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PREDICTING PERSONAL EXPOSURE LEVELS TO CARBON MONOXIDE (CO) IN TAIPEI, BASED ON ACTUAL CO MEASUREMENTS IN MICROENVIRONMENTS AND A MONTE CARLO SIMULATION METHOD

JYH-JIAN LIU,* CHANG-CHUAN CHAN† and FU-TIEN JENG*

* National Taiwan University, Graduate Institute of Environmental Engineering, 21 Fl, No. 77, Sec. 2, Tun-Hwa S. Road, Taipei 106, Taiwan; † National Taiwan University, College of Public Health, Institute of Occupational Medicine and Industrial Hygiene, Taipei, Taiwan

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Abstract—In order to evaluate the severity of carbon monoxide (CO) pollution in Taipei, this study conducted a survey of commuting patterns (in a district) for random samples of primary school students and adult workers, and carried out CO measurements in vehicles and near roadsides. A Monte Carlo simulation was then implemented to estimate 1- and 8-h CO exposure levels for the population. The microenvironment of the roadside included both the sidewalk and the corridor (a sheltered walkway farther removed from the road than the sidewalk). By computer simulations, this study showed that commuters on motorcycles and public buses were exposed to the highest CO exposure levels among all commuters on the roads in Taipei. This study also demonstrated that the Monte Carlo simulation method could better estimate CO exposure levels for the general public. It was found that roadside-fixed monitoring stations operated by the Taipei BEP (Bureau of Environmental Protection) underestimated the general population's 1-h CO exposure levels. For adult workers, the roadside-fixed monitoring stations reasonably estimated the roadside business workers' 8-h CO exposure levels, but overestimated the exposure levels of general adult workers commuting by public bus, except for bus drivers whose CO exposure levels were underestimated. It is suggested that the computer simulation method can be used to better guide air quality management plans instead of only using the fixed-site monitoring data. The simulated results indicate that the CO exposure levels of commuters on motorcycles and public buses are high enough that prompt control measures are warranted in Taipei.

Key word index: Monte Carlo simulation, carbon monoxide, urban area, exposure assessment, representativeness of fixed stations.

INTRODUCTION

Vehicular emissions have been identified as the most important sources of many air pollutants in Taipei, Taiwan. A recent study showed that mobile sources contributed about 98% of CO emissions in Taipei. Among mobile sources, motorcycles contribute as much as 44% of total CO emissions (ICF KE *et al.*, 1991). In Taipei (272 square kilometers, 12 administrative districts), there are about 4100 vehicles (66% of which are motorcycles and 30% of which are light duty gasoline cars) and 10,000 persons per square kilometer (Taiwan EPA, 1991). Furthermore, the population density (25,000 persons per square kilometer) is higher in Taipei's central area (including 65 square kilometers, 7 districts) and the motor vehicle emission intensity is about 4000 metric tons per square kilometer per year. Many people work and live in proximity to main traffic roads in such a crowded city with such a high traffic emission load. Thus the air pollution problem, especially that pollution caused by vehicular emissions, is serious and there is much

concern about population exposure levels. CO was considered an appropriate indicative air pollutant for our investigation of the urban vehicular emission problem in Taipei.

The Taipei environmental authority (Bureau of Environmental Protection, BEP) has set up 15 fixed monitoring stations to measure ambient air quality. Three of these located near roadways are classified as roadside stations and are thought to be representative of roadside CO concentrations. The municipal fixed site monitoring results are usually used to guide control strategies designed to attain national ambient air quality standards (NAAQS). Since NAAQS are based on public health considerations, measured concentrations need to be comparable to people's real exposure.

In urban areas, there are about three ways to estimate personal exposure levels to CO. The first way is simply to rely on the fixed site measurements alone. Although experts have long doubted the suitability of applying fixed site measurements alone for exposure level estimation (Cortese and Spengler, 1976; Chan

et al., 1991), this method is still widely used to guide air pollution control policy in many nations, including Taiwan. The second way is to improve the quality of CO dispersion models in urban areas. Some of the improved models are the CAL3QHC model (U.S. EPA, 1990), the ROADWAY model (Eskridge, 1987), and street canyon models (Hoydysh, 1988). The third way is to establish CO exposure models using computer simulations that combine CO concentrations in microenvironments with time activity data (indirect measurement), excluding direct personal exposure measurement. One drawback of the direct measurement method is that it is very expensive and labor-intensive (Sexton and Ryan, 1988). Some more reasonable and realistic modeling approaches (indirect measurement) to estimate CO exposure levels have been developed. For example, the Simulation of Human Activity and Pollutant Exposure model (SHAPE) (Ott *et al.*, 1988) and various Monte Carlo simulation models (Ott, 1983–84; Ryan *et al.*, 1988; Fingleton *et al.*, 1991; Billick *et al.*, 1991; Johnson *et al.*, 1990). In Taipei, based on past experiences (ICF KE *et al.*, 1991), the microscale dispersion models, such as the CALINE4 and ROADWAY, were not successful in estimating CO concentrations on the streets. The failure of these modeling methods were possibly due to the particular features of complex urban settings in Taipei, such as the relatively high density of motor vehicles, roads, and buildings.

The purposes of this study are (1) to collect commuter pattern data; (2) to carry out a survey of CO concentrations in selected microenvironments affected by vehicular emissions, such as in commuting vehicles, roadsides including both the sidewalk and the corridor (a sheltered walkway farther removed from the road than the sidewalk), bus stops, residential areas, and school areas; (3) to conduct Monte Carlo simulations (indirect approach) to estimate CO exposure levels for the population and to find the most dominant factors or events; (4) to make a comparison of the Monte Carlo simulated CO exposure levels with the fixed site monitoring data. The study estimated the population's CO exposure levels in Taipei, reflecting the special characteristics of life style, urban setting, and the strength of traffic emissions. A comparison between the fixed site measurements and the Monte Carlo simulation method showed that the fixed site stations do not adequately represent CO exposure levels for the urban population.

EXPERIMENTAL METHOD

Commuting patterns

In 1990, a questionnaire survey was conducted to establish the commuting patterns of students and adult workers in the Ta-An district, Taipei. The Ta-An district, located in Taipei's central area, was selected as a representative target population area (11 square kilometers, 100,000 household units, general socioeconomic class, population density of 31,000 persons per square kilometer, and 65, 5, and 35% of the area

in the district for residential, commercial, and open public use, respectively). A stratified cluster sampling was used to select student participants in this study. First, three grades in each primary school in the district were randomly selected. Secondly, all students from two random classes in each grade from all the eight schools were asked to fill out questionnaires, which amounted to a sample size of 1244 student participants. For adult participants, 350 families were first randomly selected from the district. Then, all working adults aged over 24 yr in each family were selected to participate. A total of 622 workers filled out questionnaires. Information about commuting modes, duration and starting times of each trip, and routes of each trip were obtained in the questionnaires.

Carbon monoxide measurements

The CO concentrations were measured for three transportation modes: bus, private car, and motorcycle. Samples were collected over three time intervals in the day: morning rush hour, midday, and evening rush hour. The survey considered variables such as commuting mode and time interval during the day, but due to limited resources, did not control for factors of window position, ventilation status, vehicle age etc., and seasonal, daily, route, or geographical variance. For these moving samples, the air was collected into a 5 l Tedlar bag by a small pump (SKC Inc., Model 224) carried by team workers (as a commuter) in or on vehicles following trips along the six major transportation mains in Taipei. Approximately 5 l of air were sampled over 30–50 min using flow rates of about 80–130 ml min⁻¹ per trip. These samples were then analysed by a NDIR-based CO analyser (Horiba Inc., APMA Model 350E). In order to compare the concentrations and obtain diurnal variations, the same type of CO analyser was used to monitor CO concentrations continuously for 24 h at 20 fixed stations set at corridors (designated as "corridor station") of main roads covering Taipei's central area. Simultaneously, moving air samples were collected in vehicle emissions-associated microenvironments, including roadsides, bus stops, small lanes in residential areas, and in schools near these 20 corridor stations. The CO field surveys were carried out between December 1989 and February 1991.

In addition, we collected CO monitoring data from 1990 from three fixed-site, continuous monitoring stations operated by the Bureau of Environmental Protection (BEP) of the Taipei City government. Among them, two stations (BEP22, BEP23) were placed near main roads (designated as "roadside station") and the other one (BEP02) was located in a residential area (designated as "regional station"). The heights of sampling inlets are about 2.5 m for the roadside stations, and about 12 m for the regional stations. The roadside stations were 1–3 m away from traffic lanes, and the regional station was located around the center of the residential area. The traffic flow data were collected from the local traffic authority's annual report.

Monte Carlo simulation

In order to estimate the most serious and common exposure events to the general population in Taipei, the study applied the Monte Carlo method to simulate exposure level distributions for the general commuters and occupational drivers. The exposure model can be expressed as:

$$E_{ij} = \frac{1}{T} \int_T C_{ij} \cdot t_{ij} \quad (1)$$

where E_{ij} is exposure level indicated as the average CO concentration over a period of exposure time (T , 1- or 8-h), C_{ij} is the CO concentration of commuting mode (or scenarios) i in time interval j during the day, t_{ij} is the duration of commuting mode i in time interval j . For 1-h simulations, t_{ij} was randomly drawn from the surveyed commuting duration data set of commuting mode i of time interval j (morning rush

Table 1. The commuting patterns for primary school students and adult workers in Taipei

Commuting mode	N	(%)	Commuting duration (h) Arithmetic mean (S.D.)	
			Leaving home	Leaving school/workplace
Students	1244	100	0.34 *	0.43 *
Walking	721	58	0.23 (0.15)	0.28 (0.19)
Bicycle	12	1	0.33 (0.24)	0.52 (0.48)
Public bus	361	29	0.50 (0.29)	0.67 (0.36)
Motorcycle	13	1	0.38 (0.23)	0.45 (0.21)
Private car	124	10	0.47 (0.29)	0.58 (0.31)
Misc.	13	1	0.82 (0.44)	1.0 (0.35)
Adult workers	622	100	0.62 †	0.74 †
Walking	75	12	0.27 (0.17)	0.30 (0.20)
Bicycle	25	4	0.31 (0.22)	0.33 (0.30)
Public bus	162	26	0.82 (0.44)	1.0 (0.50)
Motorcycle	174	28	0.53 (0.26)	0.60 (0.30)
Private car	156	25	0.63 (0.30)	0.76 (0.40)
Misc.	30	5	0.78 (0.38)	0.86 (0.51)

* Leave home at 7:10 a.m. (median) and leave school at 4:15 p.m. (median).

† Leave home at 7:45 a.m. (median) and leave workplace at 5:30 p.m. (median).

S.D., standard deviation.

Table 2. The measured CO concentrations (ppm) in various indoor and outdoor microenvironments *

Location	N	Arithmetic mean	Min.	Max.	S.D.
In vehicle					
On motorcycle	295	17.5	2.9	126	14
In bus	94	11.6	3.5	37	6
In private car	30	11.0	4.5	20	4
Near roadway, outdoor					
At bus stop	113	13.0	1.3	42	8
On roadside/corridor	854	8.1	0.5	101	7
Moving along roadside	381	7.8	0.5	101	8
Fixed at corridors	473	8.3	0.7	40	7
Residential area, outdoor	127	2.5	0.5	7	1
School area, outdoor	17	1.6	0.7	6	2

*Sampling durations were 30–50 min, except at corridor stations where durations were 60 min. Samples were taken during the time period of 7:00–19:00.

hour or evening rush hour) (Table 1), and C_{ij} was randomly drawn from measured CO concentrations from corresponded location i of time interval j . For commuting duration less than 1 h, C_{ij} of the rest of 1 h was assumed to be background levels of 1.6 ppm (in school) for students and 2.5 ppm (in office) for adult workers, based on the arithmetic means of CO concentrations in the school areas and residential areas (as shown in Table 2). Three likely 8-h exposure scenarios were assumed (Table 4). For 8-h simulations, t_{ij} was the duration of scenario i and C_{ij} , as said above, was randomly drawn. The exposure model, equation (1), assumes that C_{ij} is independent of t_{ij} , that the exposure events occurred unrelatedly, and that the SHAPE type model's assumptions (concentration superimpose hypothesis) are true. The Monte Carlo simulation was implemented by an algorithm programmed with SAS statistical software (Release 6.03, SAS Ins., Inc.) to randomly and uniformly draw (1000) samples from measured data sets (per trial). The simulation process determined the expected CO exposure level distributions and was repeated five times in this small-scale study. The simulated maximum exposure value, and the

median and range of exceedance (percent of which the simulated exposure levels exceeded the NAAQS of 35 ppm (for 1 h) or 9 ppm (for 8 h)) in five trials for each commuting mode and scenario are presented in Tables 3 and 4. The CO exposure exceedances were further weighted by the population-fraction (as shown in the third column of Table 1) for each commuting mode to estimate the expected probability of the 1 h CO exposure level exceeding the NAAQS for the general population in Taipei.

Quality assurance and quality control

The CO analysers were calibrated weekly by U.S. EPA traceable span gas. The accuracy of the CO analysers was controlled to be within 0.5 ppm throughout the experimental period. Those trials whose samples were beyond the control range were eliminated. Duplicate samples were collected and analysed to assess the precision of the Tedlar bag sampling method and the difference between the moving sampling and fixed site methods. The relative percent difference between the duplicate samples was found within 10%.

RESULTS AND DISCUSSION

Table 3. The Monte Carlo-simulated 1-h CO exposure level for primary school students and adult workers by different commuting modes

	In morning, leaving home to school/workplace			In evening, leaving school/workplace back home			Population weighted* exceedance (%) of 35 ppm		
	Exceedance (%) of 35 ppm		Simulated max. (ppm)	Exceedance (%) of 35 ppm		Simulated max. (ppm)	Morning	Evening	Total
	Median	Range		Median	Range				
Student									
Walking †	0.1	0-0.1	40	0	0-0	27	0.45	0.98	1.44
Bicycle †	0.5	0.3-0.7	55	6.7	5.7-7.6	58	0.06	0	0.06
Public bus	1.3	0.9-1.4	38	2.8	2.4-3.8	38	0.005	0.07	0.08
Motorcycle	0.6	0.3-0.9	60	8.5	7.6-10.2	58	0.38	0.81	1.19
Private car	0	0-0	20	0	0-0	20	0.006	0.09	0.10
Working adult									
Walking	0	0-0	33	0	0-0	20	1.33	4.36	5.69
Bicycle	0	0-0	33	0	0-0	28	0	0	0
Public bus	3.4	2.7-3.8	38	6.2	6.2-6.9	38	0.88	1.56	2.44
Motorcycle	1.6	1.1-1.6	59	10	10.4-11	58	0.45	2.80	3.25
Private car	0	0-0	20	0	0-0	20	0	0	0

* Weighted by commuting mode fraction, the third column of Table 1.
† The corresponding locations were assumed: walking, roadside/corridor; bicycle, roadside/corridor.

There was a significant difference in the commuting patterns and duration of commute between students and adult workers. Most students commuted between their homes and schools either by walking (58%) or by riding on public buses (29%). In contrast, most adult workers commuted between their homes and workplaces by motorcycle (28%), public bus (26%), or in private cars (25%) (Table 1). Commuting by bicycle was rare. The adult workers' commuting duration each day was about twice as long as the students' (1.36 h vs 0.77 h). Duration of commute also varied with commuting modes. Commuters using public buses had the longest commuting duration (1.82 h for adult workers and 1.17 h for students), and those that walked had the shortest commuting duration (0.57 h for adult workers and 0.51 h for students). Adult workers usually started their morning commutes 35 min later (7:45 a.m. vs 7:10 a.m.) than students and started their afternoon commutes 75 min later (5:30 p.m. vs 4:15 p.m.). The adult workers who commuted by motorcycles and public buses have greater vehicle-emitting pollutant exposure levels than students because they had longer commuting durations (Table 3). The surveyed commuting pattern in Table 1 shows two characteristics of commuting in Taipei: popularity of transportation mode and commuting duration of two types of cohorts, both of which are essential when assessing and planning control strategies for controlling population exposure level to pollutants, and which are different in the developing countries from the developed countries. The wide variation in commuting patterns in the Taipei population demonstrates that personal exposure levels cannot be sufficiently well represented by the fixed site monitoring stations alone.

The CO concentrations (average) in Taipei were significantly higher than in surveys from the U.S. which reported lower CO concentrations by 3-4 ppm in vehicles and near roads outdoor (Ott *et al.*, 1988). As expected, the CO concentration was very high on roadways, and rapidly decreased from the center of the roads to the roadsides. The highest CO concentrations were measured inside vehicles (17.5 ppm on motorcycles, 11.6 ppm in public buses, and 11.0 ppm in private cars), while the lowest were in residential areas (2.5 ppm) and schools (1.6 ppm) (Table 2). This trend generally agrees with the dispersion phenomena of CO from the line sources on the road to farther areas (Hewitt, 1992). The relatively high CO concentrations at bus stops (13.0 ppm) are one particular feature of CO pollution in Taipei. This is possibly due to many buses idling at the stops and the induced acceleration, deceleration and low traffic speed near bus stops. On the other hand, the CO concentrations were comparatively low in residential areas and schools, which were usually more than 30 m away from the roads. The findings imply that outdoor CO concentrations in residential areas and schools might not be an import-

Table 4. The Monte Carlo-simulated 8-h CO exposure level for adult workers, roadside business workers, and bus drivers in Taipei

Scenarios	Simulated max. (ppm)	Expected exceedance (%) of 9 ppm	
		Median	Range
1. Adult workers commuting by public bus daily (10:00–18:00) In office* (5 h, noon) † ‡ + on sidewalk (2 h, noon) + at bus stop (20 min., EP) + in bus (40 min., EP)	30	4	3.5–5.5
2. Roadside business workers (7:00–15:00) At corridor (2 h, MP) + at corridor (6 h, noon)	80	31	29–34
3. Bus drivers (7:00–15:00) In bus (2 h, MP) + in office* (2 h, noon) + in bus (4 h, noon)	23	65	58–68

* Background CO concentration of 2.5 ppm were assumed, as described in text.

† MP, morning rush hour (7:00–9:00); noon, midday (9:00–17:00); EP, evening rush hour (17:00–19:00).

‡ Location (duration, time period).

Fig. 1. Comparison of CO concentrations measured by fixed stations of Bureau of Environmental Protection (BEP), Taipei and by this study.

ant contributor to personal CO exposure levels. The CO concentrations (average) measured either at fixed corridors (8.3 ppm) or by moving bag sampling along the roadsides (7.8 ppm) were very close (Table 2). The similarity in CO concentrations measured at roadside stations (BEP22, BEP23), fixed corridor stations, and movings bag samplings along the roadsides can also

be observed in Fig. 1. These measurements account for the distinguishable microenvironments, such as the roadside, corridor, through which many people commute and in which many work. The discrepancy of CO measurements between these roadside stations and the regional stations (in residential areas) can be explained by differences in the location and height of monitoring

Table 5. Comparison of CO exceedance (%) of NAAQS based on various actual measured concentrations and Monte Carlo-simulated exposure levels in Taipei

	BEP fixed stations by roadside of main road *						Fixed stations at corridor						Moving bag samples along roadside*						Moving bag samples on motorcycle						Moving bag samples in bus						Monte Carlo Simulated exposure																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																		
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CO (1 hr) ‡	0	0.1	0	0	0.7	0	1.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

* Duration of CO concentrations for moving bag samples were 30–50 min, except at fixed stations where duration was 60 min.
† MP, morning rush hour (7:00–9:00); noon, midday (9:00–17:00); EP, evening rush hour (17:00–19:00).
‡ Taiwan EPA reported the 1-h CO exceedance of NAAQS (35 ppm) was 0.018 and 0.086% for BEP22 and BEP23 (the roadside fixed air quality monitoring stations operated by the Bureau of Environmental Protection (BEP), Taipei), respectively, based on yearly total effective hours (Taiwan EPA, 1992).
§ Simulated 1-h exceedance referred to in Table 3.
|| Taiwan EPA reported the 8-h CO exceedance of NAAQS (9 ppm) was 39% and 29% for BEP22 and BEP23, respectively, based on yearly total effective hours (Taiwan EPA, 1992).
¶ Not categorized by time interval.
** Simulated 8-h exceedance referred to in Table 4.

stations due to dispersion effects. CO concentrations at roadsides also showed a significant diurnal pattern (Fig. 1). This pattern corresponded to variations of traffic flow in the day in Taipei. That CO concentrations on roadsides show good correlation with urban traffic flow in the daytime suggests the direction to take in order to reduce urban air pollution. As expected, among commuters, motorcyclists suffered the highest CO exposure levels due to their close proximity to vehicle exhaust. Since motorcycles are a very popular mode of transportation in Taipei, special control measures must be implemented to protect motorcyclists, as well as the health of the general public. The long-term exposure levels of professional workers, such as bus drivers and roadside business workers, also need to be seriously considered.

In addition, the CO concentrations measured at the “regional station” (BEP02) and at the “roadside station” (BEP22, BEP23) differed greatly even though both types of stations are classified as outdoor fixed stations. These large differences demonstrated how important it is to carefully report the type of outdoor fixed stations in studies on indoor/outdoor pollutant concentration ratios and in those that assume outdoor background concentration in total exposure modeling (Fig. 1). Because the difference between CO measurements from regional stations and roadside stations is greatest during the rush hour, a large deviation (or error) in the upper extreme tail will occur if the two types of outdoor fixed site stations are not well distinguished.

Using the Monte Carlo method, based on actual CO measurements and commuting pattern data, this study simulated 1- and 8-h CO exposure distributions and compared them with NAAQS (35 or 9 ppm). It is demonstrated that the population-fraction term is meaningful and essential when investigating urban air pollutant exposure issues. This study predicts that a relatively high percentage of the population is exposed to CO levels greater than 35 ppm in 1 h (NAAQS) in Taipei (Table 3). Moreover, an adult worker’s expected CO exposure exceedance (5.69%) is about 4 times higher than a student’s (1.44%). For students, there is expected (population-weighted) exceedance of 1.19% when commuting by public buses. For adult workers, a higher expected (population-weighted) exceedance occurred when commuting by motorcycle (3.25%) or by bus (2.44%). Adult workers have higher CO exposure levels than students because they commute for longer duration, encounter more traffic jams, and are exposed to higher CO concentrations on motorcycles. The adult workers’ expected CO exposure exceedance during the evening rush hour is about 3–4 times that of the morning rush hour, probably because of the longer commuting duration (Table 1) and more extreme CO concentrations for motorcyclists during the evening rush hour. The simulated 8-h CO exposure for the three assumed common scenarios were compared to NAAQS. This study found that

the 8-h CO exposure levels for adult workers were high, and were even higher for adults working along and on the roads. The expected CO exposure exceedances for an 8-h period were 4, 31, and 65% for adult workers commuting by public buses, roadside business workers and bus drivers, respectively. In extreme cases, the 8-h CO exposure levels can be 3–8 times higher than the NAAQS. Since there are many small shops on both sides of main traffic roads in Taipei, the problems of CO exposure among roadside workers and businessmen should not be overlooked. An even more important implication of the simulated findings is that there is a need to reduce the CO exposure levels for bus drivers, taxi drivers, traffic controllers, and other people with these occupational risk in Taipei. If it is warranted, more scenarios and simulations can be undertaken and more about the simulated exposure distributions can be obtained and be assessed.

In order to test the representativeness of BEP fixed stations, this study compared the expected CO exposure levels determined by the Monte Carlo simulation with that of two BEP roadside monitoring stations (BEP22, BEP23) in Taipei (Table 5). It was found that the measurements by BEP fixed roadside stations underestimated the short-term CO exposure levels (1-h) as simulated by the Monte Carlo simulation. On the other hand, the measurements of BEP fixed roadside stations reasonably estimated the roadside business worker's 8-h CO exposure levels, as compared with the simulation results. However, the measurements of roadside stations overestimated 8-h exposure levels for adult workers commuting by bus, but underestimated 8-h exposure levels of bus drivers. The unrepresentativeness of roadside stations in estimating 1-h exposures can be explained by the dispersion effect in which CO concentrations are lower at roadside stations, which are several meters away from the side lanes of traffic roads and above the commuter's breathing zones (1–1.5 m) than in the real exposure zones. The problem of unrepresentativeness was less serious in estimating 8-h exposure levels because there is an averaging effect which evens out peak exposure events over the exposure period. The upper end of the CO concentration distribution at the exact detection point away from sources was determined through dispersion effect. It was expected that with nearer distances or shorter averaging times, greater upper extremes, higher exceedances and higher risks would be calculated. If the NAAQS level was shifted, the exceedance values would change to an extent depending on the upper tail shape. More works can be conducted to determine the severity of air pollutant exposure and the representativeness of measurements in different contexts. Although the findings in this study on representativeness of fixed site monitoring are based on Taipei's actual CO measurements only, this study emphasizes the importance and the effect that local physical settings and population lifestyle

can have on personal pollution exposure levels assessment significantly in an urban area setting.

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