

Lung Cancer, Cardiopulmonary Mortality, and Long-term Exposure to Fine Particulate Air Pollution

C. Arden Pope III, PhD

Richard T. Burnett, PhD

Michael J. Thun, MD

Eugenia E. Calle, PhD

Daniel Krewski, PhD

Kazuhiko Ito, PhD

George D. Thurston, ScD

BASED ON SEVERAL SEVERE AIR pollution events,^{1,3} a temporal correlation between extremely high concentrations of particulate and sulfur oxide air pollution and acute increases in mortality was well established by the 1970s. Subsequently, epidemiological studies published between 1989 and 1996 reported health effects at unexpectedly low concentrations of particulate air pollution.⁴ The convergence of data from these studies, while controversial,⁵ prompted serious reconsideration of standards and health guidelines⁶⁻¹⁰ and led to a long-term research program designed to analyze health-related effects due to particulate pollution.¹¹⁻¹³ In 1997, the Environmental Protection Agency adopted new ambient air quality standards that would impose regulatory limits on fine particles measuring less than 2.5 μm in diameter ($\text{PM}_{2.5}$). These new standards were challenged by industry groups, blocked by a federal appeals court, but ultimately upheld by the US Supreme Court.¹⁴

Although most of the recent epidemiological research has focused on ef-

Context Associations have been found between day-to-day particulate air pollution and increased risk of various adverse health outcomes, including cardiopulmonary mortality. However, studies of health effects of long-term particulate air pollution have been less conclusive.

Objective To assess the relationship between long-term exposure to fine particulate air pollution and all-cause, lung cancer, and cardiopulmonary mortality.

Design, Setting, and Participants Vital status and cause of death data were collected by the American Cancer Society as part of the Cancer Prevention II study, an ongoing prospective mortality study, which enrolled approximately 1.2 million adults in 1982. Participants completed a questionnaire detailing individual risk factor data (age, sex, race, weight, height, smoking history, education, marital status, diet, alcohol consumption, and occupational exposures). The risk factor data for approximately 500 000 adults were linked with air pollution data for metropolitan areas throughout the United States and combined with vital status and cause of death data through December 31, 1998.

Main Outcome Measure All-cause, lung cancer, and cardiopulmonary mortality.

Results Fine particulate and sulfur oxide-related pollution were associated with all-cause, lung cancer, and cardiopulmonary mortality. Each 10- $\mu\text{g}/\text{m}^3$ elevation in fine particulate air pollution was associated with approximately a 4%, 6%, and 8% increased risk of all-cause, cardiopulmonary, and lung cancer mortality, respectively. Measures of coarse particle fraction and total suspended particles were not consistently associated with mortality.

Conclusion Long-term exposure to combustion-related fine particulate air pollution is an important environmental risk factor for cardiopulmonary and lung cancer mortality.

JAMA. 2002;287:1132-1141

www.jama.com

fects of short-term exposures, several studies suggest that long-term exposure may be more important in terms of overall public health.⁴ The new standards for long-term exposure to $\text{PM}_{2.5}$ were originally based primarily on 2 prospective cohort studies,^{15,16} which evaluated the effects of long-term pollution exposure on mortality. Both of these studies have been subjected to much scrutiny,⁵ including an extensive independent audit and reanalysis of the original data.¹⁷ The larger of these

2 studies linked individual risk factor and vital status data with national ambient air pollution data.¹⁶ Our analysis uses data from the larger study and

Author Affiliations: Brigham Young University, Provo, Utah (Dr Pope); Health Canada, Ottawa, Ontario (Dr Burnett); University of Ottawa, Ottawa, Ontario (Drs Burnett and Krewski); American Cancer Society, Atlanta, Ga (Drs Thun and Calle); and New York University School of Medicine, Tuxedo, NY (Drs Ito and Thurston).

Corresponding Author and Reprints: C. Arden Pope III, PhD, Department of Economics, Brigham Young University, 142 FOB, Provo, UT 84602 (e-mail: cap3@email.byu.edu).

(1) doubles the follow-up time to more than 16 years and triples the number of deaths; (2) substantially expands exposure data, including gaseous copollutant data and new PM_{2.5} data, which have been collected since the promulgation of the new air quality standards; (3) improves control of occupational exposures; (4) incorporates dietary variables that account for total fat consumption, and consumption of vegetables, citrus, and high-fiber grains; and (5) uses recent advances in statistical modeling, including the incorporation of random effects and nonparametric spatial smoothing components in the Cox proportional hazards model.

METHODS

Study Population

The analysis is based on data collected by the American Cancer Society (ACS) as part of the Cancer Prevention Study II (CPS-II), an ongoing prospective mortality study of approximately 1.2 million adults.^{18,19} Individual participants were enrolled by ACS volunteers in the fall of 1982. Participants resided in all 50 states, the District of Columbia, and Puerto Rico, and were generally friends, neighbors, or acquaintances of ACS volunteers. Enrollment was restricted to persons who were aged 30 years or older and who were members of households with at least 1 individual aged 45 years or older. Participants completed a confidential questionnaire, which included questions about age, sex, weight, height, smoking history, alcohol use, occupational exposures, diet, education, marital status, and other characteristics.

Vital status of study participants was ascertained by ACS volunteers in September of the following years: 1984, 1986, and 1988. Reported deaths were verified with death certificates. Subsequently, through December 31, 1998, vital status was ascertained through automated linkage of the CPS-II study population with the National Death Index.¹⁹ Ascertainment of deaths was more than 98% complete for the period of 1982-1988 and 93% complete after 1988.¹⁹ Death certificates or codes

for cause of death were obtained for more than 98% of all known deaths. Cause of death was coded according to the *International Classification of Diseases, Ninth Revision (ICD-9)*. Although the CPS-II cohort included approximately 1.2 million participants with adequate questionnaire and cause-of-death data, our analysis was restricted to those participants who resided in US metropolitan areas with available pollution data. The actual size of the analytic cohort varied depending on the number of metropolitan areas for which pollution data were available. TABLE 1 provides the number of metropolitan areas and participants available for each source of pollution data.

Air Pollution Exposure Estimates

Each participant was assigned a metropolitan area of residence based on address at time of enrollment and 3-digit ZIP code area.²⁰ Mean (SD) concentrations of air pollution for the metropolitan areas were compiled from various primary data sources (Table 1). Many of the particulate pollution indices, including PM_{2.5}, were available from data from the Inhalable Particle Monitoring Network for 1979-1983 and data from the National Aerometric Database for 1980-1981, periods just prior to or at the beginning of the follow-up period. An additional data source was the Environmental Protection Agency Aerometric Information Retrieval System (AIRS). The mean concentration of each pollutant from all available monitoring sites was calculated for each metropolitan area during the 1 to 2 years prior to enrollment.¹⁷

Additional information on ambient pollution during the follow-up period was extracted from the AIRS database as quarterly mean values for each routinely monitored pollutant for 1982 through 1998. All quarterly averages met summary criteria imposed by the Environmental Protection Agency and were based on observations made on at least 50% of the scheduled sampling days at each site. The quarterly mean values for all stations in each metro-

politan area were calculated across the study years using daily average values for each pollutant except ozone. For ozone, daily 1-hour maximums were used and were calculated for the full year and for the third quarter only (ie, July, August, September). While gaseous pollutants generally had recorded data throughout the entire follow-up period of interest, the particulate matter monitoring protocol changed in the late 1980s from total suspended particles to particles measuring less than 10 µm in diameter (PM₁₀), resulting in the majority of total suspended particle data being available in the early to mid-1980s and PM₁₀ data being mostly available in the early to mid-1990s.

As a consequence of the new PM_{2.5} standard, a large number of sites began collecting PM_{2.5} data in 1999. Daily PM_{2.5} data were extracted from the AIRS database for 1999 and the first 3 quarters of 2000. For each site, quarterly averages for each of the 2 years were computed. The 4 quarters were averaged when at least 1 of the 2 corresponding quarters for each year had at least 50% of the sixth-day samples and at least 45 total sampling days available. Measurements were averaged first by site and then by metropolitan area. Although no network of PM_{2.5} monitoring existed in the United States between the early 1980s and the late 1990s, the integrated average of PM_{2.5} concentrations during the period was estimated by averaging the PM_{2.5} concentration for early and later periods.

Mean sulfate concentrations for 1980-1981 were available for many cities based on data from the Inhalable Particle Monitoring Network and the National Aerometric Database. Recognizing that sulfate was artifactually overestimated due to glass fiber filters used at that time, season and region-specific adjustments were made.¹⁷ Since few states analyzed particulate samples for sulfates after the early 1980s, individual states were directly contacted for data regarding filter use. Ion chromatography was used to analyze PM₁₀ filters and this data could be obtained from metropolitan areas across the

MORTALITY AND LONG-TERM EXPOSURE TO AIR POLLUTION

United States. Filters were collected for a single reference year (1990) in the middle of the 1982-1998 study period. The use of quartz filters virtually eliminated the historical overestimation of sulfate. Mean sulfate concentrations for 1990 were estimated using sulfate from AIRS, data reported directly from individual states, and analysis of archived filters.

Statistical Analysis

The basic statistical approach used in this analysis is an extension of the standard Cox proportional hazards survival

model,²¹ which has been used for risk estimates of pollution-related mortality in previous longitudinal cohort studies.^{15,16} The standard Cox model implicitly assumes that observations are statistically independent after controlling for available risk factors, resulting in 2 concerns with regard to risk estimates of pollution-related mortality.²² First, if the assumption of statistical independence is not valid, the uncertainty in the risk estimates of pollution-related mortality may be overstated. Second, even after controlling for available risk factors, survival times of par-

ticipants living in communities closer together may be more similar than participants living in communities farther apart, which results in spatial autocorrelation. If this spatial autocorrelation is due to missing or systematically mismeasured risk factors that are spatially correlated with air pollution, then the risk estimates of pollution-related mortality may be biased due to inadequate control of these factors. Therefore, in this analysis, the Cox proportional hazards model was extended by incorporating a spatial random-effects component, which provided accurate es-

Table 1. Summary of Alternative Pollution Indices*

Pollutant (Years of Data Collection)	Units	Source of Data	Data Compilation Team†	No. of Metropolitan Areas	No. of Participants, In Thousands	Mean (SD)
PM _{2.5}	µg/m ³					
1979-1983		IPMN	HEI	61	359	21.1 (4.6)
1999-2000		AIRS	NYU	116	500	14.0 (3.0)
Average				51	319	17.7 (3.7)
PM ₁₀	µg/m ³					
1982-1998		AIRS	NYU	102	415	28.8 (5.9)
PM ₁₅	µg/m ³					
1979-1983		IPMN	HEI	63	359	40.3 (7.7)
PM _{15-2.5}	µg/m ³					
1979-1983		IPMN	HEI	63	359	19.2 (6.1)
Total suspended particles	µg/m ³					
1980-1981		NAD	HEI	156	590	68.0 (16.7)
1979-1983		IPMN	HEI	58	351	73.7 (14.3)
1982-1998		AIRS	NYU	150	573	56.7 (13.1)
Sulfate	µg/m ³					
1980-1981		IPMN and NAD, artifact adjusted	HEI	149	572	6.5 (2.8)
1990		Compilation and analysis of PM ₁₀ filters	NYU	53	269	6.2 (2.0)
Sulfur dioxide	ppb	AIRS				
1980			HEI	118	520	9.7 (4.9)
1982-1998			NYU	126	539	6.7 (3.0)
Nitrogen dioxide	ppb	AIRS				
1980			HEI	78	409	27.9 (9.2)
1982-1998			NYU	101	493	21.4 (7.1)
Carbon monoxide	ppm	AIRS				
1980			HEI	113	519	1.7 (0.7)
1982-1998			NYU	122	536	1.1 (0.4)
Ozone	ppb	AIRS				
1980			HEI	134	569	47.9 (11.0)
1982-1998			NYU	119	525	45.5 (7.3)
1982-1998‡			NYU	134	557	59.7 (12.8)

*PM_{2.5} indicates particles measuring less than 2.5 µm in diameter; PM₁₀, particles measuring less than 10 µm in diameter; PM₁₅, particles measuring less than 15 µm in diameter; PM_{15-2.5}, particles measuring between 2.5 and 15 µm in diameter; µg/m³, micrograms per cubic meter; ppb, parts per billion; ppm, parts per million; IPMN, Inhalable Particle Monitoring Network; AIRS, Aerometric Information Retrieval System [Environmental Protection Agency]; and NAD, National Aerometric Database.
 †HEI indicates data were compiled by the Health Effects Institute reanalysis team, which was previously published.¹⁷ NYU indicates data were compiled at the New York University School of Medicine, Nelson Institute of Environmental Medicine (K.I. and G.D.T.).
 ‡Daily 1-hour maximums were used. Values were calculated only for the third quarter (ie, July, August, September).

estimates of the uncertainty of effect estimates. The model also evaluated spatial autocorrelation and incorporated a nonparametric spatial smooth component (to account for unexplained spatial structure). A more detailed description of this modeling approach is provided elsewhere.²²

The baseline analysis in this study estimated adjusted relative risk (RR) ratios for mortality by using a Cox proportional hazards model with inclusion of a metropolitan-based random-effects component. Model fitting involved a 2-stage process. In the first stage, survival data were modeled using the standard Cox proportional hazards model, including individual level covariates and indicator variables for each metropolitan area (without pollution variables). Output from stage 1 provided estimates of the metropolitan-specific logarithm of the RRs of mortality (relative to an arbitrary reference community), which were adjusted for individual risk factors. The correlation between these values, which was induced by using the same reference community, was then removed.²³ In the second stage, the estimates of adjusted metropolitan-specific health responses were related to fine particulate air pollution using a linear random-effects regression model.²⁴ The time variable used in the models was survival time from the date of enrollment. Survival times of participants who did not die were censored at the end of the study period. To control for age, sex, and race, all of the models were stratified by 1-year age categories, sex, and race (white vs other), which allowed each category to have its own baseline hazard. Models were estimated for all-cause mortality and for 3 separate mortality categories: cardiopulmonary (ICD-9 401-440 and 460-519), lung cancer (ICD-9 162), and all others.

Models were estimated separately for each of the 3 fine particle variables, PM_{2.5} (1979-1983), PM_{2.5} (1999-2000), and PM_{2.5} (average). Individual level covariates were included in the models to adjust for various important individual risk factors. All of these

variables were classified as either indicator (ie, yes/no, binary, dummy) variables or continuous variables. Variables used to control for tobacco smoke, for example, included both indicator and continuous variables. The smoking indicator variables included: current cigarette smoker, former cigarette smoker, and a pipe or cigar smoker only (all vs never smoking) along with indicator variables for starting smoking before or after age 18 years. The continuous smoking variables included: current smoker's years of smoking squared, current smoker's cigarettes per day, current smoker's cigarettes per day squared, former smoker's years of smoking, former smoker's years of smoking squared, former smoker's cigarettes per day, former smoker's cigarettes per day squared, and the number of hours per day exposed to passive cigarette smoke.

To control for education, 2 indicator variables, which indicated completion of high school or education beyond high school, were included. Marital status variables included indicator variables for single and other vs married. Both body mass index (BMI) values and BMI values squared were included as continuous variables. Indicator variables for beer, liquor, and wine drinkers and nonresponders vs nondrinkers were included to adjust for alcohol consumption. Occupational exposure was controlled for using various indicator variables: regular occupational exposure to asbestos, chemicals/acids/solvents, coal or stone dusts, coal tar/pitch/asphalt, diesel engine exhaust, or formaldehyde, and additional indicator variables that indicated 9 different rankings of an occupational dirtiness index that has been developed and described elsewhere.^{17,25} Two diet indices that accounted for fat consumption and consumption of vegetables, citrus, and high-fiber grains were derived based on information given in the enrollment questionnaire.¹⁸ Quintile indicator variables for each of these diet indices were also included in the models.¹⁸

In addition to the baseline analysis, several additional sets of analysis were conducted. First, to more fully evaluate the shape of the concentration-response function, a robust locally weighted regression smoother²⁶ (within the generalized additive model framework²⁷) was used to estimate the relationship between particulate air pollution and mortality in the second stage of model fitting. Second, the sensitivity of the fine particle mortality risk estimates compared with alternative modeling approaches and assumptions was evaluated. Standard Cox proportional hazards models were fit to the data including particulate air pollution as a predictor of mortality and sequentially adding (in a controlled forward stepwise process) groups of variables to control for smoking, education, marital status, BMI, alcohol consumption, occupational exposures, and diet.

In addition, to evaluate the sensitivity of the estimated pollution effect while more aggressively controlling for spatial differences in mortality, a 2-dimensional term to account for spatial trends was added to the models and was estimated using a locally weighted regression smoother. The "span" parameter, which controls the complexity of the surface smooth, was set at 3 different settings to allow for increasingly aggressive fitting of the spatial structure. These included a default span of 50%, the span that resulted in the lowest unexplained variance in mortality rate between metropolitan areas, and the span that resulted in the strongest evidence (highest *P* value) to suggest no residual spatial structure. The risk estimates and SEs (and thus the confidence intervals) were estimated using generalized additive modeling²⁷ with S-Plus statistical software,²⁸ which provides unbiased effect estimates, but may underestimate SEs if there is significant spatial autocorrelation and significant correlations between air pollution and the smoothed surface of mortality. Therefore, evidence of spatial autocorrelation was carefully evaluated and tested using the Bartlett test.²⁹ The correlations of residual mortality

with distance between metropolitan areas were graphically examined.

Analyses were also conducted of effect modification by age, sex, smoking status, occupational exposure, and education. Finally, models were fit using a variety of alternative pollution indices, including gaseous pollutants. Specifically, models were estimated separately for each of the pollution variables listed in Table 1, while also including all of the other risk factor variables.

RESULTS

Fine particulate air pollution generally declined in the United States during the follow-up period of this study. FIGURE 1 plots mean PM_{2.5} concentrations for 1999-2000 over mean PM_{2.5} concentrations for 1979-1983 for the

51 cities in which paired data were available. The concentrations of PM_{2.5} were lower in 1999-2000 than in 1979-1983 for most cities, with the largest reduction observed in the cities with the highest concentrations of pollution during 1979-1983. Mean PM_{2.5} levels in the 2 periods were highly correlated ($r=0.78$). The rank ordering of cities by relative pollution levels remained nearly the same. Therefore, the relative levels of fine particle concentrations were similar whether based on measurements at the beginning of the study period, shortly following the study period, or an average of the 2.

As reported in TABLE 2, all 3 indices of fine particulate air pollution were associated with all-cause, cardiopulmonary, and lung cancer mortality, but not mortality from all other causes combined. FIGURE 2 presents the nonparametric smoothed exposure response relationships between cause-specific mortality and PM_{2.5} (average). The log RRs for all-cause, cardiopulmonary, and lung cancer mortality increased across the gradient of fine particulate matter. Goodness-of-fit tests indicated that the associations were not significantly different from linear associations ($P>.20$).

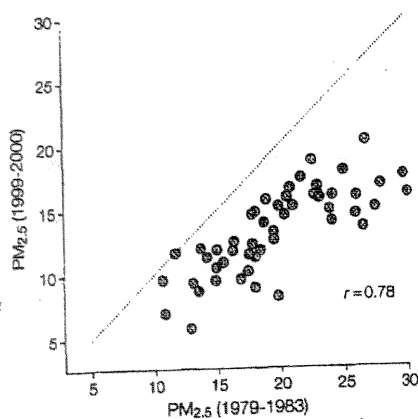
The fine particle mortality RR ratios from various alternative modeling approaches and assumptions are presented in FIGURE 3. After controlling for smoking, education, and marital status, the controlled forward stepwise inclusion of additional covariates had little influence on the estimated associations with fine particulate air pollution on cardiopulmonary and lung cancer mortality. As expected, cigarette smoking was highly significantly associated with el-

evated risk of all-cause, cardiopulmonary, and lung cancer mortality ($P<.001$). Estimated RRs for an average current smoker (men and women combined, 22 cigarettes/day for 33.5 years, with initiation before age 18 years) were equal to 2.58, 2.89, and 14.80 for all-cause, cardiopulmonary, and lung cancer mortality, respectively. Statistically significant, but substantially smaller and less robust associations, were also observed for education, marital status, BMI, alcohol consumption, occupational exposure, and diet variables. Although many of these covariates were also statistically associated with mortality, the risk estimates of pollution-related mortality were not highly sensitive to the inclusion of these additional covariates.

Figure 3 also demonstrates that the introduction of the random-effects component to the model resulted in larger SEs of the estimates and, therefore, somewhat wider 95% confidence intervals. There was no evidence of statistically significant spatial autocorrelation in the survival data based on the Bartlett test ($P>.20$) after controlling for fine particulate air pollution and the various individual risk factors. Furthermore, graphical examination of the correlations of the residual mortality with distance between metropolitan areas did not reveal significant spatial autocorrelation (results not shown). Nevertheless, the incorporation of spatial smoothing was included to further investigate the robustness of the estimated particulate pollution effect. Effect estimates were not highly sensitive to the incorporation of spatial smoothing to account for regional clustering or other spatial patterns in the data.

FIGURE 4 presents fine particle air pollution-related mortality RR ratios after stratifying by age, sex, education, and smoking status, and adjusting for all other risk factors. The differences across age and sex strata were not generally consistent or statistically significant. However, a consistent pattern emerged from this stratified analysis: the association with particulate pollution was stronger for both cardiopulmo-

Figure 1. Mean Fine Particles Measuring Less Than 2.5 μm in Diameter (PM_{2.5})



Mean PM_{2.5} concentrations in micrograms per meters cubed for 1999-2000 are plotted along with concentrations for 1979-1983 for the 51 metropolitan areas with paired pollution data. The dotted line is a reference 45°-equality line.

Table 2. Adjusted Mortality Relative Risk (RR) Associated With a 10- $\mu\text{g}/\text{m}^3$ Change in Fine Particles Measuring Less Than 2.5 μm in Diameter

Cause of Mortality	Adjusted RR (95% CI)*		
	1979-1983	1999-2000	Average
All-cause	1.04 (1.01-1.08)	1.06 (1.02-1.10)	1.06 (1.02-1.11)
Cardiopulmonary	1.06 (1.02-1.10)	1.08 (1.02-1.14)	1.09 (1.03-1.16)
Lung cancer	1.08 (1.01-1.16)	1.13 (1.04-1.22)	1.14 (1.04-1.23)
All other cause	1.01 (0.97-1.05)	1.01 (0.97-1.06)	1.01 (0.95-1.06)

*Estimated and adjusted based on the baseline random-effects Cox proportional hazards model, controlling for age, sex, race, smoking, education, marital status, body mass, alcohol consumption, occupational exposure, and diet. CI indicates confidence interval.

nary and lung cancer mortality for participants with less education. Also, for both cardiopulmonary and lung cancer mortality, the RR estimates were higher for nonsmokers.

FIGURE 5 summarizes the associations between mortality risk and air pollutant concentrations listed in Table 1. Statistically significant and relatively consistent mortality associations existed for all measures of fine particulate exposure, including $PM_{2.5}$ and sulfate particles. Weaker less consistent mortality associations were observed with PM_{10} and PM_{15} . Measures of the coarse particle fraction ($PM_{15-2.5}$) and total suspended particles were not consistently associated with mortality. Of the gaseous pollutants, only sulfur dioxide was associated with elevated mortality risk. Interestingly, measures of $PM_{2.5}$ were associated with all-cause cardiopulmonary, and lung cancer mortality, but not with all other mortality. However, sulfur oxide pollution (as measured by sulfate particles and/or sulfur dioxide) was significantly associated with mortality from all other causes in addition to all-cause, cardiopulmonary, and lung cancer mortality.

COMMENT

This study demonstrated associations between ambient fine particulate air pollution and elevated risks of both cardiopulmonary and lung cancer mortality. Each $10\text{-}\mu\text{g}/\text{m}^3$ elevation in long-term average $PM_{2.5}$ ambient concentrations was associated with approximately a 4%, 6%, and 8% increased risk of all-cause, cardiopulmonary, and lung cancer mortality, respectively, although the magnitude of the effect somewhat depended on the time frame of pollution monitoring. In addition, this analysis addresses many of the important questions concerning the earlier, more limited analysis of the large CPS-II cohort, including the following issues.

First, does the apparent association between pollution and mortality persist with longer follow-up and as the cohort ages and dies? The present analysis more than doubled the follow-up time to more than 16 years, resulting

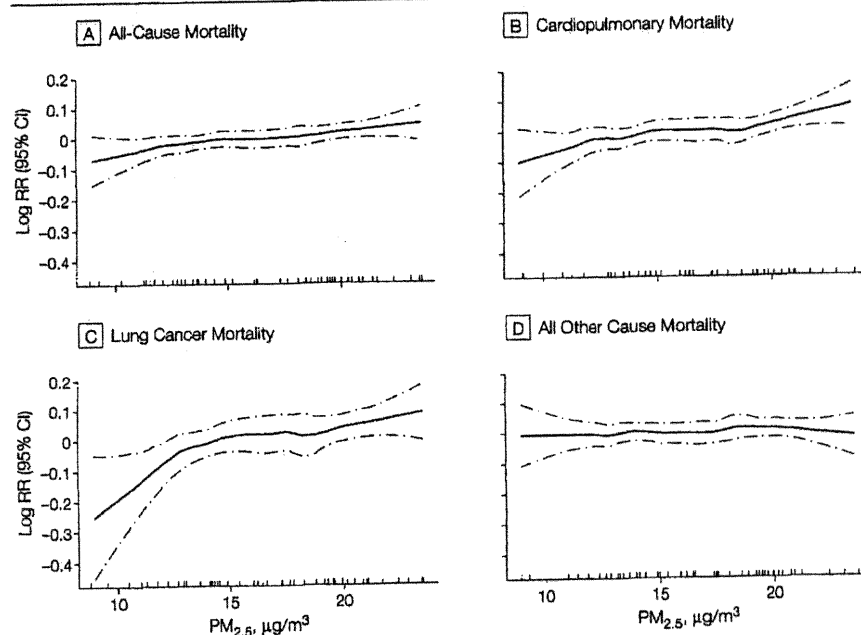
in approximately triple the number of deaths, yet the associations between pollution and mortality persisted.

Second, can the association between fine particulate air pollution and increased cardiopulmonary and lung cancer mortality be due to inadequate control of important individual risk factors? After aggressively controlling for smoking, the estimated fine particulate pollution effect on mortality was remarkably robust. When the analysis was stratified by smoking status, the estimated pollution effect on both cardiopulmonary and lung cancer mortality was strongest for never smokers vs former or current smokers. This analysis also controlled for education, marital status, BMI, and alcohol consumption. This analysis used improved variables to control for occupational exposures and incorporated diet variables that accounted for total fat consumption, as well as for consumption of vegetables, citrus, and high-fiber grains. The mortality associations with fine particulate air pollution were largely unaffected by the inclusion of these indi-

vidual risk factors in the models. The data on smoking and other individual risk factors, however, were obtained directly by questionnaire at time of enrollment and do not reflect changes that may have occurred following enrollment. The lack of risk factor follow-up data results in some misclassification of exposure, reduces the precision of control for risk factors, and constrains our ability to differentiate time dependency.

Third, are the associations between fine particulate air pollution and mortality due to regional or other spatial differences that are not adequately controlled for in the analysis? If there are unmeasured or inadequately modeled risk factors that are different across locations, then spatial clustering will occur. If this clustering is independent or random across metropolitan areas, then the spatial clustering can be modeled by adding a random-effects component to the Cox proportional hazards model as was done in our analysis. The clustering may not be independent or random across metropolitan areas due to inadequately measured or modeled

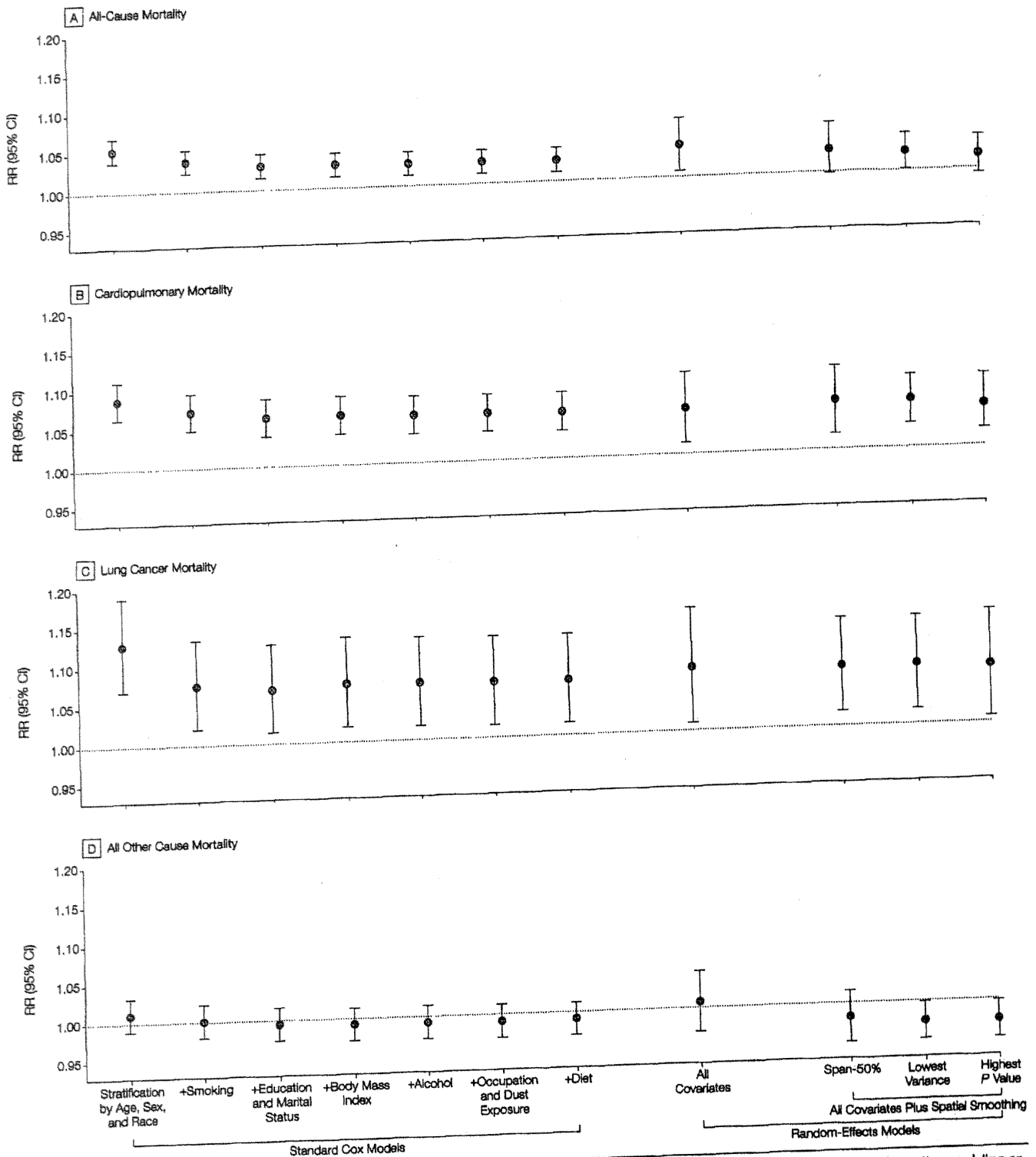
Figure 2. Nonparametric Smoothed Exposure Response Relationship



Vertical lines along x-axes indicate rug or frequency plot of mean fine particulate pollution; $PM_{2.5}$, mean fine particles measuring less than $2.5\text{ }\mu\text{m}$ in diameter; RR, relative risk; and CI, confidence interval.

MORTALITY AND LONG-TERM EXPOSURE TO AIR POLLUTION

Figure 3. Mortality Relative Risk (RR) Ratio Associated With 10- $\mu\text{g}/\text{m}^3$ Differences of $\text{PM}_{2.5}$ Concentrations



Data presented are for 1979-1983 for the different causes of death, with various levels of controlling for individual risk factors, and using alternative modeling approaches. The 3 models with spatial smoothing allow for increasingly aggressive fitting of the spatial structure. Plus sign indicates model included previous variables (ie, smoking included stratification by age, sex, and race); $\text{PM}_{2.5}$, mean fine particles measuring less than 2.5 μm in diameter; and CI, confidence interval.

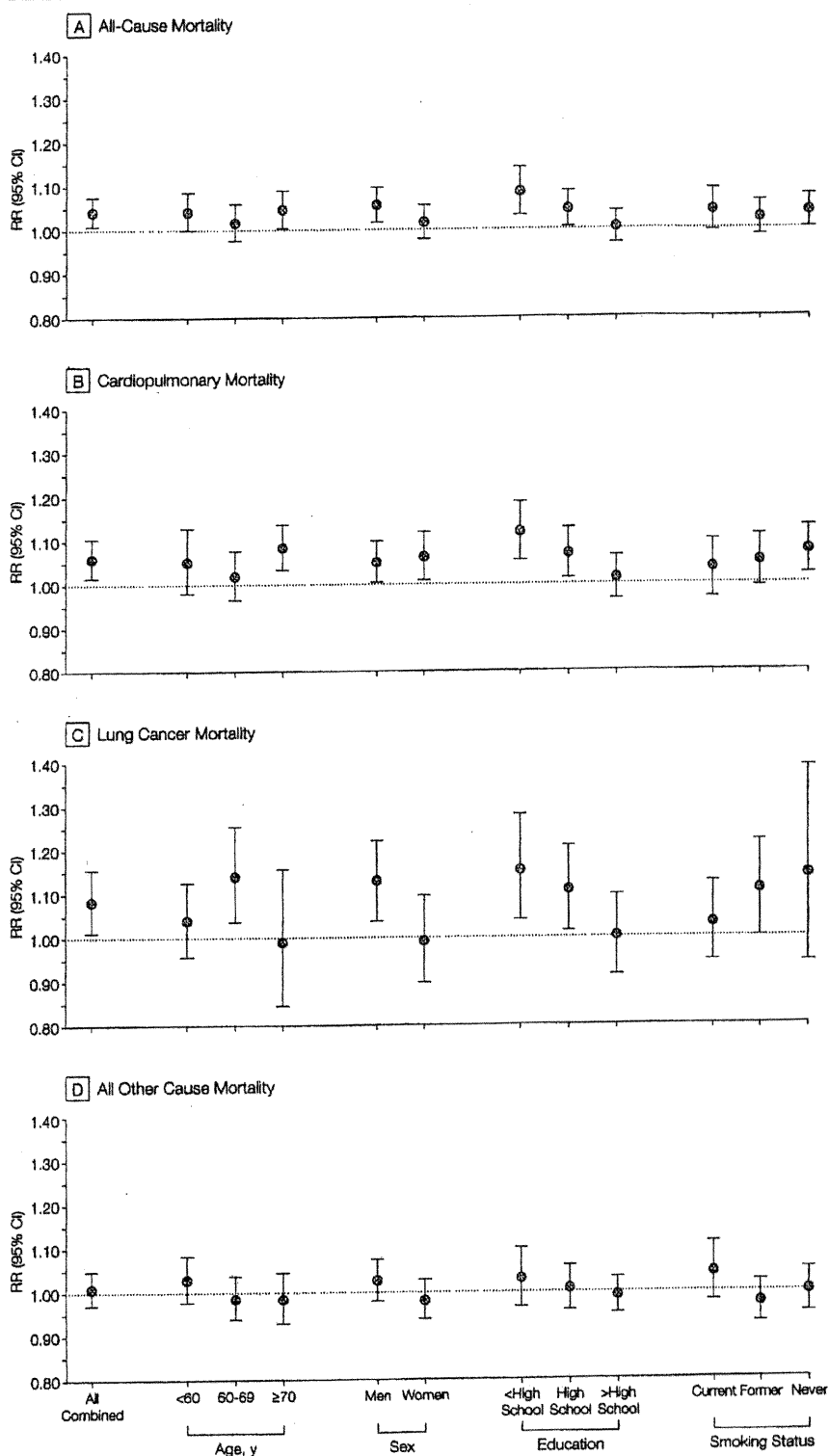
risk factors (either individual or ecological). If these inadequately measured or modeled risk factors are also spatially correlated with air pollution, then biased pollution effects estimates may occur due to confounding. However, in this analysis, significant spatial autocorrelation was not observed after controlling for fine particulate air pollution and the various individual risk factors. Furthermore, to minimize any potential confounding bias, sensitivity analyses, which directly modeled spatial trends using nonparametric smoothing techniques, were conducted. A contribution of this analysis is that it included the incorporation of both random effects and nonparametric spatial smoothing components to the Cox proportional hazards model. Even after accounting for random effects across metropolitan areas and aggressively modeling a spatial structure that accounts for regional differences, the association between fine particulate air pollution and cardiopulmonary and lung cancer mortality persists.

Fourth, is mortality associated primarily with fine particulate air pollution or is mortality also associated with other measures of particulate air pollution, such as PM_{10} , total suspended particles, or with various gaseous pollutants? Elevated mortality risks were associated primarily with measures of fine particulate and sulfur oxide pollution. Coarse particles and gaseous pollutants, except for sulfur dioxide, were generally not significantly associated with elevated mortality risk.

Fifth, what is the shape of the concentration-response function? Within the range of pollution observed in this analysis, the concentration-response function appears to be monotonic and nearly linear. However, this does not preclude a leveling off (or even steepening) at much higher levels of air pollution.

Sixth, how large is the estimated mortality effect of exposure to fine particulate air pollution relative to other risk factors? A detailed description and interpretation of the many individual risk factors that are controlled for in the analysis goes well beyond the scope of

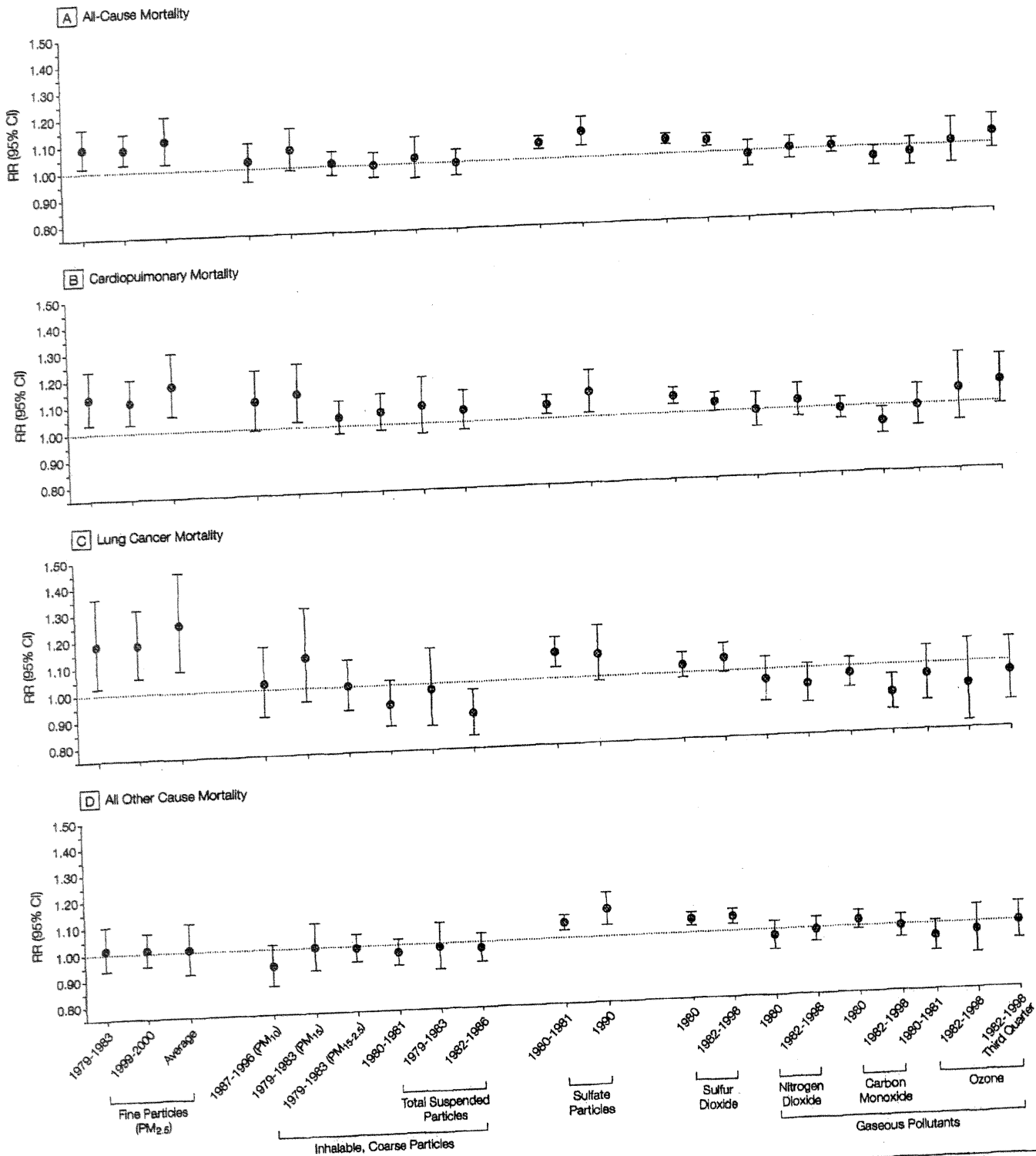
Figure 4. Adjusted Mortality Relative Risk (RR) Ratio Associated With $10\text{-}\mu\text{g}/\text{m}^3$ Differences of $PM_{2.5}$ Concentrations



Data presented are for 1979-1983 for the different causes of death stratified by age, sex, education, and smoking status. $PM_{2.5}$ indicates mean fine particles measuring less than $2.5\ \mu\text{m}$ in diameter; CI, confidence interval.

MORTALITY AND LONG-TERM EXPOSURE TO AIR POLLUTION

Figure 5. Adjusted Mortality Relative Risk (RR) Ratio Evaluated at Subject-Weighted Mean Concentrations



PM_{2.5} indicates particles measuring less than 2.5 μm in diameter; PM₁₀, particles measuring less than 10 μm in diameter; PM₁₅, particles measuring less than 15 μm in diameter; PM_{15-2.5}, particles measuring between 2.5 and 15 μm in diameter; and CI, confidence interval.

this report. However, the mortality risk associated with cigarette smoking has been well documented using the CPS-II cohort.¹⁶ The risk imposed by exposure to fine particulate air pollution is obviously much smaller than the risk of cigarette smoking. Another risk factor that has been well documented using the CPS-II cohort data is body mass as measured by BMI.³⁰ The World Health Organization has categorized BMI values between 18.5-24.9 kg/m² as normal; 25-29.9 kg/m², grade 1 overweight; 30-39.9 kg/m², grade 2 overweight; and 40 kg/m² or higher, grade 3 overweight.³¹ In the present analysis, BMI values and BMI values squared were included in the proportional hazards models. Consistent with previous ACS analysis,³⁰ BMI was significantly associated with mortality, optimal BMI was between approximately 23.5 and 24.9 kg/m², and the RR of mortality for different BMI values relative to the optimal were dependent on sex and smoking status. For example, the RRs associated with BMI values between 30.0 and 31.9 kg/m² (vs optimal) would be up to approxi-

mately 1.33 for never smokers. Based on these calculations, mortality risks associated with fine particulate air pollution at levels found in more polluted US metropolitan areas are less than those associated with substantial obesity (grade 3 overweight), but comparable with the estimated effect of being moderately overweight (grade 1 to 2).

In conclusion, the findings of this study provide the strongest evidence to date that long-term exposure to fine particulate air pollution common to many metropolitan areas is an important risk factor for cardiopulmonary mortality. In addition, the large cohort and extended follow-up have provided an unprecedented opportunity to evaluate associations between air pollution and lung cancer mortality. Elevated fine particulate air pollution exposures were associated with significant increases in lung cancer mortality. Although potential effects of other unaccounted for factors cannot be excluded with certainty, the associations between fine particulate air pollution and lung cancer mortality, as well as cardiopulmonary mortality, are

observed even after controlling for cigarette smoking, BMI, diet, occupational exposure, other individual risk factors, and after controlling for regional and other spatial differences.

Author Contributions: Study concept and design: Pope, Burnett, Krewski, Thurston.

Acquisition of data: Thun, Calle, Krewski, Ito, Thurston.

Analysis and interpretation of data: Pope, Burnett, Krewski, Thurston.

Drafting of the manuscript: Pope, Burnett, Ito, Thurston.

Critical revision of the manuscript for important intellectual content: Pope, Thun, Calle, Krewski, Thurston.

Statistical expertise: Pope, Burnett, Krewski.

Obtained funding: Pope, Thun, Thurston.

Administrative, technical, or material support: Pope, Calle, Krewski, Ito, Thurston.

Study supervision: Pope, Krewski.

Funding/Support: The research for this article was supported largely by grant ES09560-D1A1 from the National Institutes of Health/National Institute of Environmental Health Sciences (NIEHS). It was also supported in part by grant ES00260 from the New York University Center/NIEHS, grant R-827351 from the Environmental Protection Agency PM Health Effects Research Center, and funding from the R. Samuel McLaughlin Centre for Population Health Risk Assessment at the University of Ottawa.

Acknowledgment: We thank Morton Lippmann, PhD, for his help in developing the research grant application and various comments and suggestions and Yuanli Shi, MD, for computer programming and statistical analysis support.

REFERENCES

1. Firket J. The cause of the symptoms found in the Meuse Valley during the fog of December, 1930. *Bull Acad R Med Belgium*. 1931;11:683-741.
2. Ciocco A, Thompson DJ. A follow-up of Donora ten years after: methodology and findings. *Am J Public Health*. 1961;51:155-164.
3. Logan WPD, Glasg MD. Mortality in London fog incident, 1952. *Lancet*. 1953;1:336-338.
4. Pope CA III, Dockery DW. Epidemiology of particle effects. In: Holgate ST, Koren H, Maynard R, Samet J, eds. *Air Pollution and Health*. London, England: Academic Press; 1999:673-705.
5. Kaiser J. Showdown over clean air science. *Science*. 1997;277:466-469.
6. World Health Organization-European Region. *Update and Revision of the Air Quality Guidelines for Europe*. Copenhagen, Denmark: World Health Organization-European Region; 1995. Document EUR/ICP/EHAZ 9405/P801.
7. CEPA/FPAC Working Group on Air Quality Objectives and Guidelines. *National Ambient Air Quality Objectives for Particulate Matter*. Ottawa, Ontario: Public Works and Government Services; 1998. Category No. H46-2/98-220.
8. Committee of the Environmental and Occupational Health Assembly of the American Thoracic Society. Health effects of outdoor air pollution. *Am J Respir Crit Care Med*. 1996;153:3-50.
9. Committee on the Medical Effects of Air Pollution. *Non-Biological Particles and Health*. London, England: United Kingdom Dept of Health; 1995.
10. Environmental Protection Agency. *Air Quality Criteria for Particulate Matter*. Washington, DC: Environmental Protection Agency; 1996. Document EPA/600/P-95/001cf.
11. Samet JM, Dominici F, Curriero FC, Coursac I, Zeger SL. Fine particulate air pollution and mortality in 20 US cities. *N Engl J Med*. 2000;343:1742-1749.
12. National Research Council. *Research Priorities for Airborne Particulate Matter, I: Immediate Priorities and a Long-Range Research Portfolio*. Washington, DC: National Academy Press; 1998.
13. National Research Council. *Research Priorities for Airborne Particulate Matter, III: Early Research Progress*. Washington, DC: National Academy Press; 2001.
14. *Whitman v American Trucking Associations Inc*, 532 US 457 (2001).
15. Dockery DW, Pope CA III, Xu X, et al. An association between air pollution and mortality in six US cities. *N Engl J Med*. 1993;329:1753-1759.
16. Pope CA III, Thun MJ, Namboodiri MM, et al. Particulate air pollution as a predictor of mortality in a prospective study of US adults. *Am J Respir Crit Care Med*. 1995;151:669-674.
17. Krewski D, Burnett RT, Goldberg MS, et al. *Reanalysis of the Harvard Six Cities Study and the American Cancer Society Study of Particulate Air Pollution and Mortality: Special Report*. Cambridge, Mass: Health Effects Institute; 2000.
18. Chao A, Thun MJ, Jacobs E, Henley SJ, Rodriguez C, Calle EE. Cigarette smoking and colorectal cancer mortality in the Cancer Prevention Study II. *J Natl Cancer Inst*. 2000;92:1888-1896.
19. Calle EE, Terrell DD. Utility of the National Death Index for ascertainment of mortality among Cancer Prevention Study II participants. *Am J Epidemiol*. 1993;137:235-241.
20. US Postal Service. *1989 National Five Digit Zip Code and Post Office Directory*. Washington, DC: National Information Data Center; 1989.
21. Fleming TR, Harrington DP. *Counting Processes and Survival Analysis*. New York, NY: John Wiley & Sons; 1991.
22. Burnett R, Ma R, Jerrett M, et al. The spatial association between community air pollution and mortality: a new method of analyzing correlated geographic cohort data. *Environ Health Perspect*. 2001;109(suppl 3):375-380.
23. Easton DF, Peto J, Babiker GAG. Floating absolute risk: an alternative to relative risk in survival and case-control analysis avoiding an arbitrary reference group. *Stat Med*. 1991;10:1025-1035.
24. Burnett RT, Ross WH, Krewski D. Non-linear mixed regression models. *Environmetrics*. 1995;6:85-99.
25. Siemiatycki J, Nadon L, Lakhani R, Beegin D, Geerin M. Exposure assessment. In: Siemiatycki J, ed. *Risk Factors for Cancer in the Workplace*. Baton Rouge, La: CRC Press; 1991:45-114.
26. Cleveland WS, Devlin SJ. Robust locally weighted regression and smoothing scatterplots. *J Am Stat Assoc*. 1988;74:829-836.
27. Hastie T, Tibshirani R. *Generalized Additive Models*. London, England: Chapman & Hall; 1990.
28. *S-Plus 2000 Programmer's Guide*. Seattle, Wash: Math Soft; 2000.
29. Priestly MB. *Spectral Analysis and Time Series*. London, England: Academic Press; 1981.
30. Calle EE, Thun MJ, Petrelli JM, Rodriguez C, Heath CW Jr. Body-mass index and mortality in a prospective cohort of US adults. *N Engl J Med*. 1999;341:1097-1105.
31. Physical status: the use and interpretation of anthropometry: report of a WHO expert committee. *WHO Tech Rep Ser*. 1995;854:1-452.

AIR QUALITY AND ETHANOL IN GASOLINE

By

Gary Z. Whitten, Ph.D.
Smog Reyes

Ethanol in gasoline can favorably impact mobile source emissions in five main air quality areas: these areas are fine particulate matter (e.g., PM_{2.5}), carbon monoxide, toxics, ozone, and global warming. In this era of credit trading and with new data there is always a lot to do to integrate these air quality areas with respect to ethanol. For example, ethanol currently is the only compound that can be blended with gasoline to help reduce global warming; yet there is no program in place to offer any credit in this area. Below a brief overview the current situation in the other four air quality areas impacted by ethanol.

PM_{2.5}

Fine particulates can be emitted directly from vehicles (primary PM_{2.5}) or formed in the atmosphere (secondary PM_{2.5}). Ethanol can help on both fronts. Oxygen in the fuel has been shown to reduce primary exhaust particulate from cars (Mulawa et al., 1997, and Colorado, 1999) while raising aromatics has been found to increase PM (Graskow et al., 1998). The Colorado study suggests that with 3.5 percent oxygen, the PM reduction at 35F is 36 percent for the normal fleet and 64.6 percent for the high emitters studied. If the PM inventory is 50 percent from high emitters, the reduction in PM for 3.5 percent oxygen is estimated to be 50.3 percent. Since both ethanol and aromatics add octane, it can be expected that using ethanol in place of aromatics for octane would reduce primary PM_{2.5} emissions even more than had been seen in the Colorado (1999) study. Mulawa et al. (1997) also showed that PM reductions were observed from -20F to 75F and an analysis of all available data suggests the oxygen effect is proportional to the PM emission and independent of temperature.

The formation of secondary PM_{2.5} is a very complicated process currently being studied by several scientists. One notable result published by Odum et al (1997) from Caltech showed that the organic fraction of secondary PM_{2.5}, attributable to gasoline in the atmosphere could be completely accounted for by the aromatics content of the gasoline. In fact, the EPA's REMSAD model for particulates and the Caltech secondary organic aerosol model (see Griffin et al, 1999) now assume that all anthropogenic PM comes solely from aromatic compounds. Hence, the use of ethanol in place of aromatics can be expected to reduce secondary PM_{2.5} as well.

CO

Many studies have shown that the oxygen in ethanol leads to a significant reduction in mobile carbon monoxide (CO) emissions. The OSTP (1997) study notes that vehicle CO emissions are reduced from 2 to 10 percent per percent oxygen in the fuel. Moreover, emissions inventories of CO consistently show that the mobile contribution, especially in troublesome urban areas, is often as high as 90 percent. A statistical analysis of ambient CO concentrations in areas using oxyfuels indicates that these fuels appear to reduce local CO by an average of 14 percent nationally (See Whitten and Cohen, 1996).

Carbon monoxide is a major ozone precursor (National Academy, 1999). New studies (Carter et al., 2003, and Whitten, 1999 and 2001) have shown that CO can be equivalent to 25 to 50 percent of the mobile-related contribution from volatile organic compounds (VOC). A significant reduction in CO emissions is provided by the high oxygen content of ethanol. The California reformulated gasoline program does give some credit for VOC reduction due to CO from high oxygen ethanol. However, the California regulations have yet to account for new studies on CO high ozone-forming potential (e.g. Carter et al., 2003) and data that show substantial CO reduction from ethanol in new cars (Alliance, 2001). Likewise, with the partial exception of the Chicago-Milwaukee area, the federal EPA has not given any credit to ethanol as shown by these new studies. Moreover, the EPA has yet to recognize the data on new cars for its MOBILE6 emissions model.

Other studies also show that the formation of combustion chamber deposits (CCD) are strongly associated with high-boiling aromatic compounds in gasoline (See Choate and Edwards, 1993, and Price et al, 1995). Bitting et al, 1994, showed by cleaning the CCD's that emissions (of CO, hydrocarbons and NOx) seen to increase with mileage were mainly associated with CCD buildup. Ethanol should be effective in reducing CCD's when substituted for aromatics, but data is needed to show this.

Some interesting points to the oxyfuel issue are first that the impact of oxyfuels appears to be the greatest on the higher-emitting vehicles (See Mayotte et al, 1994), which can account for more than half the overall gasoline-related emissions. Pokharel et al (2001) found that 10 percent of the automobiles in the Los Angeles accounted for 73 percent of the on-road CO emissions. Second, the effect of fuel oxygen may often be more on improving catalyst efficiency (See Reuter et al, 1992) rather than just enleanment of the mixture as some have postulated. The Reuter et al. (1992) study showed that engine-out CO emissions were not significantly affected by fuel oxygen, but the tailpipe (i.e. after the catalyst) emissions were very much reduced. Assuming that ethanol improves catalyst performance is more consistent with not only the engine out versus tailpipe data, but the latest data as well (Alliance et al, 2001) that shows new cars still reducing CO in spite of having "improved" mixture control that would be expected to eliminate any enleanment from using ethanol.

Toxics

Benzene appears to be the most significant toxic compound emitted from vehicles. The EPA Complex Model indicates that benzene emissions account for nearly 70 percent of the total toxic emissions from vehicles using conventional gasoline and that exhaust benzene accounts for nearly 90 percent of the total benzene. The EPA Complex Model indicates that a 10 percent ethanol blend can reduce benzene by 25 percent compared to conventional gasoline.

In addition to a 25 percent benzene reduction, the use of 10 percent ethanol is shown by the EPA Complex Model to reduce total toxic mass emissions by 13 percent. However, the California Air Resources Board recommends that toxic mass emissions be adjusted to account for the individual potency of the toxic compounds involved. When the California potency factors are applied to the EPA Complex Model results for splash blending 10 percent ethanol into conventional gasoline the total toxics risk is predicted to be reduced by 21 percent instead of the mass-only 13 percent reduction noted above.

There are three reasons that combine to explain why adding only 10 percent ethanol to gasoline might reduce toxic benzene emissions by 25 percent or more. First, of course, there is the dilution that occurs when ethanol is added. Second, the high octane value of ethanol allows the oil refineries to scale back on all aromatics to keep octane within the same grade of gasoline. The Caldecott tunnel study by Kirchstetter et al (1996) showed quite clearly that essentially all aromatics were, in fact, scaled back by at least 20 percent when an oxyfuel program in California went into place using only 2 percent oxygen by weight. Neither benzene itself nor aromatics in general were regulated as part of the California winter oxyfuel program in 1994. Benzene is an intermediate combustion product of other aromatics. That is, reducing aromatics alone will reduce a large fraction of the benzene exhaust emissions. And as noted below, exhaust benzene typically makes up about 90 percent of total benzene emissions (even during the summer months). The third, reason why benzene can be reduced from using ethanol is the oxygen that helps reduce all organic emissions. In summary, the three reasons why only 10 percent ethanol can reduce benzene by as much as 25 percent are based on the dilution, the octane and the oxygen provided by ethanol.

Ozone

Urban ozone formation occurs from rather complex photochemistry mainly from volatile organic compounds (VOC) and CO in the presence of nitrogen oxides (NOx). The role that ethanol can play in an urban ozone abatement program has been the subject of several studies (See Whitten and Greenfield, 1993). Typically, ethanol blends have been considered "neutral" towards summer ozone formation when used in conventional gasoline with a 1 psi waiver in RVP volatility. This "neutrality" stems from the ability of the oxygen in ethanol to reduce carbon monoxide (CO) emissions (which are an ozone precursor) that compensate for the increased volatile organic compound (VOC) emissions due to the waiver. In reformulated gasoline (RFG) the role of ethanol is more complex due to the fact that fuel oxygen content is only one of several fuel properties considered.

Also the regulations supporting RFG tend not to account for high emitters, aggressive driving, combustion chamber deposits, off-road engines, and carbon monoxide reactivity, which are areas that ethanol (with its high oxygen content) has shown advantages.

One experimental study by Mayotte et al (1994) shows that ethanol significantly reduces exhaust VOC and CO emissions compared to an equal volume of MTBE, where both oxygenates were blended to essentially the same base clear gasoline. The NO_x emissions were found in that study to not be significantly different between the two oxygenates. The extra VOC and CO reductions seen in the Mayotte et al (1994) study that could be credited to the use of ethanol were mainly due to the impact of ethanol on the higher-emitting vehicles, which can account for more than half the overall gasoline-related emissions. A recent remote sensing study by Pokharel et al (2001) found that 10 percent of the vehicles in the Los Angeles area accounted for 78 percent of the on-road VOC emissions. A 1998 study of 12 vehicles by the California Air Resources Board (ARB) failed to include any higher emitting vehicles, but it did include tests involving heavy acceleration. The combined ARB tests that accounted for heavy acceleration show that even for normal-emitting vehicles CO was reduced about 10 percent due to the extra 1.5 percent fuel oxygen between 11 volume percent MTBE (i.e., 2 percent fuel oxygen) and 10 percent ethanol (i.e., 3.5 percent fuel oxygen). There is evidence showing that reformulated gasoline made with 10 percent ethanol could have a similar impact on ozone formation to that expected from the use of a reformulated gasoline made from the same clear base gasoline blended with 11 percent MTBE. In this regard, when heavy acceleration, higher-emitting vehicles, and off-road engines are accounted for, the extra exhaust reductions of the ethanol blend would at least mitigate, if not compensate, for the additional evaporative emissions due to ethanol.

Long Term Impacts

First, Bitting et al (1994) as noted above found that combustion chamber deposits (CCD) are associated with long term emissions increases of CO, NO_x, and hydrocarbons. Bitting et al (1994) further showed that removal of CCD's at high mileage can restore emissions to low-mileage levels. Second, Choate and Edwards (1993) and Price et al (1995) have shown that these CCD's are strongly associated with high-boiling aromatic compounds in gasoline. Hence, it now appears that reformulated gasoline containing oxygenates in place of aromatics may be preventing some CCD build-up and, in turn, leading to long term *de facto* emissions reductions previously not accounted for in the more or less instantaneous effects of reformulated gasoline tested to date such as used in the Complex and Predictive Models. More studies of these effects are needed.

References

Alliance, AIAM, Honda, (2001) "Industry Low Sulfur Test Program", presented at ARB Workshop, 7/2001. Available at <http://www.arb.ca.gov/fuels/gasoline/meeting/2001/071201AAPrstn.pdf>

Bitting, W.H., G.P. Firmstone and C.T. Keller (1994) "Effects of Combustion Chamber Deposits on Tailpipe Emissions" SAE Paper No. 940345.

Choate, P.J. and J.C. Edwards (1993) "Relationship Between Combustion Chamber Deposits, Fuel Composition, and Combustion Chamber Deposit Structure" SAE Paper No. 932812.

Carter W.P.L., G. Tonnessen, and G. Yarwood (2003) "Investigation of Reactivity Effects Using Existing Air Quality Models" Report to the American Chemistry Council (available at <http://pah.cert.ucr.edu/~carter/RRWG/index.htm>).

Colorado Department of Public Health and Environment, (1999) "The Impact of a 10% Ethanol Blended Fuel on the Exhaust Emissions of Tier 0 and Tier 1 Light Duty Gasoline Vehicles at 35F".

Graskow, B.R., D.B. Kittelson, I.S. Abdul-Khalek, M.R. Ahmadi, and J.E. Morris (1998) "Characterization of Exhaust Particulate Emissions from a Spark Ignition Engine" SAE Paper No. 980528.

Griffin, R.J., D.R. Cocker, and J.H. Seinfeld (1999) "Incremental Aerosol Reactivity: Application to Aromatic and Biogenic Hydrocarbons," *Environmental Science & Technology*, Vol. 33, pp 2403-2408.

Kirchstetter, T.W., B.C. Singer, R.A. Harley, G.R. Kendall and W. Chan (1996) "Impact of Oxygenated Gasoline Use on California Light-Duty Vehicle Emissions" *Environmental Science & Technology*, Vol. 30, pp 661-670.

Mayotte, S. C., C.E. Lindhjem, V. Rao and M.S. Sklar (1994) "Reformulated Gasoline Effects on Exhaust Emissions: Phase I: Initial Investigation of Oxygenate, Volatility, Distillation and Sulfur Effects" SAE Paper No. 941973.

Mulawa P., Cadle, S., Knapp, K., Zweidinger, R., Snow, R., Lucas, R., Goldbach, J., (1997) "Effect of Ambient Temperature and E-10 Fuel on Primary Exhaust Particulate Matter from light Duty Vehicles.", *Environmental Science and technology*, Vol 31, pp 1302-1307.

National Academy, 1999, Ozone-Forming Potential of Reformulated Gasoline, National Academy Press.

OSTP (1997) "Interagency Assessment of Oxygenated Fuels," Office of Science and Technology Policy, Executive Office of the President, Washington, D.C.

Odum, J.R., T.P.W. Jungkamp, R.J. Griffin, R.C. Flagan and J.H. Seinfeld (1997) "The Atmospheric Aerosol-Forming Potential of Whole Gasoline Vapor" *Science*, Vol. 276, pp 96-99.

Pokharel, S.S., G.A. Bishop, and D.H. Stedman (2001) "On-Road Remote Sensing of Automobile Emissions in the Los Angeles Area: Year 2" Univ. of Denver final report to the Coordinating Research Council, Inc., available at www.crao.com.

Price, R.J., J.P.T. Wilkinson, D.A.J. Jones, and C. Morley (1995) "A Laboratory Simulation and Mechanism for the Fuel Dependence of SI Combustion Chamber Deposit Formation" SAE Paper No. 952445.

Reuter, R.M., J.D. Benson, V.R. Burns, R.A. Gorse, A.M. Hochhauser, L.J. Painter, B.H. Rippon, and J.A. Rutherford (1992) "Effects of Oxygenated Fuels and RVP on Automotive Emissions – The Auto/Oil Air Quality Improvement Research Program" SAE Paper No. 920326.

Whitten, G.Z. (2001) "Recent UAM Simulations on the "Reactivity" of Carbon Monoxide," for Renewable Fuels Association, 2001.

Whitten, G.Z. (1999) "Potential Extra Air Quality Benefits from Oxygenates that are not Required to Meet Reformulated Gasoline Specifications," Paper presented at the 9th CRC On-Road Vehicle Emissions Workshop, San Diego, CA, April 19-21, 1999.

Whitten, G.Z., and J.P. Cohen (1996) "Regression Modeling of Oxyfuel Effects on Ambient CO Concentrations" Systems Applications Report No. 96/78, available at www.epe.com/OMSWWW/fuels.html#oxyfuel.

Whitten, G. Z. and S. M. Greenfield (1993) "Photochemical Grid Modeling Study Comparing Air Quality Impacts of Ethanol and MTBE as Alternate Oxygenates in Reformulated Gasoline", presented at the Tenth International Symposium on Alcohol Fuels, Colorado Springs, Colorado (7-10 November), full text available as SAI Final Report No. 93/083 for the Council of Great Lakes Governors, Chicago, Illinois.

Ethanol's Clean Air Impact

Latest Findings

Gary Z. Whitten, Ph.D.

Five Air Quality Areas

- Global Warming
- Fine Particulates
- Carbon Monoxide
- Toxics
- Ozone

Global Warming Gases

- Ethanol is the only gasoline component that can reduce GHG gases.
- Latest Argonne study (850,000 cars)
 - Carbon Dioxide
 - Methane (cows)

Fine Particulates: $PM_{2.5}$

- Studies show primary emissions reduced by 50 percent using 10 percent blends.
- Primary linked to aromatics which ethanol can replace.
- Primary linked to deposits, which are also linked to aromatics.
- Secondary organic formation linked to aromatics which ethanol can replace.

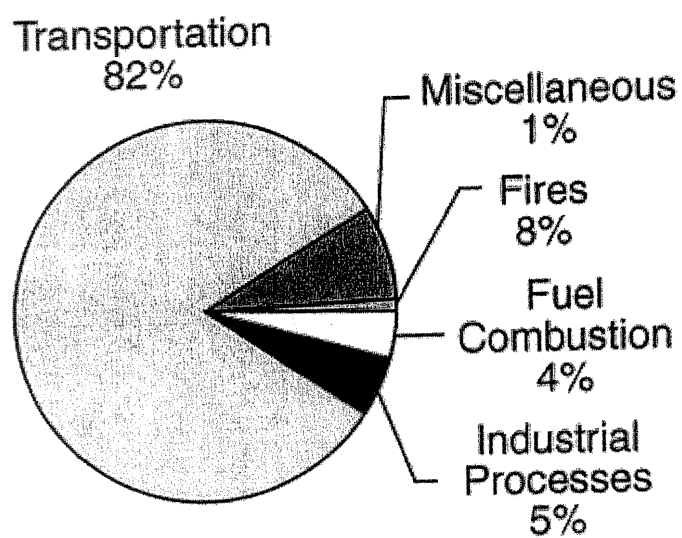
Toxics

- Main toxic is benzene.
 - Mainly from exhaust (90%)
 - Higher aromatics make benzene (65%)
- Ethanol reduces benzene.
 - Dilution
 - Substitution for aromatic octane
 - Cleaner combustion (especially high emitters)
- Acetaldehyde has low potency.
- 13% total mass reduced, 21% as potency

Carbon Monoxide

- Gas engines main source
- Ethanol significantly reduces emissions
 - Widely recognized
 - On-road 19 percent for high emitters
 - On-road normal emitters --- varies
 - Non-road 22 & 23 percent (4 & 2 stroke)
- Important ozone precursor
- Trends not so good

Figure 2-5. CO emissions by source category, 2002.



EPA Trends Report 2003
National CO Emissions (tons/yr)

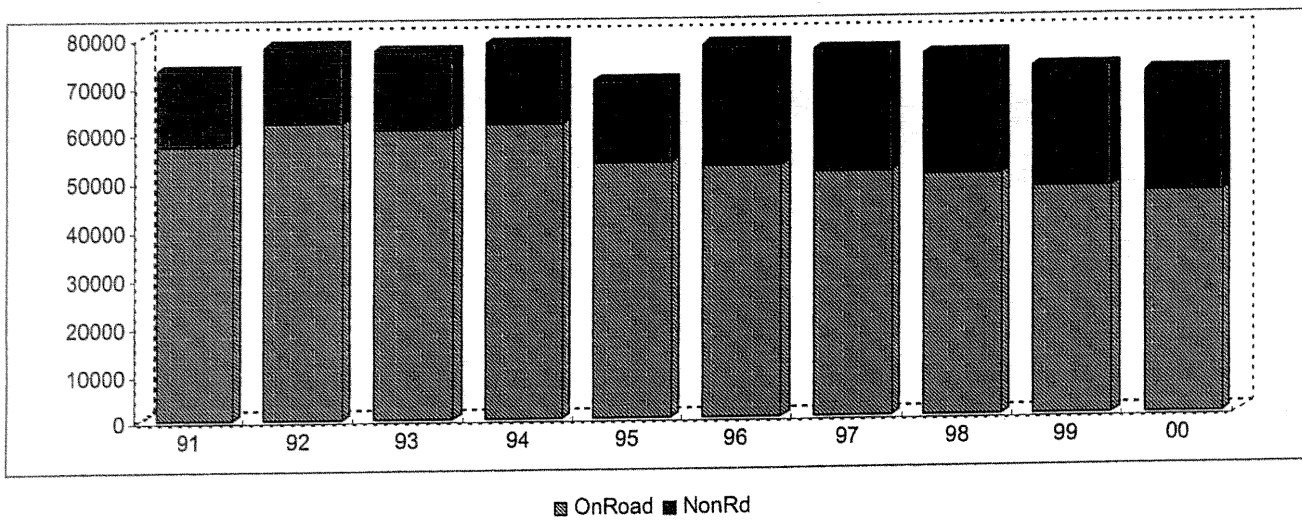
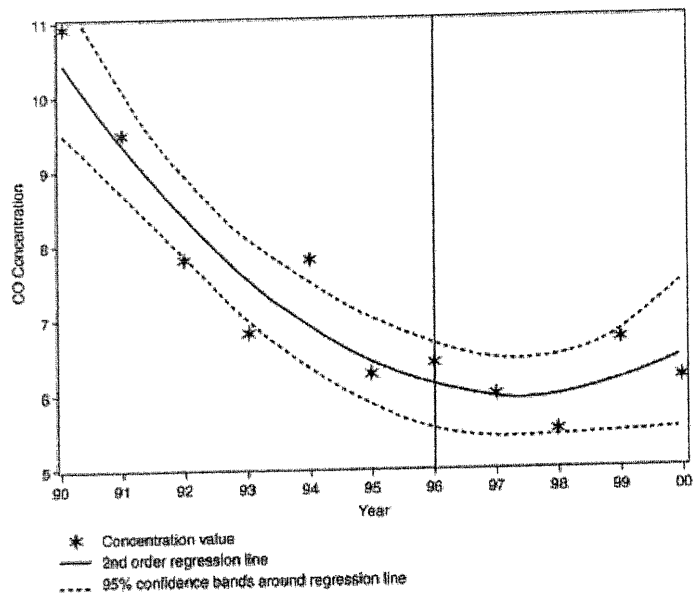
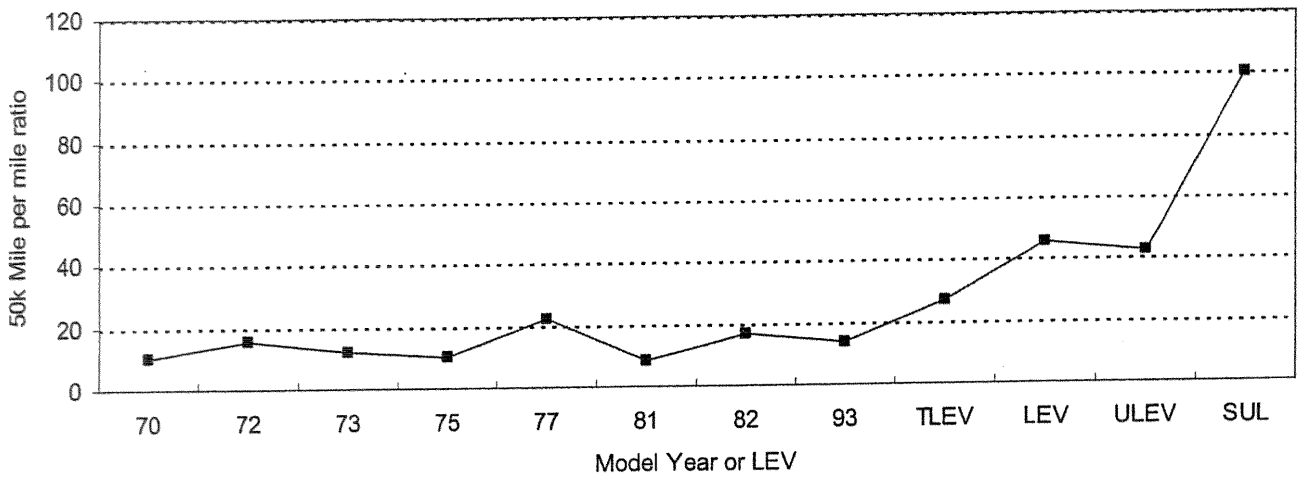


Figure 6. Example of a site with increasing trend in recent years. The vertical line indicates the year that the oxygenated gasoline requirement ended.



CERTIFICATION CO/HC
California Standards



CO From Normal Emitters

- MOBILE6 and CARB use zero impact 1994 plus
 - Yet new data show nearly 30 percent impact from 10 percent ethanol blends
- EPA claims new car oxygen sensors negate impact
 - Air oxygen is not ethanol oxygen
 - Data show zero before but big after catalyst
 - Therefore ethanol seems to help catalyst

CO makes Smog

- In 1999 the National Academy noted that CO accounts for 20% of the combined impact of VOC and CO
- However, that NAS estimate used a simplistic 1-day box model.
- New studies using multi-day grid models show that CO can account for as much as 60%.
 - CO is one molecule, VOC represents many.

SMOG

- Conventional gasoline
 - 1 psi RVP waiver with 10 percent ethanol
 - Justified mainly by CO effect
 - MOBILE6 problems for ethanol
 - Uses zero CO impact for new ('94+) vehicles
 - New data show nearly 30 percent CO reduction
 - High RVP impact vs. little data
- Federal Reformulated Gasoline
 - Does not credit CO (except in Chicago-Milwaukee with 0.3 psi RVP credit)

SMOG –California RFG

- Regulatory model stops use of 10 percent ethanol blends
 - Due to predictions of high NOx emissions
 - Latest data showing low NOx not yet in model
 - Same study (on '94+ cars) as high CO effect
 - Current model assumes high NOx.
 - CARB model under-represents high emitters
 - Fed. Model uses separate high-emitter sub-model.
 - Such a sub-model approach for CaRFG has been shown to significantly reduce overall NOx predictions.

SMOG – California RFG

- CARB concerns about permeation
 - Gives no CO debit (as a bonus for non-oxy)
 - Debit equal to 12.4 tons VOC (CARB model).
 - CARB now estimates permeation at 13 tons.
 - However, CARB model (like MOBILE6) gives no credit to '94+ cars and uses the same box model as NAS did.
 - Newer data and models show 19 to 56 tons VOC equivalent for CO debit.

Highlights to Remember

- Ethanol does not increase NO_x as currently predicted by California model.
 - A new model formulation is needed with better high-emitter treatment and one that uses new data
 - This should allow use of 10 percent blends in CaRFG
- Carbon Monoxide is THE biggest single (and growing) contributor to ozone
 - New studies support more CO credit for ethanol
 - Ethanol seems to help the catalyst, not the A/F ratio