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Worldwide On-Road Vehicle Exhaust Emissions Study by Remote Sensing

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The remote sensing technology developed by the University of Denver provides the first practical approach to routinely characterize real-world, on-road automobile CO and HC exhaust emissions. It has been used to measure the exhaust emissions of more than 1 000 000 vehicles in many locations. This study presents an analysis and comparison of 22 fleet profiles collected by the remote sensor in different regions around the world. Three patterns of emissions distributions and contributions of the fleets are revealed by a hierarchial cluster analysis. The importance of vehicle maintenance on average CO and HC emissions is revealed by a quintile analysis. Good maintenance practices in Gothenburg, Sweden, contrast with other locations such as Los Angeles, CA, and Melbourne, Australia. The absolute emissions differences between well- and badly maintained vehicles of any age are considerably larger than observable effects of emission control technology and vehicle age.

Introduction

The impact of automobile emission on urban air pollution has aroused significantly increasing public attention and research interest over the past decades. Regulated exhaust emissions include carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), and particulate matter (*1*). In many locations, photochemical transformation of nitrogen oxides and hydrocarbons gives rise to violations of the ozone standard. Carbon monoxide standards are violated as a result of direct emission of the gas under conditions of persistent meteorological stagnation. It has been reported that the contribution of automobiles to carbon monoxide air pollution was about 50% during the wintertime in the Pacific Northwest, United States, (*2*), about 68.5% in Guangzhou, People's Republic of China (*3*), and as high as 98% in Tehran, Iran (*4*).

Recent legislation has been enacted by the U.S. government to require further reduction of automobile emissions to improve air quality (*5*). Approaches to reducing vehicle emissions include lower new vehicle emission standards, inspection and maintenance (I/M) programs, use of oxygenated fuels, and use of improved catalysts and emission control systems. Numerous analytical techniques have been developed over the past 20 years in an attempt to characterize vehicle emissions, such as flame ionization detection (FID) for total hydrocarbons; nondispersive IR for carbon monoxide/carbon dioxide; chemiluminescence for total nitrogen oxides; GC for C_1-C_{12} hydrocarbons, ethers, and alcohols; and HPLC for C_1-C_8 aldehydes and ketones (*6*). Tunnel studies have been used to determine fleet average emissions (*7–9*). The developments of remote sensing technology by the University of Denver, with capabilities to accurately measure carbon monoxide and hydrocarbon exhaust emissions of many thousands of vehicles per day, provide the first practical approach to routinely characterize on-road automobile exhaust emissions from large fleets of individual vehicles.

The remote sensing system is based on nondispersive infrared spectroscopy. It measures the carbon monoxide to carbon dioxide ratio (CO/CO_2) and the hydrocarbon to carbon dioxide ratio (HC/CO_2) in the exhaust of any on-road vehicle passing through an infrared light beam that is directed across a single lane of roadway. The IR absorption caused by CO, HC, and CO_2 in the exhaust plume is determined using separate bandpass filters centered at 4.6, 3.4, and 4.3 μm, respectively. To eliminate any effect of source fluctuations or dust and smoke behind the vehicle, the results are ratioed to a reference absorption at 3.9 μm, where vehicle exhaust gases do not absorb. The signals are digitized and acquired by a computer system. Software computes exhaust %CO, %CO_2, and %HC from the measured CO/CO_2 and HC/CO_2 ratios on a dry basis corrected for the presence of any excess air. The %HC is reported as an equivalent concentration of propane. The results can be directly converted into the instantaneous mass emission rates in grams of CO and HC per gallon of gasoline burned. If emissions in gram per mile are required, then an estimate of average gas mileage is necessary. The disproportionate importance of high emitters per gallon of gasoline burned is even more important in gram emissions per mile when their poorer fuel economy is also included. For fleets of vehicles, the average age can be used to estimate gas mileage data (*10*). A video camera system is interfaced for the purpose of individual vehicle identification. On-site calibration is performed daily with a certified gas cylinder containing known concentration ratios of CO, CO_2, propane (for HC), and N_2. The details of the instrument system are described elsewhere (*11, 12*).

The technique has been validated by showing that it accurately measures the instantaneous exhaust emissions by means of single and double blind comparisons with vehicles of known emissions sponsored by the California Air Resources Board (CARB) and General Motors (GM) Research Laboratories (*13, 14*). More recent studies by CARB for both CO and HC also show that the remote sensing CO readings are correct within ±5% of the values reported by an on-board gas analyzer and within ±15% for HC (*15*).

On-road vehicle exhaust emissions studies made by remote sensing reveal a highly skewed distribution with

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TABLE 1

Remote Sensing Samples Summary

location	site description	date	records
Bangkok, Thailand	westbound single lane on the south frontage of Si Ayutthaya Road, level and high-traffic density with many motorcycles	Aug 1993	5 260
Chicago, IL	uphill, traffic light-controlled, on-ramp to eastbound I-290 from Central Ave., straight and busy with some hard accelerating vehicles	June 1992	8 733
Denver, CO	tightly curved, uphill 4% grade off-ramp from southbound I-25 to southbound Speer Blvd., speed about 30 mph	Oct 1991	35 945
Edinburgh, U.K.	generally level, straight, and high-traffic density sites	Nov 1992	4 524
Gothenburg, Sweden	uphill, curved freeway interchange ramp at Gullbergsmotet, the last exit northbound before tunnel to Hissingen Island	Sep 1991	10 285
Hamburg, Germany	level, curved on-ramp to southbound freeway	May 1994	11 128
Hong Kong	ramp from Queensway southbound onto Cottontree Dr. at the top of the steepest uphill section, high fraction of diesel powered vehicles	Aug 1993	5 891
Kathmandu, Nepal	uphill section of Ram Shah Path Rd. and a level section westbound at Martyr's Gate, many motorcycles	Aug 1993	11 227
Leicester, U.K.	similar site as in Edinburgh, but older fleet with many motorcycles	Nov 1992	4 992
Lisbon, Portugal	slightly uphill, exit from Tagus Bridge auto route to north Lisbon	May 1994	10 426
London, U.K.	similar site as in Edinburgh, but younger fleet, many motorcycles and diesel-powered taxis	Nov 1992	11 666
Los Angeles, CA	Rosemead Blvd., southbound to the Pomona Freeway (I-60) in El Monte, three-lane surface street narrowed by cones into a single lane	Jun 1991	42 546
Lyons, France	uphill, interchange ramp from northwest bound freeway to westbound circular	May 1994	14 276
Melbourne, Australia	combination of on- or off-ramps of a highway or a two-way road divided by a solid traffic island	May 1992	15 908
Mexico City, Mexico	five sites, mostly highway exit or entry ramps, traffic flow cruising at about 25 mph	Feb 1991	31 838
Milan, Italy	uphill, curved on ramp to northbound freeway to Turin	May 1994	13 943
Rotterdam, The Netherlands	Kleinpolderplatz, uphill, interchange ramp for eastbound vehicles turning north toward Amsterdam	May 1994	12 882
Seoul, South Korea	construction site just after the toll booths of Nam San Park Tunnel 1 southbound, about 2% uphill grade, slow moving congested traffic	Aug 1993	3 104
Taipei, Taiwan	northbound on-ramp to the major north–south freeway, motorcycles are not allowed on the freeway	Aug 1993	12 062
Thessaloniki, Greece	straight and level single lane of downtown one-way street, many motorcycles	Sep 1992	10 536
Toronto, Canada	Bayview Extension, northbound, 2% upgrade ramp onto the Don Valley Parkway	Apr 1990	11 290
Zurich, Switzerland	uphill section of a single-lane road leaving Zurich to southeast Switzerland	Mar 1994	11 298

the great majority of vehicles having exhaust emissions less than 1% CO and 0.1% HC (propane equivalent) while the majority of the measured on-road exhaust emissions are from the highest emitting 10% of the vehicles for CO and 15% of the vehicles for HC (*16–18*). The idle test data from the California roadside surveys also show the same skewed emission distribution as shown by remote sensing data (*19*). Most of those high emitters are the result of a combination of malfunctioning vehicles, improper or inadequate maintenance, damage, and owner/mechanic tampering (*20*). Limited studies (*17, 18*) suggest that the influence of cold starts, hard acceleration, and other normal vehicle behavior is relatively small for the on-road measurements reported herein compared to the effects of bad maintenance. A statistical γ-distribution has been shown to be a good model for on-road vehicle fleet exhaust distributions at all monitoring locations (*21*). While most previous studies have focused on emission variation at a single location, mostly in the United States, this paper describes some observations of on-road automobile CO and HC exhaust emissions by remote sensing worldwide. The study was undertaken to isolate and compare the basic on-road emission patterns in different locations.

Sample Collection and Treatment

The University of Denver's remote sensor for on-road CO and HC exhaust emissions has been used to measure the emissions of more than 1 000 000 vehicles in many locations around the world since the prototype was developed in 1987. For the present study, 22 sampling locations were chosen based upon a good urban traffic flow and representation of different regions around the world with correspondingly different fleet profiles. The sampling locations, sites, measuring dates, and numbers are shown in Table 1, which is alphabetically ordered by the names of the locations.

All the measurements in these sampling sites were digitized and acquired by an automatic data processing computer system. If the noise on the measurement exceeded preset bounds, the measurement was labeled invalid. Invalid measurements were also caused by failure to detect an exhaust plume, as occurred when the beam was blocked by pedestrians, bicycles, and vehicles with elevated exhaust pipes. Only valid measurements for all CO, HC, and CO_2 with proper calibrations were used as data for this analysis.

Results and Discussion

Overall Results. Tables 2 and 3 show a summary for remote sensing CO and HC exhaust emissions data, respectively. For CO emission, the mean values vary from 0.6% to 4.3% with an average value of 1.5%, while the median value for each fleet varies from 0.1% to 3.8%. The observation that the median of each fleet is lower than the mean indicates that the average emissions of fleets are dominated by the high emitters. Furthermore, the difference between mean and median for each fleet implies the skewed nature of the distribution. The larger difference of the mean from the median, the further away from a normal distribution. Mexico City and Kathmandu stand out as having CO

TABLE 2

Remote Sensing CO Emission Data Summary

location	mean %CO	median %CO	%gross polluter	%CO cutpoint
Bangkok	3.04	2.54	21.65	5.24
Chicago	1.04	0.25	7.50	4.20
Denver	0.74	0.11	6.68	3.42
Edinburgh	1.48	0.69	13.40	3.44
Gothenburg	0.71	0.14	8.38	2.58
Hamburg	0.57	0.12	6.80	2.43
Hong Kong	0.96	0.18	9.17	3.41
Kathmandu	3.85	3.69	24.88	5.85
Leicester	2.32	1.61	18.15	4.33
Lisbon	1.48	0.38	12.00	4.21
London	0.96	0.17	8.38	3.58
Los Angeles	0.79	0.15	6.97	3.46
Lyons	0.97	0.22	8.79	3.52
Melbourne	1.42	0.57	12.43	3.52
Mexico City	4.30	3.81	24.29	6.58
Milan	1.25	0.39	11.99	3.42
Rotterdam	0.55	0.13	6.99	2.31
Seoul	0.82	0.26	9.83	2.62
Taipei	1.49	0.88	16.78	3.09
Thessaloniki	1.40	0.55	13.32	3.46
Toronto	0.75	0.15	7.93	2.85
Zurich	0.83	0.17	6.93	3.66

TABLE 3

Remote Sensing HC Emission Data Summary[a]

location	mean %HC	median %HC	%gross polluter	%HC cutpoint
Bangkok*	0.95	0.57	17.93	1.98
Chicago	0.09	0.06	15.89	0.13
Denver	0.06	0.03	10.92	0.10
Edinburgh	0.13	0.08	11.87	0.23
Gothenburg	0.06	0.05	19.71	0.09
Hamburg	0.04	0.02	9.88	0.09
Hong Kong	0.05	0.04	15.87	0.08
Kathmandu*	0.76	0.36	16.15	1.06
Leicester*	0.21	0.13	13.78	0.33
Lisbon	0.06	0.03	10.42	0.12
London*	0.14	0.07	10.00	0.29
Los Angeles	0.07	0.04	10.27	0.15
Lyons	0.07	0.04	11.07	0.14
Melbourne	0.11	0.06	11.05	0.19
Mexico City	0.21	0.11	10.20	0.41
Milan	0.06	0.04	10.74	0.12
Rotterdam	0.04	0.02	9.91	0.08
Seoul	0.04	0.02	4.80	0.15
Taipei	0.06	0.05	20.09	0.09
Thessaloniki*	0.16	0.08	9.86	0.33
Zurich	0.03	0.02	9.34	0.06

[a] Locations marked with an asterisk (*) indicate significant fractions of two-stroke vehicles.

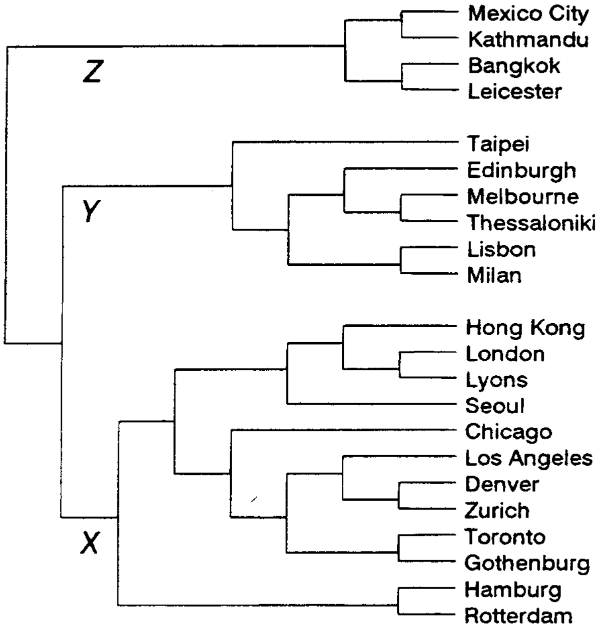

FIGURE 1. Dendrogram for the cluster analysis of CO emission distributions in 22 locations.

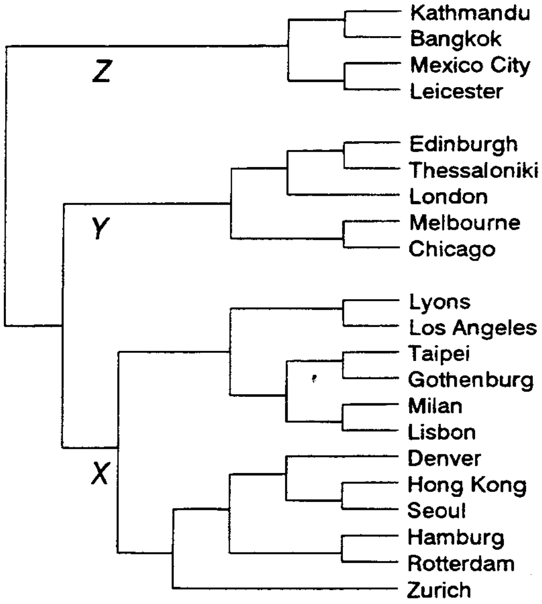

FIGURE 2. Dendrogram for the cluster analysis of HC emission distributions in 21 locations. No HC data are available for the Toronto fleet.

emission levels far above those measured in Hamburg, Rotterdam, Gothenburg, or Denver.

For all fleets, a small fraction of the vehicles is responsible for half or more of the total measured on-road exhaust emissions. This portion of the vehicles is referred to as "gross polluters". In Hamburg, half the emissions came from only 7% of the vehicles. In Kathmandu, in contrast, half the emissions came from 25% of the vehicles. The lower emitting (on average) fleets have a lower percentage of gross polluters with a lower gross polluter cutpoint than those of the higher emitting fleets.

For HCs, the mean values for each fleet vary from 0.03% to 0.95% with an average value of 0.14%, while the median values vary from 0.02% to 0.57%. Two cities in Asia, Bangkok and Kathmandu, stand out for HC emissions due to the high percentage of two-cycle engines including three-wheeled motorcycles used as economical taxis, many of which were also badly tuned and apparently poorly maintained. A study in Taiwan (*22*) shows that HC and CO emissions from one motorcycle are equivalent to the emissions from 12 catalyst-equipped cars. London, Leicester, and Thessaloniki fleets also contain a significant fraction of two-stroke vehicles, which emit high HC levels in their exhaust. Most of the same conclusions that are drawn regarding CO emissions and fleet characteristics hold true for HC emissions.

Correlation of CO and HC Emissions. When the fleet averages of %CO are plotted versus the fleet averages of

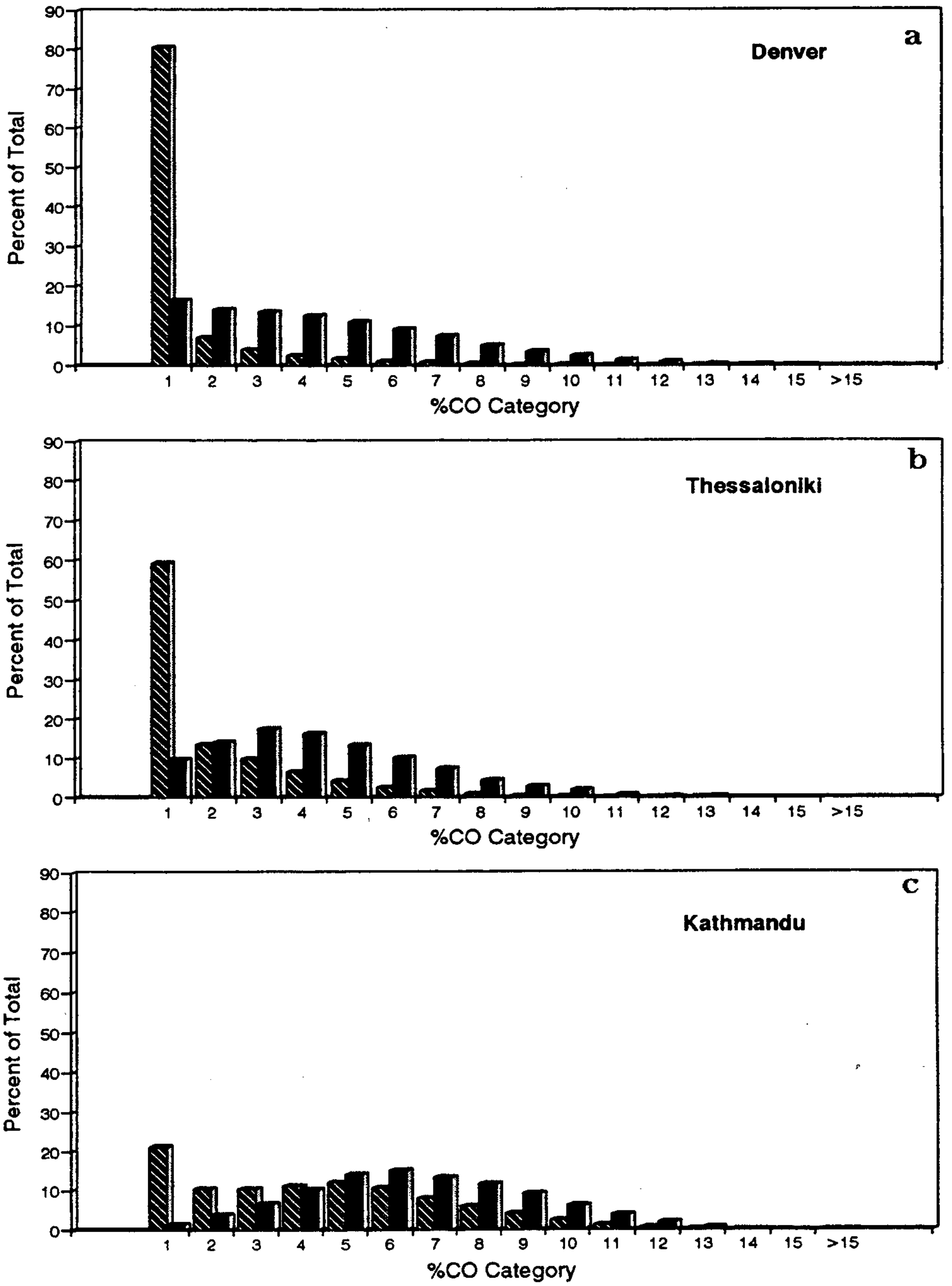

FIGURE 3. Normalized histograms for the Denver (a), Thessaloniki (b), and Kathmandu (c) CO data. Hatched bars show the percentage of the vehicles in the indicated CO emissions category, while solid bars represent the percentage of the fleet total CO emissions from that category.

%HC (fleets with significant fractions of two-stroke vehicles are not included), a regression equation is derived:

$$\%\mathrm{HC} = 0.046 \times \%\mathrm{CO} + 0.019 \qquad (R^2 = 0.81)$$

The $R^2 = 0.81$ implies that the average %HC exhaust emission could be approximately predicted by determining the average %CO exhaust emission in a given region. A region with high %CO emissions can be expected to also find a large number of high HC emitters. This is true in part because factors that may affect average CO emission in a certain region—differing levels of maintenance, average fleet age, and imposition of mandatory emission standards—have the same effect on HC emission in the same region.

Although on average, high CO emissions indicate high HC emissions, an individual vehicle emitting high CO is not necessarily a high HC emitter. In contrast to fleet average data, individual vehicle HC emissions and CO emissions show considerable scatter, as shown previously by Beaton *et al.* (*23*). There are some high HC emitters with very little attendant CO. These vehicles most likely suffer from misfire (misfire can be caused by ignition system failures) or lean misfire where the air–fuel mixture has too little fuel to ignite. For rich air–fuel mixtures, the %CO increases as combustion becomes less complete, and more unburned fuel passes through the cylinders. If there is a partially functional catalytic converter, as is present on some newer vehicles, it will convert the fuel that was not burned

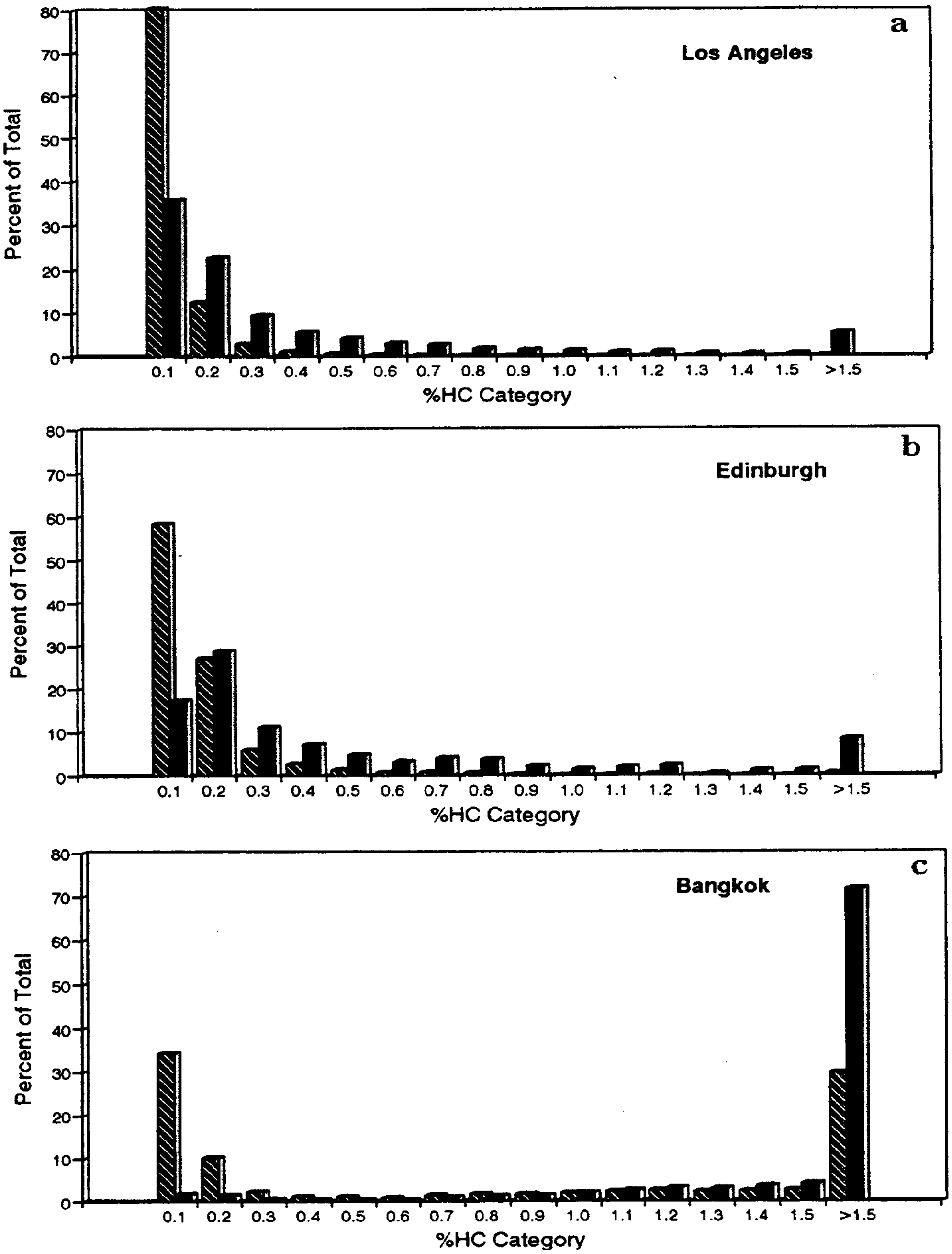

FIGURE 4. Normalized histograms for the Los Angeles (a), Edinburgh (b), and Bangkok (c) HC data. Hatched bars show the percentage of the vehicles in the indicated HC emissions category, while solid bars represent the percentage of the fleet total HC emissions from that category.

in the cylinder into CO, resulting in very high CO values and low HC values. A fully functional emissions system with air addition would also oxidize the CO to CO_2, resulting in a low emitting vehicle. A very rich mixture combined with an ineffective or no catalytic converter will result in both high %CO and high %HC. This result is also possible with a poorly maintained vehicle where, for instance, one cylinder may be misfiring due to ignition problems while the other cylinders are running rich.

Cluster Analysis for Identifying the Similarities in Emission Distributions of the Fleets. A hierarchial aggregative cluster analysis (*24*) was carried out in an effort to sort the fleet distributions of the 22 samples. In this analysis, each location represents a sample. The fraction of vehicles in each given emission range represents the value of the variable that characterizes the sample distribution. The dissimilarity between locations can be measured as the distance between samples, i.e., the larger the distance, the more dissimilar the two locations are. The distances between samples can be represented as the squared Euclidean distance (SED_{ij}) given by

$$\mathrm{SED}_{ij} = \sum (x_{jk} - x_{ik})^2$$

where x_{jk} and x_{ik} are the values for the kth variable for samples j and i. Hierarchical clustering initially considers each sample as a separate cluster. Then the clusters are joined one at a time according to an aggregative algorithm

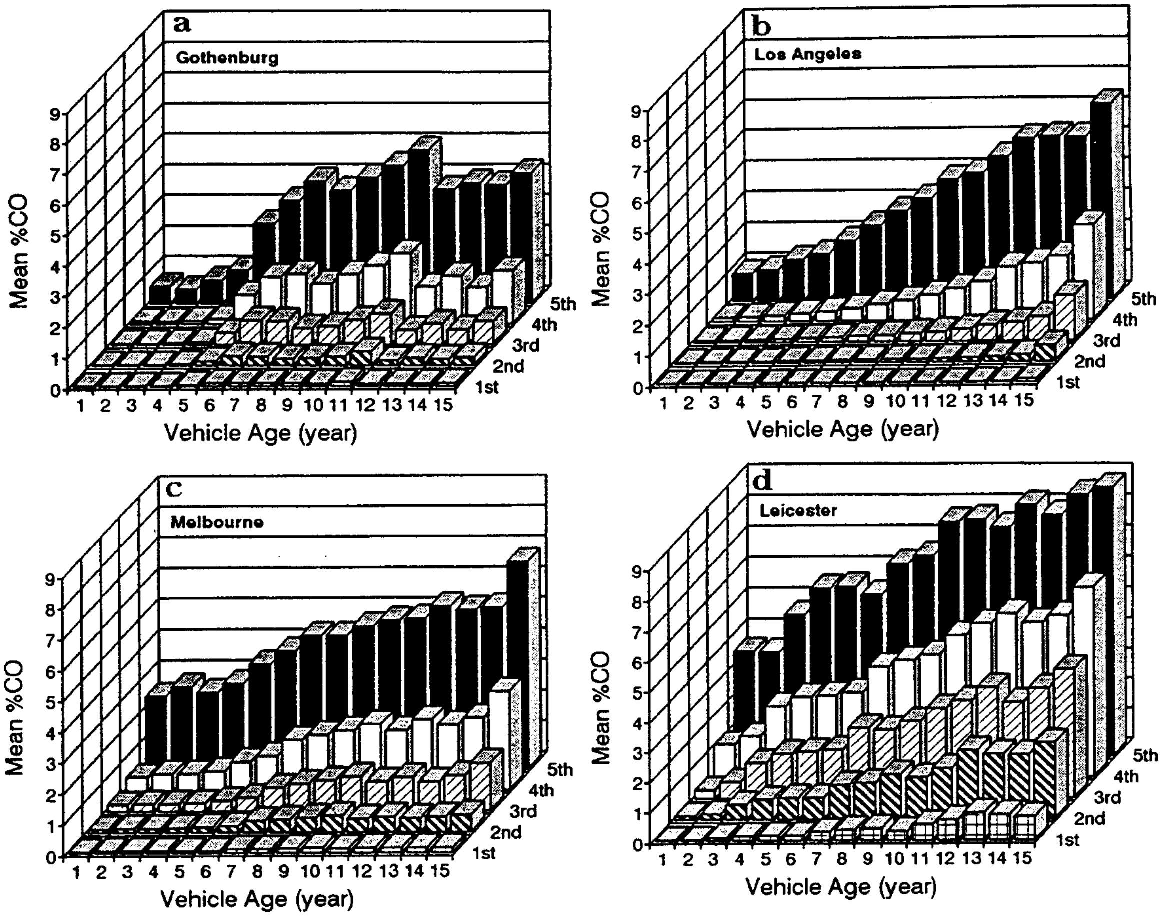

FIGURE 5. Gothenburg (a), Los Angeles (b), Melbourne (c), and Leicester (d) CO data presented as CO emission factors by vehicle age divided into quintiles.

until all the samples are joined into a single cluster. The results of a hierarchical clustering are displayed in a dendrogram, which helps to indicate the relationships between individual samples. The dendrogram is interpreted by examining the way in which the samples group together to form the clusters and the order in which the clusters combine to form large groups.

Figures 1 and 2 are dendrograms resulting from the hierarchical clustering of the CO and HC emissions distributions, respectively, at all locations. The cluster patterns for both CO and HC distributions have a major division into three large clusters. The samples in cluster *X* generally have lower average emissions than those in clusters *Y* and *Z*, while cluster *Z* contains the samples with the highest average emission rates. Note that for both dendrograms, Kathmandu, Bangkok, Mexico City, and Leicester fall in cluster *Z* while Hamburg, Rotterdam, Zurich, Denver, Los Angeles, Gothenburg, Lyons, Seoul, and Hong Kong always reside in cluster *X*. Most of the locations in cluster *X* have a relatively newer fleet and a stricter inspection program than the locations in clusters *Y* and *Z*. Especially in cluster *Z*, the fleet situation is an assortment of less maintenance, older fleet, lack of emission control legislative program, and absence of new vehicle emission standards. However, age alone cannot fully explain all the difference. This is because pre-1970 U.S. vehicles have similar emission technology to the vehicles in Mexico City or Kathmandu, but these older vehicles from Denver and Los Angeles are on average a factor of 2 lower in CO emissions. This implies that a difference in how mechanics tune the vehicles may be involved as suggested for Mexico City by Beaton *et al.* (*23*).

To assist in the understanding of the clusters, for each dendrogram three typical individual samples (one from each cluster) were chosen to illustrate the different cluster pattern. Figures 3 and 4 show the CO and HC emissions distributions for these samples in two ways. The hatched bars represent the distribution of emitters by percent emission category. The solid bars show the percentage of the total emissions from each emission category.

Comparison of the three patterns in Figure 3 shows the following phenomena. First, the Denver fleet, which is typical for the cluster *X*, presents a highly skewed distribution such that about 80% of the fleet emitted less than 1% CO and contributed only 18% of the total emission. In contrast, the Kathmandu fleet in the cluster *Z* only has 20% of the fleet within the less than 1% CO emission category. The skewness of the distribution is decreasing in the order cluster *X*, cluster *Y*, and cluster *Z*. The lower emitting the fleet, the more skewed the fleet distribution. Therefore, the moment of skewness may be used as an indicator of the average emissions of a fleet. Second, the distribution of the total emission contribution (black bars) changes as dramatically as the fleet average emission. In the cluster *X* pattern, the major contribution to the total emission is from the vehicles measured at the largest less than 1% CO category since the majority of vehicles reside in this category. As the vehicle distribution becomes less skewed, gradually the emission contribution tends to be more normally distributed.

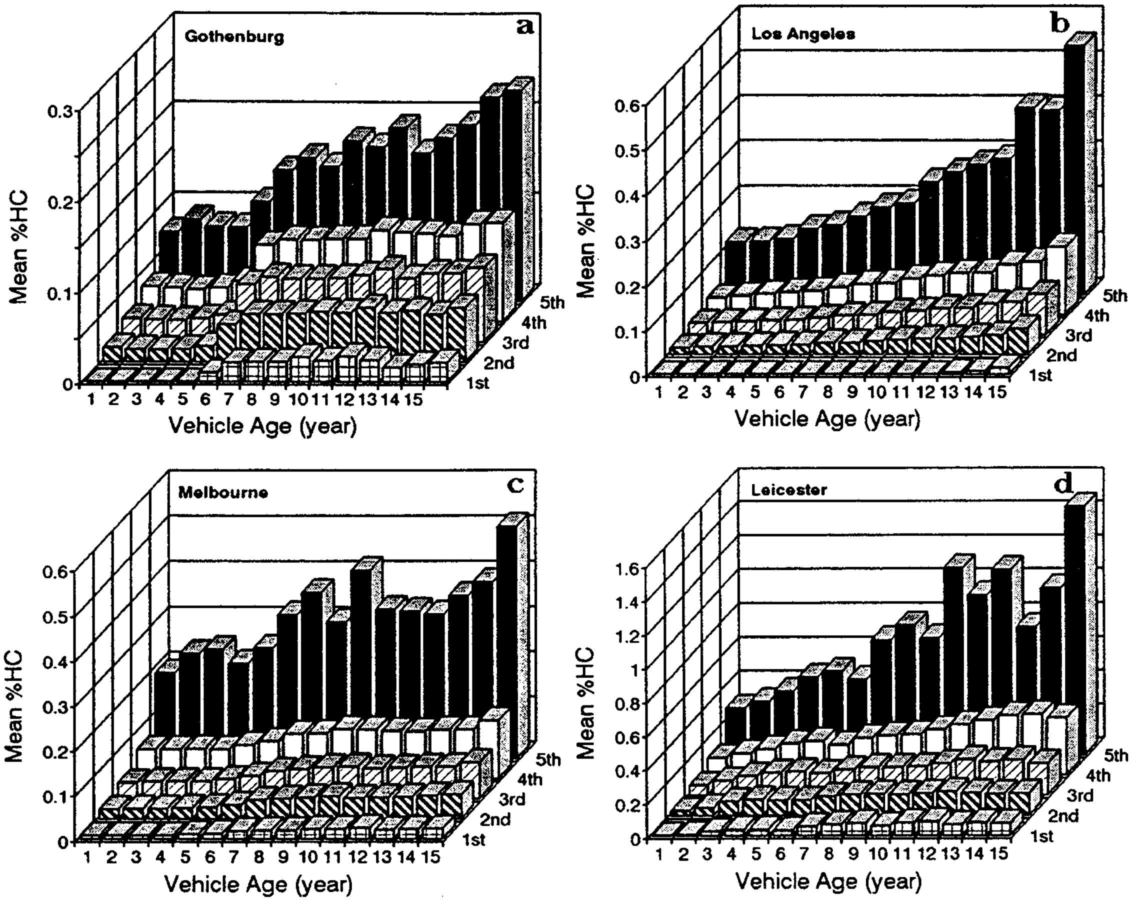

FIGURE 6. Gothenburg (a), Los Angeles (b), Melbourne (c), and Leicester (d) HC data presented as HC emission factors by vehicle age divided into quintiles.

For HC, the skewness of the vehicle distribution of the three corresponding patterns shown in Figure 4 changes in a similar manner as for CO. The exception for HC is that the contribution of the highest emitting vehicles (mostly two-stroke) is extremely large in cluster *Z*.

Quintile Analysis. In principle, the average emission rate from a fleet depends on control, vehicle, and fuel factors. Control factors include effects of maintenance, protection from tampering, and any reduction of emissions resulting from legislated emission control programs. Vehicle factors include vehicle age, manufacturer, and emission control equipment. Fuel type can be mainly divided into diesel and gasoline, the latter may further divided into oxygenated and non-oxygenated gasoline. The driving condition under which the engine is operated (i.e., speed, load, and ambient temperature) is a factor that influences the HC exhaust emission level (*25*) but is relatively insensitive for CO except that hard accelerations resulting in power enrichment lead to very high levels of CO, with much less change in HC. To investigate and understand the influences on the change of average emission rates with the age of vehicle, a quintile analysis of four typical fleets was performed.

Figure 5 shows the Gothenburg, Los Angeles, Melbourne, and Leicester measurement data sets divided into age of vehicle production ranging from 1 to 15 years old on the *X* axis. All vehicles over 15 years old are gathered into the 15-year-old group because our previous studies show little further deterioration beyond 15 years of age (*17, 18*). The lack of "deterioration" beyond 15 years of age likely arises because increasing bad maintenance, which causes the increase in emissions with age, also leads to the increased likelihood for the vehicle to remove itself from the fleet, thus achieving a steady state (*17*). The emissions within each age have been rank ordered and then split into five equal-sized sets (quintiles). Each quintile's emissions are then averaged and are presented as the height of the bar for that quintile. Reading from front to back, one can ascertain the effects of maintenance by the observation of the large absolute difference between the well-maintained vehicles (front row) and the badly maintained vehicles (back row). It can also be seen that the highest emitting quintile of the newest vehicles has much higher emissions than the lowest emitting quintile of the oldest vehicles. This phenomenon indicates that the instantaneous on-road emission difference between well-maintained and badly maintained vehicles is larger than age-dependent deterioration of emission controls and effects of emission control technology in any age.

Comparisons of the fleets at these four locations demonstrates the following:

(a) All four fleets deteriorate as the vehicle age increases. The average CO emission rate and the deterioration rate for the Leicester fleet are much higher than the ones for the Gothenburg fleet; nevertheless, most vehicle and fuel factors are quite similar in these two European locations. Swedish vehicle manufacturers introduced closed-loop catalytic converter over 2 years from 4 to 6 years of age. The effect of this is clearly observable in the jump of emissions from all quintiles of the 4–6-year-old Swedish vehicles. The big differences observed between the Leicester and Gothenburg fleets older than 5 years apparently arise from better maintenance in Gothenburg.

(b) The Australian fleet introduced catalytic converters systems between 6 and 7 years age (1986 and 1985 model years). The emissions of on-road vehicles in Gothenburg show a dramatic drop at 4 years (1988 model year) through all quintiles. In contrast, the effects of catalysts in Melbourne are detectable among the lower emitting (better maintained) quintiles but not among the important high emitters. In addition, the oxidation catalysts were introduced in the United States in early 1970s and then updated to closed-loop and three-way catalysts in early 1980s; however, there is no sign of any sharp breaks in the Los Angeles plot to coincide with those model years when emission control technologies were changed. This observation illustrates that advanced emission control technology is most effective only when combined with proper vehicle maintenance. Further reinforcing the assumption that vehicles are better maintained in Sweden, the pre-1980 (over 10-year-old) Swedish vehicles that are not catalyst equipped show lower average CO emissions than vehicles of corresponding age but originally catalyst-equipped as measured in Los Angeles. Thus, the observed deterioration of emission with age can be mainly attributed to poor maintenance and emission system tampering increasing with age. The fact that emissions system tampering in the United States increases with increasing age is clearly demonstrated by U.S. EPA tampering surveys (*26, 27*).

Figure 6 shows the same organization of plots as in Figure 5 but for HC emissions. Note that the scaling for the Gothenburg and Leicester plots are different from the other two. Most observations and deductions from the CO emissions analysis hold true for HC emissions.

Another piece of evidence to support the importance of maintenance, relative to fuel variables, comes from Melbourne database. About 7% of the Melbourne fleet were LPG (propane-based) powered vehicles. Comparison of CO emissions from vehicles using LPG and gasoline by same model years shows that the average on-road CO emissions from LPG vehicles are nearly twice that from equivalent age gasoline-powered vehicles (*28*). A similar result has been shown in Toronto with a smaller fleet (*29*). These results are contraindicative to the concept that propane usage for fleet conversions will reduce CO emissions, despite the fact that propane is sometimes mandated as a cleaner burning alternative fuel (*30*). It would appear that the low price of LPG reduces the incentive to maintain correct engine tuning and the power reduction generally inherent with LPG irritates the owner/mechanic enough to cause the engine to be adjusted for performance rather than fuel economy or low emissions.

Conclusions

Several analytical approaches are applied to real-world automobile CO and HC exhaust emissions based on remote sensing data collected from 22 locations around the world. For all the fleets, the average emissions are dominated by a small percentage of high emitters. This conclusion is supported by the fact that the median emissions values of each fleet are lower than the mean emissions values. Hierarchial aggregative cluster analysis reveals that the emissions distributions and contributions can be grouped into three patterns according to similarities in skewness of the distributions. The lower emitting the fleet, the more skewed the distribution. The results of quintile analysis show that the deterioration of mean emissions as a function of vehicle age is mainly controlled by vehicle maintenance. The fraction of the vehicles with high emission rates increases with age because of progressive lack of maintenance, more unrepaired failures, and tamping. Emissions control technology is also an effective factor to control automobile emissions but is most effective when combined with proper vehicle maintenance.

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