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Linking Air Quality and Human Health Effects Models: An Application to the Los Angeles Air Basin

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ABSTRACT: Proposed emission control strategies for reducing ozone and particulate matter are evaluated better when air quality and health effects models are used together. The Community Multiscale Air Quality (CMAQ) model is the US Environmental Protection Agency's model for determining public policy and forecasting air quality. CMAQ was used to forecast air quality changes due to several emission control strategies that could be implemented between 2008 and 2030 for the South Coast Air Basin that includes Los Angeles. The Environmental Benefits Mapping and Analysis Program—Community Edition (BenMAP-CE) was used to estimate health and economic impacts of the different emission control strategies based on CMAQ simulations. BenMAP-CE is a computer program based on epidemiologic studies that link human health and air quality. This modeling approach is better for determining optimum public policy than approaches that only examine concentration changes.

KEYWORDS: Air quality modeling, ozone, particulate matter

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Introduction

Ground-level ozone (O₃) and particulate matter (PM) are air pollutants that adversely affect human health.^{1–5} Exposure to air pollutants is of particular concern in urban areas because of the highly dense populations exposed to air pollution and the high number of emission sources. Ground-level ozone and PM cause respiratory and cardiovascular health problems. Short-term respiratory impacts range from reduced lung function, coughing, and throat irritation to asthma attacks.⁶ Longer-term impacts of air pollution include chronic obstructive pulmonary disease (COPD) and cardiovascular health disease. Particles smaller than 2.5 μm (PM_{2.5}) have the most significant health effects. PM_{2.5} can be inhaled very deeply into the lungs, enter the bloodstream, and lodge in the heart and brain where they can cause the formation of plaques.⁷

Ground-level ozone not only affects human health but also damages crops, forests, and structural materials.⁸ Extensive research^{9–15} has demonstrated the associations between exposure to common air pollutants (PM and O₃) and ill-health end points of respiratory and cardiovascular diseases (morbidity and mortality).

Particles that are emitted directly from sources are known as primary PM. Particulate matter emitted from combustion sources includes soot, black carbon, and elemental carbon. Organic compounds found in primary PM are likely to consist of minimally oxygenated organic compounds.^{16–18} Other

primary PM includes windblown crustal material, resuspended particles from tire and brake wear and fugitive dust from industrial and agricultural activities. Primary PM particles tend to be larger than particles formed in the atmosphere by atmospheric chemistry. Larger particles with effective diameters from 2.5 to 10 μm are designated coarse PM and typically account for most of the total mass of the aerosol measurements known as PM₁₀. PM₁₀ is less of a health problem than PM_{2.5} because it does not travel as deeply into the lungs, and coarse PM particles settle out relatively rapidly from the atmosphere.

Emissions of nitrogen oxides (NO_x = NO + NO₂) and volatile organic compounds (VOC) play an important role in air pollution chemistry. The combustion of fossil fuels by automobiles, electric power plants, industrial boilers, refineries, and other sources including chemical plants and painting facilities emits NO_x and VOC.¹⁹ Strategies designed to improve air quality focus on reducing NO_x and VOC emissions.

In the lower troposphere ozone and a significant fraction of atmospheric particles are formed by chemical reactions of NO_x and VOC. Ozone and PM formed in the atmosphere are known as secondary pollutants. Secondary PM particles typically are PM_{2.5}.²⁰ There is much overlap between the atmospheric chemistry that produces O₃ and PM_{2.5}, and therefore, planned air pollution control strategies for reducing O₃ may affect PM_{2.5} concentrations and vice versa. Formation rates and concentrations



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Table 1. Epidemiologic studies that have been used to estimate health effects used to develop the Environmental Benefits Mapping and Analysis Program—Community Edition used in this project.

END POINT	POLLUTANT	STUDY REFERENCE	AGE RANGE IN STUDY	RISK ESTIMATE FOUND IN THE STUDY (95% CONFIDENCE INTERVAL)
Premature mortality, all causes	PM _{2.5}	Krewski et al ³⁰	>29	RR = 1.06 (1.04–1.08) for 10 µg/m ³ increase in average PM _{2.5}
	O ₃	Levy et al ³¹	All ages	0.43% (0.29%–0.56%) change in mortality per 10 µg/m ³ change in O ₃
Hospital admissions, all cardiovascular	PM _{2.5}	Peng et al ³²	>65	0.68% (0.26%–1.10%) change in daily admission for 10 µg/m ³ increase in average PM _{2.5}
	O ₃	Schwartz ³⁴	>65	RR = 1.07 (1.00–1.15) for 50 µg/m ³ increase in average daily O ₃
Hospital admissions, all respiratory	PM _{2.5}	Zanobetti et al ³³	>65	2.07% (1.2%–2.95%) change in risk for 10 µg/m ³ increase in 2–d average PM _{2.5}
	O ₃	Peel et al ³⁶	All ages	RR = 1.14 (1.09–1.19)
Emergency room visits, asthma	PM _{2.5}	Mar et al ³⁵	All ages	RR = 1.04 (1.01–1.07) for 7 µg/m ³ in average daily PM _{2.5}
	O ₃	Ostro and Rothschild ³⁷	16–64	Effect estimate (β) = 0.00741 (0.00070)

Abbreviation: RR, relative risk.

of O₃ and secondary PM_{2.5} are highly nonlinear functions of NO_x and VOC concentrations and their VOC/NO_x ratio.^{21–23} For example, reductions in NO_x concentrations can lead to higher or lower O₃ concentrations depending on specific atmospheric conditions. Hydroxyl radical (HO) reactions with nitrogen dioxide (NO₂), sulfur dioxide (SO₂), and VOC are major sources of gas-phase production of nitrate, sulfate, and secondary organic aerosols (SOA). The concentrations of HO are highly nonlinear functions of NO_x and VOC concentrations.²⁴ Another important factor in determining inorganic secondary aerosol concentrations is ammonia concentration. The extent of the reactions that produce aerosol particles consisting of NH₄HSO₄, (NH₄)₂SO₄ and NH₄NO₃ depends on the relative concentrations of HNO₃, H₂SO₄ and NH₃, relative humidity, and temperature.^{25–28}

Meteorology is another very important factor that affects concentrations of O₃ and PM.²³ Summer days that are warm, clear, and with calm winds are associated with stagnant high-pressure conditions. On these days, NO_x and VOC concentrations increase in a polluted urban atmosphere and the resulting photochemistry increases O₃ concentrations. However, cool fall days are associated with low mixing heights and cooler temperatures that promote the condensation of ammonium nitrate particles from gas-phase ammonia and nitric acid. These conditions may cause dangerously high concentrations of PM.^{5,26–28} High O₃ and PM days are associated with health effects that are observed particularly in sensitive populations.

Air quality modeling systems that combine meteorology, emission source modeling, and atmospheric chemistry are used to predict the concentrations of air pollutants that include ozone and PM, and more recently they have been used with new software to assess health effects.^{22,29} The research presented in this article focuses on the health effects of planned emission reductions in the

South Coast Air Basin (SoCAB; Los Angeles and its surroundings). The emission reductions will affect ozone and secondary PM concentrations. Potential health benefits resulting from different emission reduction scenarios are estimated.

Air quality and health effects

Epidemiologic studies have shown that there are a large number of adverse health effects associated with ozone pollution and PM (Table 1).

The table shows several epidemiologic studies that were used to develop the Environmental Benefits Mapping and Analysis Program—Community Edition, version 1.1 (BenMAP-CE) used in this study.^{38,39} BenMAP-CE is a computer application that is widely used by federal, state, and local agencies to assess the relative benefits of air quality policies. It is a powerful open source program that can be enhanced or customized to the needs of specific users.

Health impact functions that quantitatively relate health effects to exposure to PM_{2.5} and ozone were developed from epidemiologic studies. The developers of BenMAP-CE assumed that the natural logarithm of the incidence of a health effect is linearly related to the concentration of an air pollutant (Figure 1). The figure shows a hypothetical relationship between the concentration of an air pollutant and the incidence of some adverse health effect that was derived from epidemiologic studies.³⁸ The slope, β, of the linear regression line relates the pollutant concentration to the incidence of an adverse health effect.

The slope, β, is used in a health impact function to make a health effect estimate, ΔY⁴⁰:

$$\Delta Y = Y_o \times \left(1 - e^{-\beta \times \Delta[X]}\right) \times Pop$$

The term $\Delta[X]$ is an air quality change and it is the difference between a chosen baseline air pollutant concentration and a concentration at some future year. In this study, PM and ozone concentrations during selected episodes that occurred during the year 2008 were used as the baseline concentrations, and therefore, 2008 will be referred as the base year in this article. The selected future year in this study is 2030. The same set of episodes with the 2008 meteorological conditions but with differing emission inventory scenarios for the year 2030 were modeled as discussed below. The air quality change, $\Delta[X]$, is the differences between the simulated future year and base year concentrations.³⁸

The exposed population, Pop , is the number of people in a region under consideration, and in this study, it was the SoCAB. BenMAP-CE has estimated population data sets from the year 2000 to 2040 that are derived from US Census data. BenMAP-CE can also estimate population data for different grid definitions (such as city and state) based on spatially weighted averages of original census data.⁴¹

The health baseline incidence rate, Y_0 , is the average number of people who die (or have another adverse health effect) in the population under consideration over a given period of time. One example of a health incidence rate is the probability that a person will die in a given year.³⁸

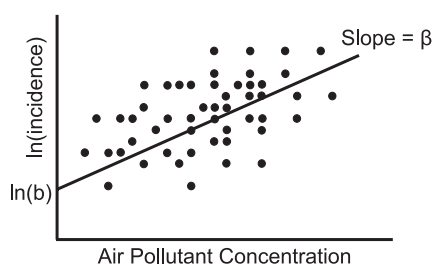


Figure 1. A hypothetical relationship between the concentration of an air pollutant and the incidence of an adverse health effect.

BenMAP-CE calculates the economic value of a change in air quality from the health effect estimate, ΔY .³⁸ The economic value estimate, V , is the product of the health effect, ΔY , and the benefit value or cost, C , of the health effect. The health effect estimate and economic value will vary from place to place across a region such as the SoCAB due to spatial variations in air pollutant concentrations and population:

$$V = \Delta Y \times C$$

The economic values for avoided mortalities are estimated according to the value of a statistical life based on 26 studies that included all ages.³⁸ The economic value for avoided emergency room visits and hospital admissions are calculated based on the cost of illness. Cost of illness includes the cost of medical treatment and the value of lost wages. The costs of medical treatment are estimated from the average length of a hospital stay for illnesses associated with poor air quality and average hospital daily charges. Wages lost are estimated based on the average length of a hospital stay per illness and the average daily wage, regardless of whether or not a particular individual is working.³⁹ The economic values associated with acute respiratory symptoms are estimated based on an individual's willingness to pay to avoid illness.

Methods

CMAQ model

The Community Multiscale Air Quality (CMAQ) model is an air quality model developed by the US Environmental Protection Agency (EPA) to simulate the formation of air pollutants, their concentrations, and distributions over spatial scales that range from urban to continental.^{42,43} CMAQ takes meteorological fields, chemical initial and boundary conditions, and emissions as input and uses these to simulate time-dependent, 3-dimensional distributions of air pollutants such as O_3 and PM (Figure 2).

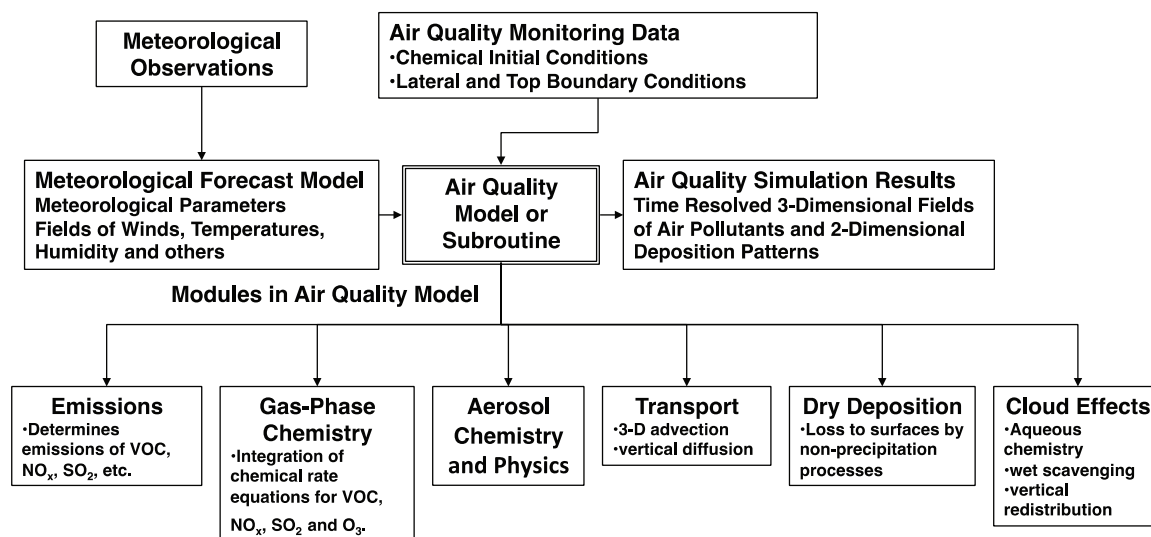


Figure 2. Components of a 3-dimensional meteorological air quality model.

Table 2. 2008 and 2030 model simulations with baseline total VOC and NO_x emissions and sensitivity cases with varying adjustments to baseline emissions.

YEAR	CASE	VOC				NO _x				RATIO, VOC/NO _x ppbC/ppbN
		TOTAL VOC, TPD	ADJUSTMENT FACTOR	Δ2008, %	Δ2030, %	TOTAL NO _x , TPD	ADJUSTMENT FACTOR	Δ2008, %	Δ2030— BASE, %	
2008	1R1N	639	1.0	0	46	723	1.0	0	155	2.9
2030	1R'2.5N'	437	1.0	-32	0	710	2.5	-2	150	2.1
	1R'1.75N'					497	1.75	-31	75	2.9
	1R'1N'					284	1.00	-61	0	5.1
	1R'.75N'					213	0.75	-70	-25	6.8
	1R'.5N'					141	0.50	-81	-50	10.4
	1R'.3N'					85	0.30	-88	-70	17.1

Abbreviation: VOC, volatile organic compounds.

CMAQ (version 4.7) was used to make the O₃ and PM simulations for this project. The aerosol module simulates both PM_{2.5} and PM₁₀. It simulates primary emissions of elemental and organic carbon, dust, and unspecified species. PM₁₀ particles include windblown dust and marine particles such as sea salt. It simulates secondary PM including sulfate, nitrate, ammonium, and SOA that are formed from anthropogenic and biogenic emissions. CMAQ's aerosol module was developed from the Regional Particulate Model (RPM),⁴⁴ and the RPM was derived from the Regional Acid Deposition Model, version 2 (RADM2).⁴⁵ The aerosol module in CMAQ represents the aerosol size distribution using a mode approach. The mode approach uses a superposition of 3 lognormal subdistributions (modes) to represent the aerosol size distribution.⁴⁶

CMAQ includes important physical processes such as coagulation. Differential equations for the number and species mass conservation are represented by analytical solutions to increase numerical accuracy. A very serious weakness in CMAQ aerosol module (and most other similar air quality models) is that it calculates PM concentrations somewhat independently of CMAQ gas-phase chemistry module. This is inconsistent with real atmospheric processes and it is a limitation on the accuracy of this and similar air quality modeling research.

Typical EPA-State Implementation Plan protocols for the development O₃ control strategies involve the selection and modeling of short-term episodes with high O₃ concentrations. The selected episodes have representative meteorology and emissions and have high-quality measurements. An analogous protocol was followed for this study of PM. Two episodes with high PM_{2.5} concentrations, representative meteorology and representative emissions, were selected for CMAQ modeling. The selected episodes had good-quality PM_{2.5} data to allow the simulations to be properly evaluated. The first episode began on Friday, September 12 and ended Monday, September 15, 2008, and the second episode began on Tuesday, November 11 and ended Monday, November 24,

2008. The selection of episodes for the base year is discussed in more detail elsewhere.^{47,48}

Base year modeling and sensitivity simulations. CMAQ model was used to make simulations of the selected high PM episodes for the base year. The South Coast Air Quality Management District (SCAQMD) provided the meteorological simulation data and emissions inventory required for CMAQ simulations.⁴⁹ The SCAQMD profile files for initialization were used.^{47,48} The modeling protocol included also running CMAQ with a 4 km × 4 km spatial grid resolution; the gas-phase chemistry mechanism was SAPRCC99 (with about 400 species of VOC) and the aerosol module with the 5-aerosol module with saprcc99_ae5_aq. A total of 18 days were simulated and analyzed (September 12-15, 2008 and November 11-24, 2008). A couple of extra days were simulated before each episode, and these extra days were regarded as "spin-up time" to fully initialize CMAQ.

Simulations were made to estimate the effect of changes in the VOC emission inventory on secondary PM_{2.5} for the base year and the effect of 6 NO_x emission reduction scenarios on PM_{2.5} for the future year (Table 2). The same meteorology that occurred during the selected high PM episodes for the base year was used to make additional CMAQ simulations with different emissions' inventory scenarios for the future year 2030. The target future year based on current SCAQMD emission reduction plans is scenario R'1N'1. The target reduction between 2008 and 2030 emissions for NO_x is 61%, and for VOC, the reduction is 32%. The target NO_x emissions for 2030 were multiplied by factors of 2.5, 1.75, 1.0, 0.75, 0.5, and 0.3 to create cases 1R'2.5N', 1R'1.75N', 1R'1N', 1R'.75N', 1R'.5N', and 1R'.3N', respectively. The VOC emissions were kept at the same levels as the target reduction in 32% for 2030.

The Environmental Benefits Mapping and Analysis Program—Community Edition. BenMAP-CE (version 1.1) was used in

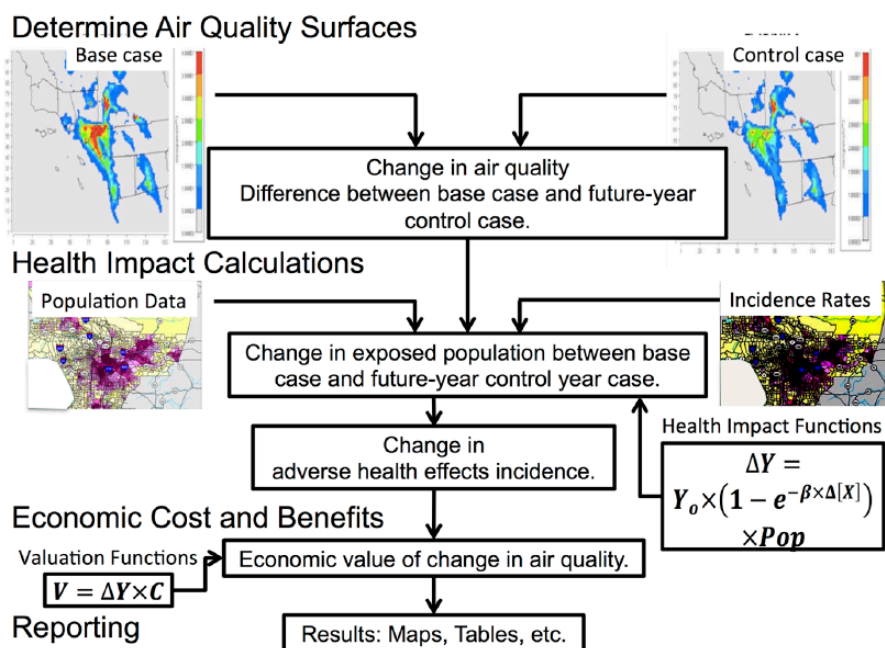


Figure 3. Steps and the input data files required to run BenMAP-CE (Environmental Benefits Mapping and Analysis Program—Community Edition).³⁸

this study to calculate health effect estimates and their economic value due to concentration changes in ozone and PM. As discussed above, epidemiologic studies were used to derive health impact functions and these functions are implemented in BenMAP-CE program. A user specifies air quality concentrations for a base case and concentrations that are expected after an emission control strategy is implemented. Concentration differences are calculated between the base year and a 2030 future year control strategy scenario. BenMAP-CE uses the concentration changes along with population data and health impact functions to estimate the health impact due to the pollutant concentration changes.

Three major steps are required for BenMAP-CE to estimate the health and economic benefits associated with changes in air quality (Figure 3). The first step is to create 2-dimensional air quality surfaces for a base case and a control strategy case. During the second step, BenMAP-CE is used to estimate the health impact due to the change in air quality between the 2 cases. In the third step, BenMAP-CE is used to estimate the economic value of the health impact.^{38,48,50} The base year case (1R1N) was used as baseline for all analysis made to evaluate the health and economic benefits of the 6 future year NO_x and VOC emission control scenarios.

Air quality surfaces were created for both O₃ and PM_{2.5} based on the difference between the base year and the future year pollutant concentrations for the SoCAB. Air quality surfaces were created for each of the 6 future year simulations; a set of 6 surfaces for PM_{2.5} and 6 for O₃ was created. These air quality surfaces were then used to make health impact estimates for the end points involved with premature death, respiratory disease, and cardiovascular disease (Table 1). The impacts due to O₃ and PM_{2.5} exposure, were examined

separately in this project, and the impacts included avoided mortalities, emergency room visits due to asthma, hospital admissions (due to both respiratory and cardiovascular causes), and acute respiratory symptoms.

In this study, the spatial region used was the SoCAB, and the population was the predicted population of the SoCAB region in the year 2030. During each BenMAP-CE run, the program was set to do 10 000 Monte Carlo simulations when estimating health outcomes. Finally, the economic value of the health impacts for each of the 6 future year sensitivity cases was calculated for both O₃ and PM_{2.5} exposure.

Results

CMAQ model base year simulations and evaluation

Simulations of the 2 high PM episodes were evaluated together by comparing simulated PM_{2.5} and other calculated components with SoCAB measurements data. The details of the evaluation are provided elsewhere.^{47,48} The simulated concentrations of PM_{2.5} were low as shown by the normalized mean error (NME) and the normalized mean bias at 6 PM_{2.5} measurement sites in the SoCAB (Figure 4). The 2008 base year simulations all displayed negative mean bias. Eder and Yu⁵¹ suggest that acceptable model performance for PM simulations is a NME within 50%. However, there is no generally accepted statistic for acceptable model performance for PM modeling.

The NME was within 50% for 4 of the 6 stations with Fontana being close. However, CMAQ simulations for Azusa did not meet this NME standard. Considering all stations, the normalized error was 47.25% and that was within the suggested standard.⁵¹

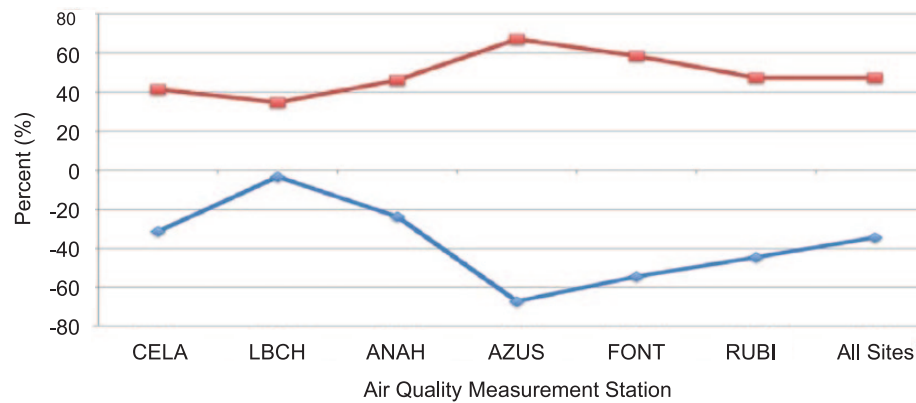


Figure 4. Normalized mean error (upper line) and the normalized mean bias (lower line) are shown for 6 $PM_{2.5}$ measurement sites in the South Coast Air Basin (Los Angeles [CELA], Long Beach [LBCH], Anaheim [ANAH], Azusa [AZUS], Fontana [FONT], and Rubidoux [RUBI]) and all 6 sites combined.

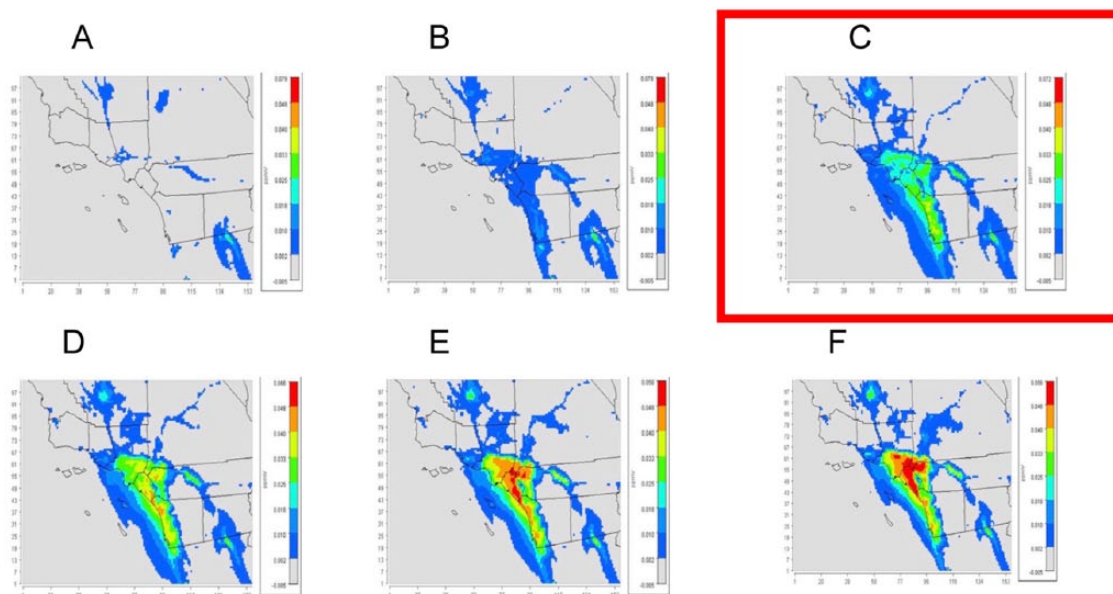


Figure 5. Contour plots showing 8-hour average O_3 concentration due to adjustments in 2030 NO_x emissions over Southern California during the aerosol season. The red box outlines the future year target emission scenario. (A) $1R'N'2.5$, (B) $1R'N'1.75$, (C) $1R'N'1$, (D) $1R'N'0.75$, (E) $1R'N'0.50$, and (F) $1R'N'0.30$.

CMAQ model future year simulations

Average 8-hour O_3 plots were made for the fall aerosol season for the future year emission cases (Figure 5). For these cases, lower NO_x emissions led to greater the O_3 concentrations across the SoCAB. The highest reduction in 2030 NO_x emissions from the base year led to the highest concentrations of O_3 across the basin. This is probably due to the relatively low rate of nitrogen dioxide photolysis during the fall. Because this is the source of O_3 , a lower production rate increases the importance of O_3 titration by NO . If there is limited NO available to destroy O_3 , there will be an increase in O_3 concentrations with lower NO_x emissions.

CMAQ simulated 24-hour average $PM_{2.5}$ concentrations over the SoCAB for the future year on November 20, 2030 during the Fall-Winter Aerosol Season are presented (Figure 6). Plot C is the simulation with the projected 2030 NO_x emission inventory and over the basin shows the highest

24-hour average $PM_{2.5}$ concentrations. Plots A and B show simulations with the projected 2030 NO_x emission inventory multiplied by factors of 2.5 and 1.75, respectively. Between plots A, B, and C, the simulated 24-hour average $PM_{2.5}$ concentrations decrease with increasing emissions. Plots D, E, and F show simulations with the projected 2030 NO_x emission inventory multiplied by factors of 0.75, 0.50, and 0.30, respectively. Over the sequence between C and F, the simulated 24-hour average $PM_{2.5}$ concentrations decrease with decreasing NO_x emissions. Therefore, the projected 2030 NO_x emission inventory is the least effective in reducing 24-hour average $PM_{2.5}$ concentrations than any of the other NO_x emission inventory scenarios simulated.

The mass concentrations of ammonium nitrate show the greatest sensitivity to changes in VOC and NO_x emissions. Simulated component compounds at Anaheim are shown as an example (Figure 7). Ammonium nitrate mass concentrations

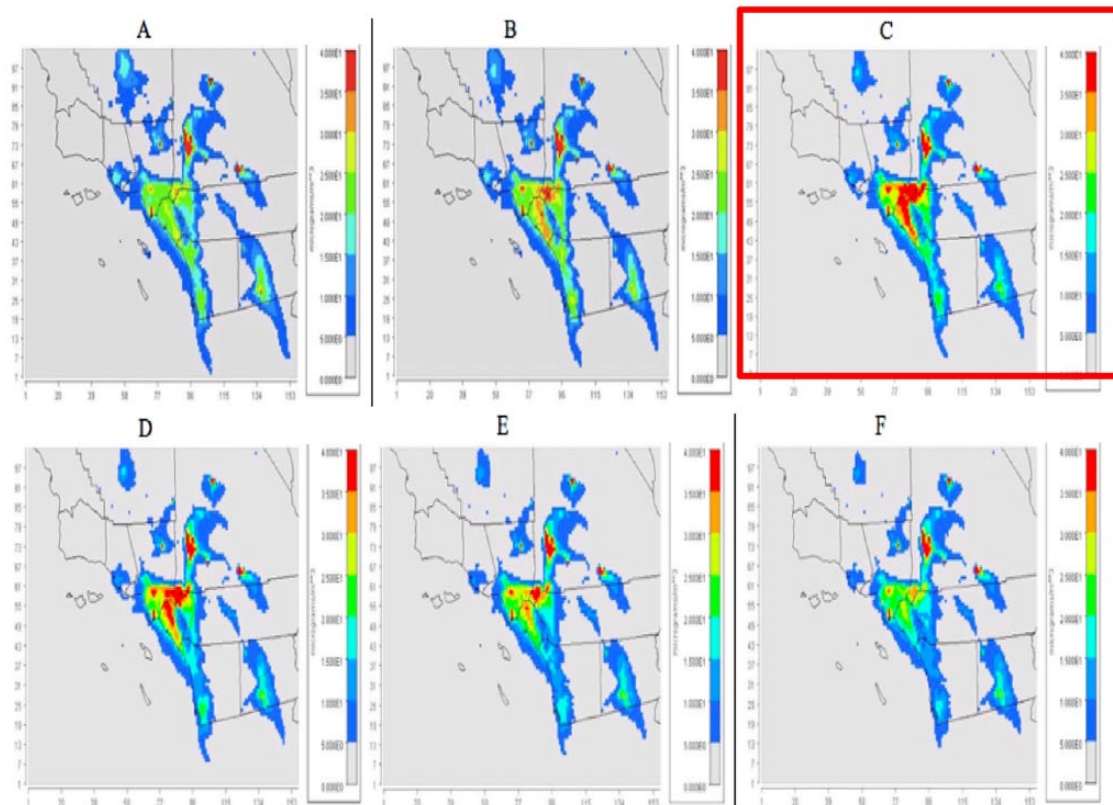


Figure 6. Community Multiscale Air Quality–simulated 24-hour average PM_{2.5} concentrations over the South Coast Air Basin for the future year on November 20, 2030 during the Fall-Winter Aerosol Season. The plot outlined in red shows the plot associated with the emission reductions in VOC and NO_x planned for the year 2030. The other plots are simulations with the NO_x emissions multiplied by the factors given about the plots and to the right of the N' labels. The VOC emissions were not varied. (A) 1R'N'2.5, (B) 1R'N'1.75, (C) 1R'N'1, (D) 1R'N'.75, (E) 1R'N'.5, and (F) 1R'N'.3. VOC indicates volatile organic compounds.

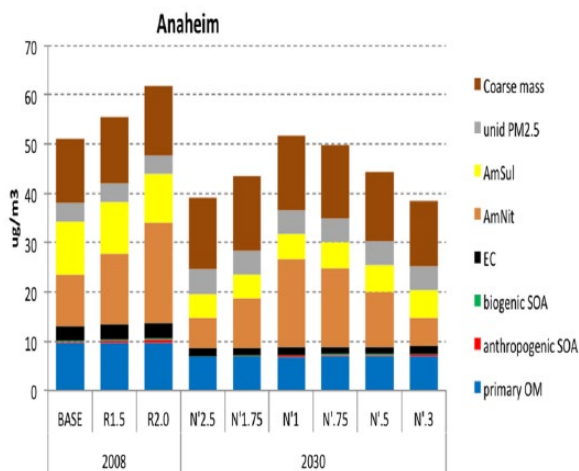


Figure 7. Stack plot of simulated particulate matter mass concentrations by component for the 2008 base year and the future year at Anaheim. The components are primary organic matter (primary OM), anthropogenic secondary organic aerosol (anthropogenic SOA), biogenic secondary organic aerosol (biogenic SOA), elemental carbon (EC), ammonium nitrate (AmNit), ammonium sulfate (AmSul), unidentified PM_{2.5} (unid PM_{2.5}), and coarse mass.

increase as VOC emissions are increased for the base year. For the future year, the ammonium nitrate mass concentration is greatest for the target 2030 NO_x emission case N'1. For cases

N'2.5 and N'1.75, the ammonium nitrate mass concentrations are less than the N'1 case and the ammonium nitrate mass concentrations decrease with increasing NO_x emissions. Cases N'.75, N'.50, and N'.3 all have lower NO_x emissions than N'1, and for these cases, there are lower ammonium nitrate concentrations as NO_x emissions are reduced.

Comparison of the PM_{2.5} components shows that the greatest change between the base year (BASE) and the target future year NO_x emissions scenario (N'1) was in the ammonium nitrate mass concentration (Figure 7). The ammonium nitrate mass concentration increased in the future year.

Health and economic benefits associated with the response of PM_{2.5} and O₃ to adjustments in VOC and NO_x emission between the base and future year

Health burden for the base year scenario. The concentration of PM_{2.5} and O₃ from the base case (1R1N) CMAQ simulation was used as the baseline air quality case for the SoCAB. The health and economic burdens associated with the 2008 baseline PM_{2.5} and O₃ concentrations in all 4 counties in the SoCAB were estimated. According to the State of California's Department of Public Health, there were 11 189, 13 137, 16 179, and 55 108 mortalities, respectively, in San Bernardino, Riverside,

Table 3. Estimated PM_{2.5}-related health burden for the base year scenario.

COUNTY	NO. OF MORTALITIES OCCURRING DURING 2008—CALIFORNIA DEPARTMENT OF PUBLIC HEALTH DATA ^a	PM _{2.5} -RELATED MORTALITIES BASED ON BENMAP-CE ESTIMATE IN 2008 BASE YEAR	PERCENT MORTALITIES DIRECTLY RELATED TO 2008 PM _{2.5} EXPOSURE
San Bernardino	11 189	131	1.17
Riverside	13 137	434	3.30
Orange	16 179	409	2.53
Los Angeles	55 108	781	1.42

Abbreviation: BenMAP-CE, Environmental Benefits Mapping and Analysis Program—Community Edition.

^aMortalities as a result of accidents and intentional self-harm or suicide are not included.

Table 4. Estimated O₃-related health burden for the base year scenario.

COUNTY	NUMBER OF MORTALITIES OCCURRING DURING 2008—CALIFORNIA DEPARTMENT OF PUBLIC HEALTH DATA ^a	O ₃ -RELATED MORTALITIES BASED ON BENMAP-CE ESTIMATES FOR 2008	PERCENT MORTALITIES DIRECTLY RELATED TO 2008 PM _{2.5} EXPOSURE
San Bernardino	11 189	301	2.69
Riverside	13 137	287	2.18
Orange	16 179	346	2.14
Los Angeles	55 108	1356	2.46

Abbreviation: BenMAP-CE, Environmental Benefits Mapping and Analysis Program—Community Edition.

^aMortalities as a result of accidents and intentional self-harm or suicide are not included.

Orange, and Los Angeles County in 2008. Mortalities caused from accidents and intentional self-harm or suicide were not included in the total deaths presented here because these deaths are not associated with poor air quality.

Using BenMAP-CE, we estimate at the 95% confidence interval (CI) that in 2008 exposure to PM_{2.5} was responsible for 131 (CI: 89-173), 434 (CI: 296-569), 409 (CI: 278-539), and 781 (CI: 596-1031) deaths, respectively, in San Bernardino, Riverside, Orange, and Los Angeles County in 2008 (Table 3). Exposure to O₃ was responsible for 301 (CI: 208-392) deaths in San Bernardino, 287 (CI: 199-375) deaths in Riverside County, 346 (CI: 234-450) deaths in Orange County, and 1356 (CI: 938-1765) deaths in Los Angeles County (Table 4). These results taken together indicate that O₃ and PM_{2.5} exposure in 2008 was responsible for at least 3.86%, 5.48%, 4.67%, and 3.88% of the total 2008 deaths in San Bernardino, Riverside, Orange, and Los Angeles County, respectively.

Avoided premature mortalities. The health impacts resulting from the change in PM_{2.5} concentrations between the base year and the future year with the target 2030 VOC and NO_x emissions (1R'N'1 case) resulted in a total of 750 (CI: 508-990) avoided mortalities (aged 30-99 years) across the SoCAB. In this reduction scenario, 53 (CI: 36-70) avoided mortality cases were estimated in Los Angeles, 161 (CI: 109-212) cases in San Bernardino, 390 (CI: 264-513) in Riverside, and 146 (CI: 99-193) in Orange County.

The target future year scenario saved the fewest lives among all the 6 control scenarios assessed (Figure 8). An 88% reduction in NO_x emissions from 2008 to the future year (1R'N'0.3 case) led to the greatest reduction in PM_{2.5} concentrations (Figure 6). The basin-wide decrease in PM_{2.5} concentrations due to the 88% reduction in NO_x emissions increased the total lives saved from 750 (CI: 508-990) to 1244 (CI: 846-1635). The number lives saved in this control strategy would increase by 17% in Los Angeles, 35% in San Bernardino, 107% in Riverside, and 8% in Orange County.

The high percentage increase in the avoided deaths in Riverside may be caused by the shift in spatial distribution of PM_{2.5} particles across the SoCAB. The decrease in 2030 PM_{2.5} concentrations based on NO_x reductions in 2% (1R'N'2.5), 31% (1R'N'1.75), 70% (1R'N'0.75), and 81% (1R'N'0.5) resulted in total avoided mortalities of 817 (CI: 554-1076), 697 (CI: 472-919), 883 (CI: 599-1165), and 1074 (CI: 729-1415), respectively, across the basin (Figure 8).

Avoided hospital admissions: respiratory and cardiovascular causes. The decrease in PM_{2.5} concentrations between the base year and the future year with the targeted 2030 VOC and NO_x emissions may lead to a total of 172 (CI: 99-245) avoided hospital admissions due to respiratory causes across the SoCAB (Figure 9). The most avoided respiratory hospital admissions due to PM_{2.5} were in Riverside County (84 avoided cases, CI: 48-119), and the fewest avoided respiratory cases were in Los Angeles County (15 cases, CI: 9-21). When NO_x emissions are

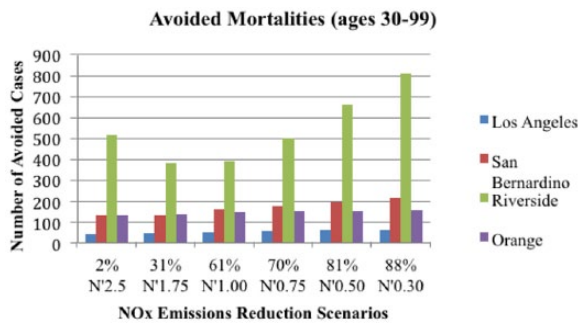


Figure 8. Estimated avoided PM_{2.5}-related future year mortalities for the 6 volatile organic compounds and NO_x emission reduction scenarios in the South Coast Air Basin region.

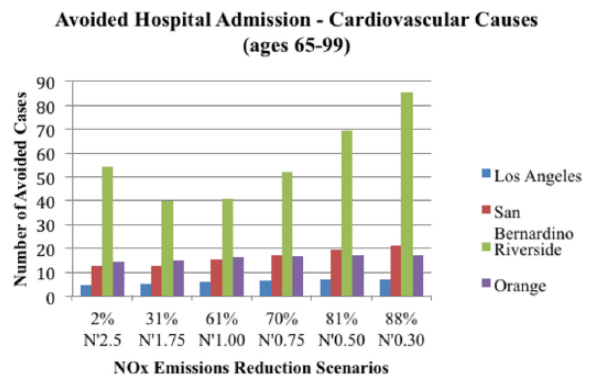


Figure 10. Estimated avoided PM_{2.5}-related future year hospital admissions due to cardiovascular causes for the 6 volatile organic compounds and NO_x emission reduction scenarios in the South Coast Air Basin region.

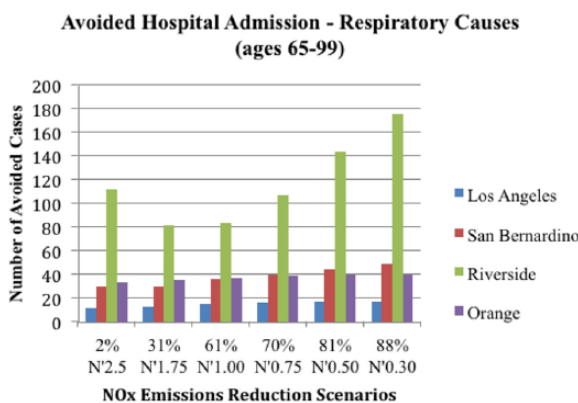


Figure 9. Estimated avoided PM_{2.5}-related future year hospital admissions due to respiratory causes for the 6 volatile organic compounds and NO_x emission reduction scenarios in the South Coast Air Basin region.

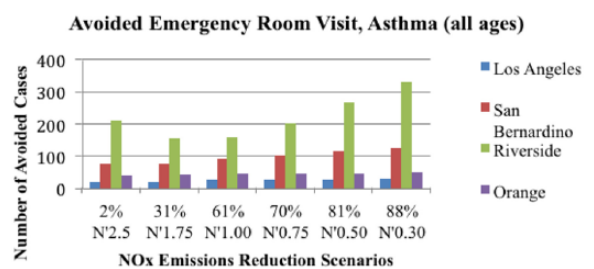


Figure 11. Estimated avoided PM_{2.5}-related future year emergency room visits due to asthma for the 6 volatile organic compounds and NO_x emission reduction scenarios in the South Coast Air Basin region.

reduced by 88% from the base year, the total number of avoided respiratory cases increased from 172 (CI: 99-245) to 282 (CI: 163-400). The number of avoided cases also increased in Los Angeles (17 cases, CI: 10-25), San Bernardino (49 cases, CI: 28-70), Riverside (175 cases, CI: 101-248), and Orange County (40 cases, CI: 23-57).

There were fewer avoided hospital admissions (78 cases, CI: 30-127) due to cardiovascular causes than respiratory causes (Figures 9 and 10) for the future year with the targeted 2030 VOC and NO_x emissions. Los Angeles had only 6 avoided cardiovascular cases (CI: 2-10). In San Bernardino, Riverside, and Orange County, there were 15 (CI: 6-25), 41 (CI: 16-66), and 16 (CI: 6-26) avoided cases, respectively (Figure 10). The most avoided hospital admissions for cardiovascular causes were estimated when 88% reductions in NO_x emissions were made across the SoCAB.

There were more avoided emergency room visits for asthma than hospital admissions for both respiratory and cardiovascular causes due to NO_x and VOC emission control in the future year (Figure 11). A total of 322 (CI: 85-555) asthma cases may be avoided if the targeted 2030 emissions are met. But similar to respiratory and cardiovascular causes, the most avoided asthma cases were in Riverside County (158 cases, CI: 42-270) and the fewest number of asthma cases were in Los Angeles

County (25 cases, CI: 7-44). There was a 16% increase in avoided asthma cases in Los Angeles with an 88% reduction in NO_x emissions. The 88% reduction in NO_x emissions scenario also increases the number of avoided asthma cases by 35.5%, 108.2%, and 6.1% in San Bernardino, Riverside, and Orange County, respectively.

Overall, Los Angeles benefited the least for avoided asthma cases from all emission control scenarios. This may be because of the spatial distribution of particles over SoCAB. The heavy pollution from this highly populated city in the SoCAB (10.02 million, US 2013 Census data)⁵² causes the PM_{2.5} particles to be highly concentrated over Los Angeles County and less affected by NO_x emission reductions for all of the control scenarios.

Ozone-related health impacts based on NO_x emissions reduction

Avoided premature mortalities due to ozone. The targeted reduction in VOC and NO_x emissions across the basin between the base year and the future year resulted in 204 (CI: 140-260) total avoided O₃-related deaths (Figure 12). Exposures to high concentrations of PM_{2.5} particles generally cause more pre-mortalities than O₃.^{53,54} The changes in O₃ concentrations for this scenario were beneficial in Los Angeles (160 avoided deaths, CI: 110-210) and San Bernardino County (45 avoided

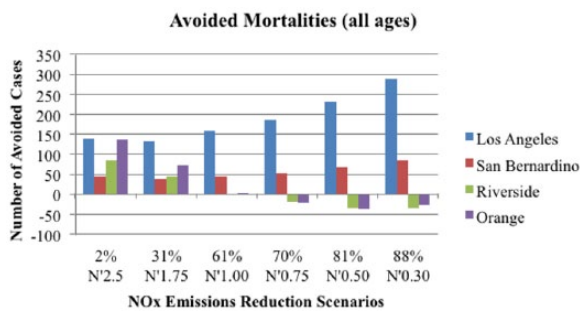


Figure 12. Estimated avoided O₃-related future year mortalities for the 6 volatile organic compounds and NO_x emission reduction scenarios in the South Coast Air Basin region.

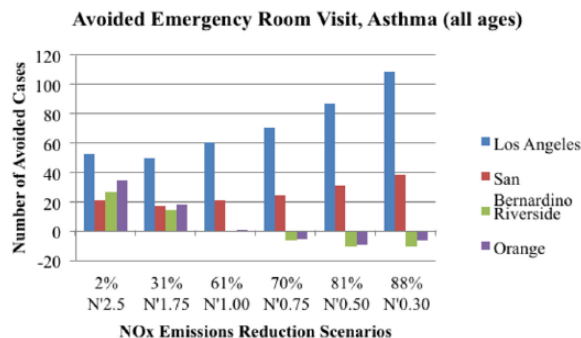


Figure 14. Estimated avoided O₃-related future year emergency room visits for the 6 volatile organic compounds and NO_x emission reduction scenarios in the South Coast Air Basin region.

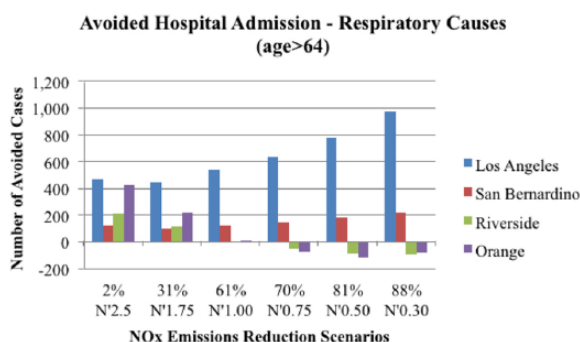


Figure 13. Estimated avoided O₃-related future year hospital admissions due to respiratory causes for the 6 volatile organic compounds and NO_x emission reduction scenarios in the South Coast Air Basin region.

deaths, CI: 31-60). However, in Riverside and Orange County, the changes in O₃ were not beneficial. It was estimated that 2030 base O₃ concentrations will cause one additional death in Riverside County and that no lives were saved in Orange County. Significant reductions in NO_x concentrations increased O₃ concentrations during the winter (Figure 5). This trend was also captured in BenMAP-CE analysis. For the 88% reduction in NO_x case, the number of deaths decreased by 81% in Los Angeles and 87% in San Bernardino County from the base year. The increase in O₃ concentrations due to the highest NO_x emission reduction scenario resulted in an increase in the number of deaths at Riverside (34 deaths, CI: 23-45) and San Bernardino (26 deaths, CI: 18-34) (Figure 12).

Avoided hospital admissions due to respiratory causes: asthma-related emergency room visits and acute respiratory symptoms due to ozone. The targeted reduction in VOC and NO_x emissions across the basin between the base year and the future year resulted in produced changes in ozone concentrations that were estimated to avoid 659 (CI: 196-1114) total hospital admissions due to respiratory causes across the SoCAB (Figure 13). Los Angeles and San Bernardino benefited from the changes in O₃ concentrations with 541 (CI: 160-914) and 122 (CI: 36-206) avoided respiratory cases. The future year O₃ concentrations led to a disbenefit for Riverside with BenMAP-CE predicting that there would be 4 (CI: 1-7) more cases of hospital admissions. In

Orange County, the number of respiratory cases was not predicted to change. Decreasing NO_x emissions to 88% of the base year led to a reduction in the number of hospital admissions by 79.6% in Los Angeles and 84.4% in San Bernardino County. At this NO_x reduction level, the O₃ concentration at Riverside increased the number of respiratory cases from 4 to 91. There was also an increase in the number of respiratory cases in Orange County (0-81 cases, CI: 24-140).

Similar trends were also observed for avoided emergency room visits due to asthma (Figure 14). For the future year target emissions case, the resulting O₃ concentrations led to 80 (CI: -16 to 176) avoided asthma cases in the SoCAB. These O₃ concentrations were beneficial in Los Angeles (60 cases avoided, CI: -12 to 131) and San Bernardino (21 cases avoided, CI: -4 to 45). However, in Riverside and Orange County, no avoided asthma cases were estimated. If 2008 NO_x emissions were reduced by 88% in 2030, this results in an estimated 109 (CI: -21 to 237) avoided asthma cases in Los Angeles and 38 (CI: -7 to 84) avoided cases in San Bernardino (Figure 14). In accordance with the other health impacts, the O₃ change for the 88% reduction scenario led to an increase in the number of asthma case at Riverside (11 more cases, CI: 2 to -24) and Orange County (6 more cases, CI: 1 to -14).

For acute respiratory symptoms, the O₃ concentrations for future year target emissions case resulted in 184 705 (CI: 76 412-291 896) avoided cases in Los Angeles, 53 134 (CI: 21 984-83 962) avoided cases in San Bernardino and 129 (CI: 55-199) avoided cases in Orange County (Figure 15). In Riverside County, the future year O₃ concentrations were estimated to increase the number of cases of acute respiratory symptoms (1520 more cases, CI: 599-2491). The O₃ concentrations from the 88% NO_x emission reduction case increased the number of acute respiratory symptoms to 39 697 (CI: 16 163-63 741) in Riverside and 29 604 (CI: 12 167-47 091) in Orange County. In Los Angeles and San Bernardino County, the numbers of acute respiratory symptoms decreased by 80% and 85%, respectively.

Total monetized health benefits for NO_x and VOC emission scenarios in the SoCAB region. The total health costs related to

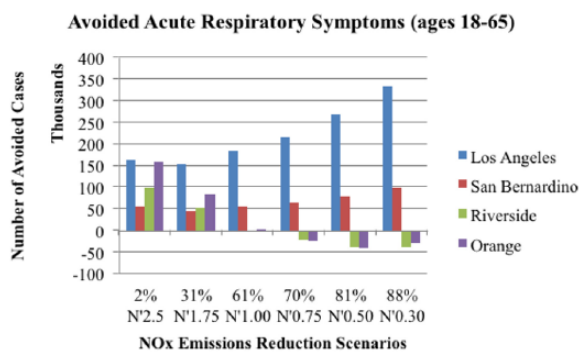


Figure 15. Estimated avoided O₃-related future year acute respiratory symptoms for the 6 volatile organic compounds and NO_x emission reduction scenarios in the South Coast Air Basin region.

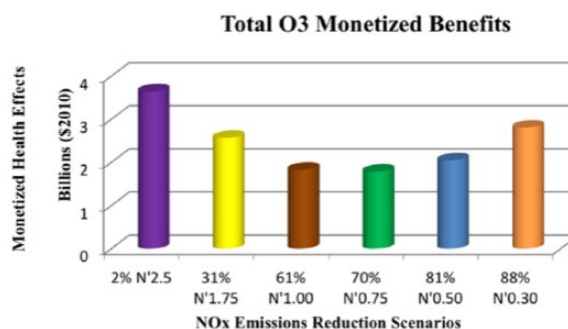


Figure 17. Total monetized health benefits for all avoided O₃-related health impacts for the 6 volatile organic compounds and NO_x emission reduction scenarios in the South Coast Air Basin region.

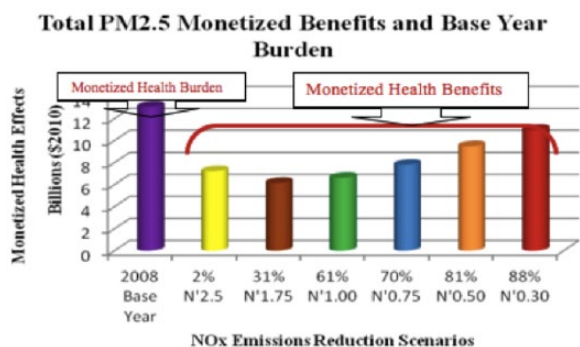


Figure 16. Total monetized health benefits for all avoided PM_{2.5}-related health impacts for the 6 volatile organic compounds and NO_x emission reduction scenarios in the South Coast Air Basin region.

PM_{2.5} in 2008 are estimated to be US \$13.06 billion (in 2010 constant dollars) (Figure 16). This base year total health cost was estimated from the sum of monetized health impacts associated with the number of mortalities, acute respiratory symptoms, hospital admissions due to respiratory causes, and emergency room visits due to asthma in all counties in the SoCAB. In the future year scenario with the target VOC and NO_x emissions, the number of deaths from PM_{2.5} exposure resulted in the highest economic burden. In this future year scenario, the decrease in PM_{2.5} concentrations led to a total avoided cost of US \$6.6 billion (in 2010 constant dollars) (Figure 16). However, the resulting economic benefits from this control strategy were significantly lower than other 2030 reduction scenarios evaluated in this study. The trend in total economic benefit of each control scenario analyzed is shown (Figure 16). For the 88% NO_x reduction strategy, there was an increase in 66% in the total avoided cost from the target emission future year scenario. This means that significantly greater NO_x reductions from 2008 emission levels might save the SoCAB region billions of dollars. For the 70% and 81% NO_x emission reduction cases, there was an increase in the total avoided costs by 17.7% and 42.3% across the basin.

For O₃, the economic benefits of future year NO_x reductions were lower than PM_{2.5}. This is consistent with previous studies that suggest that PM_{2.5} exposure can lead to more mortalities

than O₃.^{53,54} The O₃ concentrations at the 2030 target emission case resulted in a total economic benefit of US \$1.83 billion (in 2010 constant dollars). Even though there was an NO_x disbenefit for some counties in the basin (lower NO_x emissions increased O₃ concentrations), the total economic benefit increased by 54% from the 2030 target emission case to the 88% NO_x emission case (Figure 17). The increase in avoided cases in Los Angeles and San Bernardino County at the NO_x reduction level may have caused the overall increase in the economic benefit across the basin. The economic benefit at the 2%, 31%, and 81% NO_x reduction strategies results in an increase in the avoided costs by 99%, 40%, and 12% over the future year case with the target VOC and NO_x emissions, respectively. However, at the 75% NO_x emission reduction, the basin will lose 2.2% in avoided O₃-related medical costs compared with the 2030 target emission case.

Conclusions

Epidemiologic studies have shown that there are a large number of adverse health effects associated with ozone and PM. Adverse health impacts of air pollution include premature death, respiratory disease, and cardiovascular disease. CMAQ and BenMAP-CE are useful tools to assess the health impacts of proposed air quality improvement strategies.

CMAQ was used to simulate air quality of the SoCAB for selected fall season episodes. The selected episodes occurred during the year 2008 and therefore it was considered to be the base year. These episodes with the same 2008 meteorological conditions but with differing emission inventory reduction scenarios for the year 2030 were simulated and therefore the year 2030 was regarded as the future year. BenMAP-CE was used to assess health impacts of O₃ and PM_{2.5} during the base year and to evaluate the health benefits of reducing O₃ and PM_{2.5} concentrations between the base and future years.

It was found that for the base year, exposure to PM_{2.5} could be responsible for 131, 434, 409, and 781 deaths in San Bernardino, Riverside, Orange, and Los Angeles County, respectively. The economic benefits analysis estimated the total cost of 2008 PM_{2.5} health-related impacts across the SoCAB to be US \$13.06 billion (in 2010 constant dollars).

During the base year exposure to O₃ and PM_{2.5} could be responsible for a combined total of 432, 721, 755, and 2137 deaths, and these correspond to 3.9%, 5.5%, 4.7%, and 3.9% of deaths in San Bernardino, Riverside, Orange, and Los Angeles County, respectively. Exposure to PM_{2.5} may cause 30%, 60%, 54%, and 37% of the total deaths attributed to O₃ and PM_{2.5}, respectively.

The effect of NO_x emission reductions on health impacts due to O₃ exposure across the SoCAB was more complicated than PM_{2.5} during the fall due to lower temperatures and lower photolysis. Reductions in NO_x emissions increased O₃ concentrations in some areas of the SoCAB, whereas reducing them in others. The reductions in NO_x could lead to increases in adverse health outcomes during the fall season. In Riverside County, the future year O₃ concentrations were estimated to increase the number of cases of acute respiratory symptoms yielding 1520 more cases in the fall, although further reductions in NO_x emissions led to even more cases.

The current target emission control strategy for the SoCAB is not the most effective scenario for reducing health impacts resulting from PM_{2.5} exposure of the strategies evaluated for reducing harmful air quality outcomes. A strategy with lower or greater levels of NO_x emission reductions would be better for reducing PM_{2.5} concentrations. Reductions in NO_x emissions for the future year had the greatest effect on PM_{2.5} concentrations and health in Riverside County, whereas Los Angeles County was the least affected.

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Author Contributions

DRS performed the air quality modeling and led the health effects modeling, ES developed health effects modeling protocols used in this project, RAP performed air quality modeling, RF was a co-leader of the project and was responsible for the air quality modeling, DEC performed data analysis and model evaluation, and WRS conceived the project, was a co-leader, and wrote the final manuscript.

Disclosures and Ethics

As a requirement of publication, authors have provided to the publisher signed confirmation of compliance with legal and ethical obligations including but not limited to the following: authorship and contributorship, conflicts of interest, privacy, and confidentiality. No human or animal subjects were involved. The authors have read and confirmed their agreement with the ICMJE authorship and conflict of interest criteria. The authors have also confirmed that this article is unique and not under consideration or published in any other publication, and that they have permission from rights holders to reproduce any copyrighted material. There are no additional disclosures to make.

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