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Reductions in human benzene exposure in the California South Coast Air Basin

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Abstract

Benzene typically contributes a significant fraction of the human cancer risk associated with exposure to urban air pollutants. In recent years, concentrations of benzene in ambient air have declined in many urban areas due to the use of reformulated gasolines, lower vehicle emissions, and other control measures. In the California South Coast Air Basin (SoCAB) ambient benzene concentrations have been reduced by more than 70% since 1989. To estimate the resulting effect on human exposures, the Regional Human Exposure (REHEX) model was used to calculate benzene exposures in the SoCAB for the years 1989 and 1997. Benzene concentration distributions in 14 microenvironments (e.g. outdoor, home, vehicle, work) were combined with California time-activity patterns and census data to calculate exposure distributions for 11 demographic groups in the SoCAB. For 1997, the calculated average benzene exposure for nonsmoking adults in the SoCAB was 2 ppb, compared to 6 ppb for 1989. For nonsmokers, about half of the 1997 exposure was due to ambient air concentrations (including their contributions to other microenvironments), but only 4% for smokers. Passive tobacco smoke contributed about one-fourth of all exposure for adult nonsmokers. In-transit microenvironments and attached garages contributed approximately 15 and 10%, respectively. From 1989 to 1997, decreases in passive smoke exposure accounted for about one-sixth of the decrease in exposure for nonsmoking adults, with the remainder due to decreases in ambient concentrations. The reductions in exposure during this time period indicate the effectiveness of reformulated fuels, more stringent emission standards, and smoking restrictions in significantly reducing exposure to benzene.

Keywords: REHEX; Air toxics; Microenvironments; Urban air pollution; Indoor exposure

1. Introduction

Benzene is a ubiquitous and persistent volatile hydrocarbon present in automotive evaporative and exhaust emissions, gasoline and other petroleum products, and tobacco smoke.

It is an important chemical from a health risk perspective as it is a known animal carcinogen and suspected human leukemogen (ATSDR, 1997; US EPA, 1993). In the EPA's Cumulative Exposure Project, modeled ambient benzene concentrations were above the 10^{-6} lifetime cancer risk benchmark for every census tract in the US (Woodruff et al., 1998).

The source of most benzene in urban ambient air is motor vehicles. The EPA has estimated 85% of ambient benzene comes from mobile sources: 60% from on-road sources and 25% from off-road sources (US EPA, 1998).

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Benzene typically comprises 3–4% of exhaust non-methane organic compound (NMOC) emissions (US EPA, 1993) and about 1% of evaporative NMOC emissions (US EPA, 1993).

From 1989 to 1997, benzene concentrations in ambient air in the California South Coast Air Basin (SoCAB) declined more than 70% (CARB, 1998a), from a basin-wide annual average of 3.8 to 1.0 ppb, averaged over all monitoring stations (see Fig. 1). This decrease was primarily due to a combination of the use of reformulated gasolines (with lower benzene content), more stringent emission standards for newer vehicles, and fleet turnover. Important fuel milestones included California Phase I Gasoline in 1992, which reduced benzene and aromatic content and lowered vapor pressure; federal reformulated gasoline (RFG) in 1995, which further reduced benzene content; and California Phase II Cleaner Burning Gasoline in 1996, which reduced sulfur content (to allow better catalytic converter performance) and further reduced vapor pressure and air toxics.

Because people spend a small amount of time outdoors and indoor benzene concentrations are often significantly higher than outdoor concentrations, decreases in ambient benzene concentrations may not directly lead to reductions in total exposure. For example, in the total exposure assessment methodology (TEAM) studies, indoor benzene concentrations were typically about twice the outdoor concentrations, and mean personal benzene exposures were typically 3–4 times higher (Wallace et al., 1991; Wallace, 1993). In these studies, most indoor benzene was the result of cigarette smoke, although household products, and gasoline vapors and car exhaust from attached garages, were also significant sources (Wallace, 1993). [Household products sold in California no longer contain benzene (CARB, 1998b).]

To reliably determine the decreases in human exposure due to concentration reductions in particular environments, all daily activities and the benzene concentrations in the environments where the activities occur must be taken into account. This "microenvironmental" approach was first proposed by Fugas (1976) and refined by Duan (1982), where a microenvironment is defined as a location of homogeneous pollutant concentration over a finite period of time. The most recent microenvironmental approach to predicting benzene exposures was performed by MacIntosh et al. (1995) for residents in Arizona and EPA Region 5 (the Midwestern US), in support of the National Human Exposure Assessment Survey (NHEXAS).

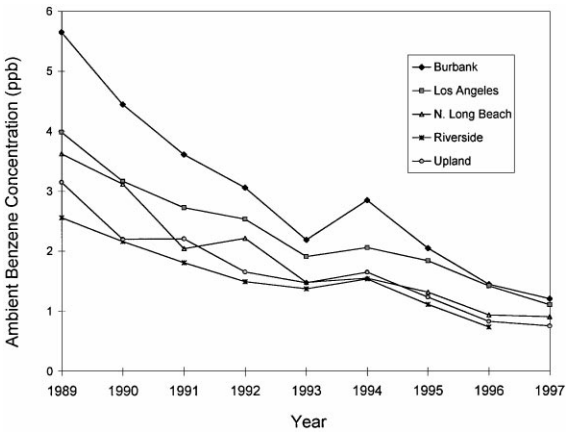

Fig. 1. Average yearly benzene concentration by monitoring station (CARB, 1998a).

The recent reductions in ambient benzene concentrations, the increased limitations on environmental tobacco smoke (ETS) in California, and the controversy surrounding the use of reformulated fuels (Keller et al., 1998) make a human exposure study for the SoCAB particularly timely. The objectives of the present study were to estimate the changes in human benzene exposures for various demographic groups in the SoCAB from 1989 to 1997; to determine exposure differences between these demographic groups; to determine the contributions individual microenvironments and sources made towards these exposures; and to determine the relative contributions each individual source reduction or microenvironmental reduction made towards the overall exposure reductions.

2. Methods

2.1. REHEX model calculations

The REHEX model calculated cumulative exposures according to the equations

$$E_i = \sum_{j=1}^{J} C_j \, \Delta t_{ij},$$

$$T_i = \sum_{j=1}^{J} \Delta t_{ij},$$

$$\mathrm{TWE}_i = \frac{E_i}{T_i},$$

where E_i was the cumulative exposure of demographic group i; C_j was the benzene concentration present in microenvironment j for the time period Δt_{ij}; Δt_{ij} was the time spent by the members of demographic group i in microenvironment j; J was the total number of microenvironments (14); T_i was the exposure averaging period (24 h); and TWE_i was the time-weighted average exposure for a demographic group.

To specify C_j, concentrations for each microenvironment were characterized by distributions based on either direct measurements or estimations from direct measurements. REHEX was designed to sample from distributions in order to simulate the range of variability found in most microenvironments.

To specify Δt_{ij}, each 15-min interval in a 24-h exposure for members of a demographic group was assigned to a particular microenvironment. This assigning process was based on the time-activity pattern surveys and diaries recorded in California in 1987 and 1988 (Wiley et al., 1991) as described in the next section. About 1100 24-h records were generated directly from the diaries, where each activity/location combination was directly transposed into one of 14 microenvironments. Each of these 1100 sequences were then assigned to one or more categories of 11 demographic groups, where demographic groupings were made by age, gender, workforce status, and smoking status. Age, gender, and workforce status were used to specify demographic groups because these three variables were found to be the most significant determinants of time spent in microenvironments containing tobacco smoke and/or volatile organic compounds (Wiley et al., 1991). Smokers uniformly had high exposures, determined primarily by smoking behavior, so they were placed into a single demographic group.

Additional details about the calculations and features of the REHEX model can be found in Winer et al. (1989), Lurmann et al. (1990), Lurmann and Colome (1991), Hall et al. (1992), and Lurmann and Korc (1994).

2.2. Time-activity sequence database generation

Time-activity sequences were generated to characterize the variability in peoples' time-activity patterns. Sequences were based on the time-use survey data of 2980 California residents conducted in 1987–1990 (Wiley et al., 1991). This survey used a 24-h, open-ended recall method. One hundred types of activities occurring in 50 locations were recorded. Supplemental survey information related to benzene exposure included the presence of an attached garage and parked cars, time spent in-transit, nontransit time spent in garages or around automobiles, gas station visits, number of cigarettes smoked, the presence of other persons' cigarette smoke, and estimates of residential open window time.

Survey data were directly transformed into time-activity sequences relevant to benzene exposure by assigning each 15-min, reported activity-location combination into one of 14 possible microenvironments (shown in Table 1). These were chosen to include all major microenvironments in which benzene concentrations from cigarette smoke, direct and indirect gasoline vapor sources, and ambient air had been measured or could be derived.

To simulate 1989 activity, time-activity sequences based on unaltered survey data were used. To simulate 1997 activity, adjustments to the sequences were made to account for the two-thirds reduction during this time period in ETS exposure at home and work, as documented in the California Tobacco Survey (Pierce et al., 1998). From 1990 to 1996, ETS exposure outside of work decreased from 29 to 13%, and workplace ETS exposure decreased from 29 to 12%. Also included in time-activity adjustments was the change in rate of active

Table 1
Characteristics of microenvironments employed in this study

Micro-environment number	Location	ETS?	Attached garage?	Windows	Concentration distribution used[a]	Geometric mean (ppb)[b]	Geometric standard deviation[b]
1	Outdoor	No	No	NA	AA	*	*
2	Home	No	No	Either	AA	*	*
3	Work	No	No	Either	AA	*	*
4	Home	No	Yes	Open	AA	*	*
5	Home	No	Yes	Closed	AA + GAR	1.0[c]	2.6[c]
6	Home	Yes	No	Open	AA	*	*
7	Home	Yes	No	Closed	ETS	22	3.2
8	Work	Yes	No	Closed	ETS	3.7	5.0
9	Home	Yes	Yes	Open	AA	*	*
10	Home	Yes	Yes	Closed	GAR + ETS	23	3.2
11 (1989)	Transit	No	No	Either	Transit	9.6	1.9
11 (1997)	Transit	No	No	Either	Transit	4.4	1.3
12	Any	No	No	NA	Gas vapor	9.8	2.2
13 (1989)	Bar/club	Yes	No	Closed	ETS	22	3.2
13 (1997)	Bar/club	No	No	Closed	AA	*	*
14	Any	Yes	No	Either	Smoking	240[d]	120[d]

[a]AA = ambient air, ETS = environmental tobacco smoke, GAR = garage.
[b]The asterisk indicates ambient measurements used.
[c]Added to ambient concentration.
[d]Normal distribution.

smoking, dropping from 22 to 18% over this time period, and the decrease in average daily cigarette consumption from 17 to 14 (Pierce et al., 1998).

2.3. Derivation of microenvironmental benzene concentration distributions

Seven benzene concentration distributions, alone or in combination, were used to characterize the benzene concentrations in the 14 microenvironments used by REHEX. Distributions composed of direct measurements included those for outdoor microenvironments, in-transit microenvironments (separate measurements for 1989 (Shikiya et al., 1989) and 1997 (Rodes et al., 1998)) and direct gasoline vapor exposures like refueling or work on vehicles. Derived distributions (involving ETS and/or attached garages, or active smoking) were assumed to be lognormal.

2.3.1. Outdoors

Outdoor microenvironmental concentrations were assumed to equal those measured at the nearest ambient air monitoring station. Ambient measurements of 24 h average benzene concentrations were taken every 12th day at eight stations in 1989 and at seven stations in 1997 (CARB, 1998a). Both the California Air Resources Board (CARB) and South Coast Air Quality Management District (SCAQMD) station measurements were used. For sites with missing data, concentrations were estimated based on the average value of neighboring stations found to have a spatial correlation of 0.80 or higher with the station in question for the given year (Gilbert, 1987). For 1997, this was needed for about 15% of the measurements.

2.3.2. Indoors with no sources

For indoor microenvironments with no distinct sources of benzene, such as microenvironments 2 and 3, it was assumed indoor concentrations matched those of the nearest ambient monitor due to the chemical stability of airborne benzene. Residential microenvironments during times of open windows were also assumed to equal outdoor ambient concentrations, due to much higher rates of air exchange when windows are open.

2.3.3. Attached garage effects

The estimated residential indoor benzene concentration frequency distribution resulting from attached garages was based on the measurements of Wilson et al. (1995) in which benzene concentrations in 300 California homes were measured from December 1991 to April 1992. On average, they found the net indoor concentration (indoor concentration minus outdoor) to be 0.2 ppb for an attached garage with no parked car, 1.1 ppb for one car, and 1.9 ppb for two cars, compared to 0.06 ppb for no attached garage. A median air exchange rate (AER) of $0.46\,h^{-1}$ was also measured during this study. AERs this low are typical of the closed-window conditions common in winter in California, and typical of average AERs throughout most of the US (Pandian et al., 1993).

To determine an appropriate lognormal distribution with an arithmetic mean of 1.5 ppb, (the 1.1 ppb average net indoor benzene concentration from one parked car divided by the average percentage time of closed windows for California homes in winter and early spring, 75%), the California Population Indoor Exposure Model (CPIEM) was used (Version 1.4F) (CARB, 1998c). For an average AER of $0.46\,h^{-1}$, and the home volume distribution measured in the TEAM studies for Los Angeles ($275 \pm 110\,m^3$), a source of $260\,\mu g\,h^{-1}$ benzene resulted in an arithmetic mean of 1.5 ppb, a geometric mean (GM) of 1.0 ppb, and a geometric standard deviation (GSD) of 2.6.

2.3.4. Environmental tobacco smoke (ETS)

The distribution to represent ETS as a source of benzene was based on differences between personal benzene exposure measurements of smokers, ETS-exposed nonsmokers, and nonexposed persons. In the February, 1984 TEAM studies carried out in Los Angeles, Wallace et al. (1987) measured daytime (6 a.m. to 6 p.m.) geometric mean differences of 1.3 ppb in benzene exposure between all ETS-exposed persons (including smokers but excluding inhaled smoke) and nonexposed persons. Hartwell et al. (1992) reported a geometric mean difference of 1.4 ppb between ETS-exposed and nonexposed nonsmokers, and a 2.3 ppb difference in geometric means between smokers (excluding inhaled smoke) and nonexposed nonsmokers, for the February, 1987 TEAM studies in Los Angeles. Differences were lower for the warmer months. For the May 1984 and July 1987 TEAM studies, the differences were only 0.3 ppb (Wallace et al., 1987). Based on these results, distributions were sought which resulted in an average winter ETS benzene exposure of about 1.6 ppb (the sample-number-weighted average TEAM winter difference) and an average summer ETS benzene exposure of about 0.3 ppb.

The fraction of time spent in the presence of cigarette smoke was calculated from the California time-activity survey data (Wiley et al., 1991; Jenkins et al., 1992). For persons exposed to ETS at home, 6% of the time spent at home was in the presence of ETS: 3.9% with closed windows and 2.1% with open windows.

Using these fractions of time exposed at home in the CPIEM model, an ETS benzene concentration distribution during times of reported exposure with a GM of 22 ppb and a GSD of 3.2 was found to result in a benzene exposure of 1.2 ppb during the winter season and 0.6 ppb during the summer season.

2.3.5. In-transit

The in-transit microenvironment was characterized by sampling directly from in-transit measurements taken in Los Angeles. Benzene concentrations for the in-transit microenvironment for 1989 were taken from the in-vehicle study conducted by the SCAQMD (Shikiya et al., 1989) for the SoCAB. Data were collected for 280 home-to-work commutes for summer (1987) and winter (1987–1988) for 140 drivers. The measured benzene concentrations had a GM of 9.6 ppb and GSD of 1.9, and were approximately lognormally distributed.

For the year 1997, benzene concentrations for the in-transit microenvironment came from a study performed by the Research Triangle Institute (Rodes et al., 1998) in Los Angeles and Sacramento. Los Angeles measurements were made for 16 2-h commutes in September and October, 1997, for 10 freeway and 6 arterial routes. Twelve of the 16 commutes were made during peak traffic hours. Concentrations were lognormally distributed, with a GM of 4.4 ppb and a GSD of 1.3.

2.3.6. Direct vapor

The distribution used for direct gasoline vapor exposure was taken from the study performed by Wilson et al. (1991), who measured benzene concentrations during refueling at breathing height (five feet) at 100 gas stations in the SoCAB in March of 1990. (All stations used vapor recovery controls.) The resulting distribution of benzene concentrations had a GM of 9.8 ppb and a GSD of 2.2.

2.3.7. Workplace ETS

Workplace benzene exposure due to ETS has not been well studied. Workplace distributions in this report were based on the study by Jenkins et al. (1996) who measured home and work ETS exposure for 1564 nonsmokers in 16 US cities. On average, personal air measurements of nicotine, solanesol, and scopoletine (all tobacco smoke indicators) were about 6–7 times higher in homes with smokers than at workplaces for ETS-exposed workers, on an equal time basis. Based on this ratio, ETS exposure was represented by a distribution with one-sixth the GM of the closed-window, home ETS distribution (3.7 ppb). Because the Jenkins et al. (1996) study found similar rates of ETS exposure at the higher concentrations, the workplace distribution spread was arbitrarily increased to a GSD of 5.0.

2.3.8. Active smoking

A normal distribution was used for active smoking, with a mean of 240 ppb and a standard deviation of 120 ppb. This was based on 7.5 min per cigarette, at a smoking rate of 10 l min^{-1}, and a benzene content of 57 μg per cigarette (Brunnemann et al., 1989).

3. Results and discussion

From 1989 to 1997, the calculated average benzene exposure for nonsmoking adults in the SoCAB dropped by 67%, from 6 to 2 ppb. Similar percentage decreases were found for all other demographic groups except smokers and adolescents (the adolescent group did not exclude smokers). While the *average* ambient concentration over this time period decreased by a similar percentage, 72% (from 3.8 to 1.0 ppb), the *ratio* of average exposure to average ambient concentration increased over this time period. In 1989, average nonsmoker exposures were about 60% higher than average ambient concentration, while in 1997 they were about 100% higher, illustrating the growing relative importance of indoor and in-transit sources of exposure as ambient benzene concentrations decrease.

The 67% reduction in average nonsmoker exposure also included significant reductions in ETS exposure. Without the reductions in ETS exposure from 1989 to 1997, the overall average exposure reduction for this time period would have been 57% for nonsmoking demographic groups.

Table 2 provides the average benzene exposure by demographic group for 1989 and 1997. Active smokers had by far the greatest benzene exposure and the smallest relative improvement over the 9-year time period. Adolescents had the second-highest average exposures, mainly due to the presence of smokers but also due to relatively high rates of ETS exposure. Men had higher exposures than women, and workers higher exposure than nonworking persons, but the differences in average exposure due to gender or work status decreased from 0.5 to 0.7 ppb in 1989 to only 0.1–0.2 ppb in 1997. Much of this decrease was due to tighter workplace restrictions on smoking which occurred over this time.

Fig. 2 provides the distributions of 24-h exposures for 1989 and 1997 for adult nonsmokers (other demographic groups show similar distributions and similar changes). From 1989 to 1997 there were not only significant decreases in average exposure, but also significant decreases in the spread of the exposure distribution, meaning relatively fewer very high exposures. For example, the number of 24-h exposures above 5 ppb decreased from 51% of the time for adult nonsmokers in 1989 to only 5% in 1997.

The contributions made by individual microenvironments also changed significantly from 1989 to 1997. Table 3 shows the contribution made by each microenvironment to average exposure for several demographic groups for 1989 and 1997. Ambient benzene concentrations dominated exposure for nonsmoking groups for both years, decreasing from about 60% of exposure for 1989 to about 50% in 1997.

ETS remained the second-most important source of exposure for nonsmokers, and even increased slightly in

Table 2
Average benzene exposure by demographic group, 1989 versus 1997

Demographic group	Average exposure 1989 (ppb)	Average exposure 1997 (ppb)	Percentage decrease
Adult smokers	28	20	28
Adolescents	7.1	3.2	55
Adult nonsmokers	6.0	2.0	67
NS men	6.2	2.0	68
NS women	5.5	1.9	66
NS working	6.3	2.1	67
NS nonworking	5.7	1.9	65
NS working men	6.4	2.1	67
NS working women	5.9	2.0	67
NS nonworking men	5.9	2.0	67
NS nonworking women	5.4	1.9	65

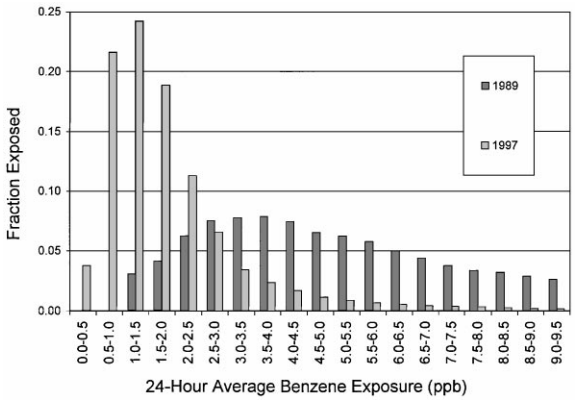

Fig. 2. Fraction of 24-h benzene exposures for adult nonsmokers, 1989 versus 1997.

relative importance, from 20 to 23% of average exposure, in spite of the large decrease in contribution in absolute terms from 1989 to 1997. This reflects the importance of continuing to reduce smoking rates while increasing restrictions on ETS exposure. For example, without the ETS decreases over this period, ETS would have contributed about 41% of overall nonsmoker exposure in 1997. Fig. 3 provides the results for 24-h benzene exposures for nonsmoking adults, both with and without this period's 60% decrease in ETS exposure. These data highlight the significance of ETS exposure reductions, especially at the higher exposure ranges.

The in-transit microenvironment continued to be an important source of benzene exposure, increasing from 15 to 16% of exposure for nonsmoking adults over the 1989–1997 time period (in spite of significantly decreased in-transit concentrations due to reduced benzene in fuels and lower vehicle emissions).

Work status and gender, in addition to age, are two of the most important variables associated with differences in how and where people spend their time (Wiley et al., 1991). Table 3 illustrates the importance of the in-transit and attached garage contributions to the effect of gender and workforce status on exposure, due to the large work-status and gender differences in commute time and time spent at home. The effect of attached garages was the only benzene source contribution that appeared to increase significantly between 1989 and 1997, but this may have been due to the unavailability of new (and presumable lower) microenvironmental concentrations for 1997. It is likely the decreased benzene content in reformulated gasoline has made the effect of attached garages on indoor benzene concentrations decrease as much as the decrease in benzene in the in-transit microenvironment, but this has yet to be quantified.

The only available studies measuring personal exposure to benzene in the SoCAB to date have been the TEAM studies of 1984 and 1987, of which the largest was the 1984 portion. Fig. 4 presents the modeled fraction of nonsmoker average exposures for 1989 versus the nonsmoker fraction of the 1984 TEAM personal monitoring results for the Los Angeles region (Wallace, 1987). The TEAM data distribution is in good agreement with our REHEX results, considering the small sample size of the TEAM data ($n = 79$).

To evaluate the relative importance of sources of uncertainty in the results of this study, sensitivity tests were conducted for the 1997 results. These tests included running the REHEX model with changes in either the GM or the GSD of each microenvironmental benzene concentration distribution, and with adjustments made to the assigning of population to different geographic areas (and therefore different ambient concentrations). In addition, the uncertainty in the CPIEM model-derived GSD estimates were tested by changing important CPIEM input variables such as AER and home volume. Overall, exposure results were by far most sensitive to changes in ambient distribution GM, ETS distribution GM, and

Table 3
Individual source percentage contributions to average benzene exposure for 1989 and 1997[a]

Source	NS adults (%)	NS W men (%)	NS W women (%)	NS NW men (%)	NS NW women (%)	Smokers (%)
1989						
Ambient air	59	54	62	58	68	12
ETS	20	24	18	22	15	6
In-transit	15	16	16	13	12	3
Residential w/ attached garage and parked vehicle	2.9	2.2	2.9	2.4	4.3	0.5
Direct gasoline vapor	1.3	1.4	1.2	0.9	1.5	0.8
Bars and nightclubs	2.0	3.6	0.5	3.6	0.4	0.8
Active smoking	0	0	0	0	0	78
1997						
Ambient air	48	46	49	51	52	4
ETS	23	25	20	27	21	8
In-transit	16	17	17	13	12	1
Residential w/ attached garage and parked vehicle	9.0	7.7	10	6.6	13	0.4
Direct gasoline vapor	4.0	4.8	4.1	2.6	3.7	0.7
Bars and nightclubs	0	0	0	0	0	0
Active smoking	0	0	0	0	0	85

[a]NS = nonsmoking, W = working, NW = nonworking.

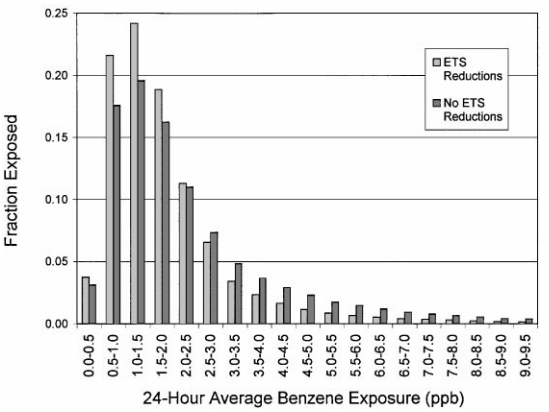

Fig. 3. Fraction of 24-h benzene exposures for adult nonsmokers with and without ETS exposure reductions, 1997.

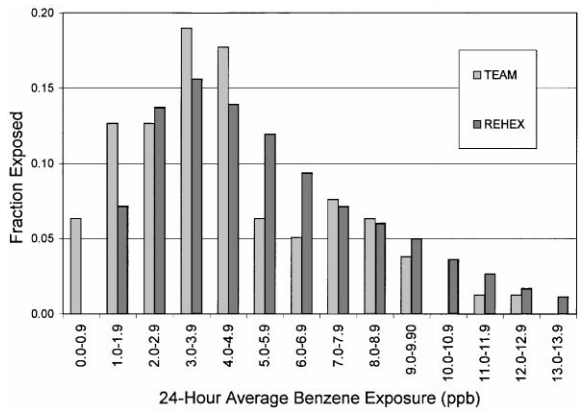

Fig. 4. Fraction of nonsmoker personal benzene exposures by interval, REHEX versus TEAM studies.

ETS distribution GSD (in order of importance). Spatial population allocations were found to have a relatively small effect on exposure results.

For 1997 ambient concentration measurements, relative uncertainty was estimated to be 30%, based on audit results and calibration studies (CARB, 2000). The uncertainty of the derived ETS distribution GM was also estimated to be about 30%, based on the range of average winter differences observed in the TEAM studies. The uncertainty of the derived ETS GSD was assumed to be much smaller than for the GM because CPIEM runs showed GSD to be rather insensitive to changes in home volume or AER while these changes strongly affected concentrations. The combined effect of relative changes of 30% to both the ambient concentration GM and the ETS concentration GM resulted in a mean exposure relative uncertainty of about 30% and upper tail uncertainties of about 50%. Most of the mean exposure uncertainty was from ambient concentration uncertainty, while most of the upper exposure tail uncertainty was due to ETS concentration uncertainty (due to the larger contributions of ETS at higher exposures).

Additional exposure uncertainty was probably created by using hourly ETS benzene concentration distributions

to represent the 15-min intervals used by the REHEX model, but this uncertainty could not be quantified. However, the ETS distribution GSD increased only 5–10% from 24-h average concentrations to 1-h concentrations, so this additional uncertainty probably does not change the overall estimates given.

4. Conclusions

Both average and peak benzene exposures for the 15 million residents of the SoCAB decreased significantly from 1989 to 1997. The majority of the decrease was attributable to reductions in ambient benzene concentrations, resulting primarily from reduced benzene content in gasoline and lower mobile source emissions. In addition, a significant portion of the overall reduction was due to decreases in exposure to tobacco smoke.

This study shows the importance of direct source reductions in limiting exposure to air toxics. Programs which have reduced benzene exposure such as gasoline vapor recovery systems, benzene content limits in gasoline, vehicle emissions standards reductions, and public smoking restrictions have proven that remarkable reductions in personal exposure to specific air toxics can be made in less than 10 years.

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