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MEASUREMENT OF CARBON MONOXIDE CONCENTRATIONS IN INDOOR AND OUTDOOR LOCATIONS USING PERSONAL EXPOSURE MONITORS

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On 15 dates, 5000 measurements of carbon monoxide (CO) were made in downtown commercial settings in four California towns and cities (San Francisco, Palo Alto, Mountain View, and Los Angeles), using personal exposure monitoring (PEM) instruments. Altogether, 588 different commercial settings were visited, and indoor and outdoor locations were sampled at each setting. On 11 surveys, two CO PEM's were carried about 0.15-6 m apart, giving 1706 pairs of observations that showed good agreement: the correlation coefficient was $r = 0.97$ or greater, and the average difference was less than 1 ppm (μL/L) by volume. Of 210 indoor settings (excluding parking garages), 204 (97.1%) had average CO concentrations less than 9 ppm (μL/L); of 368 outdoor settings, 356 (96.7%) had average CO concentrations less than 9 ppm (μL/L). For a given date and commercial setting, CO concentrations were found to be relatively stable over time, permitting levels to be characterized by making only brief visits to each setting. The data indicate that most commercial settings experience CO concentrations above zero indoors, because CO tends to seep into buildings from vehicular emissions outside. Levels in these locations usually are not above 5 ppm (μL/L) and seldom are higher than the U.S. health-related ambient air quality standards for CO. However, indoor garages and buildings with attached indoor parking areas are exceptions and can experience relatively high CO concentrations.

Introduction

In recent years, considerable progress has been made in developing small, personal air monitoring instruments, or personal exposure monitors (PEM) that can be carried by people as they go about their normal daily activities. Prior to 1970, before such PEM's were available, a person's exposure to carbon monoxide (CO) could be measured only by using small, portable pumps that filled bags which then were transported to a central laboratory for analysis. Using this bag approach, the CO exposures of pedestrians walking on downtown streets in San Jose, CA, were found to be about two times the levels observed at the same time at the city's official air monitoring station (Ott, 1971).

Several years later, Energetics Science Incorporated (ESI) introduced an electrochemical CO air monitoring instrument, the ECOlyzer, that operated on batteries and was about the size of a lunch box. This instrument was used to monitor the daytime CO exposures of commuters in Boston, MA, and the results were compared with 8-h CO concentrations measured at several fixed air monitoring stations in Boston (Cortese, 1976).

In the late 1970's, these instruments were further miniaturized so that they could be worn by workers in occupational settings with relative ease. The ECOlyzer Model 9000 CO "Dosimeter," for example, uses an electrochemical sensing cell and is about the size of a cigarette pack. It requires an external pump, but miniaturized pumps now available can operate reliably for periods of 10 h or more. The General Electric CO "Detector," introduced in the late 1970's, is slightly larger—about the size of a transistor radio—and it has the advantage that it combines the pump and digital readout in one unit that can operate for up to 10 h. Both units employ an electrochemical measurement principle in which CO is converted to CO_2 in an aqueous solution, thus freeing up electrons to generate a small electrical current that is amplified. The electrical signal can be displayed directly or integrated inside the instrument to give readings in ppm h (μL • h/L). In the ESI instrument, the sensing cell contains an acidic solution that must be humidified periodically, while the GE instrument uses distilled water in contact with a solidified electrolyte, called a Solid Polymer Electrolyte (SPE).

Although these instruments are new, they have been used to measure the CO concentrations inside buses in Washington, DC (Wallace, 1979), and the occupational CO exposures of police workers in Denver, CO (Jabara and Keefe, 1980). However, few large-scale field studies have been undertaken. The present investigation was intended to demonstrate how the new PEM could be deployed to measure CO in a metropolitan area survey.

Methodology

Visits were made to 588 different commercial settings in four California towns and cities—San Francisco, Palo Alto, Mountain View and Los Angeles—on 15 different dates from November 1979 to July 1980 (Tables 1 and 2). We define "commercial setting" as a location in which the general public conducts routine business or to which the general public has access (sidewalks, arcades, stores, offices, banks, hotels, theaters, restaurants, art galleries, etc.). A total of 220 indoor commercial settings and 368 outdoor commercial settings were visited in the four cities, which included two different districts in San Francisco: Union Square and its surrounding area, and the Financial–Chinatown district. Indoor commercial settings included department stores, hotels, office buildings, parking garages, retail stores, restaurants, consumer service centers (banks, travel agents, etc.), and theaters. Outdoor commercial settings included street intersections, sidewalk locations between intersections (midblocks), arcades, parks, plazas, and parking lots. The investigators followed a planned route and entered numerous buildings and stores along the way. Readings usually were taken both inside and outside a particular store. Two or more 1-min readings were made at each location, giving a total of 5000 observations for the entire survey (Table 2). The CO concentration was read in parts per million volume per volume (ppm) from the digital display of the instrument (Fig. 1), and the time, date, and location were recorded on a clipboard. The scope of the study was limited to daytime and weekday hours of operation of commercial settings.

On a number of survey dates, two investigators walked side-by-side along the city streets, each carrying a CO PEM at a height of approximately 1 m, and the CO reading was written down for each instrument at 1-min intervals.

Structured sampling

On one date, 13 June 1980, a structured sampling procedure was used in the Union Square district of downtown San Francisco in a geographical region that met two criteria: (1) average daily traffic on streets exceeded 10,000 vehicles, and (2) the area was designated C-3-R ("downtown retail") on a San Francisco land use map. Within this geographical area, each city block was numbered (Fig. 2). Then the numbered blocks were assigned, at random, to each of four investigators.

Investigators were instructed to begin sampling at the northwest corner of the first block assigned to them.

Table 1. Field survey dates, hours, locations, and numbers of CO samples at California locations.

Survey	Date	Hour	Geographic Location	Number of CO Samples
1	9 Nov. 1979[a]	10:13 a.m.–11:41 p.m.	Union Sq., San Francisco	181
2	13 Dec. 1979[a]	8:42 a.m.–4:45 p.m.	Union Sq., San Francisco	766
3	24 Jan. 1980[a]	2:00 p.m.–4:37 a.m.	University Ave., Palo Alto	342
4	31 Jan. 1980[a]	9:20 a.m.–11:18 a.m.	University Ave., Palo Alto	232
5	7 Feb. 1980[a]	11:14 a.m.–2:30 p.m.	University Ave., Palo Alto	370
6	6 March 1980	11:00 a.m.–12:30 p.m.	Financial–Chinatown District, San Francisco	89
7	7 March 1980[a]	4:22 p.m.–6:00 p.m.	University Ave., El Camino Palo Alto	190
8	13 March 1980	10:00 a.m.–1:15 p.m.	Castro St., Mountain View	181
9	27 March 1980	2:26 a.m.–7:27 p.m.	Westwood Village, Los Angeles	300
10	4 April 1980[a]	1:42 p.m.–3:46 p.m.	15-Story Building, Palo Alto	234
11	11 April 1980[a]	10:55 a.m.–1:47 p.m.	Financial–Chinatown District, San Francisco	336
12	11 April 1980[a]	2:06 p.m.–5:58 p.m.	Union Sq., San Francisco	434
13	9 May 1980[a]	1:20 p.m.–2:07 p.m.	15-Story Building, Palo Alto	94
14	13 June 1980[a]	10:44 a.m.–3:09 p.m.	Union Sq., San Francisco	787
15	11 July 1980[a]	2:18 p.m.–6:32 p.m.	University Ave., Palo Alto	464
				5000

[a] Instruments deployed side-by-side during some portion of sampling.

Table 2. Number of commercial settings by type of setting and geographic location.

Commercial Setting	Union Square District, San Francisco	Financial-Chinatown District, San Francisco	University Avenue, Palo Alto	Castro Street, Mountain View	Westwood Village, Los Angeles	Total
Indoor						
Department stores	6	0	0	0	0	6
Hotels	13	1	1	0	0	15
Office buildings	11	7	3	0	2	23
Parking garages	3	2	3	0	2	10
Retail goods	51	5	33	8	14	111
Restaurants[a]	14	5	5	2	2	28
Services	11	4	7	1	1	24
Theaters	2	0	1	0	0	3
Subtotal	111	24	53	11	21	220
Outdoor						
Arcades, etc.[b]	1	10	3	2	2	18
Intersections	30	15	11	9	8	73
Midblocks	155	24	66	16	16	277
Subtotal	186	49	80	27	26	368
Grand Total	297	73	133	38	47	588

[a]Includes cafeterias, coffee shops, delicatessens, bars, lounges, restaurants, and sandwich shops.
[b]Includes arcades, parks, plazas, and parking lots.

Fig. 1. Method of taking a CO measurement in downtown San Francisco using General Electric personal exposure monitor.

Each investigator took three 1-min CO readings at each corner of the intersection, proceeding clockwise around the intersection. Once finished with the intersection, each proceeded clockwise around the block, taking three 1-minute instantaneous CO observations at the kth establishment with an entrance at street level. For buildings with more than one level, such as department stores, k was set to 1; for buildings with just one floor, such as shoe stores, k was set to 3. Thus, each third single-floor building on the block was sampled.

At each establishment, the investigator made three readings outside the building and then entered and made three additional readings inside, noting whether the entrance door was open or closed. For multilevel buildings, only the street-level floor was sampled. Once a block was completed, the investigator went on to the next assigned block. Most investigators completed at least two blocks in a 5-h period.

Quality assurance evaluation of two monitors carried side-by-side

In 11 of the 15 field surveys, two investigators walked alongside each other, each carrying an instrument, thus permitting pairs of simultaneous readings to be compared on two similar instruments. In these "side-by-side" comparisons, the two instruments were separated an average horizontal distance of about 1 m (ranging between 0.15 and 6 m).

To compare the side-by-side readings, the CO readings were recorded for each instrument at 1-min inter-

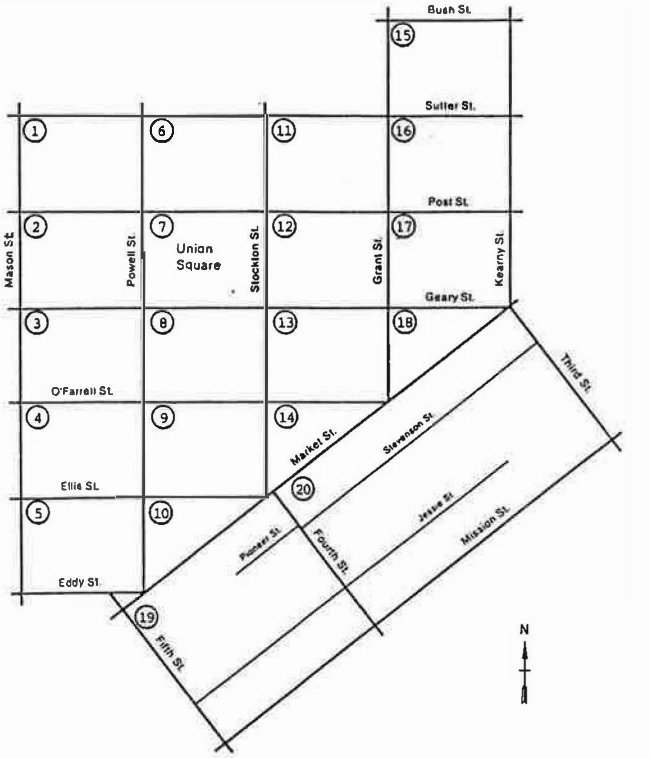

Fig. 2. Field map of Union Square District of San Francisco, California.

vals, and the difference in recorded values was computed as follows:

$$d_i = |X_2 - X_1|,$$

where d_i = absolute difference in observed simultaneous concentrations for pair i;
X_2 = CO concentration (ppm; μL/L) observed on instrument number 2;
X_1 = CO concentration (ppm; μL/L) observed on instrument number 1.

The results from these analyses show that, for 7 of the 11 surveys (1706 observations), the mean absolute difference $\bar{d}$ was less than 1 ppm (μL/L) (Table 3). The largest value of $\bar{d}$, 2.32 ppm (μL/L), occurred on the first survey, when the investigators were still learning how to calibrate the instruments, and the lowest value of $\bar{d}$, 0.26 ppm (μL/L), occurred on the fifteenth survey. The average deviation could be made quite small (less than 1 ppm; μL/L) if the two instruments were calibrated carefully.

As the CO concentration changes over time, both instruments should record either an increase or a decrease simultaneously. The correlations between simultaneous measurements were evaluated using Pearson's product-moment coefficient. For 9 of 11 surveys, these coefficients equalled or exceeded 0.97, and the low probabilities (last column of Table 3) indicate that one may reject with a high degree of confidence the hypothesis that the correlations are zero.

In general, these tests indicated that two instruments operated side-by-side on city streets were in good agreement, even if the distance between the intake probes varied from 0.15 to 6 m. However, the relative discrepancy in observed values between the two instruments increases when observed CO concentrations are very low. For example, if the typical CO concentrations in a given setting are on the order of 1–2 ppm (μL/L), then a difference in recorded values of 1 ppm (μL/L) represents a large relative error. Conversely, if the typical CO concentrations in some settings are on the order of 50 ppm (μL/L), then a difference of 1 ppm (μL/L) in recorded values represents a small relative error. In this study, there were more settings with very low readings than with very high readings.

Random error in measurement of the arithmetic mean concentration for a given setting usually can be reduced by increasing the number of samples obtained, in accordance with the central limit theorem. In this study, a larger number of measurements were made for generic settings (e.g., retail stores of all kinds) than for some particular settings (e.g., a particular shoe store). Thus, the average CO concentrations for retail settings in general have greater precision than the average concentrations reported for a specific store, unless that store was sampled intensively. Furthermore, measurement error can be minimized only if there are no systematic biases, such as improper calibration with reference gases. Consequently, as described earlier, an extensive effort was made to calibrate the instruments with both zero and span gases before and after each survey, as well as during some of the surveys.

Results

The personal monitoring instruments proved to be an effective means of collecting large quantities of data on CO concentrations in a variety of locations in the urban area. Analyses of these data permitted a number of different questions about the temporal and spatial variation of CO concentrations to be addressed. How rapidly do CO concentrations in indoor commercial settings change with time? How does an open entrance door affect the indoor CO concentrations of a commercial setting that fronts a street with heavy vehicular traffic? The names used to classify commercial settings (for example, bank, restaurant, hotel, or retail store) may or may not have relevance to air pollution levels; is one bank similar to or different from another bank in terms of CO concentrations? Do CO concentrations peak at intersections and then taper off between intersections? Do CO concentrations vary greatly for different intersections or even different corners of the same intersection? Do CO concentrations measured in commercial settings using PEM's correlate with ambient concentrations measured at fixed air monitoring stations using NDIR instruments?

Table 3. Statistical summary comparing the performance of two CO personal exposure monitors carried side-by-side.

	Descriptive Statistics			Correlation Statistics		
Survey	Mean ($\bar{d}$) (ppm; μL/L)	Std. Dev. (s) (ppm; μL/L)	No. of CO Samples (n)	Pearson's coeff. (r)	z Statistic	Probability (p)
1	2.32	3.52	88	0.98	9.14	1.2×10^{-10}
2	0.73	1.80	354	0.87	16.35	3.3×10^{-10}
3	0.88	1.14	171	0.97	11.96	1.5×10^{-10}
4	0.66	0.84	116	0.99	10.62	1.3×10^{-10}
5	0.65	0.88	185	0.99	13.43	1.5×10^{-10}
7	1.37	1.68	95	0.99	9.60	1.5×10^{-10}
10	1.02	0.86	117	0.99	10.66	1.6×10^{-10}
11	0.11	0.85	168	0.98	12.59	1.7×10^{-10}
12	0.62	1.14	217	0.99	14.55	5.9×10^{-10}
13	1.11	1.01	47	0.83	5.63	9.1×10^{-9}
15	0.26	0.89	148	0.98	11.88	1.8×10^{-10}
		Total	1706			

Temporal variation

Early in this study, it was necessary to decide how long to stay at each setting. If short visits (say 2–5 min) were made, it would be possible to sample a greater variety of commercial settings. If the CO concentrations changed rapidly over time, short visits could not be justified. If the CO concentrations were more stable, only a few readings could characterize a given setting. Thus, it was necessary to examine the change in CO concentration with time. The temporal variation of CO concentrations was studied using two approaches: (1) extended visits at a subsample of settings; and (2) repeated visits on the same date to some settings.

Extended visits were made to 74 commercial settings for times ranging from 6 to 111 min. The mean CO concentration for these settings ranged from a low of 0 ppm, observed at a real estate office and an outdoor plaza, to a high of 51.3 ppm (μL/L), recorded for an enclosed parking garage. Despite this variation, the standard deviations of the 1-min CO concentrations observed during visits to 74.3% of these settings were less than 2 ppm (μL/L). These standard deviations seemed quite small relative to the mean and did not greatly vary with the means. Furthermore, the standard deviations were greater than the mean concentrations for only 6 out of 74 (8.1%) of the settings, and, for 3 of these, the mean CO concentration was near 0 ppm. Because the PEM's are accurate only to about 1 ppm (μL/L), we concluded that, for nearly 96% of the settings visited for periods ranging from 6 to 111 min, the standard deviation was relatively small and was less than the mean CO concentration.

The standard deviations were small for both indoor and outdoor settings, although outdoor settings tended to vary more rapidly with time than indoor settings. Compared with the momentary fluctuations in CO concentrations at a given setting, the concentrations differed more from one setting to another and even from one date to another for the same setting. The results imply that only a few samples were necessary to characterize the air quality of a given commercial setting on a given date; staying in a setting for more than 6–10 min gave a great deal of redundant information.

There were exceptions to this generalization. In three cases—an intersection in Mountain View, a bus stop in Los Angeles, and an office building in Palo Alto—the standard deviation exceeded a rather large mean concentration. For the intersection and the bus stop (itself also near an intersection), this result can be explained by a few spikes in concentration, which skewed the distribution. These spikes probably were due to the proximity of these sampling locations to traffic, and traffic varied considerably from minute to minute. Without these spikes, these settings also would have fairly homogeneous CO concentrations, at least for short visits.

The group of settings visited twice on the same date consisted of 5 intersections and 12 indoor settings, and the time between visits ranged from 43 to 470 min (Table 4). The number of observations taken per visit was less than 10, too small to permit a rigorous statistical analysis. For 15 of the 17 settings, the average difference in mean CO concentration between the two visits was only 1.3 ppm (μL/L), which is consistent with the findings for settings monitored for extended periods without interruption. In 2 of the 17 visits, a parking garage (470 min between visits) and a print shop (69 min between visits), the mean CO concentration on the second visit differed greatly from the mean concentration on the first visit. For the print shop, the high mean CO concentration encountered on the first visit (32.3 ppm; μL/L) and the low mean CO concentration encountered on the second visit (8 ppm; μL/L) may have been due to a van that stood, with engine idling, in the alley outside during the first visit but not during the second.

Table 4. Statistical summary of mean CO concentrations for commercial settings visited twice on the same date.

Survey	Commercial Setting	Mean CO Concentration (ppm; μL/L) First Visit	Second Visit	Difference in Mean Concentrations Between Visits (ppm; μL/L)	Time Between Visits (min)
1	Garage	35.4	34.5	0.9	122
2	Garage	16.8	37.1	−20.3	470
3	Intersection	1.5	2.9	−1.4	142
3	Real estate office	3.5	3.4	0.1	155
4	Office bldg. lobby	5.3	7.0	−1.7	130
4	Garage	28.3	31.6	−3.3	103
4	Variety store	2.1	2.6	−0.5	44
4	Intersection	1.8	1.5	0.3	84
5	Office bldg. lobby	2.0	3.8	−1.8	115
5	Garage	26.8	27.9	−1.1	98
5	Intersection	0.0	2.0	−2.0	84
8	Intersection	1.0	0.0	1.0	179
10	Office bldg. lobby	11.6	8.6	3.0	57
10	Garage	40.0	41.6	−1.6	43
11	Garage	16.5	15.8	0.7	168
11	Intersection	1.5	1.5	0.0	70
14	Print shop	32.3	8.0	24.3	69

It appears that CO concentrations in commercial settings are reasonably stable over time for a given setting and date and that visits of several minutes usually are adequate to characterize the mean CO concentration that would be found if the visit lasted an hour or more.

In Palo Alto, commercial settings were visited on five separate dates, and winds were relatively high on two of these dates. On the majority of the dates, winds ranged from 3 to 5 mph (5–8 km/h) but on February 7 and July 11, 1980, winds ranged from 10 to 15 mph (16–24 km/h). Comparing average CO concentrations for all commercial settings (except parking garages and structures with attached parking garages) reveals that mean CO concentrations observed on the windy days—1.52 ppm (μL/L) on 7 February and 1.24 ppm (μL/L) on 11 July—were about one-half the levels observed on the calm days (Table 5). Thus, greater wind speeds appeared to be associated with lower CO concentrations for commercial settings, and this result held true for both indoor and outdoor locations. Further analyses of these data suggested that, for a given geographical area, an individual's exposure to CO in commercial settings (excluding parking garages and structures with attached parking garages) varied more from one date to another than from one setting to another on the same date.

Table 5. Statistical summary of CO concentrations for all commercial settings, except parking garages, visited on five dates in Palo Alto's central business district.

Date	Mean CO Concentration (ppm; μL/L)	Std. Dev. of CO Concentration (ppm; μL/L)	Number of Settings
24 Jan. 1980	3.61	2.50	58
31 Jan. 1980	3.56	1.54	33
7 Feb. 1980	1.52	1.65	48
7 March 1980	3.46	3.06	13
11 July 1980	1.24	1.56	81

In general, we found a statistically significant difference between indoor and outdoor CO concentrations, but only when doors were closed. When indoor and outdoor CO measurements were made within a short time span of each other in buildings with the entrance door normally closed, the indoor CO concentrations were statistically less than the outdoor levels. These findings were consistent with the predictions of indoor air quality models, which suggest that indoor CO concentrations tend to follow outdoor CO concentrations, but lag behind them in time.

Spatial variation

Do CO concentrations differ in different groupings of indoor settings? The CO concentrations measured on a particular date, 12 June 1980, in downtown San Francisco were separated into eight groups (Table 6). The following hypotheses were tested about the mean values:

$$H_0\colon \bar{X}_1 = \bar{X}_2 = \cdots = \bar{X}_8,$$

H_1: at least one mean does not.

That is, the null hypothesis (H_0) is that all eight means are the same and the test hypothesis (H_1) is that at least one mean differs. A one-way analysis of variance yields a value of $F = 1.86$. With seven degrees of freedom for the variance between groups and 76 degrees of freedom for the variance within a group, the corresponding probability $p = 0.058$, and the test hypothesis was rejected at the 0.01 level of significance.

We conclude that one's exposure to CO inside commercial settings varies as much from, say, one clothing

Table 6. Statistical summary of CO concentrations measured on 12 June 1980 for indoor commercial settings located near Union Square, San Francisco.

Indoor Commercial Setting[a]	Mean CO Concentration (ppm; μL/L)	Std. Dev. of CO Concentration (ppm; μL/L)	Number of Settings
Clothing, fabric, and shoe stores	1.6	1.1	17
Department stores	2.8	1.4	8
Home furnishings[b]	1.9	1.3	8
Hotel lobbies	3.2	1.7	11
Office building lobbies	3.6	2.7	8
Restaurants[c]	3.3	2.3	11
Service centers[d]	2.4	1.5	9
Miscellaneous[e]	2.8	1.8	12

[a]Two theaters omitted.
[b]Includes appliances, antiques, furniture, and paintings.
[c]Includes burger stands, cafeterias, coffee shops, delicatessens, and restaurants.
[d]Includes airline ticket agencies, banks, currency exchanges, real estate offices, and camera repair shops.
[e]Includes book stores, china and crystal shops, drug stores, gift shops, jewelry stores, novelty stores, and stamp stores.

store to another, as it does from a clothing store to a department store, or a department store to a hotel lobby. A notable exception to this conclusion is the parking garage. Since only one such garage was monitored in the Union Square district, it was not included in the analysis of variance. The average CO concentrations in this parking garage ranged from 30.8 to 60.5 ppm (μL/L), clearly much greater than those measured in all other classes of indoor commercial settings. Thus, with the exception of parking garages, all other indoor commercial settings in downtown San Francisco seemed to have statistically similar CO concentrations. Another exception turned out to be tall buildings with attached underground parking garages, but these constituted a relatively small proportion of the total number of structures in the downtown area. As discussed in the summary report of this investigation (Flachsbart and Ott, 1982), a small but important class of buildings were "hot" with respect to CO.

CO concentrations observed on 13 June, 1980, in commercial settings located on different blocks were compared with one another, and a statistically significant, although very small, difference was observed (Table 7). Thus, it appears that one's exposure to CO inside commercial settings varied more from one city block to another than from one setting to another on the same block. It is probable that differences in traffic volume and in micrometeorology account for these differences in indoor CO concentrations, even though they were relatively small.

Spatial variation of CO in outdoor settings

CO was measured on the corners and faces of each block surveyed in the Union Square area (Table 8). For

Table 7. Statistical summary of CO concentrations measured on 13 June 1980 for indoor commercial settings located near Union Square, San Francisco.

City Block Number	Mean CO Concentration (ppm; μL/L)	Std. Dev. of CO Concentration (ppm; μL/L)	Number of Settings
1	1.9	1.8	9
2	3.0	2.2	9
4	4.0	2.2	11
8	3.3	1.1	10
11	3.1	1.9	13
12	1.8	0.9	16
15	2.8	2.4	9
19	1.1	0.8	11

a given city block, we expected that the CO concentration measured at the corner of the block would be greater than at midblock locations along the block face. When vehicles are stopped at a given intersection, the vehicle queue may extend along the block face. Hence, the individual waiting to cross a street at an intersection may be exposed to concentrations greater than those found along the sidewalk at midblock.

For nine city blocks, the mean CO concentration (in μL/L) at the corners was 3.89 ppm (standard deviation $s = 1.15$ ppm) and the mean CO concentration at the faces of the block was 3.31 ppm (standard deviation $s = 0.99$ ppm). A two-tailed test of the hypothesis that the corner's mean was greater than the face's mean using the t statistic did not meet the desired, although somewhat stringent, criterion of significance (0.05). For the nine city blocks, $t = 1.77$; with eight degrees of freedom, $p = 0.115$. Since p was not sufficiently small to meet our criterion, we concluded that no difference in CO concentrations existed between the corners and faces of city blocks in commercial areas.

To determine if CO concentration varied more from corner to corner of the same intersection than it did from one intersection to another, a one-way analysis of variance was used. Since this test assumes that observa-

Table 8. Statistical summary of CO concentrations measured at corners and faces of city blocks located in the Union Square district, San Francisco, 13 June 1980.

City Block	Mean CO Concentration (ppm; μL/L) Corners	Faces
1	4.1	2.7
2	3.6	4.3
4	4.2	3.7
7	5.8	4.8
8	4.7	3.9
11	4.2	3.5
12	1.9	3.0
15	2.5	2.0
19	4.0	1.9

tions are normally distributed, and the normal assumption is difficult to defend for environmental data, a somewhat stringent level of significance (0.005) was specified. Data were available on average CO concentrations at four San Francisco intersections (Mason and O'Farrell, 3.9 ppm; Powell and Geary, 7.2 ppm; Stockton and Sutter, 4.4 ppm; and Stockton and Post, 2.5 ppm) and for all four corners at each intersection. A one-way analysis of variance gave $F = 8.97$; with 44 degrees of freedom for the variance within a group and three degrees of freedom for the variance between groups, $p = 9.45 \times 10^{-5}$ and the null hypothesis that all four intersection means were equal was rejected. Thus, one's exposure to CO may vary more from one intersection to another than from one corner to another at the same intersection, assuming the same geographic location and date of measurement apply for all intersections. Of course, the levels at these intersections may be different at other times of the day or other days of the year. Our overall conclusion, from examining other intersections in the survey, is that at any given time and geographic location, some intersections will differ in CO concentrations and other intersections will not. Because so many factors affect the levels at a particular intersection, it is difficult to identify a simple pattern.

Comparison of personal and fixed station monitors

The levels reported thus far are typical of the many diverse CO concentrations that a person encounters while shopping in downtown stores, walking along congested downtown streets, and carrying out daily errands. These levels are not necessarily the same as those reported by official air monitoring stations in the area. Consequently, data from personal monitors were compared with continuous data from fixed monitoring stations (FMS).

For each date, the 1-h average CO concentrations derived from FMS strip charts were compared with the CO data collected at the same time with the personal monitors (Table 9). The data for personal monitors represent the average CO concentrations broken down by indoor and outdoor commercial settings visited during the 60-min period preceding the hour reported in the table. Since the ambient concentrations measured by different types of monitors in different locations were being compared, certain indoor settings whose concentrations were largely nonambient in nature were excluded. The excluded settings consisted primarily of the parking garages and a 15-story general office building in Palo Alto in which CO concentrations could be attributed to an attached, underground garage.

Before testing the hypothesis that the CO concentrations recorded by fixed and personal monitors differed, matching the observations as pairs was evaluated. This evaluation can be made using Pearson's correlation coefficient (r). Matching is appropriate if this coefficient is both nonzero and positive, as tested by the t statistic.

For the FMS and the PEM (indoor) data, the value of $r = 0.50$, and the corresponding value of $t = 3.67$; for FMS and PEM (outdoor) data, $r = 0.30$ and $t = 1.993$. Each value of t is significant at $\alpha = 0.05$ with 40 degrees of freedom for the indoor case and 39 for the outdoor case. Hence, it was appropriate to pair observations and to proceed with a two-tailed t-test for dependent samples.

A statistical summary of the 42 pairs of observations for the indoor case indicates the following:

FMS	PEM Indoor
$\bar{x} = 2.00$ ppm (μL/L)	$\bar{y} = 3.02$ ppm (μL/L)
$s_x = 1.04$ ppm (μL/L)	$s_y = 2.03$ ppm (μL/L)

For this case, the t dependent statistic is -3.782, which is significant at 40 degrees of freedom for $\alpha/2 = 0.025$. A statistical summary of the 41 pairs of observations for the outdoor case indicates:

FMS	PEM Outdoor
$\bar{x} = 1.98$ ppm (μL/L)	$\bar{z} = 4.00$ ppm (μL/L)
$s_x = 1.04$ ppm (μL/L)	$s_z = 1.95$ ppm (μL/L)

In this case, that dependent statistic is -6.362, which is significant at 39 degrees of freedom for $\alpha/2 = 0.025$. Therefore, the average concentration of CO for both indoor and outdoor settings as measured by the personal monitors was slightly higher than that reported by the fixed monitoring station and the correlation with the fixed station values was low but was statistically significant. This conclusion is consistent, in general, with the findings of past studies.

Summary and Conclusions

This study has sought to evaluate the effectiveness of the new CO PEM instruments as a method for surveying indoor and outdoor locations in a large city. It appears that these new instruments can provide reliable data on CO concentrations extending over a large physical area, such as a city, both inexpensively and with relatively limited manpower.

This study also has characterized CO concentrations typically found in commercial settings in four California cities, as well as the temporal and spatial variability of these concentrations. The findings, described in greater detail in the survey report (Ott and Flachsbart, 1982), are summarized briefly as follows:

Comparison of monitors

1. For 7 of 11 surveys during which two PEM's were used simultaneously "side-by-side," the average difference between the instruments was less than 1 ppm (μL/L).

2. For 9 of 11 surveys during which two PEM's were used simultaneously "side-by-side," the correlation coefficients between instruments equalled or exceeded 0.97.

Table 9. Summary of CO concentrations collected simultaneously from fixed monitoring stations and personal exposure monitors.

Date	Hour	Geographic Location	Fixed Stations: Average CO (ppm; μL/L)	Personal Exposure Monitors, Indoors: Average CO (ppm; μL/L)	Indoors: Number of Settings	Outdoors: Average CO (ppm; μL/L)	Outdoors: Number of Settings
9 Nov 79	11 a.m.	Union Square	2	5.2	2	6.7	8
9 Nov 79	12 noon	Union Square	2	7.2	4	6.9	8
13 Dec 79	9 a.m.	Union Square	4	2.8	1	3.6	2
13 Dec 79	10 a.m.	Union Square	4	5.0	2	4.5	10
13 Dec 79	11 a.m.	Union Square	4	5.4	5	5.3	9
13 Dec 79	12 noon	Union Square	3	6.4	3	6.2	8
13 Dec 79	1 p.m.	Union Square	3	4.6	1	[a]	0
13 Dec 79	2 p.m.	Union Square	3	4.5	5	4.2	15
13 Dec 79	3 p.m.	Union Square	3	2.7	2	7.0	6
13 Dec 79	4 p.m.	Union Square	4	10.8	2	7.3	2
24 Jan 80	3 p.m.	Palo Alto	3	2.8	14	3.9	12
24 Jan 80	4 p.m.	Palo Alto	3	2.4	6	5.3	8
31 Jan 80	10 a.m.	Palo Alto	3	3.2	2	3.9	4
31 Jan 80	11 a.m.	Palo Alto	3	3.2	8	3.6	13
7 Feb 80	12 noon	Palo Alto	2	0.4	4	0.8	11
7 Feb 80	1 p.m.	Palo Alto	2	1.1	10	1.5	14
7 Feb 80	2 p.m.	Palo Alto	2	2.4	2	3.6	7
6 Mar 80	12 noon	Chinatown–Financial	3	1.6	7	1.4	13
7 Mar 80	5 p.m.	Palo Alto	2	2.6	4	7.9	4
7 Mar 80	6 p.m.	Palo Alto	3	2.3	2	3.1	7
13 Mar 80	11 a.m.	Mountain View	1	2.2	5	2.3	15
13 Mar 80	12 noon	Mountain View	1	1.0	2	2.6	15
13 Mar 80	1 p.m.	Mountain View	1	2.9	4	4.7	4
27 Mar 80	3 p.m.	Los Angeles	1	2.2	6	4.3	4
27 Mar 80	4 p.m.	Los Angeles	1	1.8	2	6.9	9
27 Mar 80	5 p.m.	Los Angeles	1	2.8	8	3.1	10
27 Mar 80	6 p.m.	Los Angeles	1	2.4	2	3.0	6
27 Mar 80	7 p.m.	Los Angeles	2	4.4	1	6.9	10
11 Apr 80	12 noon	Chinatown–Financial	1	0.8	10	1.8	14
11 Apr 80	1 p.m.	Chinatown–Financial	1	1.2	6	1.4	26
11 Apr 80	3 p.m.	Union Square	2	0.9	3	3.7	9
11 Apr 80	4 p.m.	Union Square	2	5.0	6	5.9	8
11 Apr 80	5 p.m.	Union Square	1	4.1	10	4.9	14
11 Apr 80	6 p.m.	Union Square	1	3.0	3	5.2	12
13 Jun 80	11 a.m.	Union Square	1	[a]	0	2.4	2
13 Jun 80	12 noon	Union Square	2	1.6	9	2.7	11
13 Jun 80	1 p.m.	Union Square	1	1.9	6	3.2	7
13 Jun 80	2 p.m.	Union Square	1	4.2	7	5.2	8
13 Jun 80	3 p.m.	Union Square	1	1.8	6	1.7	8
11 Jul 80	3 p.m.	Palo Alto	1	2.6	10	2.2	9
11 Jul 80	4 p.m.	Palo Alto	1	1.4	11	2.5	6
11 Jul 80	5 p.m.	Palo Alto	1	0	2	0.9	8
11 Jul 80	6 p.m.	Palo Alto	1	2.2	1	[a]	0

[a]Insufficient data.

Typical values

1. Of 210 indoor commercial settings, excluding parking garages, 204 (97.1%) had an average CO concentration less than 9 ppm (μL/L).

2. Of 368 outdoor settings, 356 (96.7%) had an average CO concentration of less than 9 ppm (μL/L).

3. CO concentrations measured in parking garages were distinctly different from those in other commercial settings and sometimes were quite high.

Temporal variation

1. Of 74 commercial settings visited for relatively long periods of time (6–111 min), the standard deviation of CO concentrations of 55 (74.3%) did not exceed 2 ppm (μL/L), indicating that for a given setting and date, the CO concentration appears relatively stable over time.

2. Of 17 settings (12 indoor locations and 5 street intersections) visited twice on the same date, the average

difference in mean CO concentration between visits was small (1.3 ppm; μL/L) for 15 of the cases, further indicating that CO concentrations are relatively stable over time.

3. CO concentrations for both indoor and outdoor settings tended to vary with date and were affected by wind speed, with lower CO values encountered on windier days.

4. If two days had dissimilar wind speeds, the CO concentration varied more from one date to another than from one setting to another on the same date; this was true for settings of all types, except parking garages.

Spatial variation

1. CO concentrations indoors were statistically, but not substantially, less than those outdoors, and then only when the entrance door was closed to the street and both measurements were made within a short time of each other (e.g., 3 min).

2. On a given date, CO concentrations indoors varied as much from, for example, one retail store to another, as they did from a retail store to a bank, hotel, office building, or other commercial setting. A notable exception was the parking garage, from which CO concentrations were greater than for all other types of indoor settings. Structures with attached parking garages also differed from other indoor commercial settings.

3. For geographic locations with heavy traffic, such as the Union Square district of San Francisco, indoor CO concentrations varied more from one city block to another than from one setting to another on the same block. This conclusion does not imply, however, that adjacent indoor settings in commercial areas have identical concentrations.

4. In the Union Square district of San Francisco, there was no statistically significant difference in CO concentrations between the corners and faces of city blocks for sidewalk settings.

5. For the same geographic area and date, CO concentrations varied more from one intersection to another than from one corner to another of the same intersection.

6. For the same geographic area and date, CO concentrations were similar for some intersections and different for others, although the differences usually were small.

7. CO concentrations inside settings varied as much within a given geographic location as they did between geographic locations. This implied that data for different locations could be consolidated, if precautions were taken to use dates with similar wind speeds and no precipitation. These findings are discussed at greater length in the report by Flachsbart and Ott (1982).

Comparison with fixed monitoring stations

1. For indoor commercial settings, excluding parking garages and one "hot" building in Palo Alto, the average CO concentration as determined by personal monitors was 3.02 ppm (μL/L). This value was statistically, but not substantially, greater than the average CO concentration of 2.00 ppm (μL/L) as determined simultaneously by fixed monitoring stations.

2. For outdoor commercial settings, the average CO concentration as determined by personal monitors was 4.00 ppm (μL/L). This CO level was statistically, but not substantially, greater than the average CO concentration of 1.98 ppm (μL/L) as determined simultaneously by fixed monitoring stations.

Seepage

From these findings, it is evident that CO emissions from traffic in downtown areas tend to seep into buildings and stores. Although indoor levels are above zero, they seldom are very high – except in the case of parking garages and buildings with attached parking garages. And only a very small percentage (2.9%) of the indoor commercial settings gave readings above 9 ppm.

As found in other studies (Cortese, 1976; Jabara and Keefe, 1980; Ott, 1971; Wallace, 1979), the CO concentrations in commercial settings are above the values measured by nearby fixed air monitoring stations and have little relationship to the fixed station values. Elevated CO concentrations in the commercial settings of downtown areas are measurable, stochastically similar, and ubiquitous in different stores and on different streets of the cities covered in this investigation. The new PEM's offer an efficient tool for surveying CO concentrations in these areas. In future studies, it is important that such surveys use a structured sampling design, such as the one applied to the Union Square district in San Francisco, to allow comparison of results from different geographical areas.

Note

Mention of trade names of products or names of manufacturers does not constitute endorsement or recommendation for use by the Environmental Protection Agency or by the federal government.

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