

Daily Mortality and Air Pollution in Santa Clara County, California: 1989–1996

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Since the last revision of the national particulate standards, there has been a profusion of epidemiologic research showing associations between particulates and health effects—mortality in particular. Supported by this research, the U.S. Environmental Protection Agency promulgated a national standard for particulate matter ≤ 2.5 μm in aerodynamic diameter ($\text{PM}_{2.5}$). Nevertheless, the San Francisco Bay Area of California may meet this new standard. This study investigates the relationship between daily mortality and air pollution in Santa Clara County (a Bay Area county) using techniques similar to those utilized in earlier epidemiologic studies. Statistically significant associations persist in the early 1990s, when the Bay Area met national air pollution standards for every criteria pollutant. Of the various pollutants, the strongest associations occur with particulates, especially ammonium nitrate and $\text{PM}_{2.5}$. The continuing presence of associations between mortality and air pollutants calls into question the adequacy of national standards for protecting public health. **Key words:** air pollution, ammonium nitrate, carbon monoxide, epidemiology, National Ambient Air Quality Standards (NAAQS), ozone, $\text{PM}_{2.5}$, Poisson regression. *Environ Health Perspect* 107:637–641 (1999). [Online 25 June 1999] <http://ehpnet1.niehs.nih.gov/docs/1999/107p637-641/fairley/abstract.html>

The past decade has seen a burgeoning of epidemiologic research investigating the relationship between air pollution and health effects. Dozens of these studies have analyzed the relationship of daily mortality to various air pollutants, especially particulates. The U.S. EPA analyzed many of these studies in Chapter 12 of *Air Quality Criteria for Particulate Matter* (1). This criteria document and the later staff report (2) concluded that the preponderance of evidence supports a causal connection between fine particulate levels and various health effects, including mortality. This led to the establishment of national standards for particulate matter ≤ 2.5 μm in aerodynamic diameter ($\text{PM}_{2.5}$).

A previous study (3) showed that an association existed between particulates [measured as coefficient of haze (COH)] and mortality in Santa Clara County (SCC), California, during the years 1980–1986. Since that time, the Bay Area Air Quality Management District (BAAQMD) has monitored particulate matter ≤ 10 μm in aerodynamic diameter (PM_{10}), and since 1990, the California Air Resources Board has operated $\text{PM}_{2.5}$ monitors, including one in SCC. An analysis of SCC $\text{PM}_{2.5}$ data shows that SCC would have met the $\text{PM}_{2.5}$ standard between 1991 and 1996. The present study is motivated by the concern that, although SCC may attain the new $\text{PM}_{2.5}$ standard, particulates there may still cause substantial health effects.

Air quality in SCC. Most of the studies of mortality and air quality have been based on eastern or midwestern U.S. cities, whose air quality dynamics differ markedly from those of the San Francisco Bay Area. Among the gaseous pollutants, ozone and carbon monoxide levels are similar, but Bay Area sulfur

dioxide levels are an order of magnitude lower than in the eastern United States. In fact, sulfur dioxide is so low that it is no longer measured in SCC, but nearby San Francisco's 24-hr design value is < 0.01 ppm, compared with typical design values of approximately 0.05 ppm in many eastern cities (4).

SCC's particulate composition, dynamics, and sources also differ markedly from those of eastern cities. In eastern cities, ammonium sulfate represents approximately 45% of $\text{PM}_{2.5}$ (1), whereas in SCC it represents 5%. For many eastern and midwestern cities, particulate levels peak in the summer months (1). For SCC, however, particulates (especially fine particulates) are higher in winter. Specifically, mean San Jose, California, $\text{PM}_{2.5}$ levels in November, December, and January averaged 25 $\mu\text{g}/\text{m}^3$ in 1990–1996, but < 10 $\mu\text{g}/\text{m}^3$ during the rest of the year.

Wood-burning and ammonium nitrate each contribute approximately 40% of SCC's wintertime $\text{PM}_{2.5}$ (5). These sources, combined with wintertime stagnation periods, are the main causes of SCC's elevated wintertime particulate levels. As a result of this seasonality, the new SCC 15 $\mu\text{g}/\text{m}^3$ annual standard appears no more stringent than the 65 $\mu\text{g}/\text{m}^3$ 24-hr standard (6). This is in spite of the EPA's stated intention to make the annual average the more stringent controlling standard (7).

Particle size also varies by season. During the winter, SCC $\text{PM}_{2.5}$ averages approximately 70% of PM_{10} compared with 50% for the year as a whole. Wintertime PM_{10} is dominated by combustion sources, with approximately 10% coming from geological dust. During the rest of the year, geological dust makes up a larger fraction, marine sea

salt becomes significant, and the amount of ammonium nitrate decreases by half.

For several years during the early 1990s, SCC and, in fact, the entire Bay Area, had air quality that complied with air quality standards for all criteria pollutants. Moreover, the Bay Area would have attained the new 8-hr ozone standard and, based on research monitoring results, would have attained the new $\text{PM}_{2.5}$ standard, had those standards been in effect. In contrast, in the early 1980s, when the previous study was done, SCC violated the 8-hr CO standard, the 1-hr ozone standard, and would have violated the 8-hr ozone standard had that been in effect. Although PM_{10} and $\text{PM}_{2.5}$ were not measured in the 1980s, SCC violated the 150 $\mu\text{g}/\text{m}^3$ total suspended particulate (TSP) standard almost every year.

Methodology

This study attempts to draw on the extensive experience of previous studies to determine a modeling approach. The sensitivity of conclusions to model choice, meteorological adjustment, and covariates has been extensively investigated [e.g., (1,8–10)]. These studies have reached similar conclusions, namely that the choices of (reasonable) model and (reasonable) meteorological adjustment do not appear to greatly affect conclusions on the relationship between mortality and particulates, but the inclusion of other air contaminants often causes a substantial increase in the standard error of the particulate regression coefficient and sometimes a drop in the level of the coefficient. In other words, there can be substantial confounding of these variables.

Based on these considerations, various models were tried, including Poisson regression with either linear predictors or generalized additive models (GAMs) for temporal and weather variables, and models with an overdispersion fit using quasi likelihood.

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The disadvantage of the GAM approach is that it does not provide simple coefficients. Because the focus is on pollutant variables, however, this lack is not of great concern. The advantage is that the GAM approach is less likely to induce lack of fit. Thus, we will use the GAM approach. Models with an overdispersion parameter are useful for certain deviations from the Poisson model. However, if the Poisson model appeared adequate, it would be used.

The modeling strategy follows that of Samet et al. (10), first fitting terms for season and trend, then adding terms for meteorology, and finally adding pollutant terms, with the number of seasonal, trend, and meteorology terms determined by optimizing Akaike's information criterion (AIC).

Tests of goodness of fit. A goodness of fit test of the Poisson model was performed based on deviance. Under the null hypothesis that the data derive from this model, the deviance has an approximately χ^2 distribution with the residual degrees of freedom. Specifically, the χ^2 test is a likelihood ratio test versus a saturated model, where each day is fitted with a different mean. Serious lack of fit would result in unusually large values of the deviance.

Residuals were checked for extreme values. The GAM approach minimizes problems with any nonlinearity between the response and the temporal and weather variables.

To test the sensitivity of the results to the use of GAM, a parallel modeling approach was performed using sine and cosine terms for time and day of year and polynomials in minimum and maximum temperature.

A simulation of the model-fitting process. The statistical significance level for testing a parameter in a model is based on the assumption that the selection of the model was made before the data were gathered. In practice, this is rarely the case, so the *de facto* assumption is that the process of model-building has a minimal effect on the significance level.

An approach to finding more realistic significance levels is to simulate the model-building process itself. To that end, an S-Plus function was developed to simulate the following approximation of model-building. The idea was to simulate data from a true model that contains no pollutant term, then simulate the building up of the model and the fitting of a pollutant variable. The set of pollutant variable coefficients thus obtained should form a more realistic distribution than the simple one where model-building is ignored.

The steps of the simulation were as follows. Initially, a vector of Poisson means was generated by fitting daily mortality data to the seasonal, trend, and weather variables using the GAM approach. An S-Plus function was

then invoked repeatedly with different random seeds that performed the following steps:

1. The function simulates a vector of Poisson variates from the initial mean vector.
2. It fits this simulated variate vector to GAM terms for time and day of year in a Poisson regression, increasing the degrees of freedom until there is no improvement in AIC from the addition of another degree of freedom in either GAM term.
3. It uses the optimal number of degrees of freedom for time and day of year from step 2, and adds GAM terms for minimum and maximum temperature, again adding terms until there is no improvement in AIC.
4. It fits the simulated variates to $PM_{2.5}$ in addition to the optimal number of time, day of year, and minimum and maximum temperature GAM terms found in steps 2 and 3, with the fitted $PM_{2.5}$ coefficient output.

The coefficient found from the actual data is then compared to the resulting distribution of simulated coefficients, providing what may be a more realistic *p*-value.

The data. California mortality data were obtained from the California Department of Health Services (Sacramento, CA) for the years 1989–1996. Counts of daily total nonaccidental mortality (henceforth described as mortality), respiratory mortality, and cardiovascular mortality were extracted for SCC residents who died in-county, using the same *International Classification of Diseases, Ninth Revision (11)* codes as in the previous study (3).

Pollutant data were obtained from the BAAQMD pollutant database. Long-term PM_{10} data were available for only one SCC site—San Jose 4th Street. These data cover the full period on an every-6-day schedule, with an every-other-day schedule during the first 3 years. This site also provided PM_{10} constituents nitrate and sulfate on the 6-day schedule and daily COH values. $PM_{2.5}$ and $PM_{10-2.5}$ were also available from a research model dichotomous sampler that operated at this site from 1990 through 1996 on the same 6-day schedule.

Ozone, carbon monoxide, and nitrogen dioxide data were also obtained for the 4th Street site. Although data for ozone were available from some other SCC sites, these were not included in the interests of simplicity. Because national standards are health-based it seemed reasonable to include variables with

averaging times as defined in the standards, namely maximum 8-hr ozone, maximum 8-hr CO, and 24-hr NO_2 . Nevertheless, 24-hr CO and ozone were also considered.

Comparisons of 4th Street ozone with other SCC sites consistently show correlations above 0.8 in seasonally adjusted ozone concentrations. Thus, 4th Street ozone concentrations represent a reasonably good surrogate for outdoor ozone exposure in SCC. Based on data from the late 1970s when the district operated a number of COH monitors in SCC, correlations with the 4th Street site were quite high. The correlation between season- and trend-adjusted $PM_{2.5}$ for Fremont and 4th Street was 0.86.

Weather data were obtained from the BAAQMD meteorological database for San Jose Airport. Previous studies have found nonlinear relationships between mortality and weather variables. Because mortality can be affected by both hot and cold weather, it seemed reasonable to consider both minimum and maximum temperature as variables. Therefore, both daily maximum and minimum temperature as well as 24-hr average relative humidity data (rh) were obtained. Missing values were filled in by regressing against temperature and rh values at other nearby BAAQMD meteorological sites—Alviso and Union City.

Comparison with previous results. To compare the results for 1989–1996 with the previous 1980–1986 results it was necessary to reanalyze the earlier results paralleling the new analysis as closely as possible.

For the 1980–1986 reanalysis, $PM_{2.5}$ and PM_{10} and its species were not available. COH was used along with NO_3 from the TSP filter. The other pollutants— NO_2 , O_3 , and CO—were measured, although the results were read from strip charts and recorded with one less significant digit. San Jose Airport data were not available for this time period; therefore, San Jose city temperatures were used.

Results

Table 1 provides summary statistics for $PM_{2.5}$ related to the new $PM_{2.5}$ standards. Note that from 1993 through 1996 the 4th Street site would have met the new $PM_{2.5}$ standards, based on results from the dichotomous sampler. Although the new $PM_{2.5}$ network will include many sites, the 4th Street site has historically had the highest particulate (PM_{10}) levels in the Bay Area.

Table 1. $PM_{2.5}$ design values ($\mu g/m^3$): San Jose, CA, 4th Street, 1990–1996.

	1990	1991	1992	1993	1994	1995	1996
98th percentile	88	51	48	50.0	44	32	25
3-Year average			62.4	50.0	47.2	42.0	33.6
Annual mean	18.4	15.5	13.8	12.9	12.6	10.3	9.5
3-Year average			15.9	14.1	13.1	11.9	10.8

$PM_{2.5}$, particulate matter $\leq 2.5 \mu m$ in aerodynamic diameter.

Thus, there is a good chance that the Bay Area (including SCC) would have met the standards had PM_{2.5} samplers been in operation at other BAAQMD monitoring sites.

Table 2 presents summary statistics for all the variables considered. Note that PM_{2.5} and PM_{10-2.5} do not sum to PM₁₀, and that the number of observations for the PM₁₀ fractions was 408 compared with 823 for PM₁₀. This is because the fractions were measured with a dichotomous sampler whereas the PM₁₀ was measured with the district high-volume sampler. Although the dichotomous sampler averages lower than the district sampler, the two PM₁₀ measurements have a correlation of 0.94.

Season and trend fits. Rather than predicting mortality from a single temporal GAM term, separate GAM terms in time and day of year were fit because a good-fitting model could be obtained using many fewer degrees of freedom. Terms were added sequentially until there was no further improvement in AIC.

The best model contained a GAM term for time with 7 degrees of freedom (*df*) and a day of year term with 12 *df*. The resulting deviance was 3,038.5, with AIC 3,078.5.

Meteorological variables. GAM terms were fit for minimum and maximum temperature in addition to a 7-degree term for time and a 12-degree term for day of year, yielding an optimum AIC with 3 *df* for minimum temperature and 2 *df* for maximum. (Subsequently, this set of GAM terms will be referred to as the optimal GAM terms.) The inclusion of a minimum–maximum cross-product term did not improve the AIC, nor did the inclusion of relative humidity. The model had a deviance of 2,998.1 on 2,897 *df*, and an AIC of 2,897 *df*.

To test for lack of fit, a quasi likelihood model was fit. The overdispersion parameter of 1.02 is barely larger than 1, the value for the Poisson. The *p*-value for a χ^2 of 2,998.1 with 2,897 *df* is 0.09, so that the Poisson model cannot be rejected at the 0.05 level.

Table 2. Summary statistics for mortality, weather variables, and pollutant concentrations, San Jose CA, 1989–1996.

Variable ^a	Obs (no.)	Mean ± SD	Min	Lower quartile	Med	Upper quartile	Max
Mortality (count)	2,922	20 ± 5	6	17	20	24	40
Respiratory mortality (count)	2,922	2.5 ± 1.7	0	1	2	3	14
Cardiovascular mortality (count)	2,922	8.7 ± 3.2	0	6	9	11	24
Min temperature (°F)	2,922	50 ± 8	22	45	51	56	70
Max temperature (°F)	2,922	70 ± 10	39	62	70	77	101
Relative humidity (%)	2,922	70 ± 12	24	63	70	77	100
PM ₁₀ ^b (µg/m ³)	823	34 ± 23	6	19	27	40	165
PM _{2.5} ^b (µg/m ³)	408	13 ± 13	2	6	9	14	105
PM _{10-2.5} ^b (µg/m ³)	408	11 ± 6	0	7	11	15	45
COH (COH units)	2,780	0.5 ± 0.4	0.0	0.2	0.3	0.5	3.1
NO ₃ (µg/m ³)	523	3.0 ± 3.7	0.0	0.9	1.8	3.7	33.1
SO ₄ (µg/m ³)	534	1.8 ± 1.3	0.0	0.9	1.5	2.5	7.9
O ₃ (ppb)	2,856	16 ± 9	0	10	16	22	51
8-hr O ₃ (ppb)	2,908	29 ± 15	0	19	29	37	105
CO (ppm)	2,849	1.4 ± 1.0	0.0	0.8	1.1	1.7	7.6
8-hr CO (ppm)	2,865	2.1 ± 1.6	0.2	1.0	1.5	2.5	12.0
NO ₂ (ppb)	2,888	28 ± 13	5	19	25	34	96

Abbreviations: COH, coefficient of haze; Max, maximum; Med, median; Min, minimum; Obs, observations; PM_{2.5}, particulate matter ≤ 2.5 µm in aerodynamic diameter; PM₁₀, particulate matter ≤ 10 µm in aerodynamic diameter; SD, standard deviation. ^aValues are 24-hr averages unless otherwise noted. ^bThe fine and coarse fraction of PM₁₀ do not add to total PM₁₀ because they derive from the dichotomous sampler, whereas total PM₁₀ was collected with a separate high-volume sampler.

Table 3. Partial correlations among mortality and pollutant variables.^a

Variable	Mortality	Mortality vs. lagged variable	PM ₁₀	PM _{2.5}	PM _{10-2.5}	COH	NO ₃	SO ₄	O ₃	8-hr O ₃	CO	8-hr CO
PM ₁₀	0.116	-0.026										
PM _{2.5}	0.142	-0.084	0.849									
PM _{10-2.5}	0.037	-0.031	0.649	0.508								
COH	0.026	0.041	0.827	0.772	0.476							
NO ₃	0.141	-0.061	0.689	0.830	0.496	0.493						
SO ₄	0.100	-0.040	0.509	0.499	0.444	0.318	0.614					
O ₃	0.025	-0.013	-0.064	-0.122	-0.026	-0.289	-0.103	0.102				
8-hr O ₃	0.037	-0.016	-0.102	-0.153	-0.070	-0.330	-0.108	0.085	0.844			
CO	0.033	0.048	0.609	0.435	0.326	0.736	0.270	0.146	-0.215	-0.210		
8-hr CO	0.029	0.024	0.620	0.542	0.378	0.750	0.285	0.155	-0.236	-0.277	0.810	
NO ₂	0.036	0.022	0.800	0.662	0.590	0.826	0.459	0.293	-0.228	-0.219	0.651	0.643

Abbreviations: COH, coefficient of haze; PM_{2.5}, particulate matter ≤ 2.5 µm in aerodynamic diameter; PM₁₀, particulate matter ≤ 10 µm in aerodynamic diameter.

^aCorrelations of residuals from regressions on generalized additive model terms of degree 12 for day of year, degree 7 for time, degree 3 minimum temperature, and degree 2 for maximum temperature.

Pollutant variables. Table 3 presents partial correlations between mortality and the pollutant variables. Specifically, mortality and each pollutant variable were regressed against the optimal GAM terms, and the residuals saved. Several of the Poisson regressions did not converge, so least squares regressions were used. The table presents the correlations among these residuals.

Of the pollutant measures, PM_{2.5} and NO₃ have the highest partial correlations with mortality. There are also reasonably high correlations with PM₁₀ and SO₄. Interestingly, in contrast to other studies, there are actually negative correlations between mortality and the lags (previous day) of these variables. Another change is that COH is only weakly correlated with mortality, although there is a statistically significant correlation with lagged COH. The relationship with 24-hr CO is similar to that of COH. NO₂ is also highly correlated with COH, but lag NO₂ has a lower partial correlation with mortality than unlagged NO₂. The correlation between ozone and mortality is weak, although the correlation with 8-hr ozone is borderline significant.

Except for ozone, there are positive correlations between the other pollutant variables, with high correlations between some of the particulate measurements (PM_{2.5} and PM₁₀, PM₁₀ and COH, and PM_{2.5} and NO₃). There are also high correlations between NO₂ and PM₁₀, and NO₂ and COH.

Various combinations of pollutants were tried in Poisson regressions that also included the optimal GAM terms. The results are shown in Table 4. As with the partial correlations, both NO₃ and PM₁₀ were highly significant. PM_{2.5}, SO₄ and 8-hr ozone were also marginally statistically significant. Among lagged variables, COH and CO were highly significant and NO₂ was marginally so. PM_{10-2.5} was not significant, nor was its lag.

Because NO₃ and PM_{2.5} had the highest partial correlations with mortality, these were included in regressions with other pollutants.

NO₃ was statistically significant paired with every other pollutant except PM_{2.5}. PM_{2.5} was statistically significant paired with every pollutant except NO₃ and PM₁₀. No other pollutant was statistically significant in regressions with either of these pollutants. Two runs of all four categories of pollutant were made (particulate, NO₃, CO, and ozone), using either PM_{2.5} or NO₃ as the particulate variable. In these regressions, the particulate variable was highly statistically significant and the others were not.

Goodness of fit. In the fitted models in Table 4 that included PM_{2.5}, the deviance is actually 364.7—less than its degrees of freedom (382). This implies *p*-values of 0.5 or higher, i.e., there is no indication of lack of fit. Similarly, for the model with NO₃, the deviance is 503.4, with 497 *df*; the *p*-value is 0.31.

There are no large *y*-outliers, the largest daily mortality value being 40, approximately 4 standard deviations (SDs) above the mean. Several of the pollutant variables are right-skewed—PM_{2.5} and NO₃ in particular. However, taking the log of PM_{2.5} (after first adding 5 μg/m³ to reduce undue influence of small PM_{2.5} values) eliminates much of the skewness, and the transformed variable is still statistically significant in a Poisson regression with the trend, seasonal, and meteorological terms.

The raw mortality values have an autocorrelation of 0.18, but the residuals from the multiple regression of mortality on trend, season, and weather terms has an autocorrelation of only 0.04. Thus, autocorrelation of residuals is not a significant issue.

The fact that the deviance is approximately equal to the value expected under the null hypothesis suggests that it would be

difficult to improve the fit substantially. The lack of *y*-outliers, the lack of influential *x*-values, and the lack of autocorrelation suggest that the Poisson model fits reasonably well.

Analysis using a parametric approach. To check the adequacy of the GAM approach, a parallel analysis was performed using sine/cosine functions for season and trend, and polynomials for weather variables. The results were similar both qualitatively and quantitatively to those found in Table 4.

A simulation of the model-fitting process. The simulation described in "A Simulation of the Model-Fitting Process" in "Methodology" was repeated 1,000 times. It yielded four fitted coefficients greater than that observed so that, based on the simulation, the *p*-value is approximately 0.004. This *p*-value is, if anything, smaller than that found using statistical theory, where the *p*-value was 0.012.

Comparison with 1980–1986 results. Table 5 presents a reanalysis of the 1980–1986 data using methods paralleling those of Table 4. In particular, the same variables for season, trend, and weather were used (although they were refit with 1980–1986 data). To make coefficients comparable, the same deltas are used; that is, 50 × SD(*p*)/SD(PM₁₀), where the SDs are from the 1989–1996 data.

Generally, the results for the 1980–1986 period are similar to those of 1989–1996. In particular, with the exception of ozone, the coefficient for every pollutant or the lagged pollutant is statistically significant. In pairwise models with lagged COH, the other pollutants are no longer statistically significant. Lagged COH remains highly significant in combination with NO₂ and ozone; with CO, it is not statistically significant, but its regression coefficient is little changed. NO₃ is

borderline significant (*p* = 0.06) with the ozone, but not significant with CO or NO₂. Oddly, in combination with NO₃, NO₂ was significant. Note that the sample size for NO₃ is only 354, compared with over 2,000 for the other pollutants. The small sample size makes it more difficult to detect an effect. When both lag COH and NO₃ are in the model, the COH coefficient is smaller and no longer statistically significant, whereas the NO₃ coefficient changes only slightly and is borderline significant (*p* = 0.09).

One difference with the 1989–1996 results is that the 1980–1986 COH coefficient is highly significant, with a relative risk of 1.06, compared with 1.03 for 1989–1996. A comparison of the two coefficients—taking their difference and dividing by the square root of the sum of their sample variances—yields a value of *z* = 1.36, not statistically significant. Pooling the two periods, fitting the same coefficient for season, trend, and weather, but with different COH slopes and intercepts did not result in a statistically significant difference in COH coefficients.

One possible reason that the COH coefficient might have changed is that COH has diminished from the early 1980s to the 1990s. Thus, if the effect of COH is not linear, this could result in different coefficients. However, neither a quadratic nor a hockey-stick function of COH was significant in the pooled regressions for either period.

Respiratory and cardiovascular regressions. Table 6 shows relative risks from Poisson regressions using each pollutant or their lags (depending on which had the greater risk based on Table 4). SO₄ and CO were significantly associated with respiratory mortality.

Table 4. Pollutant relative risks^a for models^b with pollutant alone, lagged, and with other pollutants, Santa Clara County, CA, 1989–1996.

Pollutant	PM ₁₀	PM _{2.5}	PM _{10-2.5}	COH ^c	NO ₃	SO ₄	NO ₂ ^c	CO ^c	8-hr O ₃
Alone	1.08**	1.09*	1.02	1.03	1.07**	1.05*	1.03	1.02	1.03*
Lagged	0.99	0.96	0.98	1.05**	0.98	0.98	1.03*	1.04**	0.99
With									
PM ₁₀	—	1.13	—	—	1.07*	—	—	—	—
PM _{2.5}	0.96	—	0.97	0.99	1.09	1.00	0.96	0.98	1.04
PM _{10-2.5}	—	1.13*	—	—	1.11**	—	—	—	—
Lag COH ^c	—	1.11*	—	—	1.07**	—	—	—	—
NO ₃	1.02	1.00	0.95	1.01	—	1.01	0.99	1.01	1.05
SO ₄	—	1.10*	—	—	1.07*	—	—	—	—
Lag NO ₂ ^c	—	1.12**	—	—	1.08**	—	—	—	—
Lag CO ^c	—	1.11**	—	—	1.07**	—	—	—	—
8-hr O ₃	—	1.10**	—	—	1.08**	—	—	—	—
Four-pollutant ^d	—	1.13**	—	—	—	—	0.96	1.00	1.05
Four-pollutant ^d	—	—	—	—	1.09**	—	0.95	1.06	1.07

Abbreviations: SD, standard deviation; COH, coefficient of haze; PM_{2.5}, particulate matter ≤ 2.5 μm in aerodynamic diameter; PM₁₀, particulate matter ≤ 10 μm in aerodynamic diameter.

^aRelative risks calculated by $\exp(b \times \Delta p) - 1$, where *b* is the pollutant coefficient from the Poisson regression, and $\Delta p = 50$ for PM₁₀, corresponding to the increment used in the criteria document (1). For other pollutants, *p*, the increment was 50 × SD(*p*)/SD(PM₁₀); e.g., SD(PM_{2.5}) = 13, SD(PM₁₀) = 23, so for PM_{2.5}, $\Delta p = 50 \times 13/23 = 28$. ^bAll models include 7 generalized additive model terms for trend, 12 for season, 3 for minimum temperature, and 2 for maximum temperature. ^cLagged variables were used if they appeared to fit better lagged than unlagged. Thus, lagged CO and lagged COH were used when fitting jointly with other pollutants. ^dPollutants are lagged CO, lagged NO₂, 8-hr ozone, and either PM_{2.5} or NO₃. *Statistical significance at the 0.05 level. **Statistical significance at the 0.01 level.

Table 5. Pollutant relative risks^a for models^b with pollutant alone, lagged, and with other pollutants, Santa Clara County, CA, 1980–1986.

	COH	NO ₃	NO ₂	CO	8-hr O ₃
Alone	1.05**	1.04*	1.04**	1.04**	1.01
Lag 1 ^c	1.06**	1.00	1.03**	1.05**	1.02
Lag COH ^c	—	1.03	1.01	1.00	1.02
NO ₃	1.03	—	1.08*	1.03	1.03
NO ₂	1.05**	1.01	—	—	—
Lag CO ^c	1.06	1.03	—	—	—
Lag O ₃ ^c	1.06**	1.04	—	—	—
Four-poll ^d	1.06	—	1.01	1.00	1.02

Abbreviations: COH, coefficient of haze; poll, pollutant; PM₁₀, particulate matter ≤ 10 μm in aerodynamic diameter; SD, standard deviation.

^aRelative risks calculated by $\exp(b \times \Delta p) - 1$, where *b* is the pollutant coefficient from the Poisson regression, and $\Delta p = 50 \times \text{SD}(p)/\text{SD}(\text{PM}_{10})$ for the pollutant, *p*, where SD(*p*) and SD(PM₁₀) are computed on 1989–1996 data. ^bAll models include 7 generalized additive model terms for trend, 12 for season, 3 for minimum temperature, and 2 for maximum temperature. ^cLagged variables were used if they appeared to fit better lagged than unlagged. Thus, lagged CO, COH, and 8-hr O₃ were used when fitting jointly with other pollutants. ^dPollutants are lagged CO, NO₂, lagged 8-hr O₃, and lagged COH.

*Statistical significance at the 0.05 level. **Statistical significance at the 0.01 level.

Table 6. Respiratory and cardiovascular mortality relative risks^a for models^b with pollutant^c alone, Santa Clara County, CA, 1989–1996.

	PM ₁₀	PM _{2.5}	PM _{10-2.5}	Lag COH	NO ₃	SO ₄	Lag NO ₂	Lag CO	8-hr O ₃
Respiratory	1.11	1.13	1.16	1.07	1.10	1.15*	1.07	1.08*	0.96
Cardiovascular	1.09*	1.07	1.03	1.03	1.09*	1.04	1.02	1.04*	1.02

Abbreviations: COH, coefficient of haze; PM_{2.5}, particulate matter ≤ 2.5 μm in aerodynamic diameter; PM₁₀, particulate matter ≤ 10 μm in aerodynamic diameter.

^aRelative risks calculated by $\exp(b \times \Delta p) - 1$, where b is the pollutant coefficient from the Poisson regression and $\Delta p = 50$ for PM₁₀ and $50 \times \text{SD}(p)/\text{SD}(\text{PM}_{10})$ for other pollutants, p ; e.g., $\text{SD}(\text{PM}_{2.5}) = 13$, $\text{SD}(\text{PM}_{10}) = 23$, so for PM_{2.5}, $\Delta p = 50 \times 13/23 = 28$. ^bAll models include 7 generalized additive model terms for trend, 12 for season, 3 for minimum temperature, and 2 for maximum temperature. ^cLagged variables were used if they appeared to fit better lagged than unlagged. Thus, lagged CO and lagged COH were used when fitting jointly with other pollutants.

*Statistical significance at the 0.05 level.

and PM_{2.5}, NO₃, and CO were associated with cardiovascular mortality. For PM₁₀, PM_{10-2.5}, NO₃, and CO the point estimates for risk were higher than those in Table 4.

Analyses by season. Analyses were performed by season for pollutants with the highest partial correlations with mortality (Table 7). In most cases, the change in relative risk is not statistically significant. Based on Tukey's studentized range distribution, the risks differ significantly from season to season for NO₃. For the other pollutants, the differences in risk between seasons are not statistically significant.

Discussion

One striking result of the analysis is that although the Bay Area met every air quality standard in the early 1990s (and would have met the new 8-hr ozone and PM_{2.5} standards had they been in effect), there is a statistically significant correlation between each pollutant considered (except coarse fraction PM₁₀) and mortality. Second, the regression coefficients of other pollutants that are correlated with particulates—CO and NO₂—drop to nonsignificance in a regression that also includes some measure of fine particulates (either PM_{2.5} or NO₃), whereas there is little change in the fine particulate coefficients. This suggests that fine particulates (or what fine particulates may be a surrogate for) may be the real culprits. The result that NO₃ had the strongest association with mortality is clearly of practical importance and worth investigating for other areas.

The level of PM₁₀ effect found—a relative risk of 1.08 for an increase of 50 μg/m³ PM₁₀—is larger than that found in many other studies [see the EPA's Table 12-37 and Figure 12-43 (1)]. This may reflect a better correlation between monitored values and exposure in SCC. Part of the explanation may be that buildings in SCC are not as tight because of its mild climate, which could lead to a higher correlation of indoor and outdoor particulate levels. A second point is that the correlation between particulate values measured at the San Jose 4th

Street monitor and other SCC monitors is high. Particulate levels at the 4th Street monitor exceed those of other SCC monitors (12); therefore, the relative risk as a function of SCC average levels could be higher than 1.08.

No evidence for a threshold was found. Although the COH coefficient was substantially lower for the 1989–1996 period than for 1980–1986, the result did not appear to be due to the lower particulate levels in the later period. One point that is important to keep in mind is the role of chance in these comparisons; because there is marginal power to detect effects of this magnitude, some data sets may yield nonsignificant results whereas others yield highly significant results.

Although the results for respiratory and cardiovascular mortality showed fewer significant results than for mortality as a whole, the level of effects appeared somewhat higher. The number of cardiovascular and respiratory deaths is considerably smaller than all deaths (Table 2), so the power to detect an effect is less unless the effect is much larger.

The results by season were ambiguous. The lack of statistical significance of most of the coefficients can be attributed to lack of power. The criteria document (1) found that a minimum sample size of 400 was necessary to achieve reasonable power in epidemiologic studies such as this. For PM_{2.5}, NO₃, and SO₄, there were approximately 100 observations per season, far below the 400 observations necessary to achieve reasonable statistical power. Nevertheless, a statistically significant difference in effect was found for NO₃, with positive effects for winter, spring, and summer, and a negative effect for fall; although only the winter coefficient was statistically significant, the range of coefficients was larger than expected by chance.

This analysis has found associations between air pollution variables and mortality—especially with fine particulate variables—similar to the levels of associations found in the studies that were used to justify the new PM_{2.5} standards. Yet the Bay Area probably meets these new standards. The

Table 7. Relative risks by season.^{a,b}

Season	Lag				
	PM ₁₀	PM _{2.5}	COH	NO ₃	SO ₄
Spring ^c	1.08	1.07	1.02	1.07	1.06
Summer ^d	1.10	1.05	1.13	1.32*	1.11*
Fall ^e	1.07	1.04	1.08	0.87	1.03
Winter ^f	1.06	1.05	1.04*	1.07*	1.00

Abbreviations: COH, coefficient of haze; PM_{2.5}, particulate matter ≤ 2.5 μm in aerodynamic diameter; PM₁₀, particulate matter ≤ 10 μm in aerodynamic diameter.

^aRelative risks calculated by $\exp(b \times \Delta p) - 1$, where b is the pollutant coefficient from the Poisson regression and $\Delta p = 50$ for PM₁₀ and $50 \times \text{SD}(p)/\text{SD}(\text{PM}_{10})$ for other pollutants, p ; e.g., $\text{SD}(\text{PM}_{2.5}) = 13$, $\text{SD}(\text{PM}_{10}) = 23$, so for PM_{2.5}, $\Delta p = 50 \times 13/23 = 28$. ^bAll models include 7 generalized additive model terms for trend, 12 for season, 3 for minimum temperature, and 2 for maximum temperature.

^cFebruary, March, April. ^dMay, June, July. ^eAugust, September, October. ^fNovember, December, January.

*Statistical significance at the 0.05 level.

new PM_{2.5} standards may be protective in other areas where seasonal PM variations are not as great. In the Bay Area, however, the seasonal variation in PM_{2.5} is large, with winter concentrations averaging more than double that of summer concentrations. The results of this analysis suggest that current national air quality standards, specifically those for particulates, may not be protective of public health for the Bay Area.

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