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Measuring the gains from improved air quality in the San Joaquin Valley

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Abstract

Many regions worldwide are experiencing rapid urbanization, and often along with growth in the local economy and population comes worsening air quality. Such regions typically find that addressing the additional challenge of polluted air is difficult. This paper reports the results of an assessment of the present health and related economic costs of poor air quality in the San Joaquin Valley of California. Further, it suggests how such assessments can support strategies to pursue pollution reductions that offer the largest near-term gains, by rigorously modeling the associations between pollution levels, demographic groups, and recognized adverse health effects.

Keywords: Air pollution; Health effects; Control strategies; Economic costs; Benefit maximization

1. Introduction

Within the United States, only the Los Angeles and Houston regions have air pollution levels that rival those in the San Joaquin Valley (SJV) of California, which is classified by the U.S. Environmental Protection Agency (EPA) as a serious nonattainment area for both ozone and fine particulate matter ($PM_{2.5}$). Further, the region's maximum 8-h ozone concentrations have barely declined from 1990 to 2004 and annual $PM_{2.5}$ levels must be reduced by almost 30% to comply with the National Ambient Air Quality Standards (NAAQS). Attaining the current federal $PM_{2.5}$ standard, which is under review to be tightened, will be especially difficult, and exposure to this pollutant is now viewed as carrying the greatest air pollution-related health risks of the criteria pollutants. In the context of setting priorities and determining how best to improve air quality, assessment of the relative contributions of fine particle and ozone pollution to adverse health impacts and the economic losses associated with these impacts can help policymakers understand how emissions reductions can generate the largest near-term health gains.

Adverse effects clearly associated with ozone range from school absences and hospitalizations to symptoms that limit normal daily activity. $PM_{2.5}$ exposure is linked to a range of effects from premature death and the onset of chronic bronchitis to lost work days and respiratory symptoms. Recent research (Bell et al., 2004) confirms an association between ozone exposure and premature mortality, but the impact is significantly less than that of fine particles.

Between 1990 and 2004, ozone concentrations in the SJV exceeded the health-based 8-h NAAQS on from 84 to 134 days a year. Ozone levels are typically elevated in the summer months, so this suggests that air is unhealthful on most summer days. Not only is the NAAQS frequently violated, but between 2001 and 2004 the maximum 8-h concentration was 65% above the standard (see Fig. 1). While the region has achieved reductions in coarser particle (PM_{10}) levels, concentrations of the more dangerous fine particles—$PM_{2.5}$—remain unhealthful. To meet the maximum 24-h NAAQS, levels must fall by more than 10%, and annual average concentrations must fall by nearly 30% (see Fig. 2). Attaining the California standard (CAAQS) requires a drop of 50%. These health-based standards will

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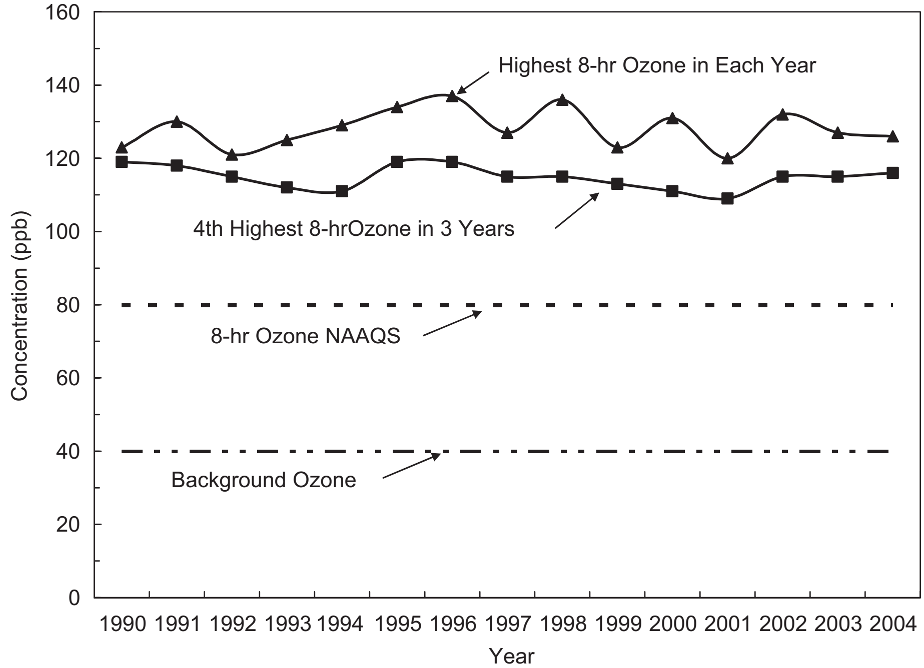

Fig. 1. Maximum 8-h ozone concentrations in the San Joaquin Valley relative to the NAAQS.

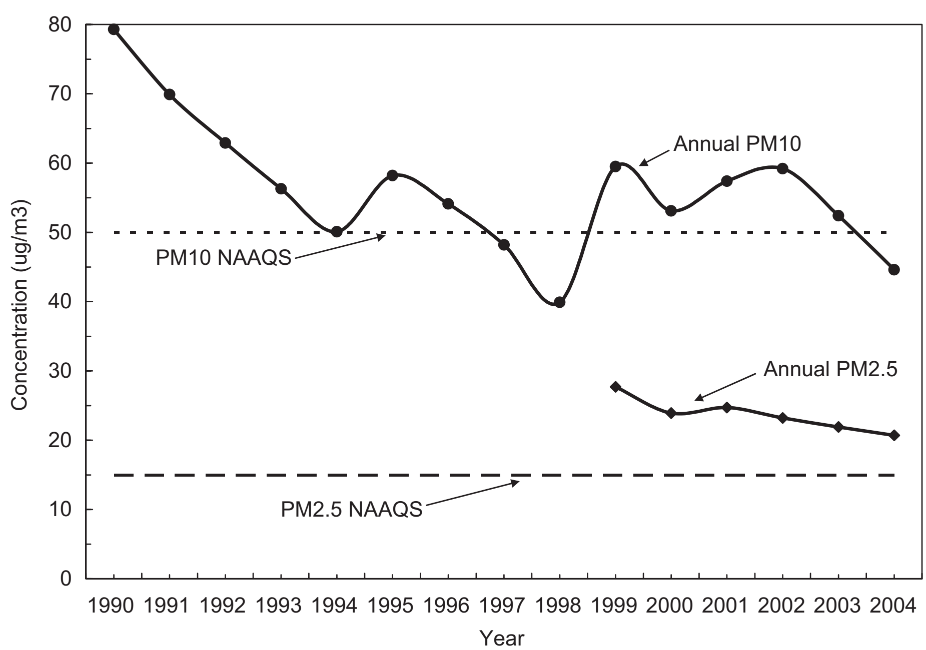

Fig. 2. Annual average $PM_{2.5}$ and PM_{10} concentrations in the San Joaquin Valley relative to the NAAQS.

be very difficult to achieve in the SJV because of the high population and economic growth rates, and the topographic features of the valley which tend to trap both locally emitted pollutants and pollutants transported from the San Francisco and the Sacramento areas (Blumenthal et al., 1997; MacDonald et al., 2006).

In this study, a well-established three-stage approach is used to determine the benefits of attaining the ozone and $PM_{2.5}$ air quality standards by identifying and quantifying the links between air quality and exposure, exposure and ill health, and avoiding ill health and the associated economic gains from better health (Hall et al., 1992). First, a regional human exposure model (REHEX) estimates the population's exposure to concentrations above the air quality standards, accounting for the spatial and temporal pollution and demographic patterns across the region.[1] Second,

[1]For more detail on the REHEX model, see Lurmann et al. (1989, 1999), Lurmann and Korc (1994), Lurmann and Kumar (1996), and Fruin et al. (2001).

these exposure estimates are coupled with concentration–response functions from the health science literature to calculate how many fewer adverse health effects and premature deaths would be expected if the 2004 population instantaneously experienced attainment of the NAAQS. Finally, dollar values are applied to the avoided adverse health effects and extended lives to estimate the social value of more healthful air.

2. Materials and methods

2.1. The exposure assessment approach

Accurate estimates of human exposure to inhaled air pollutants are necessary to assess the health risks these pollutants pose and for the design and implementation of strategies to control and limit those risks. Most exposure estimates are based on concentrations of outdoor (ambient) air concentrations measured at fixed-site air monitoring stations. These ambient concentrations thus serve as surrogates for personal exposure. Despite the recognized discrepancies between personal exposure and exposures based on ambient concentrations, compliance with the NAAQS depends exclusively on outdoor measurements of pollutants. Moreover, most epidemiologic studies of air pollution health effects use ambient concentrations as surrogates for actual population exposures.

The population exposure assessment approach used for this study involves representing the population and ambient concentrations on a spatial grid covering the SJV, shown in Fig. 3. Each grid square is 5×5 km. Five-kilometer resolution is sufficient to capture the urban- and regional-scale spatial gradients in between air quality monitoring stations, which are located from 10 to 50 km apart in the SJV. We developed gridded population data for eight age groups: <1, 1, 2–4, 5–17, 18–21, 22–29, 30–64, and >64 years, and four racial groups: white non-Hispanic, black non-Hispanic, other non-Hispanic, and Hispanic. The age groups were defined by the concentration–response relationships chosen for use in the benefits evaluation, while racial groups were defined by the US Census. As expected, the highest population densities ($>1200\,\mathrm{km}^{-2}$) occur in the major cities, such as Lodi, Stockton, Modesto, Turlock, Fresno, Visalia, and Bakersfield. A total of 1708 grids were used for assessing exposure.[2]

The baseline period selected for exposure assessment was 2002–2004. To be consistent with this period, population data for 2000 were projected to 2004, using county-specific growth rates (as reported in the US Census (www.censuscope.org)). The estimated total population in the region is 3.34 million persons in 2004. About 25% of the residents live in Fresno County and another 35% live in San Joaquin and Kern Counties. Whites (46.2%) and Hispanics (41.7%) are the largest racial/ethnic groups. Adults, ages 30–64 years, are the largest age group (41%), followed by children ages 5–17 (23.5%). Estimates of the population of children attending school were also needed to determine the benefits of reduced school absences associated with air quality improvements. Public school enrollment and schedules for the 2005–2006 school year were obtained from SJV school districts.

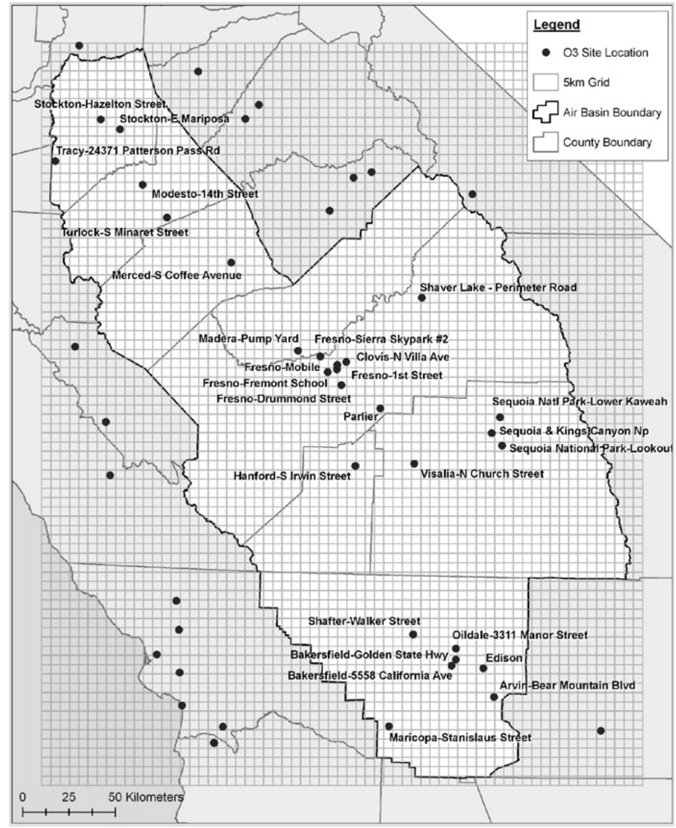

Fig. 3. The population exposure grid and locations of air quality monitoring stations in the San Joaquin Valley.

Finally, we note that while the SJV is experiencing high population growth, we have not considered the likely population growth beyond 2004 in our estimates. This approach is conservative in that it results in underestimation of the likely benefits, but avoids having to predict when the region will actually reach its air quality goals.[3]

2.1.1. Spatial mapping

Ambient air quality data from California's network of monitoring stations were used to spatially map concentrations to the exposure grids. For the 2002–2004 baseline period, hourly ozone data were available for 27 stations within the SJV and daily $PM_{2.5}$ data were available once every 3 days for 14 stations within the SJV. The ozone data

[2]Grid squares with extremely low population density (below 1 person per km^2 or 25 persons per grid) were not included; they were large in number of grids but accounted for less than 1% of the total population.

[3]Because the population is growing at about 2% per year, the benefits are likely to be 16–20% greater than estimated if attainment is achieved in 8–10 years.

were used to create maps of hourly concentrations for each day of the baseline period (1096 days and 26,304 maps). Daily $PM_{2.5}$ data collected using the federal reference method (FRM) were available on an everyday basis at several sites and on an every third-day sampling schedule at many more sites. Annual average $PM_{2.5}$ concentrations were calculated from the FRM data using EPA's methodology (that is, annual average = average of quarterly averages) and mapped for each year.

2.1.2. *Current ambient air quality*

The most relevant NAAQS for ozone is the 8-h daily maximum standard of 0.08 parts per million (ppm) or 80 parts per billion (ppb). It has essentially replaced the 1-h daily maximum ozone standard of 0.12 ppm, which is less stringent[4] in the SJV. Federal standards exist for maximum 24-h average and annual average $PM_{2.5}$ and PM_{10}. The 65 $\mu g/m^3$ 24-h $PM_{2.5}$ standard and 15 $\mu g/m^3$ annual $PM_{2.5}$ standard are generally more stringent than the 150 $\mu g/m^3$ 24-h PM_{10} standard and 50 $\mu g/m^3$ annual PM_{10} standard. The SJV will reach federal attainment when the more stringent federal standards are reached. Thus, this study focuses on the 8-h ozone standard and the 24-h and annual average $PM_{2.5}$ standards.

The SJV data for ozone show that the ambient concentrations exceeded the level of the federal standard on 82–134 days per year between 1990 and 2004. This high frequency indicates that on most days during the summer, levels were hazardous. Unlike other parts of California, the frequency of exceedances is not noticeably declining with time, which is a concern for residents and government agencies. The 8-h NAAQS will be achieved when the 3-year average of the annual fourth-highest concentration is below the level of the standard. The 3-year average of the annual fourth-highest concentration was 116 ppb for 2002–2004 and 113 ppb for 2003–2005. This value is referred to as the ozone design value for the baseline period. Attainment of the 8-h NAAQS is expected when the annual fourth-highest concentration is reduced from 116 to 85 ppb.[5] Attainment then requires a 27% decrease in the ozone design value. However, because there is a global background concentration of about 40 ppb, the required reduction in ozone in excess of the background level is 41% to reach attainment.

Even though the region achieved compliance with the PM_{10} NAAQS in 2003–2005, $PM_{2.5}$ levels remain unhealthful. The highest 24-h average $PM_{2.5}$ concentration in 2002 was 91 $\mu g/m^3$ at Corcoran, which is 40% above the level of the standard. The highest annual average concentration in 2002 was 24 $\mu g/m^3$ in Bakersfield. High 24-h fine particulate concentrations tend to occur in the fall and winter in this area. Like the ozone standard, the $PM_{2.5}$ standards are based on 3-year periods. The annual $PM_{2.5}$ NAAQS is achieved when the 3-year averaged annual mean $PM_{2.5}$ concentration is less than or equal to 15 $\mu g/m^3$. The 24-h $PM_{2.5}$ standard is achieved when the 3-year average of the annual 98th percentile values at each $PM_{2.5}$ monitoring site is less than or equal to 65 $\mu g/m^3$. The $PM_{2.5}$ design values are 20.6 and 73.2 $\mu g/m^3$ for the annual average and 24-h standards, respectively. The design values are based on data from Bakersfield for the 2002–2004 baseline study period. The current design values indicate that maximum 24-h and annual averages need to decrease by 11% and 27% to achieve compliance with the federal standards. The San Joaquin Valley Air Pollution Control Agency (SJCAPCA) is charged with developing an air quality management plan by 2008 that will result in attainment of the $PM_{2.5}$ NAAQS by 2013.

California has an annual average $PM_{2.5}$ standard of 12 $\mu g/m^3$, never to be exceeded. Compliance with this standard would require that the 2002 annual concentration of 24 $\mu g/m^3$ in Bakersfield be reduced by 50%. This health-based standard will be very difficult to achieve in the SJV.

2.1.3. *Pollution sources*

The principal sources of ozone in the SJV are oxides of nitrogen (NO_x) and volatile organic compound (VOC) emissions from on-road and off-road mobile vehicles, and VOC emissions from the evaporation of chemical solvents and fuels. The principal source of $PM_{2.5}$ is direct emissions; however, atmospheric reactions of gaseous NO_x, VOC, and SO_2 emissions contribute about 40% of $PM_{2.5}$ on average. The principal sources of directly emitted $PM_{2.5}$ are residential fuel combustion, farming operations, paved and unpaved road dust, managed burning and disposal, construction and demolition, and wind blown fugitive dust.

2.1.4. *Population exposure estimates*

For purposes of analyzing changes in exposure as the NAAQS are attained, we are interested in the spatial and temporal distribution of ambient concentrations for a 3-year period. We use a simple linear rollback model that assumes that concentrations in excess of the background concentration with attainment will be linearly reduced in proportion to the ratio of the standard (adjusted for background, or "natural" levels) to the design value (also adjusted for background). This ignores much of the detailed knowledge of the atmospheric chemistry and physics that influence concentrations, yet it is probably the most suitable model when the specific emission control measures needed to reach attainment in a region are not yet identified. Attainment can be achieved with different sets of control measures that will produce different spatial and temporal patterns of concentrations; and without knowledge of the specific path to attainment in the SJV, it is best to keep the projection method as simple as possible.

The REHEX model uses population and air quality data for the SJV to estimate the population exposure to ozone and $PM_{2.5}$ in the baseline period and with attainment. The exposure metrics of interest for ozone include the 1-h daily

[4]Here, stringent means more limiting in terms of the difficulty of attainment.

[5]*Note*: 84.99 ppb is used instead of 80 ppb because of agency guidance on rounding concentrations for compliance with the "0.08 ppm" standard.

maximum, the 2-week average 1-h daily maximum, the 5-h daily maximum, the 8-h daily maximum, and the 24-h average concentrations. The exposure metrics for $PM_{2.5}$ include the 24-h average concentration and the annual average concentrations.

The concentration–response relationships used in this study apply to all days of the year, except for the school-absence concentration–response relationship. For this endpoint, exposures occurring on Fridays and Saturdays were excluded as well as the day preceding each holiday.

2.2. Ozone and PM-related health effects

Ozone and fine particles ($PM_{2.5}$) have long been associated with adverse human health effects, and a growing body of health science literature enables us to quantify how changes in air quality translate into changes in the number of such effects in a specific population. In order to select studies on which to base estimates of such changes for this study, we consider a number of factors. In particular, to be used a study:

- must be peer-reviewed;
- must account for potential confounders such as other pollutants and weather;
- must use reasonable measures of pollutants;
- must be based on a population not significantly different from the population being assessed;
- must provide a basis to estimate changes in an effect that can be valued in economic terms;
- is preferred if it is more recent, using more advanced analytical methods and reflecting more recent demographics;
- is preferred if it covers longer periods and larger populations;
- is preferred if it meets the other criteria and is also region-specific; and
- is preferred if it meets the other criteria and has been used in previous peer-reviewed benefits assessments.

Given this, we identified five ozone-related and seven $PM_{2.5}$-related effects that would be appropriate for inclusion in this study.[6]

[6]Some effects, such as individual respiratory symptoms or eye irritation are not included here because they are at least in part captured by effects such as MRADs, work loss days, school absence days and upper and lower respiratory symptom days. (An MRAD is a day on which an individual reduces most usual daily activities and replaces them with less strenuous activities or rest, but does not miss work or school.) Also, individually these effects carry relatively small economic values. Others that are not reported occur in very small numbers, generally because the population at risk is small or because the concentration–response relationship requires a large change in pollution levels to generate substantial reductions in the effect in the exposed population. For example, we estimate that attaining the NAAQS for $PM_{2.5}$ would result in five fewer cardiovascular hospital admissions annually in the entire eight county region. Summing and including all of those small effects does not change the overall results. For more detail, see Hall et al. (2006).

Table 1
Health values used

Health endpoint	β value	Source
School absences	0.004998	Chen et al. (2000) Gilliland et al. (2001)
ER visits	0.0323	Cody et al. (1992) Weisel et al. (1995)
Respiratory hospital admissions <65	0.001655	Thurston and Ito (1999)
Respiratory hospital admissions >65	0.004536	Schwartz (1994a, b, 1995), Moolgavkar et al. (1997)
Asthma attacks	0.001843	Whittemore and Korn (1980)
MRADs—ozone	0.0022	Ostro and Rothschild (1989)
Acute bronchitis	0.0272	Dockery et al. (1996)
Lower respiratory symptoms	0.01698	Schwartz and Neas (2000)
Upper respiratory symptoms	0.0072	Pope et al. (1991)
Premature death	0.005827	Pope et al. (2002)
MRADs—particulates	0.00741	Ostro and Rothschild (1989)
Chronic bronchitis	0.0137	Abbey et al. (1995)
Work loss days	0.0046	Ostro (1987)

2.2.1. Developing concentration–response functions

To quantify the expected reductions in adverse health effects associated with less exposure to ozone and $PM_{2.5}$, we use the basic exponential concentration–response (C–R) function developed in the Environmental Protection Agency's Report to Congress (EPA, 1999), which evaluates the benefits and costs of emissions controls required by the Clean Air Act.[7]

Specifically, the functional form used is as follows:

$$\Delta C = -C_0(e^{-\beta\Delta P} - 1),$$

where ΔC is the change in the number of cases (of a particular health outcome); C_0 is the number of baseline cases (of the health outcome); ΔP is the change in ambient pollution concentrations and β is an exponential "slope" factor derived from the health literature pertaining to that specific health outcome.

In most of the recent health literature, "relative risk" (RR) factors are reported, which relate change in pollution levels to the increased odds of developing various health effects. These risk factors are related to the β in the EPA concentration–response functions in the following manner:

$$\beta = \frac{\log(\text{RR})}{\text{Change in pollution}},$$

where log refers to the natural logarithm function. The β values used for each health endpoint and the specific health studies used to develop these values are listed in Table 1.[8]

[7]The one exception is the case of ozone-related emergency room visits, for which we use a linear concentration–response function.

[8]The number of baseline cases comes from a variety of sources, including Adams et al. (1999), OSHPD (2003) and U.S. Department of Health and Human Services (2005).

2.2.2. Morbidity

Extensive research conducted over several decades has identified and quantified an association between air pollutants and adverse health effects. Here, we focus on those endpoints that can be quantified in economic terms, as well as in number of events. We rely on many of the same underlying health studies that have been used in other California-specific and national assessments (Ostro et al., 2006; Hubbell et al., 2005, EPA, 2003, 2004, 2005, CARB, 2006a, b) and that have been recently recommended for use in a regulatory impact analysis being completed for the Los Angeles region (Chestnut and Deck, 2006).

For reducing ozone exposure, we estimate reductions in minor restricted activity days (MRADs), emergency room visits associated with asthma, school absences, asthma attacks, and hospital admissions. Considering $PM_{2.5}$, we estimate reductions in acute and chronic bronchitis, lost days of work, MRADs, and non-asthma respiratory symptoms. Studies used to develop concentration–response functions are cited in Table 1. It is important to note that there are other, potentially significant, endpoints that are not included because we presently have no way to attach an economic value to them. One of the most important is reductions in lung function observed in children exposed to vehicular pollution that are expected to result in life-long reduction in respiratory capacity.

2.2.3. Mortality

The scientific literature that assesses associations between $PM_{2.5}$ and premature mortality in adults has expanded rapidly over the past decade, with several large-scale multi-city studies that extend or reanalyze earlier studies (for example, Pope et al., 1995, 2002; Krewski et al., 2000; Laden et al., 2006) as well as a California-specific study that focuses on the Los Angles basin (Jerrett et al., 2005). To estimate $PM_{2.5}$-related mortality for the SJV requires determining which of these studies is most appropriate for conditions in this region.

Both EPA and the California Air Resources Board (CARB) have conducted recent benefit assessments for $PM_{2.5}$ reduction (EPA, 2003, 2004, 2005; CARB, 2005, 2006b), and these assessments have also undergone peer-review of the analytical approaches used, including the choice of C–R functions. The conclusion generally is that Pope et al. (2002) remains the preferred basis to estimate adult mortality. At the same time, it is important to note that expert opinion elicited by EPA regarding mortality and fine particles concluded that Pope et al. underestimate mortality. The difficulty lies in knowing how to adjust their result (Industrial Economics, 2006; Chestnut and Deck, 2006).

Other experts have argued that Jerrett et al. (2005) likely better represents California (CARB, 2005 and peer-review comments therein). For purposes of assessing benefits in the SJV, the Jerrett et al. work may be more appropriate than Pope et al. in that the exposure measure more closely fits the approach that we use in REHEX. Chestnut and Deck, however, point out that the reasons Jerrett et al. find a much higher level of effect is not well understood. It is also specific to the Los Angeles area population and the profile of traffic-related PM emissions in that region, so we take the more conservative approach of relying on Pope et al. for our primary assessment and provide estimates based on Jerrett et al. as a sensitivity test. This is also the approach recommended by a peer-review group recently asked by ARB to consider the use of the Jerrett et al. result for a regulatory analysis (CARB, 2005).[9]

2.3. Economic valuation

If we know how much illness and premature death could be avoided by meeting the health-based air quality standards, why assign monetary values at all, and what is the basis for those values? First, there are more worthwhile things to do than either society or individuals can afford. As a result, we must make choices. The social choice to control emissions in order to improve air quality and health is one of these things, and one that is a high priority for Californians. It is therefore useful to have a sense, in economic terms, of the scale of gains from successfully implementing pollution control policies and programs.

A critical aspect of such a measure is determining the value that society places on avoiding specific adverse effects. These range from symptoms that are fairly minor, such as eye irritation, through hospitalization, emergency room visits, asthma attacks and the onset of chronic bronchitis, to premature death. We value reducing these effects to avoid:

- loss of time (work and school) and the direct medical costs that result from avoiding or responding to adverse health effects;
- the pain, inconvenience and anxiety that result from adverse effects, or efforts to avoid or treat them;
- loss of enjoyment and leisure time; and
- adverse effects on others resulting from their own adverse health effects.

For most goods, market prices are accepted as reasonable measures of value. However, there is no market in which cleaner air (like many other environmental goods) can be bought. Consequently, values for such goods cannot be directly observed from prices. Economists have developed alternative ways to measure the value of environmental improvements, including health benefits resulting from cleaner air.

Two generally accepted measures of the value of reducing the adverse health effects of air pollution are the cost of illness (COI) measure and the willingness to pay (WTP) or willingness to accept (WTA) measures. All three have limitations but, when taken together, they yield a

[9] In this paper, we report only what we consider as our best case estimates. For a range of how and high values, see Hall et al. (2006).

generally accepted range of values for the health benefits of improvements in air quality. In this study, we use the most appropriate available value for each health endpoint, and use four criteria to choose specific values from the literature.

1. The value should be appropriate for the type of risk. For example, involuntary risk might carry a higher value than voluntary risk. The degree of risk (1 in 10,000 or 1 in 1,000,000) is a factor, as is whether the risk of harm in increasing or decreasing. Whether harm is prospective or has already occurred is a consideration.[10]
2. A measure should represent gains or losses in well-being as fully as possible.
3. If similar values are derived from studies using different methods, for example from market-based studies and contingent valuation (CV) studies, those values are given greater weight on the premise that convergence implies a closer representation of true value.
4. If more than one valid study produces values that are similar for comparable adverse affects, those values are given greater weight.

Given these criteria, CV results for WTP are most highly ranked for appropriateness and validity, followed by WTA from wage-risk studies (supported by WTP from valid consumer behavior studies) and then COI measures.

2.3.1. *Specific values for premature death*

Premature mortality is the most significant effect of exposure to air pollution that can presently be quantified. Consequently, determining a socially appropriate value of reducing the risk of premature mortality is a crucial part of any benefit assessment. It is very important to keep in mind that we are not valuing the life of any identifiable individual, but rather the value of reducing a very small risk over a large population enough so that some people would live longer than would otherwise have been the case. This is then the value of a statistical life (VSL).

There is a very wide range across all the studies that assess VSL. However, this range can be narrowed significantly by considering characteristics of the population in each study relative to the population with which we are concerned, and by reviewing the methods used in each study. In a recent meta-analysis of VSL from US wage-risk studies (Viscusi and Aldy, 2003), most estimates fell into the range of \$3.8–\$9.0 million (in 2000 dollars) with a median for "prime-aged workers" of \$7 million. Converting this to 2005 dollars (using the US all-item CPI) produces a range of \$4.3–\$10.2 million.

Table 2
Economic values used

Health endpoint	Dollar value	Source
School absences	65–79	Smith et al. (1997)
ER visits	335	EPA (2005)
Respiratory hospital admissions <65	32,000	Chestnut et al. (2006)
Respiratory hospital admissions >65	32,000	Chestnut et al. (2006)
Asthma attacks	50	Rowe and Chestnut (1986)
MRADs—ozone	61	Tolley et al. (1986), CARB (2005)
Acute bronchitis	110	Loehman et al. (1979)
Lower respiratory symptoms	20	EPA (2005)
Upper respiratory symptoms	32	EPA (2005)
Premature death	6.7 million	Viscusi and Aldy (2003)
MRADs—particulates	61	Tolley et al. (1986), CARB (2005)
Chronic bronchitis	374,000	Krupnick and Cropper (1989), Viscusi et al. (1991)
Work loss days	123–141	EDD (2003)

The most recent final EPA regulatory analysis (EPA, 2005) used \$5.5 million in 1999 dollars.[11] Converting this to 2005 dollars gives us \$6.5 million. We further adjust this for the increase in per capita income in California from 1999 to 2004,[12] and assume an income elasticity of 0.5[13] (Viscusi and Aldy, 2003). This leads to a VSL of \$6.7 million, which is the value used in this study.[14]

2.3.2. *Specific values for morbidity endpoints*

Generally accepted values for many endpoints have been developed over the past decade and are widely used in benefit assessments and regulatory analyses by USEPA and the states. These values have been peer-reviewed by advisory bodies, including committees of the EPA's Scientific Advisory Board (EPA SAB), and many have also been published in the peer-reviewed literature. We generally follow this established protocol, adjusting specific values for inflation and California-specific incomes. Where California-specific COI data are available, as for hospitalizations, we use those values. A summary of the values used, and their sources, appear in Table 2.

[10]The human capital method used in damage award legal cases is not used here, for example, because harm has already occurred. In assessing the benefits of environmental improvements we are considering the avoidance of harm, not compensation for harm.

[11]We note that this value has not yet been peer reviewed by the EPA SAB, and that body previously endorsed a slightly higher value.

[12]The most recent final data available.

[13]As incomes rise, consumers place greater value on many goods. The degree to which this value rises with income and leads to more consumption of a good is called income elasticity. While EPA most recently used 0.4 as the adjustment for this effect, Viscusi and Aldy found that the appropriate value for the income elasticity of VSL is 0.5–0.6.

[14]We note that if we assume the lag structure applied in EPA (2005), VSL would be \$5.7 million. This applies a discount rate of 3% with 30% of deaths occurring in the first year, 50% over years 2–6 and 20% over years 6–20.

Table 3
The estimated SJVAB population exposure to 8-h daily maximum ozone concentrations above 70, 85, and 100 ppb in the 2002–2004 baseline period and with NAAQS attainment by region

Region	Person-days of exposure per year in the 2002–2004 baseline period			Person-days of exposure per year with NAAQS attainment[a]	
	$O_3 > 70$ ppb	$O_3 > 85$ ppb	$O_3 > 100$ ppb	$O_3 > 70$ ppb	$O_3 > 85$ ppb
SJV air basin	234,844,480	68,981,644	10,263,964	33,831,101	292,757
San Joaquin county	5,841,758	272,877	4696	5314	0
Stanislaus county	13,347,645	2,102,079	80,860	684,963	0
Merced county	14,889,810	4,626,388	577,332	2,480,696	362
Madera county	12,873,744	3,436,128	538,545	1,625,296	45,633
Fresno county	76,781,642	25,510,837	5,514,961	14,614,819	211,237
Kings county	10,824,809	2,567,352	301,929	1,030,735	0
Tulare county	38,564,534	10,767,642	1,071,872	4,520,114	62
Kern county	61,720,538	19,698,341	2,173,769	8,869,163	35,463

[a]Person-days of exposure to ozone >100 ppb is estimated to be zero with attainment of the 8-h NAAQS.

3. Results and discussion

3.1. Pollution exposures

3.1.1. Ozone

The estimated number of exposures to 8-h daily maximum ozone concentrations above 70, 85, and 100 ppb are listed in Table 3 for the entire air basin. The REHEX model estimates 10, 69, and 235 million person-days of exposures per year to 8-h concentrations above 100, 85, and 70 ppb, respectively, during the baseline period. With NAAQS attainment, the estimated person-days of annual exposures above 85 ppb decrease from 69 million to 293 thousand. The estimated exposures above 70 ppb decrease from 235 to 34 million with attainment. These changes represent large reductions in unhealthful ozone exposures.

When the results are averaged over the population the number of days per year above 100, 85, and 70 ppb 8-h daily maximum ozone is estimated as 3, 21, and 70 days annually. With NAAQS attainment, the average number of days of exposure above 85 and 70 ppb is estimated to be less than 1 and 10 days, respectively, for the air basin population. In addition, the model results indicate children are exposed slightly more frequently than adults over age 30 in the SJV, and that Hispanics are exposed more frequently than other racial groups to 8-h ozone levels above 70 and 85 ppb. Spatial differences in the population's racial/ethnic makeup for different counties and within counties are probably responsible for these differences.

Population exposure to ozone was also estimated for 1- and 5-h daily maxima and 24-h average for use in the health benefits evaluation, with similar results.

3.1.2. 24-h average $PM_{2.5}$ exposures

The REHEX results for the baseline period indicate that about 88 and 8.7 million person-days of exposure to concentrations above 40 and 65 μg/m^3 occur annually in the SJV. With attainment of the 24-h NAAQS, SJV population exposure to 24-h average $PM_{2.5}$ concentrations above 40 and 65 μg/m^3 is estimated to be 61 and 3.2 million person-days per year above 40 and 65 μg/m^3, respectively. This represents a 63% decrease in person-days of exposure above the level of the standard on average. REHEX results also show the estimated daily $PM_{2.5}$ exposures by racial/ethnic group. These suggest that blacks and Hispanics have slightly more frequent exposure to elevated $PM_{2.5}$ concentrations than whites and other ethnic groups in the SJV.

3.1.3. Annual average $PM_{2.5}$ exposures

The estimated annual average exposure of SJV residents to $PM_{2.5}$ in the baseline period (2002–2004) and with attainment is summarized in Table 4. The exposure calculations indicate 98%, 74%, and 33% of the SJV population are exposed to annual average $PM_{2.5}$ concentrations above 12, 15, and 18 μg/m^3. With attainment of the annual NAAQS, the model estimates that 73%, 16%, and 0% of the SJV population will be exposed to annual concentrations above 12, 15, and 18 μg/m^3, respectively. The estimated reduction of population exposed to annual $PM_{2.5}$ greater than 15 μg/m^3 from 2.5 million people (74% of the population) in 2002–2004 to 520 thousand people (16% of the population) with NAAQS attainment represents a substantial improvement in air quality and a decrease in associated PM-related health effects (including premature mortality) for residents of the SJV.

3.2. Health effects

3.2.1. Reductions in ozone-related effects

The reductions in effects that would be expected with attainment of the ozone NAAQS are summarized below in Table 5. Typically, there are fewer of the more severe effects and fewer effects in smaller groups (for example, the population age 65 and older). However, while there are relatively few reductions in ozone-related hospital admissions, at 260 per year, this is an effect with considerable impacts on patients and their families. The relatively larger numbers of days of avoided school absences (188,000) reflects the larger population and the sensitivity of children

Table 4
The estimated SJVAB population exposure to annual average $PM_{2.5}$ concentrations above 12, 15, and 18 $\mu g/m^3$ in the 2002–2004 baseline period and with NAAQS attainment by region

Region	Person-days of exposure per year in the 2002–2004 baseline period			Person-days of exposure per year with NAAQS attainment[a]	
	$PM_{2.5} > 12\ \mu g/m^3$	$PM_{2.5} > 15\ \mu g/m^3$	$PM_{2.5} > 18\ \mu g/m^3$	$PM_{2.5} > 12\ \mu g/m^3$	$PM_{2.5} > 15\ \mu g/m^3$
SJV air basin	3,266,891	2,485,816	1,110,165	2,429,546	520,575
San Joaquin county	548,259	180,226	733	179,474	0
Stanislaus county	465,500	155,140	140,181	155,101	0
Merced county	209,607	148,200	55,780	107,450	0
Madera county	139,758	135,335	44,189	134,303	0
Fresno county	802,163	784,847	214,722	783,162	182,782
Kings county	137,234	134,433	45,745	130,317	41,082
Tulare county	380,256	363,833	156,907	356,090	102,345
Kern county	584,114	583,802	451,908	583,649	194,366

[a]None of the SJVAB population is estimated to be exposed to annual average $PM_{2.5}$ concentrations above $>18\ \mu g/m^3$ with attainment of the annual $PM_{2.5}$ NAAQS.

Table 5
Ozone-related effects and economic value

	Fresno	Kern	Kings	Madera	Merced	San Joaquin	Stanislaus	Tulare	Total
Respiratory hospital admissions ages 0–64	55	45	10	10	10	15	20	30	195
Respiratory hospital admissions ages 65+	25	15	0	5	5	0	5	10	65
Respiratory hospital admissions all ages	80	60	10	15	15	15	25	40	260
Value ($ millions)	2.56	1.92	0.32	0.48	0.48	0.48	0.8	1.28	8.32
Asthma attacks asthmatic population all ages	5900	4700	900	1100	1300	1500	1900	3000	23,300
Value ($ thousands)	295	235	45	55	65	75	95	150	1015
Emergency room visits all ages	20	15	5	5	5	5	5	10	70
Value ($ thousands)	6.70	4.31	1.68	1.68	1.68	1.68	1.68	3.35	23.45
School absences ages 5–17	34,000	28,700	4900	6000	8000	8200	9300	18,400	117,500
Days of school absences ages 5–17	54,500	45,900	7800	9600	12,800	13,100	14,900	29,400	188,000
Value ($ millions)	3.60	3.12	0.53	0.66	0.87	1.03	1.13	1.91	12.85
Minor restricted activity days ages 18–64	49,900	38,200	9000	9200	10,800	13,200	16,200	24,600	171,100
Value ($ millions)	3.04	2.33	0.55	0.56	0.66	0.80	0.99	1.5	10.43
Total value ($ millions)	9.5	7.61	1.45	1.76	2.08	2.39	3.02	4.84	32.64

to ozone. For the age 5–17 population of 783,740 this suggests that, on average, one in four children experiences a day of absence each year due to elevated ozone levels.

3.2.2. Reductions in $PM_{2.5}$-related effects

The most serious consequences of exposure to fine particles are associated with $PM_{2.5}$, and this is reflected in the estimate of nearly 500 deaths averted each year,[15] as seen below in Table 6. To put this in perspective, we note that in 2001–2003 an average of nearly 770 people in the SJV died in motor vehicle accidents. This means that reducing pollution could account for the equivalent of avoiding nearly two-thirds of motor vehicle deaths, or reducing flu deaths by more than 72% in the SJV. It represents a benefit five times greater than that realizable from eliminating AIDs-related deaths entirely (DHS, 2005).

[15]Using Jerrett et al.'s work raises this estimate to more than 1200.

This illustrates the real consequences of elevated fine particle levels, and the substantial gains from attaining the NAAQS.

The avoidance of chronic bronchitis, an illness that can significantly limit activity, is also noteworthy at 325 cases a year. In addition, children also experience over 3000 fewer cases of acute bronchitis, and asthmatic children avoid more than 16,000 additional days of upper respiratory symptoms (in addition to ozone-related school absences and asthma attacks).

3.2.3. Omitted effects

In our preliminary search for quantifiable health outcomes, we identified 7 ozone-related and 14 $PM_{2.5}$-related effects that would be appropriate for inclusion in the study. Those that are not reported here include: premature mortality and asthma hospital admissions for ozone; and cardio hospital admissions, asthma hospital admissions, asthma emergency room visits, neo-natal mortality, non-fatal heart attacks, and elderly respiratory hospital

Table 6
$PM_{2.5}$-related effects and economic value

	Fresno	Kern	Kings	Madera	Merced	San Joaquin	Stanislaus	Tulare	All counties
Minor restricted activity days ages 18–64	4610	3800	870	880	1050	2070	2160	1840	17,280
Value ($ thousands)	281.2	231.8	53.1	53.7	64.1	126.3	131.8	112.2	1054.2
Premature mortality ages 30 and older	130	100	15	15	20	65	65	50	460
Value ($ millions)	871.0	670.0	100.5	100.5	134.0	435.5	435.5	335.0	3082.0
Work loss days ages 18–64	800	660	150	150	180	360	380	320	3000
Value ($ thousands)	106.0	93.1	21.0	19.8	22.0	50.8	52.0	39.7	403.8
Lower respiratory symptoms ages 5–17	240	195	35	40	60	100	105	100	875
Value ($ thousands)	4.8	3.9	0.7	0.8	1.2	2.0	2.1	2.0	17.5
Upper respiratory symptoms asthmatic children	4440	3670	660	760	1100	1860	1940	1880	16,310
Value ($ thousands)	142.1	117.4	21.1	24.3	35.2	59.5	62.1	60.2	521.9
Acute bronchitis ages 5–17	860	750	130	140	210	390	360	390	3230
Value ($ thousands)	94.6	82.5	14.3	15.4	23.1	42.9	39.6	42.9	355.3
Chronic bronchitis ages 27 and older	85	75	15	15	20	40	40	35	325
Value ($ millions)	31.8	28.1	5.6	5.6	7.5	15.0	15.0	13.1	121.6
Total value ($ millions)	903.4	698.6	106.2	106.2	141.6	450.8	450.8	348.4	3206

admissions for $PM_{2.5}$. Our REHEX/SYMVAL runs estimate very small occurrences for these effects, generally because the population at risk is small or because the concentration–response relationship requires a large change in pollution levels to generate substantial reductions in the effect in the exposed population. For example, we estimate that attaining the NAAQS for $PM_{2.5}$ would result in five fewer cardiovascular hospital admissions annually in the entire eight county region. Similarly, attaining the ozone standards would lead to fewer than five premature deaths annually for the entire SJV. The omission of these infrequent outcomes does not change our relative assessment of the magnitude of ozone and particulate effects.

More significantly, $PM_{2.5}$-related premature death in the population under age 30 is not estimated because the underlying health studies did not include that population. More subtle impacts, such as reduced lung function that cannot be assessed in economic terms, are also not included here.

3.3. Economic results

Unsurprisingly, given the great value that individuals and society place on life, the overall benefits of attaining the NAAQS are dominated by premature mortality. Across the SJV, 460 people are estimated to avoid premature death each year when the standards are attained, accounting only for the effect of $PM_{2.5}$ and only for the population age 30 and older. With a value for each life of $6.7 million, this effect alone offers an attainment benefit of more than $3 billion each year. While this consequence of elevated fine particle levels is by far the most striking, other effects are also important.

For example, an additional 325 new cases of chronic bronchitis could be avoided annually with attainment of the $PM_{2.5}$ NAAQS. At a value of $374,000 per case—reflecting the significant costs of treatment and loss of enjoyment and activity—avoiding this effect would generate benefits of over $120 million annually. Ozone attainment offers thousands fewer school absence days, conservatively valued at nearly $13 million a year. It should be noted that this only reflects the value of time lost to an adult caregiver and not any medical costs or loss of educational opportunity. Minor restricted activity days (MRADs) would cost adults over 190,000 days a year when their daily routine is limited to some degree by exposure to elevated ozone or $PM_{2.5}$. Avoiding this restriction offers an economic benefit of over $10 million annually.

Tables 5 and 6 show the overall benefits, both in numbers of effects and in dollars, for ozone and $PM_{2.5}$, respectively. Looking at the overall benefits, residents of the SJV could expect annual benefits of $3.2 billion if both the ozone and $PM_{2.5}$ NAAQS were attained. Measured in per capita terms, these benefits reach nearly $1000 per person.

4. Conclusions and implications

Almost every resident of the SJV regularly experiences air pollution levels known to harm health and to increase the risk of early death. For example, from 2002 through 2004 on average each person was exposed to unhealthful levels of ozone on 70 days a year. This is unsurprising, given how frequently and pervasively the health-based air quality standards are violated. These exposures translate directly into poorer health and an elevated risk of premature death. Valley-wide, the economic benefits of meeting the current federal $PM_{2.5}$ and ozone standards average nearly $1000 per person per year, or a total of more than $3 billion.

Clearly, residents of the SJV face significant public health risks from the present unhealthful levels of ozone and fine particles. This is in addition to other health challenges, including a high rate of poverty, which exceeds 30% in Fresno County, compared to a statewide rate below 20%, and high rates of debilitating diseases such as diabetes and asthma (DHS, 2004, 2006). The region overall would experience substantial economic and health gains from effective policies to reduce pollution levels. For the more populous and more polluted areas in Kern and Fresno Counties, this is even more pronounced. Attaining the California air quality standards, which are more protective of health, would roughly double the health benefits listed above.

The adverse impacts of air pollution are not distributed equally. Both Hispanics and non-Hispanic blacks are exposed to more days when the health-based standards are violated. Residents of Fresno and Kern Counties experience many more days when the $PM_{2.5}$ standards are violated than the Valley-wide average. Tulare County joins Fresno and Kern in being well above average for the number of days of exposure above the ozone standards. Children under age 5 are exposed to ozone concentrations above 70 ppb on more days than older adults.

Because ozone is elevated during the spring, summer, and fall seasons, and the daily $PM_{2.5}$ standard is typically violated more frequently in the fall and winter seasons, there is no "clean" season in this region. Moreover, as the population continues to increase, with associated increases in vehicle traffic and economic activity, the gains from attaining the health-based air quality standards will grow, but also become more difficult to achieve. Identifying and acting on opportunities now would produce substantial gains to the people of the SJV.

Given the public health needs of the SJV, and the limited resources available to meet multiple pressing needs, it is especially critical that pollution controls are implemented in a way that produces the largest benefits at the earliest time. This research suggests that emissions of $PM_{2.5}$ and $PM_{2.5}$ precursors should receive priority. This is not in any way to suggest that ozone is not a priority, but given that controls are adopted as part of established regulatory processes over a period of time, with a deadline of 2013 attainment, early attention to $PM_{2.5}$ will yield the largest benefits.

This will be at best a difficult task. For example, in the SJV 80% of directly emitted $PM_{2.5}$ comes from area sources, including residential fuel use, farming operations, fugitive dust, re-suspended road dust, and managed burns. These distributed emission sources are typically difficult to control, and are typically under the jurisdiction of a local authority. In contrast, in the South Coast Air Basin (SoCAB) of southern California, area sources contribute only about 50% of directly emitted $PM_{2.5}$. Similarly, area sources such as pesticides and fertilizers, farm operations and managed burns contribute twice the proportion of reactive organic gases (ozone precursors) to emissions in the SJV than is the case in the SoCAB (CARB, 2006a, b). Both regions depend on regulation of on- and off-road mobile sources by CARB and the USEPA, but in the SJV local decisions regarding local sources will be especially critical.

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