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EXPOSURE OF COMMUTERS TO CARBON MONOXIDE IN MEXICO CITY—I. MEASUREMENT OF IN-VEHICLE CONCENTRATIONS

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Abstract—The aims of this study were to determine in-vehicle carbon monoxide (CO) levels in major commuting modes in the Metropolitan Area of Mexico City (MAMC) and to identify the main factors affecting the variation in these CO concentrations. CO concentrations were measured inside public and private transport vehicles during the winter of 1991 in Mexico City. Measurements were taken along several commuting routes, during the morning and evening rush hours. Significant differences in CO concentrations were found between different transport modes. The highest CO concentrations were found inside autos and collective taxis, while metro trains, trolleybuses and buses had lower concentrations. In-vehicle CO concentrations in Mexico City were much higher than those reported for previous studies in the U.S.A.

Key word index: Carbon monoxide, air pollution, exposure, Mexico City.

INTRODUCTION

Two types of study have provided information on commuters' exposure to CO; direct approach and indirect approach studies (Duan, 1982). The first type includes the few studies in which members of the population (a representative sample, a sample of convenience, or a group of volunteers) have worn CO monitors for 24 h periods (e.g. Hartwell *et al.*, 1984; Johnson, 1984), or for shorter periods of time including commuting (e.g. Cortese and Spengler, 1976). A common finding of these studies is that for non-smokers without occupational exposures, commuting is the activity with the largest contribution to individuals' total personal exposure to CO.

In the second type of study the investigator generally selects or designs standard routes representative of the commuting trips undertaken by the population or group of interest (e.g. Haagen-Smit, 1966; Brice and Roesler, 1966; Wallace, 1979; Petersen and Allen, 1982; Holland, 1984; Flachsbart, 1985; Flachsbart *et al.*, 1987; Shikiya *et al.*, 1988; Chan *et al.*, 1991). A review of the literature (see Flachsbart, 1992; Fernández-Bremauntz, 1993) reveals that although a few studies have measured CO concentrations inside public transport vehicles (e.g. Wallace, 1979; Flachsbart, 1985; Flachsbart *et al.*, 1987), the large majority of studies have focused on private cars. This is expected since travelling by car is the predominant mode of travel in the U.S., where most of the studies have been conducted so far. Furthermore, the design of these studies does not allow systematic comparison of public and private transport modes, e.g. by carrying out simultaneous measurements along the same routes.

This paper reports the findings of a large study of commuters' exposure to CO which, unlike these earlier U.S. studies, focused on public transport vehicles. The study was carried out in Mexico City where, as in many of the other large urban centres of developing countries, public transport is the dominant mode of transport. The two specific objectives of this paper are: (i) to report in-vehicle CO levels in major commuting modes; and (ii) to identify the main factors affecting the variation in CO concentrations between the different modes.

Measuring concentrations of CO (and other pollutants) inside public transport vehicles was important because travel patterns data for Mexico City (COVITUR, 1984; DDF/EDOMEX, 1990) had indicated that up to 85% of the total person-trips d^{-1} are made by public transport and that many people spend several hours commuting to an from work every day. Although carbon monoxide is only one of several pollutants for which exceedances have been recorded at fixed-site monitoring stations in Mexico City (CONADE, 1988; DDF, 1990), this pollutant was selected because suitable personal exposure monitors were available and had been successfully used in previous studies (e.g. Hartwell *et al.*, 1984; Johnson, 1984).

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METHODS

The field work design was based on the EPA study on commuters' exposure to CO in Washington, DC (Flachsbart *et al.*, 1987), and by Flachsbart's study on the effect of priority lanes in reducing exposure to CO in a Honolulu arterial highway (Flachsbart, 1985). Data collection basically consisted of taking measurements of CO concentrations inside public transport vehicles while travelling as a passenger, along five selected standardized commuting routes. Measurements were taken on weekdays between mid-January and mid-March 1991 using six General Electric COED-1 personal exposure monitors (PEMs) lent by the U.S. EPA. For a description of the PEM used in this study see Ott *et al.* (1986).

Transport mode and route selection

CO levels were investigated inside the following transport modes: bus, collective taxi (both 22-seater minibus and nine-seater minivan, called "combi" in Mexico City), trolleybus, metro (including light train) and auto. With the exception of the trolleybus, these transport modes make a substantial contribution to the 29.5 million person-trips made in the MAMC every day, with values as follows: automobile, 4.4 million; metro, 4.8 million; bus, 4.2 million; and minivan and minibus, 7.2 million (DDF/EDOMEX, 1990). The public transport system of Mexico City was described in detail in a previous paper (Fernández-Bremauntz and Merritt, 1992). Concerning private transport, most trips were made using a 1983 VW "Rabbit", a 1972 VW "Beetle", and a 1987 Nissan Sedan. However, on two different occasions it was necessary to use two other vehicles, a 1982 VW Rabbit and a 1988 VW Golf (due to the program "A day without a car", which restricts the use of autos on one weekday every week). All cars were four-cylinder vehicles and run with regular (leaded) petrol.

Five large commuting corridors were selected for this study. A commuting corridor is defined as a fixed-travel route from origin to destination which is followed by at least two different types of public transport. Buses and minibuses run in four of the five corridors, minivans in two corridors, and trolleybuses only in one. The autos were driven along two of the five corridors. Additionally, three of these road vehicle routes were closely matched by combining several metro lines and the only existing line of the light train. The 12.3 km of light train in operation and about 35 of the 141 km of the metro network were surveyed.

The selected commuting corridors are shown in Fig. 1. These corridors were selected because they:

1. bring together six of the 10 zones of the city which have been identified as the origin or destination of the largest number of person-trips d^{-1} in the MAMC (COVITUR, 1984);
2. pass within 2 km of at least one fixed monitoring station with CO monitoring capability;
3. include roads with different traffic volume: a highway with 10,000–11,000 vehicles h^{-1} (e.g. Tlalpan Av.); arterial roads with 6000–8000 vehicles h^{-1} (e.g. Insurgentes, F. Servando and Reforma) and ejes viales* with 3000–5000 vehicles h^{-1} (e.g. Eje 1 Norte).

To a large extent, the corridors are two-way roads. Thus, the inbound journey followed the same roads of the outbound trip. However, there were also some segments of the commuting corridors which consisted of one-way roads. In these cases inbound and outbound trips followed parallel roads. The starting points of most of the selected commuting routes are located near the boundaries of the Federal District, about 10–15 km away from the central business district. At these points, urban and suburban vehicles share the same terminals (e.g. Indios Verdes and La Villa at the north; Pantitlán at east; Tacuba-Cuatro Caminos at the west). On the one hand, these points are the final destination of buses and collective taxis bringing people from the neighbouring municipalities of the State of Mexico (some of which are located 20–40 km away from the centre of the city). On the other hand, these terminals are the origins of bus, collective taxi and metro routes which transport people from the outskirts towards the city centre.

Sampling design and procedure

For public transport vehicles, a target of six sampling days was established for each of the five corridors. Since logistical constraints prevented a randomized allocation of sampling days, the six monitoring days were split into two periods. The first period comprised four consecutive days of a single week. The complementary period consisted of two additional (but not consecutive) days of a different week. The second sampling period for each corridor took place not less than two weeks after the first sampling period for the same corridor. On any given sampling day, at least one vehicle of each transport mode available in the corridor was sampled. This applied to both the morning and the evening sessions. Autos were sampled only on four consecutive days, and in any given monitoring session the maximum numbers of cars used was two.

There were two monitoring sessions per day, corresponding to the morning (06:30 to 09:30) and evening (17:30 to 20:30) rush hours. With the exception of corridor 1, the 3 h time-window permitted each operator to make a return trip from one terminus to the other (one outbound and one inbound trip within a single monitoring session). The inbound trip was always made in the same mode of transport as the outbound trip. In corridor 1 (Insurgentes Av. from Indios Verdes to San Angel/C.U.), due to the length of the route and the low speed of travel, only one-way trips from terminus to terminus were made in a given monitoring session. In order to follow the actual commuting pattern along this route, the morning trips were made from north to south and the evening trips were made in the opposite direction.

Before every monitoring session, each operator was assigned a transport mode, and was given a monitor and a paper form. Specific forms were designed for each corridor and travel mode. The forms included the following standard information: route, travel mode, shift, date, times, monitor number and operator's name. If, after allocation of one monitor for every travel mode available in a given corridor, there was still one (or more) monitor available, that monitor was used in another vehicle to obtain a replicate of one (or more) of the travel modes already sampled. These replicated trips are particularly important in order to determine variation in CO concentrations found among vehicles of the same type. The PEMs were carried on the operator's lap when travelling on public transport or in the passenger front seat when using an auto.

The driver/drivers of the auto kept travelling in the central lanes of the road (usually the second or third lane from the curb), where vehicles travel at a speed which is intermediate between the faster and the slower lanes. In order to make the car trips as "concurrent" as possible with the public transport vehicles (without needing to drive at an unrealistically low speed), the car trips departed from the terminus about 10–15 min after the bus and minibus trips. The car usually passed the public transport vehicles at about the midpoint of the trip, and arrived a few minutes earlier at the final destination.

Cars were always driven with one-third of the driver's window open (while the other windows were closed) during the morning monitoring session. During the evening session, the driver's window was open at least halfway. This was selected to represent ventilation conditions found among surrounding vehicles. No air-conditioning or heating system

* Ejes viales are one-way multiple-lane roads arranged in an orthogonal pattern with synchronized traffic lights controlled by a computer.

was used in the vehicles. It should be noted that, in public vehicles too, there are always some windows open and vehicles do not use heating or air-conditioning systems.

Quality assurance and quality control

Several quality assurance procedures were included during the field sampling, following the standard procedures applied by the U.S. EPA in its own research with this kind of monitoring equipment (Hartwell *et al.*, 1984; Johnson, 1984; Flachsbart, 1987; Wallace *et al.*, 1988). These procedures included: weekly calibration of CO monitors; daily check of zero and span and dual precision test (side-by-side monitoring). As suggested by the EPA (Wallace *et al.*, 1988), monitors were always calibrated running with fully charged batteries instead of using the mains. This procedure prevents differences in the monitor performance when it is operated using a different source of power.

To prevent interferences or biases due to tobacco smoke, all collaborators taking part in the study were nonsmokers. Additionally, smoking is not allowed in all public transport modes in Mexico City. Concerning the private cars used for this experiment, all had passed the 1990 I/M test for in-use vehicles, although the CO emission standards are not stringent: 4.0 vol% for 1986 and older models, and 3.0 vol% for post-1986 models (CONADE, 1988).

Sources of CO inside the autos were also checked. Besides smoking, intrusion of CO from the engine and/or tail pipe leaking exhaust may be a problem. Three of the test vehicles were taken to the countryside to be checked for CO intrusion. This was done by operating the vehicle in an environment free of motor vehicle traffic (in a narrow rural road), where ambient CO concentrations were less than 1 ppm. None of the vehicles tested in this way showed CO intrusion problems.

RESULTS

Vehicle variation and monitor precision

CO concentrations on replicated trips were used to estimate vehicle-to-vehicle variation and to assess its influence on commuting exposures. During the experiment, a total of 155 trips had "duplicates" and an additional 54 trips had "triplicates". Duplicated trips were made on all five commuting corridors. These 209 trips with replicates were distributed among modes as follows: bus, 74; minibus, 66; metro, 35; trolley, 18; minivan, 8; automobile, 8. This allocation pattern was primarily influenced by the availability of vehicles in the different corridors.

For analysing the precision of replicates only pairs of trips were considered. In the case of "triplicates", the two trips that started within a smaller time-window were selected for these comparisons. This criterion aims to reduce differences in road conditions due to changes in traffic or meteorology. The variation between replicates given as a percentage of the mean CO concentration (combining all routes for a given transport mode) was found to be as follows: metro, 6.8%; trolleybus, 11.9%; bus, 10.3%; minibus, 15.1%; car, 13.3%; minivan, 21.4%.

The precision of the monitoring equipment was also quantified. For this purpose, a pair of monitors was carried and operated side-by-side on 19 different commuting trips. Analysis of these paired data indicated that the average difference of two colocated monitors was 1.8 ppm (for CO concentrations averaging 38 ppm). This clearly indicates that the variation between monitors is very small compared to the variation between in-vehicle CO measurements. Nevertheless, this monitor variation (about 5%) could account for a substantial part of the vehicle-to-vehicle variation found for metro bus and trolleybus.

Descriptive statistics

A total of 641 single trips were made, of which 573 provided data of adequate quality for subsequent analysis. Of the 573 trips providing good quality data, 549 were made at rush hours and the remaining 24 trips were made at mid-day (11:00–14:00) and the afternoon (14:00–17:00) to investigate the variation of in-vehicle concentrations of CO throughout the day. It is estimated that during the whole experiment, the survey team travelled more than 11,000 km, of which 93% were on board public transport vehicles and the remaining 7% in private automobiles. The total number of terminus-to-terminus rush-hour trips by transport mode were as follows: auto, 34; minivan, 35; minibus, 152; bus, 170; trolleybus, 47; metro (including light rail), 111.

The minimum number of monitors available at any time was four (due to pump clogging of two monitors), which was enough to sample at least one vehicle of each type per commuting corridor (see Table 2). In some corridors, certain vehicles did not run very frequently. This problem occurred for minivans in corridors 3 and 4. Therefore, in these cases, instead of the desired number of trips by minivan, replicate trips were made by other transport modes such as bus and minibus, which run more often than the minivans.

The commuting corridors were split into 5–9 segments or links. Although the basic measurement of carbon monoxide was the average concentration for every link of the route, all statistical analyses presented in this paper will use a time-weighted average (TWA) CO concentration for complete trips, calculated from the mean concentration and transit times recorded for each link.

Table 1 shows the summary distribution of TWAs of all commuting trips. Mean CO concentrations of individual trips ranged as follows: auto, 34.9–83.7 ppm; minivan, 23.2–99.7 ppm; minibus, 17.9–109.3 ppm, bus, 12.9–59.4 ppm; trolley, 14.8–42.4 ppm; metro, 12.0–33.5 ppm. Since the actual distribution of TWAs depends on the number of trips made on particular commuting corridors, days and shifts, it is not possible to use the values in this table to compare CO concentrations between different transport modes. Nevertheless, it is interesting to note that: all commuting trips made by car have a TWA of 35 ppm or above; the median values for minivan and minibus are also above 35 ppm; and the metro was the only mode in which the 35 ppm value (which is the air quality standard for 1 h exposure to CO) was never exceeded.

Table 1. Percentiles of CO concentrations (ppm) by transport mode

Transport mode	No. of trips	Min.	10%	25%	Median	75%	90%	Max.
Auto	34	34.9	43.6	48.3	57.5	63.7	78.5	83.7
Minivan	35	23.2	33.9	44.4	58.6	65.1	83.8	99.7
Minibus	152	17.9	29.6	34.8	42.7	55.2	67.3	109.3
Bus	170	12.9	18.2	24.2	30.2	36.5	42.5	59.4
Trolley	47	14.8	18.8	21.6	25.6	33.5	38.4	42.4
Metro and light rail	111	12.0	15.9	17.5	20.6	25.5	29.0	33.5

Basic data are time-weighted average for every (one-way) trip made from terminus to terminus on all commuting corridors.

Table 2. CO exposure and trip duration by route, transport mode and shift

Commuting corridor	Travel mode	Shift	CO exposure mean (ppm)	CO exposure S.E. (ppm)	Travel time mean (min)	Travel time S.E. (min)	No. of days	No. of trips
1. Indios V. to Sn. Angel/CU	Bus	AM	37.5	2.4	59.9	3.5	5	9
		PM	30.8	2.1	98.9	4.1	6	10
	Minibus	AM	55.3	4.6	56.2	2.4	5	10
		PM	37.1	3.4	83.1	1.8	4	9
	Metro	AM	24.6	1.8	37.8	1.2	4	16
		PM	18.1	3.4	38.7	0.9	2	10
	Auto	AM	55.2	7.7	39.4	2.1	4	4
		PM	57.1	3.7	63.0	4.6	4	4
2. Tacuba to Pantitlán	Minibus	AM	63.2	3.3	47.5	0.8	6	29
		PM	43.4	2.2	56.5	1.8	6	24
	Metro	AM	22.3	1.3	45.6	2.7	7	28
		PM	16.8	0.9	39.2	1.7	6	22
	Auto	AM	57.0	3.0	35.3	1.2	5	10
		PM	55.2	3.6	40.4	2.0	4	16
3. P. Suarez to Xochimilco	Bus	AM	41.1	2.2	57.8	1.6	7	20
		PM	28.9	1.1	57.5	2.7	7	24
	Minibus	AM	64.4	6.8	54.9	1.2	7	20
		PM	33.9	2.0	47.9	1.3	7	16
	Metro	AM	26.5	1.4	56.1	1.7	7	18
		PM	18.8	1.1	57.2	1.6	7	17
	Minivan	AM	66.1	2.9	49.8	1.6	5	12
		PM	57.1	7.3	47.2	1.6	4	10
4. La Villa to Auditorio N.	Bus	AM	34.0	2.7	39.8	2.2	6	18
		PM	26.0	3.5	44.5	1.1	6	20
	Minibus	AM	42.9	2.9	39.0	1.6	6	22
		PM	31.6	2.9	45.3	1.0	6	22
	Minivan	AM	39.5	3.8	34.4	1.4	3	6
		PM	43.6	6.8	43.1	1.7	4	7
5. Marina N. to Pantitlán	Bus	AM	32.1	2.0	46.3	0.9	6	30
		PM	20.5	1.5	51.7	1.3	6	39
	Trolley	AM	31.9	2.5	52.5	2.3	6	27
		PM	21.6	1.1	58.5	1.4	6	20

Means and standard errors were calculated using daily averages (the number of observations for each calculation corresponds to the column "Days").

Trip CO mean concentrations were used to calculate a morning and evening average for every monitoring day. These values were calculated by averaging all trips made within a single monitoring session (AM or PM session). In most sessions, there were only two trips per vehicle type: one outbound and one inbound trip. However, in some monitoring sessions it was possible to sample two or even three vehicles of the same type.

For public transport vehicles, the survey protocol set an original target of sampling six different days per travel mode per shift (four days for private cars) for each corridor with the relevant mode. However, this was not always possible due to: problems in setting the monitors properly when sampling corridor number 1 (first two days of the experiment); and the lack of enough minivans to board (corridor numbers 3 and 4). By contrast, in corridor 3 the original target of days was exceeded for transport modes other than minivan (see Table 2).

Table 2 summarizes the in-vehicle CO concentrations by route and transport mode. In-vehicle CO and travel time means, and standard errors were calculated using the daily means for each shift (which were calculated first by averaging the TWA of all trips made in a monitoring session). CO concentrations measured at commuting rush time varied with transport mode, route and shift. Average CO concentrations for all commuting trips made ranged as follows: metro, 16.8–26.5 ppm; bus, 20.5–41.1 ppm; minibus, 31.6–64.4 ppm; minivan, 39.5–66.1 ppm; trolley, 21.6–31.9 ppm; auto, 55.2–57.0 ppm.

Statistical analysis

One of the main purposes of this study was to compare CO concentrations among the different transport modes used by Mexico City's commuters. This hypothesis cannot be tested by comparing all transport modes together in a single analysis because not all modes were surveyed over the same routes at the same time. However, it is possible to compare pairs of transport modes by pooling together CO concentrations from all days and all routes in which the two modes were concurrently monitored. This was done by carrying out an ANOVA for each pair of modes, with mode, shift and route used as factors when appropriate. The tests performed in this way made it possible to use the maximum number of concurrent measurements for every pair of transport modes. Differences between means were tested using the Bonferroni test at the 95% significance level. Pooled standard errors were used for these tests. All statistical analyses were performed using log transformed data. Although this statistical analysis provides estimates of the effect of route and shift, these cannot be properly interpreted because, unlike the modal comparisons, the measurements were not made simultaneously. These effects need to be considered in the context of the CO concentrations recorded by the fixed-site monitors (FSMs) on different days and shifts. Relationships between in-vehicle measurements and those at the FSMs will be considered in a subsequent paper.

Transport mode effect

In-vehicle concentrations were found to be significantly different between vehicle types (see Table 3). Metro had lower CO concentrations than bus, minibus, minivan and automobile ($p < 0.001$ in all cases). Trolleybus could only be compared with the bus, which shared corridor number 5. No significant difference was found between these two transport modes. CO concentrations for both vehicle types were indeed very similar. CO concentrations inside buses were found to be lower than minibus, minivan and automobile ($p < 0.001$ in all cases). The overall CO concentrations on board minibuses were significantly lower than on board minivans ($p < 0.05$). Minibus concentrations were also lower than the concentration for automobiles, but the difference was not significant ($p = 0.052$).

Travel speed

When all road vehicles were combined it was found that the speed of travel was on average 21.2% higher in the morning than in the evening, ranging from 6.8% in corridor 3 to56% in corridor 1. Travel speeds were calculated by dividing the total travel time (from terminal to terminal) by the length of the route. The range of travel speeds by transport mode is shown in Table 4.

Statistical analysis of differences between modes was carried out independently for each route, with shift as an additional factor in the analysis of variance. Intermodal comparisons showed that the auto was significantly and consistently faster than the bus and minibus ($p < 0.01$). Although minibus and minivan were consistently faster than the bus this difference was only significant (at $p = 0.05$) in one route. The trolleybus was significantly slower than the bus ($p = 0.001$), on the one route in common. Finally, the metro speeds were variable in relation to other modes, being significantly faster than the auto in route 1, but

Table 3. Summary of geometric means of CO concentration from 10 ANOVA analyses

Test no.	CO geometric means (ppm)					No. of values	Routes used
1***	Metro	21.3		36.1	Bus	36	1, 3
2***	Metro	20.6		46.4	Minibus	56	1, 2, 3
3***	Metro	23.2		61.9	Minivan	16	3
4***	Metro	20.6		56.5	Auto	16	2
5	Bus	25.3		26.0	Trolley	24	5
6***	Bus	31.6		41.8	Minibus	68	1, 3, 4
7***	Bus	30.4		48.5	Minivan	28	3, 4
8***	Bus	31.1		53.9	Auto	12	1
9#	Minibus	49.5		55.2	Auto	28	1, 2
10*	Minibus	39.9		48.6	Minivan	28	3, 4

The significance level is indicated as follows: ***$p < 0.001$; **$p < 0.01$; *$p < 0.05$; #$p = 0.052$.

Table 4. Summary of in-vehicle CO concentrations and travel speed by transport mode

Transport mode	Range of travel speed (km h^{-1})	No. of routes	No. of trips
Auto	20.4–30.4	2	43
Minivan	16.7–27.9	2	44
Minibus	14.3–27.3	4	185
Bus	12.1–24.2	4	205
Trolley	14.3–16.0	1	53
Metro	21.4–31.3	3	111

Tabulated values correspond to mean of different routes and shifts.

Table 5. Comparison of carbon monoxide concentrations measured inside autos in the mid-60s in American cities and the present study in Mexico City

City	Mean (ppm)	90% (ppm)	Max. (ppm)	No. of trips
Mexico City[a]	56.1	78.5	83.7	34
Los Angeles[b]	37.0	—	58.0	8
Washington, DC[c]	25.0	36.0	43.0	44
St. Louis[c]	36.0	51.0	77.0	47
Chicago[c]	37.0	50.0	59.0	16
Denver[c]	40.0	60.0	72.0	28

[a] Present study. TWA of 16–20 km trips lasting an average of 44 min.

[b] Haagen-Smit (1966). TWA of 48 km trips lasting an average of 71 min.

[c] Brice and Roesler (1966). Integrated samples over drives of 30 min.

significantly slower than auto in route 2, which involved a change of routes. Furthermore, speeds in some metro journeys were reduced by major delays or by overcrowding.

DISCUSSION

Comparison with other studies

Results of the surveys reveal that the three types of petrol vehicles—minibus, minivan and auto—had higher CO concentrations than the diesel bus and the metro. The mean CO levels for bus trips were between 63 and 85% of the values for minibus trips (depending on the route); and the mean CO values for metro trips were only between 32 and 40% as high as the automobile CO averages. The mean CO concentration of trips made by trolley and those made by bus in the same commuting corridor were very similar.

The relative positions of commuting exposures among transport modes are in good agreement with the data from the few studies where some measurements have been taken of commuters' exposure in public transport vehicles. For example, in Boston, MA, the transport mode was a major variable affecting personal CO exposure levels. In this city, automobile commuters were exposed to approximately twice as much CO as public transport commuters (Cortese and Spengler, 1976). Another commuter study in Washington, DC, also found that the CO values for the bus routes were on the average about 52% as high as those for the automobile routes, and the rail routes average was only about 25% as high as the automobile value (Flachsbart *et al.*, 1987). However, it must be noted that none of the studies mentioned above were designed to compare, in a rigorous way, the differences among transport modes, this is by making concurrent trips along the same commuting routes.

Concerning the auto trips, the overall mean CO concentration of all trips was 56.1 ppm. These CO levels are only comparable to the upper range of in-vehicle concentrations measured in American cities in the mid-60s. Table 5 compares the results of studies in which CO measurements have been taken inside automobiles. Later studies in American cities have found lower CO concentrations inside autos than those reported for the 1960s. For example, the average CO concentration for commuting trips was found to be 13.4 ppm in Boston (Cortese and Spengler, 1976), 10.9–15.3 ppm in Los Angeles (Petersen and Allen, 1982), 9–14 ppm in Washington, DC (Flachsbart *et al.*, 1987), and 9.8 ppm in a year-long study in an arterial highway in California (Ott *et al.*, 1991). The results from the study presented here suggest that CO concentrations inside autos in Mexico City are much higher than those now measured in American cities. However, it is clear that formal comparisons cannot be made across studies because they were designed and implemented in a different way. Furthermore, since the measurements in the current study were made in the period January–March, the mean concentrations may be higher than those measured over the whole year.

Differences among transport modes

The differences in CO concentrations found between transport modes may have been due to two factors: the height of the vehicle and the lane of travel. Before explaining these factors it is important to remember that a number of studies with autos have found that, irrespective of the ventilation conditions, the inside and outside CO concentrations are very similar (Petersen and Allen, 1982; Rudolf, 1990; Chan *et al.*, 1991).* In the absence of self-contamination it can be assumed then that the CO measured inside a vehicle comes mainly from the surrounding vehicles on the road. Additionally, the air exchange rate of public and private vehicles in Mexico City must be high, since the large majority of vehicles are driven with some windows open.

* Colwill and Hickman (1980) carried out a study in London in which CO concentrations were considerably higher outside than inside. However, this discrepancy may have been due to the fact that while the inside measurements were taken at the driver's mirror height the outside inlet was placed in the bumper of the car.

Height of the vehicle

Since CO is emitted by exhaust pipes near ground level, there must be a strong vertical gradient of CO concentration; therefore, the lower the vehicle, the higher the CO concentrations encountered on roads. This gradient has been measured at pavement level (Wright *et al.*, 1975) but not at a microscale level (at different heights within 3 m from the ground) in the actual roads. Some dispersion modelling studies have also noted that under low wind speed conditions (like those found in the morning in Mexico City), the buoyancy effect plays an important role in dispersion of emissions, because the thermal plume rises substantially before being mixed downwind (Chock, 1977; Green *et al.*, 1979). There should thus be a gradient of CO concentrations from ground level upwards, and the CO concentration on the roads at the "window height" of autos, minivans, minibuses and buses should be progressively lower. The approximate heights of the windows of these vehicle types are 1.30, 1.60, 1.90 and 2.20 m, respectively.

Lane of travel

Concerning the travel lane, it should be pointed that while autos travel in the middle lanes of the road, the public transport vehicles tend to travel near the curb of the road (the right lane in Mexico). Among public transport vehicles, the larger the capacity of the vehicle (minivan = 9 seats; minibus = 22 seats; bus = 40 seats), the slower the speed of travel (more stops) and the stronger the trend to keep in the right lane of the road. Arterial roads with heavy traffic, like most of those sampled in Mexico (four lanes in each direction with a narrow central partition), can be visualized as bell-shaped tunnels of CO, in which the lane adjacent to the pavement has, on average, lower concentrations than the central lanes of the road. This concept is consistent with the idealized model of spatial distribution of CO in urban areas described by Ott (1977) and with the spatial pattern of CO on motorways described by Rudolf (1990). During the fieldwork of the Mexico City commuter study, some CO measurements were taken at pavement level and at the central reservation along parts of the commuting corridors. These data provide some evidence to suggest that, at least in some of the routes (e.g. Insurgentes Avenue), the central reservation has, on average, higher CO levels than the pavements (see Fernàndez-Bremauntz *et al.*, 1993).

CONCLUSIONS

This paper described typical in-vehicle CO concentrations to which public and private transport commuters were exposed on typical commuting corridors during the winter of 1991. In-vehicle CO levels in Mexico City are much higher than those reported for previous studies in U.S. cities. These high levels may also have implications for other "mega-cities" of the developing world.

The present study has demonstrated that there are statistically significant differences in the CO concentrations found inside different transport modes in Mexico City. The differences between modes are consistent with the hypothesis that they are due to gradients in outdoor CO concentrations over small distances within the road. Specific studies are necessary to find out if factors such as the height of vehicle and the lane of travel are important to determine in-vehicle concentrations of CO.

As a result of travelling more than 11,000 km on board different types of vehicles, the present study has produced a rich database that offers an opportunity to make a comparative assessment in a few years time of changes in commuter exposures resulting from the different transportation and emission control strategies currently being introduced in Mexico City.

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