281/400	3.12	103	F
73	Plymouth	Roadrnnr.	138,880	10 min	2	4.8	Pass	957/1100	3.39/5.5	572/400	1.32	58	F
72	Datsun	B510	146,856	5 hr	300	6.2	Tamp	914/1100	3.48/6.5	439/350	4.43	211	F
72	GMC	Vandura	177,867			2.7	Non	/1100	4.99/2.5	1664/300			F
72	VW	Bug	111,435	10 min	2	3.6	Pass	1627/1100	4.82/6.5	174/350	4.18	132	F
70	Ford	Maverick	176,843	15 min	5	11.6	Tamp	1037/1100	8.39/5.5	1620/400			F
70	Ford	Van	94,640	15 min		10.4	?	/1100	6.15/5.5	275/500			F
70	Plymouth	Valiant	168,315	50 min	40	4.5	Pass	811/1100	0.94/5.5	.98/500	0.94	55	P
69	VW	Sq. back	118,215	3 min	1	3.3	Pass	1114/1100	7.57/6.0	423/700	8.92	467	F
68	VW	Bug	116,559			5.8	Pass	986/1100	6.51/6.0	643/700	5.42	340	F
67	Ford	Mustang	128,685			11.7	Tamp	653/1100	12.74/5.5	452/500			F
66	VW	Bug	239,338	5 min	5	6.4	Tamp	1226/1100	3.29/6.5	1059/1200	3.27	1065	F
65	Ford	Mustang	164,977	20 min	12	5.1	Tamp	957/1100	5.31/7.0	314/800	3.73	>2000	F
65	Ford	Mustang	128,565	10 min	2	8.3	Pass	912/1100	7.91/7.0	289/800			F
64	Ford	Falcon	165,810	10 min	5	8.6	Pass	1217/1100	8.17/7.0	329/800	3.49	143	F

Table IIA. Comments from the ARB roadside inspection.

Model year	Make	Model	Comments from roadside visual inspection
89	Honda	Civic	
89	Plymouth	Reliant	
89	Toyota	Camry	
89	Toyota	Corolla	
88	Honda	Accord	
88	Honda	Civic	
88	Honda	Civic	
88	Mazda	626	
87	Hyundai	Excel	Wrecked; hood could not be opened.
86	Chevrolet	Sprint	
86	Toyota	MR-2	
84	GMC	1500	Engine change from 6.2 L diesel to 350 CID gas; all emission components missing.
84	Renault	Alliance	
84	Toyota	Pickup	
83	Chevrolet	Camaro	
83	Dodge	Ram 50	
82	Nissan	200SX	
81	Buick	Regal	Fuel cap missing.
81	Chevrolet	Camaro	
81	Chevrolet	Malibu	
81	Dodge	Omni	Air injection—belt missing; temp. contr. air cleaner—hot air tube missing.
80	Chevrolet	Caprice	Engine change; air injection, EGR and ox. cat. removed; evap. control—hoses plugged; PCV—breather missing.
80	Chevrolet	Monza	
80	Datsun	510	
80	Dodge	200 Van	
80	Mercury	Capri	
80	Olds	Cutlass	Engine change; current engine has only 20,000 miles on it.
79	Buick	Century Wgn	Temp. contr. air cleaner—hot air tube missing.
[illegible]	Ford	Mustang	
79	Ford	Mustang	
79	Olds	Cutlass	
78	Chevrolet	Malibu	
78	Dodge	Omni	Idle excessive; no 2500 rpm test.
78	Ford	Mustang	
78	Ford	T-Bird	
78	Olds	Omega	Temp. contr. air cleaner—hot air tube missing; fuel restrictor—gouged out.
77	AMC	Hornet	Air Cleaner removed; TCAC/PCV removed; catalyst removed; air guard system removed; broken exhaust manifold.
77	Ford (Dual exhaust)	800	Air injection, EGR hoses, and air cleaner heat stove/hot air tube removed; Purge hose dangling.
75	Chevrolet	10	
74	Chevrolet	Malibu	
74	Chevrolet (Dual exhaust)	Nova	Temp. contr. air cleaner—heat stove/hot air tube removed.
74	Ford	Mustang	PCV-breather hose missing; temp. contr. air cleaner—vac. hoses removed; heat stove removed.
74	Honda	Civic	
73	Chevrolet	Nova	Air injection—belt missing.
73	Ford	Courier	
73	Olds	Cutlass	EGR—inoperative.
73	Plymouth	Roadrunner	
72	Datsun	B510	Temp. contr. air cleaner—removed; Non OEM carburetor.
72	GMC	Vandura	Temp. contr. air cleaner—hot air tube missing.
72	VW	Bug	
71	Ford	Maverick	Temp. contr. air cleaner removed.
70	Ford	Van	Small hood opening; parts inaccessible.
70	Plymouth	Valiant	
69	VW	Squareback	
68	VW	Bug	
67	Ford	Mustang	Air injection—removed; temp. contr. air cleaner—heat stove removed. (Idle only—belt almost coming off.)
66	VW	Bug	Distributor advance vac. system—009 race distributor; carb. throttle positioner removed.
65	Ford	Mustang	Temp. contr. air cleaner and PCV breather missing.
65	Ford	Mustang	Low idle only—coolant leak.
64	Ford	Falcon	

Table IIB. Previous measurements from the required biennial Smog Check program and comments from the biennial Smog Check records. Vehicles from 1988 and newer model years and 1967 and older model years were exempt from the program.

				Bureau of Automotive Repair Biennial Smog Check Data						
				Last		Low idle		High idle		
Model year	Make	Model	Regis. status	test mo/yr	Pass/ fail	CO (%)	HC (ppm)	CO (%)	HC (ppm)	Comments & reasons for failure
89	Honda	Civic								
89	Plymouth	Reliant								
89	Toyota	Camry								
89	Toyota	Corolla								
88	Honda	Accord								
88	Honda	Civic								
88	Honda	Civic	EXPIRED							
88	Mazda	626								
87	Hyundai	Excel		8/89	P	0.05	17	0.36	148	
86	Chevrolet	Sprint								
86	Toyota	MR-2		10/88	F	0.53	212	0.58	97	Low RPM HC
84	GMC	1500		EXEMPT—Originally had diesel engine; changed to gasoline engine						
84	Renault	Alliance		1/87	P	0.01	79	0.10	100	
84	Toyota	Pickup	EXPIRED							
83	Chevrolet	Camaro	EXPIRED							
83	Dodge	Ram 50								DMV says it's an '86 model
82	Nissan	200SX		6/88	P	0.09	23	0.08	15	
81	Buick	Regal		1/89	F	1.63	66	>10.0	607	Low & high RPM CO; high RPM HC
81	Chevrolet	Camaro		2/88	P	0.38	85	0.17	9	Recorded by Smog check test operator as a Honda
81	Chevrolet	Malibu		8/89	P	0.00	22	0.08	0	
81	Dodge	Omni		6/89	P	0.00	0	0.00	0	Recorded by Smog check test operator as '82 model
80	Chevrolet	Caprice		8/88	FR	0.58	226	0.66	57	2nd try; low RPM HC
80	Chevrolet	Monza								
80	Datsun	510								
80	Dodge	200 Van		9/88	P	0.00	11	0.00	9	
80	Mercury	Capri		10/89	P	0.02	19	0.07	19	
80	Olds	Cutlass								
79	Buick	Cent. Wgn.	EXPIRED	11/89	P	0.15	37	0.09	59	
79	Ford	Mustang		7/89	P	0.01	35	0.01	71	2nd try
79	Ford	Mustang		12/88	P	0.00	25	0.00	98	2nd try
79	Olds	Cutlass		4/88	P	0.68	68	0.05	36	
78	Chevrolet	Malibu		4/88	P	0.00	30	0.03	67	
78	Dodge	Omni		5/87	P	0.07	33	1.53	73	
78	Ford	Mustang		8/88	P	0.85	113	1.85	121	
78	Ford	T-Bird		1/89	F	0.01	15	0.01	6	2nd try—EGR, Spark adv, others dismantled
78	Olds	Omega		8/88	P	0.09	37	0.06	22	
77	AMC	Hornet	EXPIRED	9/88	P	0.00	19	0.00	26	
77	Ford (Dual exhaust)	800		EXEMPT—Heavy Duty Gas Vehicle						ARB says it's a '77; DMV says it's a '76
75	Chevrolet	10		12/88	P	0.35	34	0.70	9	
74	Chevrolet	Malibu								
74	Chevrolet (Dual exhaust)	Nova								
74	Ford	Mustang	EXPIRED							
74	Honda	Civic		6/89	P	0.06	118	1.96	167	
73	Chevrolet	Nova		8/89	P	0.66	100	0.32	353	
73	Ford	Courier		11/88	P	1.96	244	3.30	84	
73	Olds	Cutlass		10/87	P	2.94	156	0.40	13	
73	Plymouth	Roadrunner		10/87	P	2.07	205	0.97	182	2nd try
72	Datsun	B510		4/88	P	4.36	265	0.85	124	2nd try
72	GMC	Vandura		11/88	P	0.04	57	0.04	175	
72	VW	Bug								
71	Ford	Maverick		1/88	P	1.75	202	1.62	120	ARB & BAR says it's a '71; DMV says it's a 70
70	Ford	Van		10/87	F	5.34	238	8.69	265	Air cleaner missing; low RPM CO
70	Plymouth	Valiant		3/89	P	1.41	97	0.61	44	2nd try
69	VW	Squareback		2/89	F	6.80	>2000	>10.0	1927	Low RPM CO & HC
68	VW	Bug		11/89	P	3.31	112	1.72	50	
67	Ford	Mustang								
66	VW	Bug								
65	Ford	Mustang	EXPIRED							
65	Ford	Mustang								
64	Ford	Falcon								

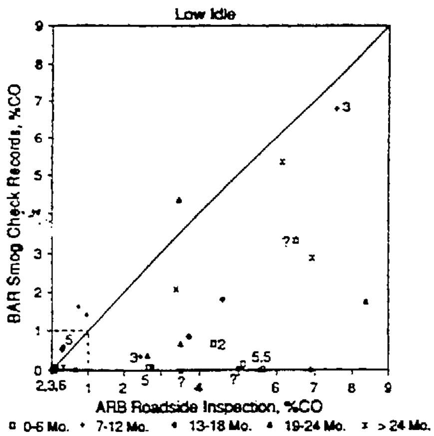

Figure 6. Comparison of the CO concentration at idle measured in the roadside inspection and in the routine biennial Smog Check. The points are coded to show the number of months since the biennial Smog Check. The number near the point is the number of minutes the vehicle had been driven before being inspected for only those cars driven 5 minutes or less. The dashed lines at 1.0% CO represent the low idle standard for several 1980 and later model years.

roadside inspection, 20 were emitting higher CO than when the required Smog Check took place: only three were not. We observed the same general features with the HC emissions in this data set. For the cars that had received their Smog Check less than six months prior to the roadside inspection, more than half the vehicles failed the emissions portion of the roadside test. These data show the need for understanding the reasons why these vehicles become high emitters in a relatively short time period following the Smog Check.

Acknowledgments

We gratefully acknowledge the support of the California Air Resources Board and General Motors Research Laboratories in conducting this work. Financial assistance was provided to the University of Denver through ARB contract A832-135. We also thank Tom Cackette and John R. Holmes of the ARB for their support and Bart Croes, Eric Fujita and John Moore of the ARB Research Division for their assistance in this analysis. We are grateful to the ARB Mobile Source Division for conducting the roadside inspections and the quality assurance for the study. We also thank the California Highway Patrol for their assistance in this project. We especially acknowledge the assistance of Phil Wilson of the BAR and Betty Stanfield of the DMV in helping us acquire vehicle inspection and registration data.

The statements and conclusions in this paper are not necessarily those of the California Air Resources Board. The mention of commercial products, their source or their use in connection with material reported is not to be construed as either an actual or implied endorsement of such products.

References

1. California Health and Safety Code, Division 26, Part 1, Chapter 1, section 39002, 1990.
2. 1987 Emission Inventory, California Air Resources Board, Technical Support Division, 1990.
3. D. H. Stedman, G. A. Bishop, "An Analysis of On-Road Remote Sensing as a Tool for Automobile Emissions Control," final report to the Illinois Department of Energy and Natural Resources, ILENR/RE-AQ-90/05 (1990).
4. R. D. Stephens, S. H. Cadle, "Remote Sensing Measurements of Carbon Monoxide Emissions from On-Road Vehicles," General Motors Research Laboratories Publication GMR-7030, 1990.
5. G. A. Bishop, D. H. Stedman, "On-road carbon monoxide emission measurement comparisons for the 1988–1989 Colorado oxy-fuels program," *Environ. Sci. Technol.* 24: 843 (1990).
6. G. A. Bishop, J. R. Starkey, A. Ihlenfeldt, W. J. Williams, D. H. Stedman, "IR long path photometry: a remote sensing tool for automobile emissions," *Anal. Chem.* 61: 671A (1989).
7. Arizona Auditor General, "Performance Audit: Department of Environmental Quality, Vehicle Emissions Inspection and Maintenance Program," report to the Arizona Legislature, 1988.

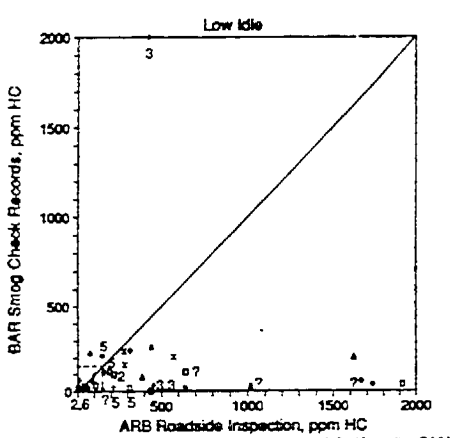

Figure 7. Similar to Figure 6, but for exhaust hydrocarbons. The dashed lines at 150 ppm HC represent the low idle standard for several 1980 and later model years.

Dr. Lawson is with the Research Division of the California Air Resources Board, P.O. Box 2815, Sacramento, California 95812. Dr. Groblicki is with the Environmental Science Department of General Motors Research Laboratories, Warren, Michigan 48090. Dr. Stedman is Brainerd Phillipson Professor of Chemistry, Dr. Bishop is Research Scientist, and Mr. Guenther is Graduate Research Assistant in the Department of Chemistry, University of Denver, Denver, Colorado 80208.
This paper was submitted for peer review on April 27, 1990. The revised manuscript was received June 18, 1990.

APPENDIX 2 Repeat Vehicle Measurements

Repeat measurements of vehicles

YEAR	MAKE	PERCENT CO	PERCENT CO	PERCENT CO	PERCENT CO	PERCENT CO	PERCENT CO	PERCENT CO	MEAN	VARIANCE
79	MAZD	0.47	0.55	1.1	10.82				3.24	19.24
75	PONT	0.25	0.26	3.17	5	9.13			3.56	11.02
71	DODG	3.08	3.65	9.52	9.75				6.50	9.88
82	FORD	-0.05	1.01	1.78	4.18	7.24	8.22		3.73	9.70
78	PLY	-0.07	0.01	0.07	7.15				1.79	9.58
		4.08	5	8.49	11.23	11.43			8.05	9.36
79	OLDS	1.73	3.87	5	9.57				5.04	8.21
78	BUIC	2.21	8.17	8.84	8.86				7.02	7.79
81	BUIC	3.48	6.35	7.31	10.17	10.6			7.58	6.84
74	CHE	2.82	4.51	8.28	9.16				6.19	6.84
79	MERC	0.92	1.27	5.6	6.59				3.60	6.39
77	CHEV	0.12	0.33	1.24	5.56	5.66			2.58	6.26
79	DODG	0.51	3.53	6.13	6.77				4.24	6.10
83	FORD	2.87	3.59	6.32	8.8				5.40	5.52
68	BUICK	1.93	1.96	6.59	6.67				4.29	5.49
89	GMC	0.04	0.61	0.7	1	4.44	6.22		2.17	5.34
72	FORD	5.18	6.91	9.05	10.42	11.25			8.56	5.02
79	CAPRI	3.79	6.28	8.34	9.38				6.95	4.57
83	BUIC	1.49	2.01	3.56	6.65				3.43	4.04
80	OLDS	2.41	6.54	6.88	7.36				5.80	3.91
76	CHEV	0.14	0.18	3.37	3.97				1.92	3.13
84	NISS	2.11	2.85	3.76	6.45				3.79	2.70
70	CHRYS	2.21	5.15	5.7	5.99	7.05			5.22	2.65
88	HOND	0.08	0.09	2.95	3.6				1.68	2.60
69	FORD	0.42	2.56	3.12	4.4				2.63	2.07
81	CHEV	1.82	3.14	4.25	4.68	5.44	6.08		4.24	2.01
82	CHEV	0.43	0.61	1.21	1.38	1.48	3.87	4.15	1.88	1.96
74	FORD	3.79	5.32	6.69	6.69				5.62	1.43
80	BUIC	1.61	3.17	3.2	4.56				3.14	1.09
80	OLDS	-0.09	-0.02	0.01	0.18	0.2	1.75	2.56	0.66	0.96
85	TOYT	0.01	0.14	0.23	0.33	2.34			0.61	0.76
84	RENA	0.01	0.11	0.65	1.1	1.77	2.43		1.01	0.76
81	BUIC	1.17	1.37	2.39	3.34				2.07	0.75
80	VLK	1.05	1.47	1.81	2.2	3.31			1.97	0.59
88	MITSU	-0.12	0.02	1.14	1.36	1.79			0.84	0.57
86	ISU	0.09	0.23	0.38	1.56				0.57	0.34
89	FORD	0.05	0.06	0.29	0.72	1.28			0.48	0.22
89	CHEV	0.11	0.12	0.13	0.2	1.3			0.37	0.22
78	CHEV	0.21	1.14	1.18	1.36				0.97	0.20
78	CHEV	0.15	0.2	0.24	1.17				0.44	0.18
78	CHEV	-0.27	0.1	0.24	0.31	0.84	0.94		0.36	0.17
81	CHEV	0.64	0.73	1.27	1.56				1.05	0.14
78	CHEV	-0.02	0.21	0.78	0.85				0.46	0.14
85	CHEV	-0.01	0.11	0.14	0.3	0.99			0.31	0.13
78	TOYT	0.41	0.58	0.65	1.01	1.09	1.41		0.86	0.12
88	DODG	0.07	0.15	0.18	0.28	0.3	1.09		0.35	0.12

86	CHEV	-0.04	0.01	0.17	0.7			0.21	0.09
89	FORD	0.00	0.01	0.01	0.06	0.13	0.76	0.16	0.07
72	CADI	1.54	1.82	1.83	2.21	2.23		1.93	0.07
81	CHEV	0.31	0.45	0.66	0.98			0.60	0.06
88	MAZD	0.04	0.05	0.32	0.38	0.72		0.30	0.06
86	TOYT	0.06	0.21	0.3	0.44	0.59	0.76	0.39	0.05
81	DATS	0.11	0.21	0.23	0.69			0.31	0.05
85	CADI	-0.01	0.2	0.38	0.59			0.29	0.05
87	PONT	-0.01	0.01	0.06	0.48			0.14	0.04
82	CHEV	-0.28	0.05	0.12	0.18	0.31		0.08	0.04
90	TOYT	-0.15	0.02	0.18	0.33			0.10	0.03
84	FORD	0.04	0.08	0.1	0.48			0.18	0.03
77	FORD	-0.01	0.02	0.04	0.42			0.12	0.03
64	CHEV	0.25	0.61	0.64	0.69			0.55	0.03
80	CHEV	-0.03	0.03	0.04	0.4			0.11	0.03
78	CHEV	-0.16	-0.09	0.1	0.25			0.03	0.03
81	BUIC	0.05	0.05	0.29	0.39			0.20	0.02
89	PONT	-0.07	-0.02	0.01	0.02	0.03	0.38	0.06	0.02
87	HOND	-0.13	0.03	0.07	0.07	0.28		0.06	0.02
84	FORD	0.07	0.11	0.11	0.32	0.39		0.20	0.02
86	FORD	0.08	0.19	0.34	0.36			0.24	0.01
89	BMW	-0.10	-0.03	0	0.08	0.15	0.22	0.05	0.01
85	BUIC	0.03	0.04	0.05	0.24			0.09	0.01
78	VOLVO	-0.02	0.07	0.08	0.21			0.09	0.01
88	FORD	0.01	0.02	0.03	0.2			0.07	0.01
84	TOYT	0.03	0.05	0.17	0.18			0.11	0.00
83	BUICK	-0.04	-0.02	0.01	0.12			0.02	0.00
84	BUIC	0.02	0.14	0.16	0.18	0.19		0.14	0.00
89	BUICK	0.01	0.01	0.03	0.13			0.05	0.00
85	CHEV	-0.09	-0.04	-0.01	0.01	0.05		-0.02	0.00
86	PONT	-0.03	-0.02	0.02	0.08			0.01	0.00

APPENDIX 3 Diesel Vehicles

Date	Time	%CO	Make	Year	Fuel
12/11/89	11:48:14	-0.49	FORD	86	D
12/18/89	13:25:00	-0.43	FORD	87	D
12/13/89	10:31:06	-0.42	GMC	89	D
12/19/89	11:53:26	-0.34	CHEV	81	D
12/13/89	09:02:55	-0.30	KW	84	D
12/14/89	16:05:38	-0.25	ISU	88	D
12/14/89	09:35:28	-0.21	MACK	84	D
12/12/89	11:41:31	-0.17	GMC	71	D
12/13/89	13:24:29	-0.17	INTL	89	D
12/07/89	10:00:03	-0.17	FORD	88	D
12/16/89	09:43:04	-0.16	INTL	89	D
12/18/89	11:29:07	-0.15	MAGIS	82	D
12/16/89	09:22:57	-0.15	MBZ	80	D
12/12/89	13:27:17	-0.14	FORD	86	D
12/16/89	12:58:20	-0.14	FORD	87	D
12/14/89	08:44:41	-0.12	MBZ	80	D
12/07/89	10:46:32	-0.11	VOLK	82	D
12/14/89	12:05:21	-0.11	GMC	87	D
12/08/89	11:58:35	-0.11	FORD	84	D
12/14/89	12:24:51	-0.10	FORD	81	D
12/14/89	10:39:31	-0.10	BUIC	82	D
12/13/89	10:53:55	-0.09	INTL	90	D
12/18/89	17:22:06	-0.08	HINO	87	D
12/06/89	13:47:36	-0.08	MERZ	79	D
12/12/89	11:42:44	-0.08	VLKSW	82	D
12/16/89	10:07:34	-0.08	MERZ	77	D
12/07/89	09:31:39	-0.05	TOYT	84	D
12/14/89	15:07:40	-0.05	MERZ	76	D
12/14/89	13:55:44	-0.05	IVEC	86	D
12/16/89	09:26:41	-0.05	ISU	88	D
12/16/89	14:37:34	-0.04	MERZ	77	D
12/15/89	10:29:16	-0.03	FORD	89	D
12/16/89	09:28:08	-0.03	FORD	88	D
12/12/89	12:39:47	-0.02	CHEV	83	D
12/13/89	10:22:07	-0.02	HINO	87	D
12/08/89	12:20:05	-0.02	INTL	89	D
12/13/89	09:44:53	-0.02	INTL	90	D
12/14/89	08:49:01	-0.02	GMC	89	D
12/11/89	13:50:27	-0.02	MERZ	79	D
12/12/89	12:28:51	-0.02	MERZ	82	D
12/08/89	09:45:36	-0.02	GMC	85	D
12/08/89	12:01:51	-0.02	GMC	80	D
12/07/89	11:58:21	-0.02	PEUG	82	D
12/14/89	13:13:15	-0.01	GMC	86	D
12/07/89	09:24:56	-0.01	MBZ	81	D
12/16/89	13:30:28	-0.01	OLDS	79	D
12/08/89	12:16:36	-0.01	MERZ	84	D
12/16/89	11:05:31	-0.01	FORD	89	D
12/11/89	11:09:10	-0.01	GMC	82	D
12/08/89	11:28:44	-0.01	FORD	87	D
12/08/89	09:39:37	0.00	FORD	87	D
12/14/89	10:02:20	0.00	MERZ	84	D
12/14/89	13:57:11	0.00	MBZ	83	D

Date	Time	%CO	Make	Year	Fuel
12/08/89	12:14:23	0.00	GMC	83	D
12/18/89	11:34:59	0.00	MERZ	87	D
12/12/89	15:41:43	0.01	GMC	86	D
12/16/89	13:48:15	0.01	MERZ	79	D
12/13/89	11:11:23	0.01	MERZ	80	D
12/14/89	14:20:00	0.01	FORD	89	D
12/14/89	11:47:00	0.01	FORD	87	D
12/16/89	09:28:03	0.01	FORD	88	D
12/14/89	10:38:37	0.02	MBZ	79	D
12/13/89	13:22:44	0.02	FORD	87	D
12/14/89	13:30:25	0.02	INTL	79	D
12/14/89	14:56:58	0.02	MACK	84	D
12/16/89	13:27:20	0.02	FORD	89	D
12/14/89	10:29:31	0.02	FORD	89	D
12/14/89	15:15:31	0.02	PETRB	84	D
12/14/89	11:52:52	0.02	GMC	89	D
12/14/89	13:50:36	0.02	GMC	83	D
12/13/89	08:24:07	0.02	INTL	90	D
12/12/89	14:55:19	0.02	GMC	85	D
12/13/89	13:18:31	0.02	INTL	86	D
12/07/89	13:34:24	0.02	MBZ	81	D
12/14/89	16:13:21	0.02	VOLV	84	D
12/14/89	13:40:44	0.02	FORD	84	D
12/14/89	13:01:00	0.02	GMC	86	D
12/13/89	11:06:48	0.02	VLKSW	81	D
12/15/89	11:29:18	0.03	INTL	83	D
12/13/89	13:50:38	0.03	INTL	84	D
12/13/89	10:26:10	0.03	CADI	82	D
12/13/89	11:25:40	0.03	FORD	85	D
12/14/89	10:16:34	0.03	VOLK	82	D
12/16/89	14:52:21	0.03	FORD	86	D
12/16/89	14:00:30	0.03	MZB	84	D
12/15/89	14:33:35	0.03	FORD	89	D
12/13/89	09:26:20	0.03	GMC	85	D
12/13/89	08:45:27	0.03	FORD	87	D
12/14/89	11:20:21	0.03	GMC	88	D
12/13/89	13:56:47	0.04	FORD	86	D
12/14/89	15:36:35	0.04	CHEV	87	D
12/16/89	12:57:18	0.04	FORD	88	D
12/13/89	10:59:47	0.04	FORD	88	D
12/16/89	13:27:27	0.04	FORD	86	D
12/14/89	10:32:23	0.04	FORD	89	D
12/14/89	12:26:36	0.04	MERZ	84	D
12/15/89	13:57:50	0.04	INTL	87	D
12/18/89	15:25:35	0.04	FORD	86	D
12/07/89	09:29:51	0.04	MERZ	82	D
12/12/89	15:22:27	0.05	GMC	86	D
12/13/89	12:24:56	0.05	INTL	80	D
12/11/89	14:16:34	0.05	MERZ	83	D
12/14/89	14:16:03	0.05	DATS	82	D
12/16/89	12:08:03	0.05	MERZ	84	D
12/14/89	12:09:49	0.05	OLDS	81	D
12/12/89	12:47:33	0.05	ISU	85	D

Date	Time	%CO	Make	Year	Fuel
12/16/89	13:35:53	0.05	MERZ	87	D
12/13/89	11:22:36	0.05	ISUZU	83	D
12/14/89	10:09:16	0.05	FORD	84	D
12/14/89	14:13:02	0.05	GMC	81	D
12/14/89	09:50:44	0.05	CADI	79	D
12/08/89	09:39:44	0.05	FORD	87	D
12/13/89	12:56:15	0.05	FORD	88	D
12/19/89	09:56:53	0.05	CHEV	84	D
12/14/89	14:07:07	0.05	FORD	88	D
12/14/89	12:08:48	0.06	MERZ	87	D
12/13/89	12:29:42	0.06	KENWO	88	D
12/08/89	11:45:01	0.06	INTL	89	D
12/14/89	10:38:29	0.06	MERZ	89	D
12/14/89	11:30:02	0.06	FORD	89	D
12/16/89	12:57:36	0.06	MERZ	79	D
12/13/89	13:13:44	0.06	GMC	83	D
12/14/89	16:05:56	0.06	MERZ	84	D
12/14/89	10:38:59	0.06	MERZ	87	D
12/08/89	15:09:20	0.06	CHEV	85	D
12/14/89	10:35:18	0.06	FORD	86	D
12/13/89	10:46:32	0.06	FORD	86	D
12/13/89	08:29:47	0.06	INTL	86	D
12/14/89	08:58:55	0.06	VOLV	83	D
12/19/89	13:06:22	0.06	MERZ	84	D
12/19/89	14:56:44	0.06	MERZ	85	D
12/14/89	11:18:57	0.06	PEUG	84	D
12/13/89	12:27:39	0.06	FORD	84	D
12/14/89	10:59:23	0.06	PEUG	79	D
12/12/89	14:08:57	0.06	GMC	86	D
12/13/89	13:35:01	0.07	OLD	80	D
12/14/89	14:14:47	0.07	MITSU	84	D
12/13/89	08:33:05	0.07	INTL	90	D
12/13/89	09:24:51	0.07	GMC	85	D
12/19/89	13:01:01	0.07	CHEV	84	D
12/18/89	15:42:24	0.07	MBZ	83	D
12/19/89	11:53:34	0.07	IVEC	88	D
12/13/89	10:45:38	0.07	FORD	88	D
12/14/89	13:17:15	0.07	IVECO	89	D
12/16/89	10:56:01	0.07	MACK	89	D
12/15/89	14:36:00	0.07	NISS	87	D
12/13/89	13:20:54	0.07	INTL	87	D
12/08/89	14:58:01	0.08	FORD	86	D
12/13/89	10:20:31	0.08	HINO	87	D
12/15/89	10:58:08	0.08	FORD	87	D
12/15/89	13:30:44	0.08	FORD	87	D
12/13/89	08:35:39	0.08	GMC	85	D
12/12/89	11:44:18	0.08	INTL	88	D
12/12/89	10:33:05	0.08	PTRB	89	D
12/14/89	09:22:11	0.08	CROWN	70	D
12/14/89	11:29:01	0.08	INTL	84	D
12/16/89	15:02:09	0.08	MERZ	79	D
12/14/89	10:52:18	0.08	FORD	86	D
12/15/89	14:56:10	0.08	FORD	85	D

Date	Time	%CO	Make	Year	Fuel
12/08/89	14:04:29	0.09	GMC	87	D
12/13/89	08:48:04	0.09	INTL	82	D
12/14/89	12:11:31	0.09	FORD	83	D
12/18/89	15:41:27	0.09	BUICK	83	D
12/18/89	11:04:11	0.09	INTL	84	D
12/14/89	11:05:59	0.09	MERZ	84	D
12/13/89	08:32:00	0.09	INTL	81	D
12/12/89	13:42:53	0.09	DODG	89	D
12/13/89	08:48:45	0.09	FORD	89	D
12/14/89	14:33:45	0.09	INTL	77	D
12/08/89	12:08:06	0.10	INTL	87	D
12/11/89	14:44:24	0.10	VLKSW	79	D
12/19/89	14:41:37	0.10	YORD	86	D
12/19/89	13:31:43	0.10	CAD	80	D
12/14/89	11:30:48	0.11	OLDS	78	D
12/13/89	11:16:47	0.11	FORD	80	D
12/14/89	13:02:28	0.11	GMC	86	D
12/14/89	13:17:32	0.11	MERZ	87	D
12/14/89	09:43:34	0.11	GMC	87	D
12/15/89	10:20:43	0.11	INTL	83	D
12/07/89	14:29:27	0.11	CADI	78	D
12/13/89	13:36:41	0.11	WHITE	78	D
12/15/89	10:58:19	0.11	FORD	87	D
12/12/89	13:54:45	0.11	FORD	88	D
12/13/89	12:06:40	0.12	ISU	86	D
12/16/89	11:23:11	0.12	FORD	86	D
12/14/89	08:54:43	0.12	FORD	88	D
12/19/89	15:22:48	0.12	FORD	89	D
12/14/89	09:27:56	0.12	MACK	85	D
12/14/89	11:37:46	0.12	MERZ	83	D
12/07/89	11:41:55	0.12	PEUG	81	D
12/16/89	09:34:12	0.12	MERZ	86	D
12/18/89	15:21:10	0.13	TOYT	85	D
12/16/89	12:01:16	0.13	IVECO	84	D
12/14/89	09:11:24	0.13	MBZ	83	D
12/13/89	09:19:49	0.13	MBZ	84	D
12/13/89	10:46:45	0.13	CADI	82	D
12/16/89	14:33:14	0.13	INTL	84	D
12/07/89	13:25:38	0.13	MERZ	78	D
12/13/89	10:21:18	0.13	MERZ	84	D
12/13/89	12:18:26	0.13	MAGUS	82	D
12/13/89	13:06:28	0.13	ISU	89	D
12/13/89	09:29:58	0.13	INTL	90	D
12/13/89	08:28:41	0.13	CHEV	86	D
12/13/89	10:40:13	0.13	FORD	87	D
12/13/89	10:16:20	0.14	GMC	86	D
12/14/89	13:11:39	0.14	CHEV	86	D
12/14/89	10:28:50	0.14	MERZ	82	D
12/13/89	09:40:22	0.14	FORD	80	D
12/16/89	14:44:25	0.14	MERZ	82	D
12/19/89	11:56:40	0.14	TOYT	83	D
12/14/89	09:19:24	0.15	VOLK	84	D
12/14/89	09:55:58	0.15	INTL	80	D

Date	Time	%CO	Make	Year	Fuel
12/08/89	13:02:51	0.15	ISU	86	D
12/14/89	09:37:34	0.15	VLKSW	81	D
12/16/89	12:53:04	0.15	VOLV	83	D
12/14/89	09:54:35	0.15	MERZ	0	D
12/14/89	15:29:34	0.15	INTL	87	D
12/08/89	14:08:05	0.15	MERZ	63	D
12/14/89	13:13:58	0.15	FORD	83	D
12/13/89	13:03:50	0.15	INTL	79	D
12/13/89	11:25:22	0.15	FORD	86	D
12/08/89	14:02:33	0.15	NISS	87	D
12/08/89	09:55:14	0.15	FORD	84	D
12/14/89	12:47:56	0.15	FORD	88	D
12/13/89	08:04:02	0.16	UD	87	D
12/14/89	14:52:56	0.16	MERZ	88	D
12/14/89	10:43:15	0.16	IVECO	82	D
12/11/89	14:10:32	0.16	MERZ	82	D
12/07/89	11:42:39	0.16	MERZ	85	D
12/13/89	10:16:17	0.17	FORD	78	D
12/12/89	13:31:44	0.17	CHEV	84	D
12/16/89	11:40:51	0.17	FORD	86	D
12/13/89	09:33:43	0.17	PETER	87	D
12/18/89	11:39:55	0.17	GMC	83	D
12/19/89	14:04:03	0.18	FORD	87	D
12/14/89	08:59:40	0.18	MERZ	78	D
12/16/89	14:27:28	0.18	MERZ	82	D
12/07/89	14:10:26	0.18	FORD	86	D
12/14/89	15:57:23	0.18	INTL	78	D
12/13/89	10:38:07	0.18	COLNS	87	D
12/14/89	15:03:09	0.19	FORD	82	D
12/16/89	12:38:53	0.19	MERZ	80	D
12/06/89	14:47:02	0.19	DATS	82	D
12/14/89	13:44:52	0.19	ISU	88	D
12/08/89	09:57:10	0.20	GMC	87	D
12/19/89	14:04:00	0.20	FORD	87	D
12/13/89	11:22:34	0.20	MERZ	76	D
12/13/89	12:02:32	0.20	MERZ	84	D
12/14/89	15:33:19	0.20	MERZ	79	D
12/14/89	13:16:27	0.20	OLDS	82	D
12/13/89	10:54:32	0.20	MERZ	84	D
12/13/89	11:30:26	0.21	OLDS	81	D
12/13/89	13:31:11	0.21	IZUZU	81	D
12/12/89	11:21:33	0.21	OLDS	79	D
12/07/89	13:58:40	0.21	CHEV	82	D
12/13/89	11:27:43	0.21	INTL	80	D
12/14/89	09:02:19	0.22	INTL	89	D
12/14/89	10:32:36	0.22	VOLK	80	D
12/16/89	13:32:00	0.22	VLKSW	82	D
12/14/89	09:19:03	0.23	MBZ	83	D
12/14/89	13:35:31	0.23	PETER	78	D
12/14/89	14:33:47	0.23	INTL	77	D
12/14/89	12:04:48	0.23	ISU	88	D
12/14/89	09:19:58	0.24	INTL	79	D
12/18/89	14:44:35	0.24	FORD	87	D

Date	Time	%CO	Make	Year	Fuel
12/14/89	13:39:24	0.24	PTRB	0	D
12/13/89	10:54:27	0.24	INTL	81	D
12/13/89	07:38:26	0.24	CADI	83	D
12/14/89	15:41:21	0.25	KW	85	D
12/13/89	13:09:52	0.26	MACK	87	D
12/16/89	10:08:44	0.26	MERZ	87	D
12/07/89	10:25:49	0.26	PEUG	83	D
12/16/89	14:47:29	0.26	MBZ	84	D
12/14/89	13:46:39	0.27	CHEV	82	D
12/18/89	10:15:08	0.27	FORD	87	D
12/13/89	07:38:53	0.27	HINO	88	D
12/06/89	15:29:05	0.28	MERZ	78	D
12/13/89	08:18:19	0.28	GMC	78	D
12/13/89	11:25:52	0.28	IVECO	84	D
12/12/89	13:42:58	0.28	GMC	83	D
12/19/89	15:09:45	0.30	CHEV	86	D
12/13/89	08:35:52	0.30	MACK	88	D
12/07/89	10:34:43	0.30	FORD	88	D
12/07/89	12:55:28	0.30	MERZ	78	D
12/13/89	09:32:32	0.31	MACK	87	D
12/19/89	14:44:36	0.32	MBZ	83	D
12/15/89	14:56:47	0.33	VOLK	85	D
12/13/89	12:17:18	0.33	MACK	86	D
12/06/89	15:21:34	0.34	GMC	86	D
12/12/89	10:11:13	0.35	WARD	78	D
12/14/89	11:59:48	0.35	MERZ	74	D
12/07/89	11:37:52	0.36	VOLK	82	D
12/13/89	12:10:31	0.36	INTL	81	D
12/11/89	16:11:20	0.37	CROWN	82	D
12/13/89	09:13:42	0.38	FORD	80	D
12/19/89	13:42:21	0.39	TYOTA	84	D
12/08/89	14:39:21	0.41	OLDS	80	D
12/13/89	11:53:12	0.41	MACK	85	D
12/14/89	15:37:39	0.42	OLDS	0	D
12/07/89	08:58:50	0.43	CAD	81	D
12/18/89	15:43:44	0.43	FORD	86	D
12/13/89	09:16:37	0.44	MACK	88	D
12/13/89	08:12:13	0.44	OLDS	79	D
12/12/89	11:56:12	0.45	MERZ	82	D
12/07/89	09:16:46	0.45	MERZ	80	D
12/16/89	14:40:14	0.48	MERZ	85	D
12/13/89	12:15:47	0.49	FORD	85	D
12/14/89	10:29:21	0.49	PTRB	89	D
12/07/89	10:34:51	0.51	VOLK	80	D
12/15/89	10:22:49	0.52	PTRB	68	D
12/14/89	14:07:20	0.54	HINO	86	D
12/13/89	08:58:46	0.54	MACK	85	D
12/13/89	13:07:06	0.56	MACK	82	D
12/13/89	11:11:43	0.56	MACK	84	D
12/19/89	12:15:31	0.56	FORD	89	D
12/08/89	12:00:18	0.60	FORD	87	D
12/15/89	12:05:49	0.62	OLDS	82	D
12/13/89	12:07:29	0.68	MACK	84	D

Date	Time	%CO	Make	Year	Fuel
12/08/89	11:52:46	0.68	GMC	83	D
12/13/89	10:27:12	0.72	MACK	85	D
12/13/89	08:23:43	0.72	GMC	82	D
12/14/89	13:51:15	0.85	MACK	89	D
12/14/89	16:24:55	0.90	INTL	79	D
12/15/89	09:47:27	0.91	MACK	87	D
12/15/89	11:21:51	0.97	OLDS	80	D
12/11/89	12:25:32	1.03	INTL	80	D
12/08/89	14:29:45	1.11	HINO	88	D
12/13/89	08:00:20	1.12	CHEV	79	D
12/12/89	15:28:32	1.14	BUIC	82	D
12/13/89	11:27:05	1.17	MAGI	80	D
12/12/89	11:19:21	1.24	FORD	87	D
12/07/89	12:17:46	1.36	CHEV	84	D
12/12/89	13:36:38	1.46	DATS	82	D
12/15/89	14:23:58	1.50	OLDS	81	D
12/08/89	10:56:41	1.56	CADI	79	D
12/14/89	15:48:19	1.83	CHEV	82	D
12/14/89	13:57:09	1.85	OLDS	79	D
12/13/89	08:42:55	1.96	MERZ	80	D
12/11/89	12:47:12	2.22	CADI	78	D
12/15/89	10:49:10	2.23	OLDS	80	D
12/08/89	11:47:10	2.24	OLDS	80	D
12/07/89	09:33:12	2.31	FGTLN	79	D
12/07/89	11:02:14	2.31	OLDS	80	D
12/13/89	10:39:30	2.32	FORD	87	D
12/08/89	10:03:37	2.56	FORD	87	D
12/14/89	11:57:05	2.63	OLDS	81	D
12/08/89	13:57:03	2.81	CADI	78	D
12/08/89	09:36:40	2.92	FRHT	87	D
12/07/89	13:58:17	3.01	CADI	79	D
12/15/89	12:16:45	3.12	CADI	79	D
12/14/89	14:52:36	3.15	CADI	79	D
12/12/89	15:44:38	3.49	OLDS	79	D
12/13/89	12:29:22	3.50	CHEV	80	D
12/06/89	15:20:25	3.61	OLDS	81	D
12/13/89	11:21:07	3.62	CADI	80	D
12/11/89	12:19:22	3.71	VOLK	79	D
12/12/89	10:13:54	3.71	BUIC	81	D
12/07/89	09:15:15	4.08	CADI	79	D
12/08/89	11:10:04	4.20	CADI	79	D
12/08/89	15:02:20	4.29	OLDS	79	D
12/14/89	12:41:34	4.31	MACK	87	D
12/12/89	12:25:44	4.46	BUIC	81	D
12/07/89	11:11:39	4.64	CADI	75	D
12/11/89	11:22:53	4.74	OLDS	79	D
12/14/89	15:47:30	4.85	OLDS	80	D
12/14/89	12:48:58	4.98	CADI	79	D
12/07/89	09:48:15	5.10	CADI	79	D
12/12/89	12:53:43	5.55	BUIC	82	D
12/12/89	12:09:20	5.72	OLDS	80	D
12/14/89	15:15:16	5.97	MACK	76	D
12/15/89	14:54:21	6.11	OLDS	80	D

Date	Time	%CO	Make	Year	Fuel
12/12/89	13:47:43	6.43	OLDS	79	D
12/15/89	09:12:33	6.44	OLDS	79	D
12/14/89	15:35:21	6.69	MACK	89	D
12/14/89	13:55:28	6.78	GMC	84	D
12/08/89	13:35:21	7.16	OLDS	79	D
12/13/89	13:43:10	7.19	GMC	84	D
12/15/89	12:51:46	7.47	OLDS	80	D
12/11/89	16:07:11	7.68	OLDS	79	D
12/15/89	11:18:36	8.03	OLDS	80	D
12/19/89	11:58:52	8.09	GMC	84	D
12/11/89	11:41:37	8.97	CHEV	79	D
12/12/89	12:02:19	9.48	OLDS	79	D
12/08/89	13:04:00	9.49	OLDS	80	D
12/19/89	12:26:22	10.26	GMC	82	D
12/15/89	13:31:21	13.29	OLDS	81	D

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
PB92-162148	August, 1991	Final Report

4. TITLE AND SUBTITLE
On-Road CO Remote Sensing in the Los Angeles Basin

5. FUNDING NUMBERS
A932-189

6. AUTHOR(S)
D.H. Stedman, G. Bishop, J.E. Peterson, P.L. Guenther

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Denver
Chemistry Department
Denver, CO 80208

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
California Air Resources Board
Research Division
1800 15th Street
Sacramento, CA 95814

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARB/R-92/479

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Release unlimited. Available from National Technical Information Service
5285 Port Royal Road, Springfield, VA 22161

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The University of Denver used its remote sensor for motor vehicle carbon monoxide emissions to measure carbon monoxide (CO) emissions in the Lynwood area of the South Coast Air Basin during eleven days in December 1989. This work was performed in support of a larger study to investigate the reasons for high CO concentrations near Lynwood on winter nights. Vehicles were measured in a mix of driving conditions ranging from deceleration preceding a traffic light through idling in heavy congestion to acceleration and cruise on a freeway on-ramp. The ARB validated the performance of the instrument in a double blind test using an instrumented vehicle provided by General Motors Research Laboratories. Over 27,000 valid CO measurements were collected during the study - 16,000 of these were matched to license plate information through the California Department of Motor Vehicles to obtain make and model year information.

The data collected indicate that, for the driving modes encountered, more than half of the CO was emitted by only 11% of the vehicles. These vehicles emitted more than 5% CO in their exhaust, and are referred to as "gross polluters." A model of vehicle emissions based on vehicle age suggests that emissions increase linearly with average age of the fleet, and that the linear increase is dominated by the steady increase in the fraction of gross polluters with age. The model helps explain the higher concentration of CO near Lynwood, as the vehicle fleet in the Lynwood area is older by two to three years than the fleets in other areas measured.

14. SUBJECT TERMS
Air Pollution, Motor Vehicle Emissions
Carbon Monoxide

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited