Environmental Health Evaluation of Rule 4901: Domestic Wood Burning

A Case Study of the Fresno/Clovis and Bakersfield Metropolitan Areas

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Executive Summary

The San Joaquin Valley experiences severe, chronic temperature inversions during winter months. In this environment, wood smoke, which is known to contain harmful chemicals and fine particulates, concentrates near ground level. For densely settled urban neighborhoods, the concentration levels and number of individuals at risk is magnified. Highly concentrated nighttime wood smoke also makes a significant source contribution to the violation of state and federal clean air standards for fine particulates (PM 2.5).

In light of this threat to public health, on Nov. 1, 2003 the San Joaquin Valley Air Pollution Control District adopted Rule 4901--a 150 AQI-triggered ban on wood burning in areas that have natural gas service and are below 3,000 ft elevation. The Central Valley Health Policy Institute was funded by the SJVAPCD to evaluate the relative effectiveness of this air pollution control measure. In particular, the evaluation sought to: (1) estimate the ability of Rule 4901 to reduce PM 2.5 concentrations during Valley winter months, including evidence of public compliance with daytime prohibitions of wood burning by the SJVAPCD, (2) estimate the corresponding health benefits as measured by the reduced incidence of air pollution-related disease (morbidity) and premature death (mortality), and (3) estimate the economic value of these health benefits. Bakersfield and Fresno/Clovis were used as study areas.

Hourly PM 2.5 monitors in each area made it possible to construct diurnal (24 hr.) profiles of hourly concentrations. Comparing average profiles from clusters of days with comparable meteorological conditions in the pre- and post-Rule 4901 revealed a clear difference in the magnitude of evening and daily PM 2.5 concentrations. This provided evidence of a seasonal reduction in the volume of wood burning. Daily bans have also been effective. Days with wood burning bans had, on average, clearly lower 24 hr. and evening PM 2.5 levels when compared with adjacent days with very similar meteorological conditions.

A statistical analysis of the relationships between Fresno/Clovis PM 2.5 levels (the dependent variable) and meteorological factors such as wind speed, temperature, and atmospheric stability (independent variables) was conducted using data from the three winters prior to Rule 4901. Extensive sensitivity analyses resulted in a meteorological model capable of estimating PM 2.5 concentrations for evening hours and for daily (24 hr.) averages that were very close to the observed levels in Fresno. The model also accurately predicted the observed evening PM 2.5 concentrations in Bakersfield.

Once calibrated with meteorological and PM 2.5 relationships in a period where there were no controls on wood burning, meteorological data in the post-rule period was fed into the model to see if predicted PM 2.5 levels were in excess of actually observed evening and daily concentrations. Over-prediction did consistently occur and it grew in successive years, providing solid evidence of Rule 4901's effectiveness. Over the course of the four winters in the post-rule period, the model over-estimated Fresno/Clovis PM 2.5 from 26% to 36% in evening PM 2.5 (8 pm to 12 am) and from 18% to 28% in overall daily PM 2.5 levels. For Bakersfield, overestimations of evening PM 2.5 ranged from 22% to 35%. Converted to a 12 month metric, Rule 4901's contributed to an average annual daily PM 2.5 reduction of 13.63% in Bakersfield and 12.94% in Bakersfield.

Well-defined epidemiological relationships have been established between PM 2.5 exposures and a range of health endpoints, including ischemic heart disease, asthma, chronic bronchitis, and premature mortality. Epidemiological studies of PM 2.5 health impacts have made it possible to scientifically establish concentration-response (C-R) relationships for these diseases and deaths.

Developed by the U.S. EPA, BenMAP is a software program designed to estimate the morbidity (disease) and mortality (premature death) benefits from a specified reduction in a given form of air pollution for a given population on an annual basis. C-R functions for a range of health endpoints affected by PM 2.5 are contained in the program. In this application, BenMAP was used to look backward into the pre-Rule 4901 period and answer these questions: Based on the model's overestimation of PM 2.5 concentrations in the post-rule period, how many morbidity and mortality cases could have been avoided in 2001, 2002, and 2003 if Rule 4901 had been in effect in that period? And second, what is the economic cost of that excess morbidity and mortality?

For the pre-rule years of 2001, 2002, and 2003, a baseline air quality grid (including spatially resolved demographic data) was created in BenMAP for Fresno and Kern Counties based on the observed PM 2.5 data. Next, a second control air quality grid was specified with a 13.63% annual reduction for Fresno/Clovis and a 12.94% annual reduction for Bakersfield. Using the C-R functions for major health endpoint groups contained in the program, BenMAP estimated the annual reductions in the incidence (frequency) of new disease cases, aggravated symptoms, lost work days, pre-mature deaths, etc. for each county. These incidence results were then scaled downward to match the proportion of county residents residing in the metro study areas. Finally, information about health care costs, wage losses from illness, and the estimated value of a premature death contained in the program resulted in annual dollar value estimates for each health endpoint group.

Estimated excess cases for 2001, 2002, and 2003 in each study area for health endpoint group are summarized in Tables 2, 3, and 4, respectively. For example, excess cases of acute myocardial infarction (heart attacks) in Fresno/Clovis ranged from 64 (2001) to 77 (2002) and from 32 (2003) to 43 (2002) in Bakersfield. Mean excess mortality (premature death) cases for Fresno/Clovis were between 35 (2001) to 85 (2002) and from 18 (2003) to 48 (2002) in Bakersfield. Adjusted for 2008 dollars, mean annual excess morbidity costs in Fresno/Clovis ranged from $11 million to $26.6 million and $5.7 million to $14.1 million in Bakersfield (Figures 36 and 37). Estimated mean annual mortality costs ranged from $367.5 million to $430.6 million in Fresno/Clovis and from $189.1 million to $239.9 million in Bakersfield (Figures 38 and 39).

Overall, the evaluation of Rule 4901 generated a range of empirical evidence attesting to Rule 4901's effectiveness. The retrospective analysis of pre-rule excess cases of mortality and morbidity provides clear evidence that, at the margin, Rule 4901 is saving lives, preventing illness, and reducing suffering from airborne fine particulates throughout the San Joaquin Valley. This is particularly true for south Valley urban areas where density of settlement coincides with powerful and persistent nighttime inversions.

Study Overview

This final project report by the Central Valley Health Policy Institute (CVHPI) provides an evaluation of the regulatory and public health effectiveness of Rule 4901 as adopted by the San Joaquin Valley Air Pollution Control District on November 1, 2003. Rule 4901 set in place a 150 AQI-triggered ban on wood burning in areas of the San Joaquin Valley that have natural gas service and are below 3,000 ft elevation. With the Bakersfield and Fresno/Clovis metro areas as comparative case studies, the primary purposes of this evaluation were to (1) estimate the impact of Rule 4901 on reducing PM 2.5 concentrations during Valley winter evenings when thermal inversions, stagnant meteorological conditions, and wood burning coincide to produce excessive exposure to the public, (2) estimate the reduced incidence of air pollution-related disease (morbidity) and premature death (mortality) that accrue from these reduced concentrations, and (3) estimate the corresponding economic value of these morbidity and mortality benefits.[1] The results of the evaluation, described below, contribute to the growing body of knowledge about the relative contribution of domestic wood burning to PM 2.5 exposures in the urban centers of the San Joaquin Valley. And finally, the results provide the District staff and Board with a solid scientific justification for their adoption on October 16, 2008 of an amended Rule 4901 that employs a wood burning ban threshold at a predicted AQI of 80 rather than the current AQI threshold of 150.[2]

The analyses described below were undertaken as a team effort between David Lighthall of CVHPI, Tim Tyner of UCSF-Fresno, and David Nunes of the SJVAPCD. Dr. Lighthall took principal responsibility for (1) overall project management and data collection, (2) background research, (3) comparative, qualitative assessment of diurnal profiles, (4) BenMAP analysis, (5) project presentations, and (6) the final report. Tim Tyner played a critical role in hypotheses testing and early development of the meteorological model employed in the report via extensive graphing of diurnal meteorological and PM 2.5 data. David Nunes took primary responsibility for the development and implementation of the meteorological model used to estimate the seasonal and daily (evening) reductions in PM 2.5 attributable to Rule 4901. Project team meetings of the project team played a key role in the success of the project.

The remainder of the report is composed of the following sections:

1. A brief background on wood smoke, PM 2.5 and associated health effects as they pertain to the study areas;
2. An overview on data acquisition and data management;
3. An overview of the hypotheses testing process;
4. The meteorological model development process and related issues;
5. Meteorological model results and discussion;

[1] While the project sought to estimate the health benefits of Rule 4901, the methodological means for this was based on estimating, via the BenMAP program, the excess cases of disease and premature death that occurred in the three years prior to the Rule's passage--2001, 2002, and 2003.

[2] An Air Quality Index of 150 is the function equivalent of a 24 hr. average concentration of 65 micrograms (µg) per cubic meter of PM 2.5. The amended Rule 4901's burning ban threshold of a 80 AQI is equivalent to a 24 hr. average concentration of 30 $\mu g/m^3$

6. BenMAP analysis and results;
7. Conclusions and Recommendations.

As indicated above, all figures and tables are contained in sequence in Appendix A. Citations will be listed as footnotes and not as endnotes.

Background

The San Joaquin Valley experiences some of the highest annual average concentrations of PM 2.5 in the nation. Unlike areas such as southern California where PM 2.5 levels are distributed throughout the year, fine particulates are seasonally concentrated in the Valley. The region experiences multi-day periods of atmospheric stagnation during which very little air mass is transferred in and out of the Valley. The net result is a day to day buildup of PM 2.5 levels, well beyond the federal standard of 65 $\mu g/m^3$.[3] This effect is shown in Figure 1, whereby daily PM 2.5 concentrations for south Valley monitors gradually work upwards, driven by an accumulation of secondary ammonium nitrate. Because of this seasonal concentration effect, wintertime PM 2.5 sources like wood burning make a disproportionate impact on daily and yearly PM 2.5 concentration. The south Valley, from Fresno south, experiences the greatest concentrations often well above the federal annual average daily exposure standard of 15 $\mu g/m^3$.

The epidemiological relationship between PM 2.5 exposure and pulmonary disease, cardiovascular disease, and premature mortality is well established in the scientific literature. For example, Jerrett et al. (2005) found a well-established statistical relationship between premature mortality and PM 2.5 exposure levels in the Los Angeles region.[4] Relative risk factors for mortality resulting from ischemic heart disease and lung cancer deaths were elevated, in the range of 1.24-1.6, depending on the model used.

An excellent overview of this literature is found in Arden and Pope (2006, p. 709)[5]. They summarize the current state of knowledge in the field:

> ". . . There has been substantial progress in the evaluation of PM health effects at different time-scales of exposure and in the exploration of the shape of the concentration-response function. There has also been emerging evidence of PM-related cardiovascular health effects and growing knowledge regarding interconnected general patho-physiological pathways that link PM exposure with cardiopulmonary morbidity and mortality. Despite important gaps in scientific knowledge and continued reasons for some skepticism, a comprehensive evaluation of the research

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[3] The current federal standard is 35 $\mu g/m^3$ but for the purposes of this report the old standard of 65 $\mu g/m^3$ will be referenced due to the fact that the San Joaquin Valley is currently being officially required to meet the 65 $\mu g/m^3$ standard.

[4] Jerrett, M., R. Burnett, R. Ma, C. Pope, D. Krewski, K. Nebold, G. Thurston, Y. Shi, N. Finkelstien, E. Calle, and M. Thun. (2005). Spatial Analysis of Air Pollution and Mortality in Los Angeles. *Epidemiology* 16(6): 727-736.

[5] Pope, C.A., and D. Dockery (2006) Health Effects of Fine Particulate Air Pollution: Lines that Connect. *Journal of Air and Waste Management Association* 56: 709-742.

> findings provides persuasive evidence that exposure to fine particulate air pollution has adverse effects on cardiopulmonary health. Although much of this research has been motivated by environmental public health policy, these results have important scientific, medical, and public health implications that are broader than debates over legally mandated air quality standards."

Well-defined epidemiological relationships have been established between PM 2.5 exposures and a range of health endpoints, including ischemic heart disease, asthma, chronic bronchitis, premature mortality, and others. This extensive literature has made it possible to create concentration-response functions that reflect the incremental impact of increased PM 2.5 exposure on the rate of a given disease or form of premature mortality. Examples of concentration-response relationships are depicted in Figure 2.[6] These C-F functions form the heart of the BenMAP program employed in this study to estimate the health and related benefits of Rule 4901 and will be discussed in detail below.

For example, Hall et al. (2006) were able to estimate the morbidity and mortality reductions that would occur in the San Joaquin Valley if PM 2.5 annual exposure levels were rolled back to the 15 $\mu g/m^3$ standard.[7] In addition, a body of previous studies on (1) the cost of illness for PM 2.5-related disease, (2) disease impacts on household income, and (3) survey's of individual willingness-to-pay for the absence of air pollution-related symptoms have allowed the Hall et al. (2006) and other researchers to also estimate the corresponding economic benefits of achieving the federal PM 2.5 ambient air quality standard. As described below, this scientific knowledge and technical capacity has been employed in this study via the U.S. EPA's BenMAP health benefit estimation program.

Wood smoke is increasingly understood to be a particularly harmful form of PM 2.5 relative to other sources such as ammonium nitrate. Naeher et al. (p. 68) provide this overview:

> The sentiment that wood smoke, being a natural substance, must be benign to humans is still sometimes heard. It is now well-established, however, that wood-burning stoves and fireplaces as well as wild land and agricultural fires emit significant quantities of known health-damaging pollutants, including several carcinogenic compounds (e.g., polycyclic aromatic hydrocarbons, benzene, aldehydes, respirable particulate matter, carbon monoxide [CO], nitrogen oxides [NOx], and other free radicals).[8]

This scientific knowledge, coupled with the propensity for severe evening temperature inversions in the San Joaquin Valley wintertime to create very high concentrations of

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[6] Graphs shown in Figure 2 are reprinted from Pope and Dockery (2006, p. 720).

[7] Hall, J., V. Brajer, and F. Lurmann. (2006) The Health and Related Economic Benefits of Attaining Healthful Air in the San Joaquin Valley. California State University Fullerton, Institute for Economic and Environmental Studies (March).

[8] Naeher, L, M. Brauer, M. Lipsett, J. Zelikoff, C. Simpson, J. Koenig, and K. Smith. (2007) Woodsmoke Health Effects: A Review. *Inhalation Toxicology* 19: 67-106.

nighttime PM 2.5, underscores the importance of controlling wood smoke emissions through such regulations as Rule 4901.

Table 1 (Appendix A) provides a summary view of population levels over time for the two metro study areas and their counties. Fresno and Bakersfield were selected as study areas due to the presence in both areas of two BAM (hourly) PM 2.5 monitors and two FRM (24 hr average) monitors. This spatial density of monitors allowed for relatively accurate exposure estimates for their residential populations relative to other urban areas of the region where PM 2.5 exposure estimates would depend on a single monitor and/or long-distance extrapolation of PM 2.5 concentrations. Annual average PM 2.5 in these urban areas is consistently among the highest recorded in the region. As seen in Figure 2, annual average 24 hr. exposure concentrations have been well above the federal 15 $\mu g/m^3$ standard. Furthermore, wood smoke emissions during winter inversion events tend to concentrate at the neighborhood level.[9] As a result, the populations of densely populated cities such as Fresno and Bakersfield are particularly vulnerable to breathing excessive concentrations of fine particulates from wood combustion. From a public health perspective, therefore, it is particularly important to establish scientifically the relative effectiveness of fine particulate control measures in areas where such high populations are being exposed to excessive concentrations.

Data Acquisition and Management

The primary data challenge in the study was to assemble a consistent, complete, and comprehensive dataset for meteorology and air quality in Fresno and Bakersfield for the months of November, December, January, and February for the years 2000 through 2006. The evaluation was made possible by the availability of numerous secondary datasets, including the following:

1. Meteorological data from the National Oceanic and Atmospheric Agency (NOAA)[10] and the California Irrigation Management Information System (CIMIS)[11] for Fresno and Bakersfield including such parameters as minimum/maximum temperatures, hourly temperature, wind speed, atmospheric stability, and precipitation;
2. PM 2.5 data collected hourly by BAM monitors and daily by FRM monitors sourced from the California Air Resources Board (CARB) and the SJVAPCD;
3. Information from the SJVAPCD regarding the days when the agency has issued bans on wood burning and no-burn advisories for Fresno and Kern Counties;
4. Data from the California Office of Statewide Health Policy and Development Department (OSHPD) on emergency department (2005-07) and hospital admissions (2000-07) for San Joaquin Valley and other selected California counties (see comment below).

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[9] Countess Environmental. (2003) Quantifying the Role of Vegetative Burning to Ambient PM 10 and PM 2.5 Concentrations in the San Joaquin Valley (Final Report for Amendment 1 to Agreement No. 60157). Prepared for the San Joaquin Valley Unified APCD (March 27).

[10] See http://www.nesdis.noaa.gov/datainfo.html.

[11] See http://wwwcimis.water.ca.gov/cimis/data.jsp.

As the lead team member in charge of developing the meteorological model used to estimate the PM 2.5 reductions from Rule 4901, David Nunes of the SJVAPCD took responsibility for the acquisition and management of meteorological data. With the exception of atmospheric stability indicators such as the Oakland 850 millibar sounding and related regional reanalysis files, meteorological data employed was collected within the respective study areas. As discussed below, the integration of regional atmospheric stability parameters with local meteorological data was critical to the development of the predictive model.

Regarding the PM 2.5 data, BAM and FRM data dating from 2000 to 2006 was obtained from CARB and supplemented with speciated PM 2.5 data generated by previous intensive research conducted by the California Regional Particulate Air Quality Study (CRPAQS) during the winter of 2000-2001.[12] The hourly BAM data was closely examined for outliers and missing entries. In addition, the BAM and FRM data was found to be well-correlated in respect to 24 hour average values, with the BAM data consistently registering slightly lower concentrations. While there are two BAM monitors in each city, for much of the early years of the evaluation (2000 to 2003) data was only available from the Fresno First St. monitor (Site ID 060190008) and for the Bakersfield California Ave. monitor (Site ID 0602900014). These are the only monitors that operate each day during winter months as well. Each of these monitors is operated by CARB and is well-situated within the residential cores of the study areas. For the hourly data, missing information for individual hours was interpolated. In cases were multiple hours were missing, parallel data from the given city's other BAM monitor was adjusted and imported. In a small number of cases, the number of missing hours necessitated removal from the dataset of that day's data.

Regarding the OSHPD data, the project had originally intended to examine the statistical relationship between wintertime PM 2.5 concentrations and the rate of emergency room and hospital admissions for cardiovascular and respiratory diseases in the study areas. This involved making custom data requests to OSHPD for patient record files that included the zip code of the patient. Unfortunately, the long lead time involved in gaining approval from OSHPD for these custom data requests made it impossible to complete the analysis within the project timeframe. The CVHPI has just received the files, however, and now has the capability to examine the temporal relationships between wintertime PM 2.5 concentrations and hospital/ER admissions in the future.

Hypotheses Testing

In order to lay the foundation for an well-performing predictive model, a considerable amount of time, discussion, and empirical analysis was devoted to (1) ascertaining the relative contribution of wood smoke to PM 2.5 concentrations in the study areas and (2) the temporal dynamics of wood smoke concentrations during wintertime diurnal cycles. While previous CRPAQS-funded studies provided small time windows where wood smoke tracers such as levoglucosan were quantified, this study would necessarily

[12] CRAPQS speciated data was used primarily during the hypothesis-testing phase as a means of determining the best period during the diurnal cycle for assessing the impact of Rule 4901 on wood smoke emissions (see further discussion below). Hourly BAM data was not available until late 2001 (11-29-01 for the California Ave. monitor and 11-14-08 for the First St. monitor.

depend on inferring daily wood smoke concentrations based on daily cycles of PM 2.5 and meteorological parameters. The specific stages of analysis included the following:

1. Identifying the key findings of prior wood smoke research funded by CRPAQS;
2. Comparing diurnal plots of hourly PM 2.5 data during winter days with comparable meteorological conditions and elevated PM 2.5;
3. Examining the effects of periodic wood burning bans on evening concentrations of PM 2.5 when compared to days with similar meteorological conditions but with no ban in effect;
4. For days with similar meteorological conditions, comparing diurnal profiles of hourly data in the pre-Rule 4901 period with profiles in the post-Rule 4901 period.

Key Findings Regarding Wood Smoke's Contribution to PM 2.5: Overall, urban PM 2.5 concentrations in wintertime are composed of about 50% secondary ammonium nitrate and 20-40% organic carbon (OC) and inorganic carbon (IC), with the rest accounted for by ammonium sulfate and suspended dust.[13]

Diurnal cycles of PM 2.5 are, in essence, dominated by these two aerosol regimes. The first is a daytime rise and fall in PM 2.5 concentration closely related to solar energy and dominated by ammonium nitrate. The second is a nighttime cycle dominated by organic carbon (OC) and to a lesser extent, inorganic carbon (IC) aerosols. The net outcome of this is characteristic "double hump" 24 hr. cycle as depicted in Figures 4 and 5. During the nighttime, ammonium nitrate formed by daytime reaction of plentiful ammonia and nitrogen oxides is dissipated in the inversion layer while being sequestered above the inversion layer.[14] The onset of sunlight and the inversion breakup, ammonium nitrate concentrations increase during daylight hours. Sunset witnesses the simultaneous dissipation of ammonium nitrate and the buildup of localized OC-based aerosols due to the collapse of the mixing layer. This buildup coincides with the lighting of wood stoves and fireplaces in households.

Regarding wood smoke's contribution to overall OC, a Fresno speciated PM 2.5 study based on the use of levoglucosan as a tracer for wood smoke collected during the CRPAQS winter intensive study in 2000-2001 concluded as follows: "Combined, the emissions from wood smoke, meat cooking, and motor vehicles appear to contribute ~65--80% to measured OC, with wood smoke, on average, accounting for ~41% of OC and ~18% of PM 2.5 mass."[15]

Diurnal Comparisons: In this stage of the analysis, categories of days based on comparable meteorological conditions and elevated PM 2.5 levels were grouped and

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[13] Watson, J., and J. Chow. (2002) A Wintertime PM 2.5 episode at the Fresno, CA, Supersite. *Atmospheric Environment* 36: 465-475.

[14] Hering, S., B. Kirby, B. Wittig, and K. Magliano. (2003) Wintertime Spatial and Temporal Distribution of Fine Particulate Nitrate in the San Joaquin Valley of California, USA. American Association for Aerosol Research (AAAR), 22nd Annual Conference, October 20-24, Anaheim, CA.

[15] Gorin, C, J. Collett, and P. Herckes. (2006) Wood Smoke Contribution to Winter Aerosol in Fresno, CA. *Journal of the Air and Waste Management Association* 56: 1584-1590 (quote on p. 1584).

compared. Clusters of days with comparable meteorological conditions in the pre- and post-Rule 4901 were assembled and composite diurnal profiles were created. As shown in Figure 4, there was a clear difference in the magnitude of evening PM 2.5 concentrations during violation days in the pre-rule period vs. those in the post-rule period.[16] This provided evidence of a seasonal impact of the rule--that overall Rule 4901 had the effect of reducing the ambient concentration of wood burning in Fresno. In addition, following adoption of the rule, days when a burning ban was in effect averaged significantly lower overall concentrations relative to violation days where no ban was in effect. Also, the daily average of Fresno ban days was below the 65 microgram standard, suggesting that overall the rule was an effective means of reducing PM 2.5 and protecting public health. These conclusions, however, are tempered by the fact that meteorological conditions were not fully controlled in the analysis.

Another example of this analysis for Bakersfield is depicted in Figure 5. In this case, all pre-rule days that violated the 65 microgram daily average were averaged and compared with similar post-rule days with violations (61.4 $\mu g/m^3$).[17] In addition, all days in the post-rule period where a ban was in effect in the post-rule period were averaged. Despite the fact that bans on wood burning are called on days with the highest emission concentration potential, the ban days witnessed a noticeably lower concentration during the evening period, defined as the time period from 8 pm until 12 midnight.

It is important to note that the Bakersfield metro area experiences a higher level of what can be termed the ammonium nitrate baseline, a result of the higher concentration of NOx from vehicular and energy production sources and the richer ammonia environment tied to south Valley dairy production. As a result, burning ban days in Kern County still exceeded the 65 microgram standard (70.8 $\mu g/m^3$). Figure 6 summarizes the differences in the NOx environment between Fresno and Kern Counties.

In addition, we examined evening concentrations of PM 2.5 in consecutive multiday periods in the post-rule period for evidence of suppression of the evening PM 2.5 spike during days when bans were in effect. Numerous examples of this “ban effect” were found, as seen in Figure 7. This sequence of days represents a typical stagnation period in the San Joaquin Valley, characterized by high daytime spikes of ammonium nitrate and evening spikes of localized directly emitted OC aerosols. Wood burning was discouraged on all days with the exception of November 18, when a ban was in effect. The evening average concentration (55 $\mu g/m^3$) is significantly lower than adjoining days despite the marked similarity in the meteorological variables.

Model Development

The graphs shown in the preceding section represent a small fraction of the overall output during the diurnal profiling stage of the evaluation. By the end of this stage of the analysis, clear evidence of evening and seasonal differences in PM 2.5 during the pre-

[16] Through March 2008, there were 26 violation days following rule adoption and 33 violation days in the pre-rule period for Fresno. Through the winter of 2008, there were a total of 33 ban days Fresno County.

[17] There were 28 violation days in the pre-rule period and 24 violation days in the post-rule adoption period for Bakersfield. Through the winter of 2008, there was a total of 39 wood burning ban days in Kern County.

and post-rule periods provided the project team with the basis for the next stage of the evaluation--developing a predictive PM 2.5 model based on meteorological variables. The primary purpose of the model was to control for variations in meteorological conditions in the pre- and post-Rule 4901 period in order to statistically infer the relative effectiveness of the rule in the period following its incorporation on November 1, 2003. In other words, the model was based on the statistical relationships between independent meteorological variables and dependent PM 2.5 concentrations as established through regression analyses using meteorological and PM 2.5 data in the pre-Rule 4901 period.

There were two objectives in this analysis, the first being the extent to which daily bans were able to suppress evening concentrations of PM 2.5. The second, based on the prediction of the 24 hr. average PM 2.5, served as an indication of the overall, seasonal effect of the rule in reducing population exposure to harmful fine particulates. The model was tested and refined through sensitivity testing, whereby different combinations of daily meteorological parameters under different assumptions about linear vs. non-linear relationships to PM 2.5 was employed in order to see which combination best predicted the observed PM 2.5 concentrations.[18]

To summarize, the primary elements of the model development included:

1. A goal of predicting average PM 2.5 levels in two time periods (the dependent variables):
    a. The 8 pm to 12 am period where wood smoke had been established as a predominant source based on BAM monitor data and speciation research;
    b. The overall daily PM 2.5 average (Fresno only) based on FRM monitor data.
2. Parameterization of the model was based on the relationship between selected meteorological factors (i.e. independent variables) and average PM 2.5 concentrations in the two time periods during the pre-rule period
3. Incorporation of both linear and non-linear regression relationships between the dependent and independent variables;
4. An extended process of sensitivity testing in order to assemble the most predictive combination of variables as well as linear vs. non-linear relationships as indicated by regression coefficients.

Technical details of the model include the following:

1. Model data based on November through February PM 2.5 data for 2000, 2001, 2002, and 2003:
    a. Days with significant precipitation were excluded;
    b. Days with potential impact from the Fresno area Crippen fire were excluded from the model.

[18] David Nunes of the SJVAPCD conducted the modeling analyses, with periodic input from Tim Tyner and David Lighthall.

2. Model variables for the FRM Daily Model (Fresno only):
    a. Fresno daily minimum temperature;
    b. Log of Fresno evening average wind speed;
    c. Oakland morning (12 GMT) 850 mb height;
    d. Fresno morning stability: (i.e. Oakland morning [12 GMT] 850 mb temp minus Fresno minimum temp);
    e. Number of days in a row with stability.
3. Model variables for the BAM Evening Model:
    a. Evening average temperature;
    b. Log of evening average wind speed;
    c. Daily average 850 mb height;
    d. Number of days in a row with stability.

Model Results

The evidence provided by the diurnal profiling for Rule 4901's effectiveness was borne out by the modeling results. The following sequence of graphs depict the differences between the model's predictions of PM 2.5 vs. actually observed concentrations in the pre-rule period (which was the basis of the model) and in the post-rule period. The net difference represents Rule 4901's estimated impact on evening and seasonal concentrations.[19]

Figures 8-11 summarize the model findings for Fresno. The left portion of Figure 8 indicates the model's estimation of evening (8 pm to 12 am) PM 2.5 vs. the actually observed values, recognizing that the model had been calibrated on this same dataset. The right portion graphs the model's prediction of evening concentrations in the post-Rule 4901 years vs. observed values. Mass differences were significantly different, providing further evidence that constrained wood burning on ban days, combined with an overall reduced intensity of burning, can be attributed to Rule 4901. A similar phenomenon can be seen in Figure 9 for daily (24 hr.) model prediction using daily average data from the 1st St. FRM monitor. Differences in estimated vs. observed PM 2.5 for the daily and evening time periods are further presented in Figure 10 (mass) and Figure 11 (percentage difference in mass). Modeled mass reductions in fine particulate concentrations were higher for the evening timeframe. Figures 12 and 13 present parallel findings for Bakersfield in the evening timeframe only.

It is noteworthy to observe that mass and percentage reductions attributable to Rule 4901 have consistently increased in successive years for both urban areas. This provides further evidence that, over time, Rule 4901 has triggered reductions in household wood burning through various mechanisms, daily bans being only one pathway. Anecdotal evidence suggests that the rule has triggered greater awareness of the harmful effects of urban wood emissions during wintertime inversions. For example,

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[19] Modeled PM 2.5 concentrations in the Bakersfield study area were limited to the evening (8 pm to 12 am) period.

in a previous CVHPI research project, six focus groups were conducted with a range of Valley residents (8 to 12 participants in each).[20] Focus group discussions included the topic of Rule 4901 and wood burning. A number of participants indicated that they had ceased to burn wood on a regular basis, citing an increased recognition of the health effects from the smoke (indoor and outdoor) on family members or neighbors. A significant majority of participants supported further tightening of the rule based on the need to protect those most vulnerable to fine particulate exposure.

However, it should also be noted that other source control measures have been instituted during this same time period, and that these may be partially responsible for the reduced PM 2.5 levels observed in the post-rule period. This would certainly be the case for reductions in the daily 24 hr. average concentrations. Motor vehicle fleet turnover, in particular, can likely account for some fraction of the reduction in observed daily average but are less likely to have had much impact on evening concentrations.

BenMAP Analysis

BenMap Overview: The final stage of the Rule 4901 evaluation involved the estimation of the morbidity (disease) and mortality (pre-mature death) benefits that can be attributed to improved air quality stemming from the rule. There are two goals in this estimation process. The first is to infer reductions in the incidence rate for diseases and pre-mature death that have been shown to be statistically associated with elevated PM 2.5 by previous epidemiological studies. The second goal involves assigning an economic value to those estimated reductions in morbidity and mortality. As noted above, a similar methodological approach was employed in the Hall et al. (2006) study that estimated the health and economic benefits of achieving federal ozone and PM 2.5 standards in the San Joaquin Valley.[21]

The program employed for this study was BenMAP, a sophisticated but user friendly program developed by the U.S. EPA that is well-suited for the empirical objectives of this evaluation.[22] Key elements of the BenMAP analysis process include:

1. BenMAP determines the change in ambient air quality as specified by the user. BenMAP does not include an air quality model. Instead, this data is either loaded in from external modeling sources or generated from a national set of air pollution monitoring data that is pre-loaded into BenMAP.
2. Next, BenMAP calculates the relationship between the reduction in air pollution (either ozone or PM 2.5) and certain health effects typically referred to as health endpoints, e.g. premature mortality, asthma attacks, and chronic bronchitis.

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[20] Lighthall, D., and J. Capitman. (2007) The Long Road to Clean Air in the San Joaquin Valley: Facing the Challenge of Public Engagement. Fresno, CA: California State University, Fresno.

[21] Hall, J., V. Brajer, and F. Lurmann. (2006) The Health and Related Economic Benefits of Attaining Healthful Air in the San Joaquin Valley. California State University Fullerton, Institute for Economic and Environmental Studies (March).

[22] In July, 2008 David Lighthall completed a three-day BenMAP training program conducted by the Community Modeling and Analysis System in Chapel Hill, NC under contract to the U.S. EPA. See http://www.epa.gov/air/benmap/ for more information on BenMAP, downloading the program, and for technical documents.

Discussed above and shown in Figure 2, this entails the utilization of a concentration-response (CR) function based on prior epidemiological studies.

3. In the final step, BenMAP estimates the incidence reduction for specified health endpoints for the target population, depending on the level of pollution reduction specified. Custom demographic information can be employed or default population data contained within BenMAP can be used for past, current, and future years based on population growth functions in the program.

A simplified example of estimating the health effect can be summarized as:[23]

Health Effect = Air Quality Change * Health Effect Estimate * Exposed Population * Health Baseline Incidence

1. Air Quality Change: The air quality change is the difference between the starting air pollution level (i.e. the baseline), and the air pollution level after some change, such as a new regulation (i.e. the control).
2. Health Effect Estimate: The health effect estimate is an estimate of the percentage change in adverse health effect due to a one unit change in ambient air pollution. Epidemiological studies provide a good source for effect estimates.
3. Exposed Population: The exposed population is the number of people affected by the air pollution reduction.
4. Health Baseline Incidence: The health incidence rate is an estimate of the average number of people that die or become ill over a given period of time. For example, the health incidence rate might be the probability that a person will die in a given year or become asthmatic.

Finally, BenMAP calculates the economic value of avoided health effects due to reduced ozone or PM 2.5 air pollution. To summarize:

Economic Value = Health Effect * Value of Health Effect

There are several ways to calculate the value of health effect changes. For example, the value of an avoided premature mortality is generally calculated using the Value of a Statistical Life (VSL). The VSL is the monetary value that people are willing to pay to slightly reduce the risk of premature death. For other health effects, the medical costs of the illness may be the only valuation available. In other cases, prior research has provided survey-based generalizations about participant's willingness to pay (WTP) for avoidance of health symptoms and/or diseases. These economic valuation functions are contained within the BenMAP program for its "canned" health endpoints and can also be imported.

BenMAP Application: The foundation of any BenMAP application is the specification of the difference in air pollution concentration attributable to the control measure in question. In other words, what is the difference between the baseline and control air quality grids that are generated in the first stage of its application? In the case of this

[23] Abt Associates Inc. (2008) BenMAP Environmental Benefits Mapping and Analysis Program: User's Manual. Prepared for Office of Air Quality Planning and Standards, U.S. EPA, Research Triangle Park, NC (September). Summary above taken from pp. 8-9.

evaluation, this entailed estimating the percentage excess ambient PM 2.5 that occurred in Bakersfield and Fresno that could have been prevented had Rule 4901 been in effect during the years 2001, 2002, and 2003. It is important to note at this juncture that it is impossible to make such estimations without making a number of assumptions that, while guided by accepted principles of scientific inference, nonetheless are subject to alternative assumptions and corresponding estimations.

One of the fundamental assumptions in this analysis was the assignment of uniform PM 2.5 exposure estimates to each study area population on the basis of FRM and BAM data collected by a single monitor location in each study area (California Ave. in Bakersfield and 1st St. in Fresno). Support for assuming a uniform exposure to wood smoke-based PM 2.5 across the metro study areas is found in Gorin et al. (2005, p. 59).[24] In this CRPAQS-funded tracer study of wood smoke, five monitors were employed across Fresno and Clovis from 12-25-03 to 1-15-04. The authors found that inter-site variability of PM 2.5, TC, and levoglucosan (the wood smoke tracer) throughout the city was generally small (typically 15% or less). In addition, person to person and neighborhood to neighborhood variations in exposure to daily PM 2.5 related to time spent in traffic, proximity to local sources such as restaurants, neighborhood-level wood burning, and other random localized sources also undermine the logic of assuming linear gradations in population exposure across the urban landscape. Finally, in contrast to the approach taken by Jerrett et al's study of PM 2.5 and mortality in the Los Angeles air basin, there is not a reliable method for empirically estimating an alternative, spatially-resolved population exposure surface at this geographic scale of analysis.[25]

In preparation for the BenMAP analysis described below, the average daily (24 hr.) percentage mass reductions estimated by the predictive model were calculated for Fresno and Bakersfield for the winter months of November through February for 2003-04, 2004-05, 2005-06, and 2006-07. Because daily average values were not calculated for Bakersfield, it was necessary to estimate Bakersfield's daily average reduction over the years 2003-04, 2004-05, 2005-06, and 2006-07 by extrapolating from estimated evening reductions in PM 2.5 for the same time period. In fact, the average seasonal percentage reduction in evening PM 2.5 mass was essentially equivalent between Fresno and Bakersfield--31%. Fresno's average wintertime reduction in estimated daily (24 hr.) PM 2.5 was 22.75%. Because of the similarity in estimated reductions in evening concentrations, Fresno's 22.75% reduction in estimated daily PM 2.5 during the winter months was applied to the Bakersfield case as well.

The next step involved calculating the average 12 month percentage reduction in PM 2.5 mass resulting from the wintertime reductions attributable to Rule 4901. Total daily mass of PM 2.5 was tallied for each study area monitor (Fresno 1st St. and Bakersfield

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[24] Gorin, C., P. Herckes, and J. Collett, Jr. (2005) Wood Smoke Contributions to Ambient Aerosol in Fresno During Winter 2003-2004. Prepared for the San Joaqiun Valley Air Pollution Control Agency

[25] Jerrett, M., R. Burnett, R. Ma, C. Pope, D. Krewski, K. Nebold, G. Thurston, Y. Shi, N. Finkelstien, E. Calle, and M. Thun. (2005) Spatial Analysis of Air Pollution and Mortality in Los Angeles. *Epidemiology* 16(6): 727-736.

California Ave.) for the baseline calendar year of 2002.[26] For Fresno, 59.9% of the annual PM 2.5 mass was measured in the four winter months. For Bakersfield, the comparable figure was 56.9%. The net result was an estimated 13.63% annual reduction in PM 2.5 mass attributable to Rule 4901 for Fresno, and an estimated 12.94% annual reduction for Bakersfield.

These percentages were then employed in the BenMAP analyses reported below. That is, for Bakersfield the control air quality grid had a 12.94% lower annual average PM 2.5 concentration relative to the baseline air quality grid and 13.63% for Fresno.

The Application Geography, Timeframe, and Related Assumptions: BenMAP contains PM 2.5 data from air quality monitors nationally, including Fresno and Kern Counties, for the years 2000 through 2007. These monitors are in fact located in the cities of Fresno, Clovis, and Bakersfield. Based on the findings of the Gorin et al. study cited above as well as the similarity in average annual PM 2.5 concentrations between Fresno and Clovis monitors (see Figure 3), the Fresno and Clovis populations were combined in the BenMAP analysis and a uniform level of PM 2.5 exposure across this combined metro area was assumed. County vs. study area populations and their corresponding percentages are shown in Table 1 for 2000 through 2006.

Upon consultation with SJVAPCD staff, the years 2001, 2002, and 2003 were selected as the application years for the BenMAP analysis.[27] In short, the goal of the analyses was to determine the reduction in incidence for key health endpoints that would have occurred if Rule 4901 had been in place at that time.[28] Results from this rollback in population exposure (called a monitor rollback in BenMAP) were reported at the county level. These estimates in incidence reduction were then proportionally scaled back on the basis of each study area's fraction of the total county population. The same was done for the economic valuation results.

Stages of the BenMAP Analysis and Related Issues: Prior to presenting the BenMAP results, the specific steps employed in this application will be described. These steps include: (1) creating a baseline and control air quality grid to estimate population exposure, (2) estimating incidence rates for the exposed population in the baseline vs. control scenario and attendant changes (deltas), (3) aggregation of incidence changes for specific health endpoints into health endpoint groups,[29] (4) selection among valuation options for health endpoint groups and estimation of overall excess costs for each endpoint group, (5) creating incidence and valuation reports for each run, and (6) creating audit reports that summarize all technical specifications used in each run.

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[26] 2002 was chosen because it was the only year in the pre-rule period that had a nearly complete daily FRM dataset. The wintertime fraction of annual PM 2.5 mass was somewhat elevated in 2002 due to an above average level of stability during the winter inversion season.

[27] Personal communication with Scott Nester, SJVAPCD Planning Director, October 14, 2008.

[28] It should be noted that Rule 4901 was in effect during November and December of 2003 but its relative impact on wood burning during these first two months is assumed to be relatively small.

[29] Health endpoint groups subsume specific health endpoints within a given morbidity category, e.g. Upper Respiratory Symptoms.

In the case of the baseline and control air quality grids, the 12.94% and 13.63% monitor rollback levels cited above were employed for Bakersfield and Fresno/Clovis respectively. Via a mapped user interface, BenMAP allows for flexible specification of counties and/or states in the rollback analysis.[30] County annual average daily PM 2.5 levels are displayed for each area specified in the baseline and control grids, making it easy to verify the accuracy of the rollback specification. Average annual daily PM 2.5 concentrations contained within the BenMAP database corresponded very well to the FRM-based design values displayed in Figure 3.

While space precludes a detailed discussion, the next stage of the analysis--incidence estimation for health endpoints--presents BenMAP users with the option of selecting from a menu of epidemiological studies for each health endpoint. Each of the studies has a unique concentration response function (beta) and, in many cases, a concentration response curve. In respect to the C-R curve, the user has the option of selecting whether a “cut point” C-R curve will be employed or not. Typically set at either 7.5 or 10 $\mu g/m^3$, the slope of the cut point C-R curve steepens at the cut point level. In other words, once PM 2.5 exposure levels reach this level, the health response intensifies. Evidence of cut points can be found in several of the graphs in Figure 2. Cut points should not be confused with thresholds for health effects for air pollution exposure. Thresholds typically refer to concentration levels below which no health effects occur. Because epidemiological studies have found evidence of effects from PM 2.5 at very low thresholds, many PM 2.5 researchers do not recommend use of thresholds.[31] In this case, the scientific literature pointed to the specification of the cut point option in this analysis, reflecting the relatively high levels of PM 2.5 in the San Joaquin Valley (Kern and Fresno County annual concentrations are in the top 1% nationally).

Incidence aggregation of health endpoints into health endpoint groups in BenMAP was straightforward in this case because it involved summing the effects of discrete diseases such asthma and chronic lung disease. In cases where the user has specified different C-F functions drawn from different epidemiological studies for the same disease (endpoint), alternative mathematical techniques for averaging incidence changes within the endpoint (or endpoint group) can be employed by the BenMAP user.

The next step--assigning an economic value to incidence changes within health endpoint groups--also provides the user with options for most endpoint groups. These options are based on alternative studies that may employ cost of illness (COI), lost wages, and/or willingness to pay (WTP) metrics. In cases where disease impacts are long-term, as in the case of myocardial infarction (heart attack), there are also options for the selection of alternative discount rates for future medical costs and/or lost wages.

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[30] Users have the option of rolling back population exposures in a uniform way according to the reading from the nearest monitor or the exposure reductions can be interpolated between monitors. In this case, the populations in question were centered around the PM 2.5 monitors in each county. As a result, the nearest monitor option was always selected.

[31] For a detailed discussion of thresholds and related methodological issues see: Tran, H., A. Alvarado, C. Garcia, N. Motallebi, L. Miyasato, and W. Vance. (2008) Methodology for Estimating Premature Deaths Associated with Long-term Exposures to Fine Airborne Particulate Matter in California. Staff Report, California Air Resources Board, Sacramento.

In this analysis, a 3% annual discount rate was selected, with 5% and 7% typically provided as alternative options by the program.

An extended period of time was spent in sensitivity analysis for this BenMAP analysis. In this phase, different assumptions about cut point vs. non-cut point, selection of alternative studies within a given health endpoint, etc. were employed in multiple runs and multiple years. While not mentioned above, there were multiple options within the premature mortality endpoint group for both the incidence estimation (alternative C-R functions, cut point vs. non-cut point, etc.) and valuation portion of the analysis. At the end of the sensitivity analysis, a final combination of C-R functions and valuation options was chosen that provided overall results in the mid-range of total incidence and valuation estimates.

BenMAP Results

The BenMAP analysis is best described as an estimation of the excess morbidity, premature mortality, and associated health costs that occurred in the years 2001, 2002, and 2003 as a result of the fact that Rule 4901 was not in place. The findings from the BenMAP analysis will be presented in this sequence: (1) Tables of reductions in incidence for each study area for 2001, 2002, and 2003, respectively, (2) valuation tables of estimated excess health costs for 2001, 2002, and 2003, (3) summary valuation graphs for each health endpoint group over the three year period, (4) graphs of total excess morbidity costs for each year, and (5) graphs of total excess mortality costs for each year.

Tables 2 through 4 provide a synoptic look at the estimated excess morbidity and mortality incidence resulting from the percentage rollback in PM 2.5 concentrations. The county level reductions were scaled back to reflect the fraction of the counties' populations that are accounted for by the two metro study areas. Note that there are considerable differences in the standard deviations from one health endpoint group to another. This reflects the relative incidence frequency of the given health effect, the statistical relationships uncovered by the corresponding epidemiological studies, and the relative degree of uniformity in findings from one epidemiological study to the next.

Figures 14 through 36 provide a valuation summary for each health endpoint group for Bakersfield and Fresno/Clovis for 2001 through 2003. In each graph, the mean value is presented for each of the three years, along with the high and low estimates as determined by the standard deviation. Overall county values are presented for reference but these estimates do not have the same degree of accuracy due to the spatial separation from urban-centered monitors and residents in outlying area. The values presented have been adjusted for inflation to reflect 2008 dollar values. One of two inflation indices were used for each health endpoint group, depending on whether the value represented lost wages or medical costs. Figures 36 and 37 present the annual morbidity cost totals for each study area.

In the case of mortality, it is arguably best to focus simply on the number of lives that could have been saved had Rule 4901 been effect. These can be found in Tables 2 through 4 and are also presented in Figures 38 and 39. The fundamental problem with assigning a dollar value to cases of premature mortality is the disconnection between the value of a statistical life (VSL) and the economic circumstances of real people. The values reported do not involve actual economic expenditures or losses, but are instead the cumulative WTP for a slight reduction in mortality risk as extrapolated from survey research. In any case, the figures are presented here in keeping with the standard established by the Hall et al. (2006) report and others.

The mortality C-R functions selected in this analysis were relatively conservative. Separate C-R functions were specified from options within the adult and infant mortality health endpoints. BenMAP reports indicated that there were in fact no cases of infant mortality estimated, only cases of adult mortality.

Conclusions and Recommendations

This evaluation of Rule 4901 provides a large body of empirical validation for the precedent-setting decision by the SJVAPCD to institute the rule in November, 2003. As seen in the initial rollout of the Rule, resistance by wood burning households to the amended Rule 4901's more stringent ban threshold is likely to be considerable. The clear-cut evidence of the considerable health benefits from Rule 4901 can and should serve to counter public resistance to stricter controls on wood burning.

While it is true that each of the analytical steps in this evaluation involved some stochastic estimation assumption(s), it must be concluded that the reductions in PM 2.5 attributable to the rule are substantial in any case. Based on the large body of prior epidemiological research, combined with the evidence from Fresno and Bakersfield of concrete reductions in seasonal daily and evening PM 2.5 concentrations, lives are indeed being saved at the margin, not to mention considerable reductions in disease onset and symptom exacerbation.

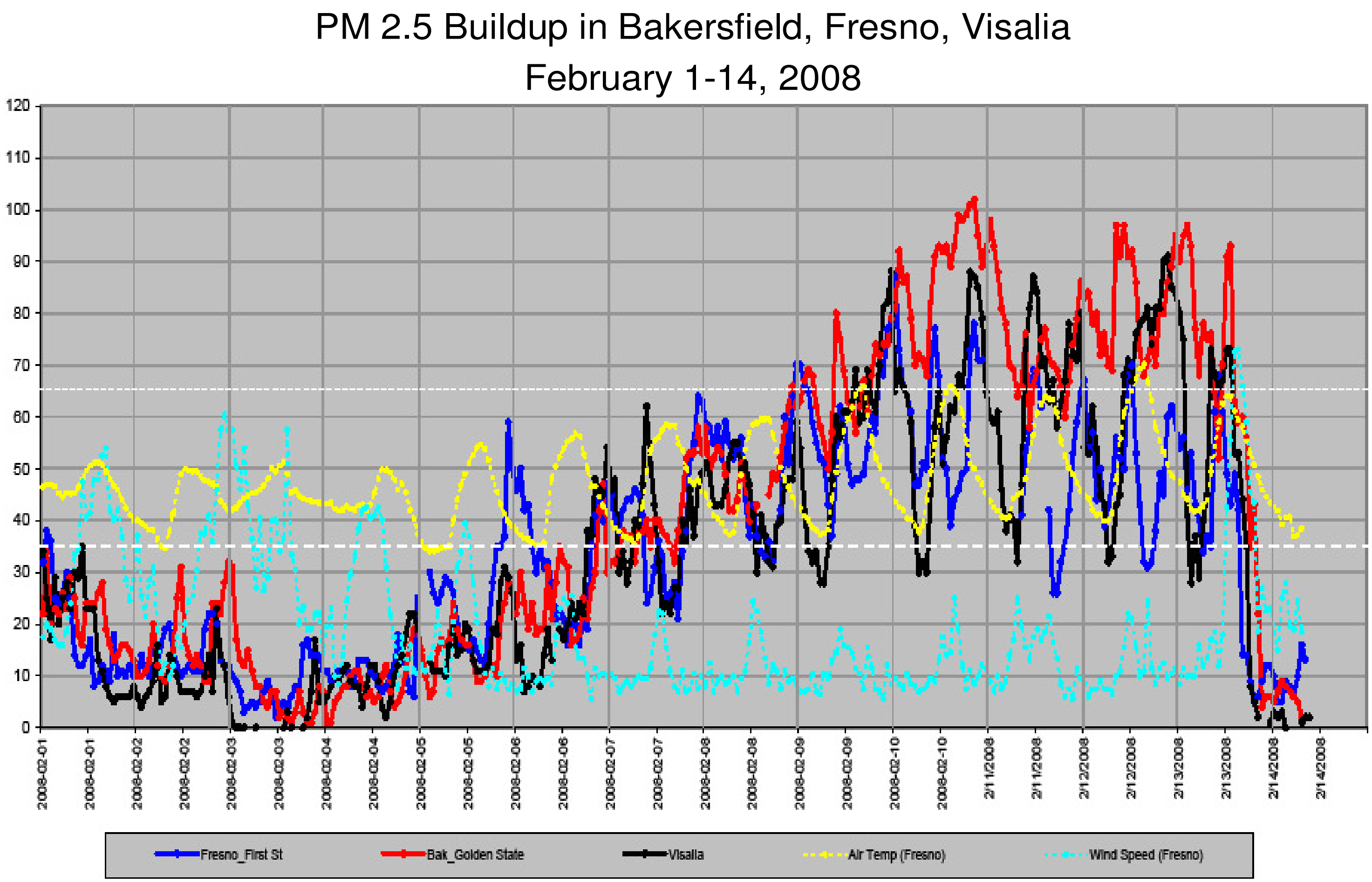
In respect to the qualitative diurnal profiling of hourly meteorological conditions and PM 2.5 concentrations, it should be noted that a number of cases of daily violations in the 24 hr. 65 µg/m^3 standard occurred on days when bans were not called. Clearly the former standard for a burning ban threshold at the predicted 150 AQI level did not provide a sufficient margin for forecaster error and public health protection. The recent decision by the SJVAPCD Board to amend Rule 4901 so that the ban threshold is set at the 90 AQI level is well-justified. As seen in Figure 3, the current rate of progress in design value reduction is insufficient and will be accelerated by the amended Rule 4901. Further lives will be saved and the region, particularly in the south San Joaquin Valley, and further progress towards the ultimate goal of PM 2.5 compliance with the new federal 35 µg/m^3 standard by 2020 will be insured.

The modeling effort undertaken by David Nunes of the SJVAPCD was noteworthy for it provided a solid inference foundation for the BenMAP application. The SJVAPCD now has the opportunity to further refine this predictive model over time via its daily forecasting process.

The BenMAP program represents an exciting new tool for air quality researchers and public health analysts to evaluate existing air quality regulations and prospective regulatory options. The U.S. EPA has put a considerable amount of resources into the refinement of the program in the past three years. The result is a user-friendly but sophisticated software program that performed consistently and predictably in this application. However, while the program is easy to operate in a technical sense, the level of user knowledge required to make informed selections among various epidemiological study options is relatively high. For this application, this complexity necessitated a considerable amount of time spent in sensitivity testing via the selection of alternative C-R functions. This aspect of the program makes it essential that users undergo the EPA-sponsored training in BenMAP.

Finally, it is also important to note that concentrations of urban wood smoke under the chronic inversion environments so commonly found in the Valley can be highly concentrated at the household and neighborhood scale. Wood burners as well as the general public must understand that these localized spikes in wood smoke inhalation create an unjustifiable concentration of risk, particularly to vulnerable groups such as elders and children, i.e. environmental injustice. Furthermore, the public and those most vulnerable would benefit from a greater public recognition of the particularly harmful effects triggered by the various chemical species found in wood smoke. San Joaquin Valley media sources as well are not sufficiently appraised of these health risks. As a result, they tend to inadequately emphasize the health risks posed from wood smoke relative to other pollutants such ozone. This evaluation report, and the empirical evidence provided regarding the health benefits from Rule 4901, provides the SJVAPCD with the basis for addressing these gaps in public and media knowledge through its public outreach efforts.

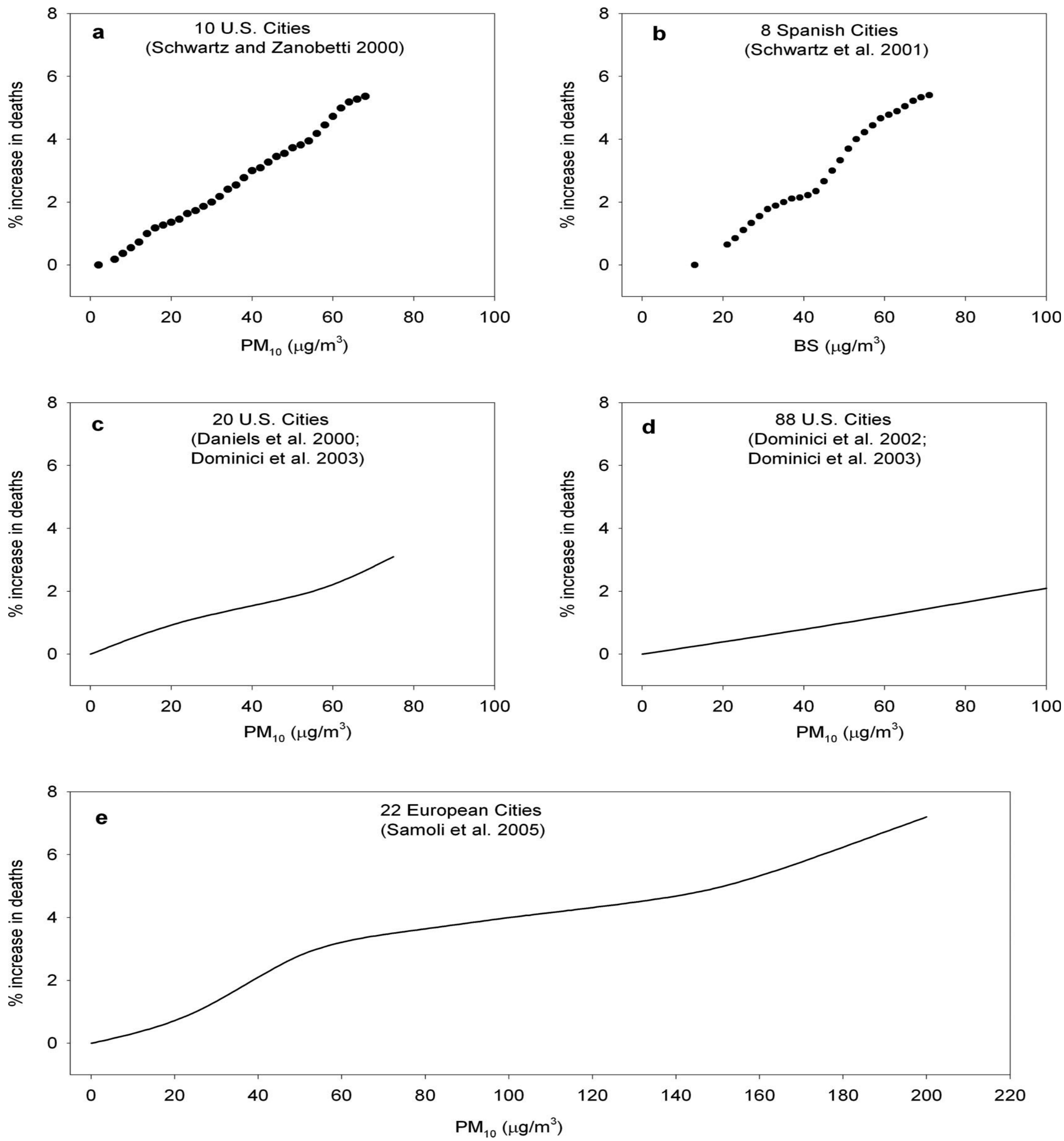
Figure 1



PM 2.5 Buildup in Bakersfield, Fresno, Visalia
February 1-14, 2008
Fresno_First St
Bak_Golden State
Visalia
Air Temp (Fresno)
Wind Speed (Fresno)

Figure 2

Selected Concentration-Response Relationships



(Reprinted from Pope, C.A., and D. Dockery (2006, p. 720) Health Effects of Fine Particulate Air Pollution: Lines that Connect. *Journal of Air and Waste Management Association* 56: 709-742.)

Figure 3

Annual Average PM 2.5 for the South San Joaquin Valley: 2001-2006

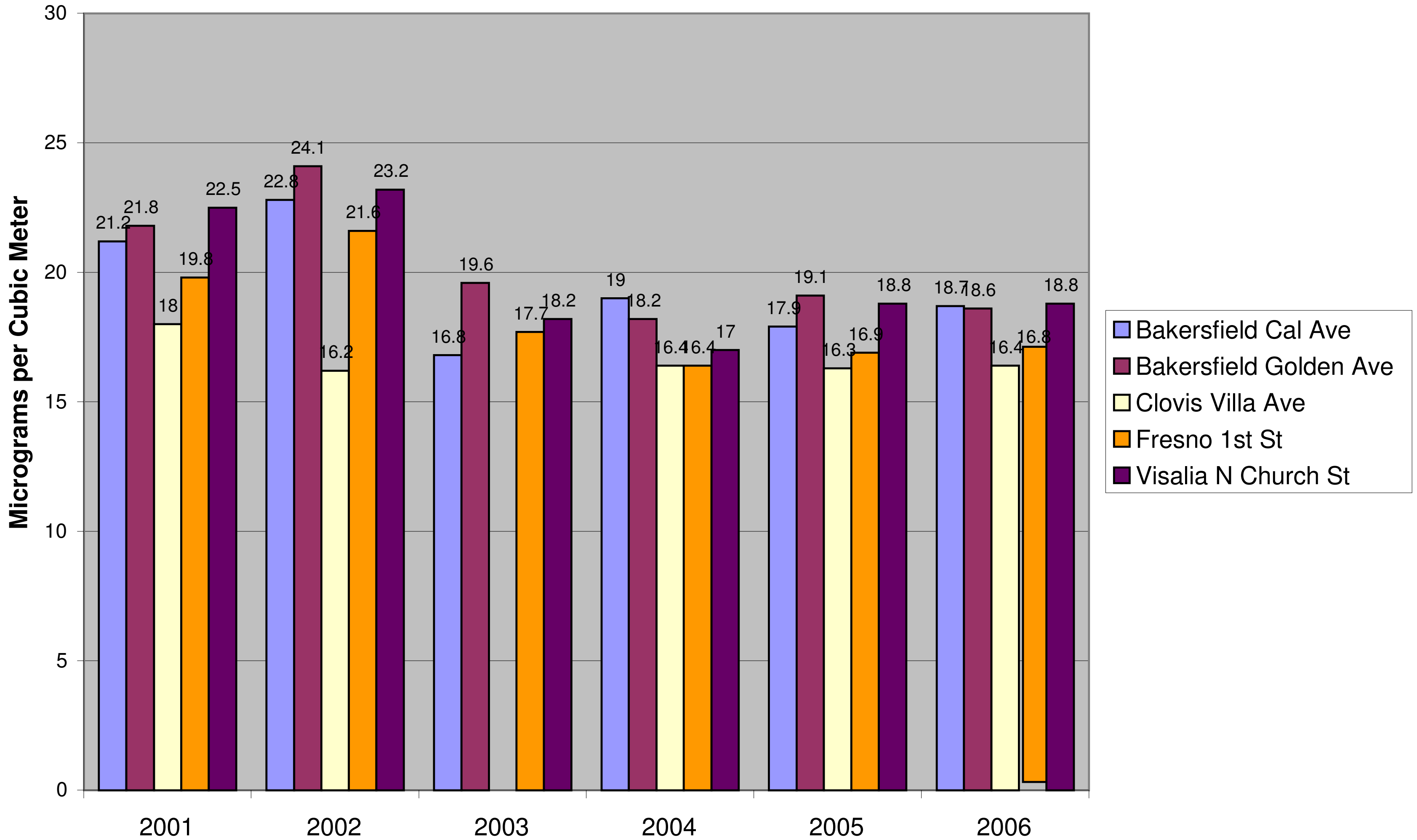


Table 1

Population Totals for Study Sites: 2000-2006

	2006	**2005**	**2004**	**2003**	**2002**	**2001**	**2000**
Fresno County	891,756	878,089	865,468	850,360	832,415	814,910	802,273
Clovis city, Fresno County	89,316	86,626	82,392	78,723	74,512	71,122	69,485
Fresno city, Fresno County	466,714	461,454	457,148	451,881	444,404	436,161	430,296
Total Fresno/Clovis	556,030	548,080	539,540	530,604	518,916	507,283	499,781
Fresno/Clovis % of County	**0.5234**	**0.5255**	**0.5282**	**0.5314**	**0.5339**	**0.5352**	**0.5363**
Kern County	780,117	756,981	733,784	712,860	693,125	675,997	663,864
Bakersfield city, Kern County	308,392	295,769	283,156	271,249	260,778	251,804	244,934
Bakersfield % of County	**0.3953**	**0.3907**	**0.3859**	**0.3805**	**0.3762**	**0.3725**	**0.3690**

Figure 4

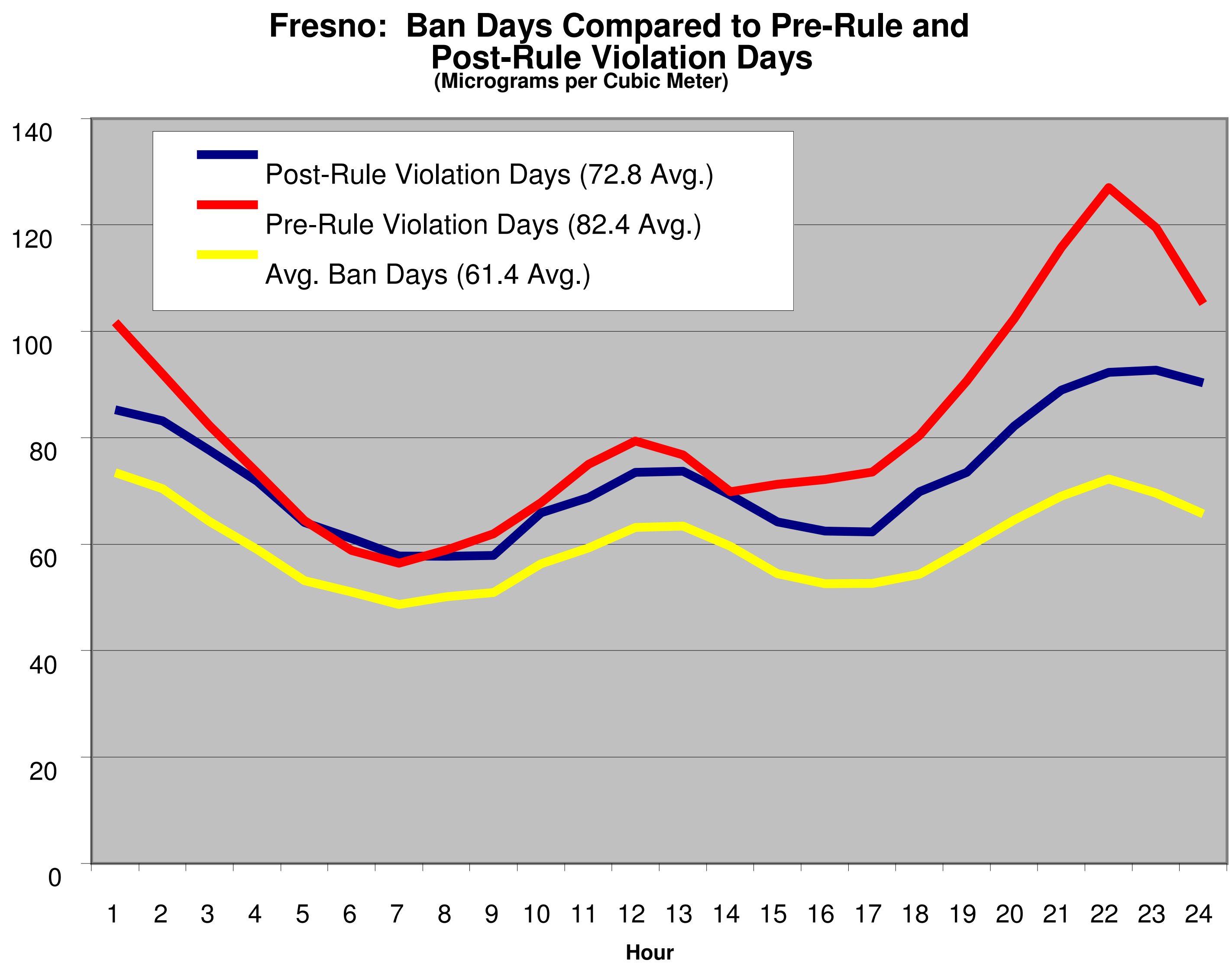
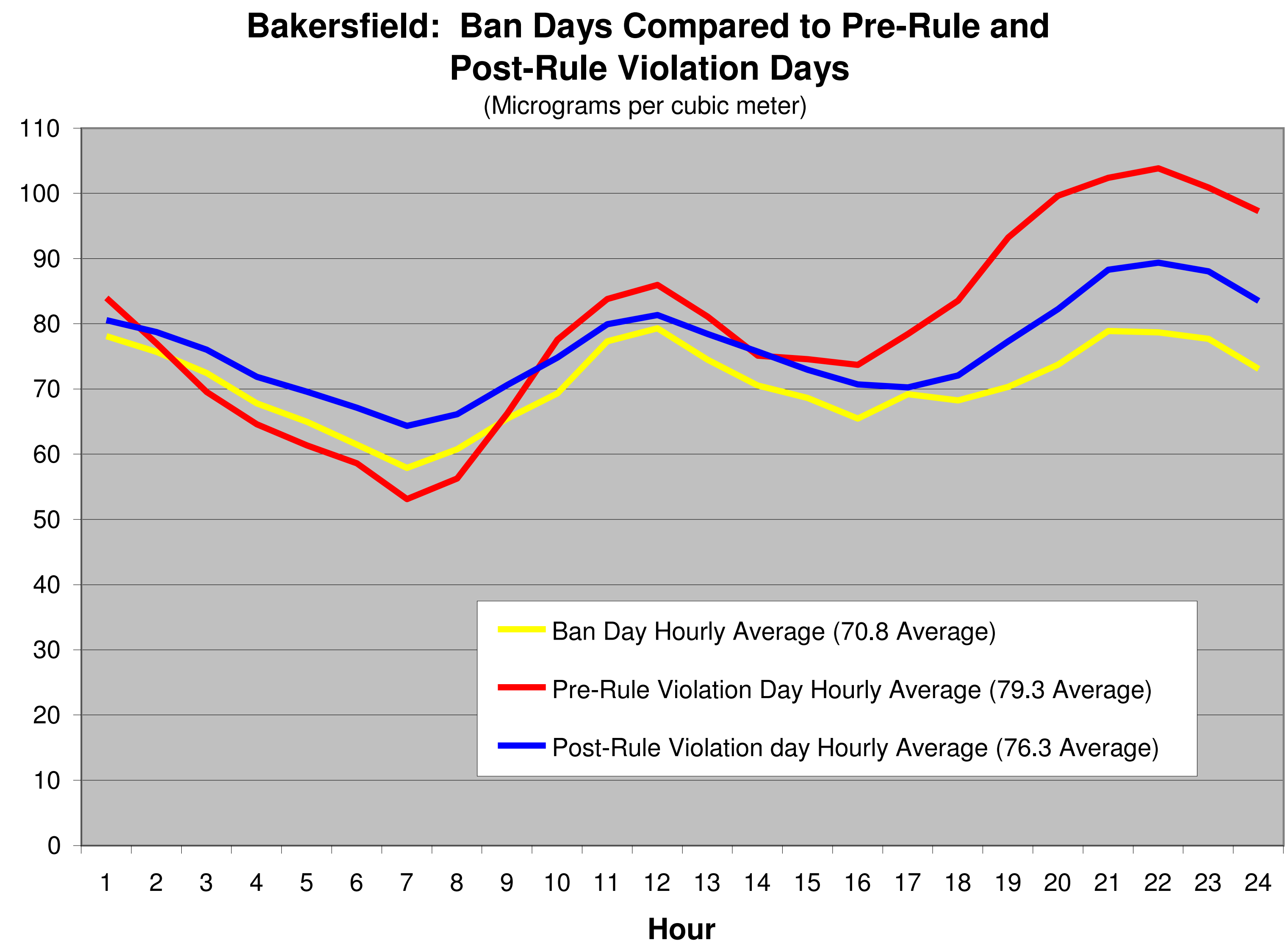

Fresno: Ban Days Compared to Pre-Rule and Post-Rule Violation Days
(Micrograms per Cubic Meter)
Post-Rule Violation Days (72.8 Avg.)
Pre-Rule Violation Days (82.4 Avg.)
Avg. Ban Days (61.4 Avg.)
0
20
40
60
80
100
120
140
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour

Figure 5



Bakersfield: Ban Days Compared to Pre-Rule and Post-Rule Violation Days
(Micrograms per cubic meter)
110
100
90
80
70
60
50
40
30
20
10
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour
Ban Day Hourly Average (70.8 Average)
Pre-Rule Violation Day Hourly Average (79.3 Average)
Post-Rule Violation day Hourly Average (76.3 Average)

Figure 6

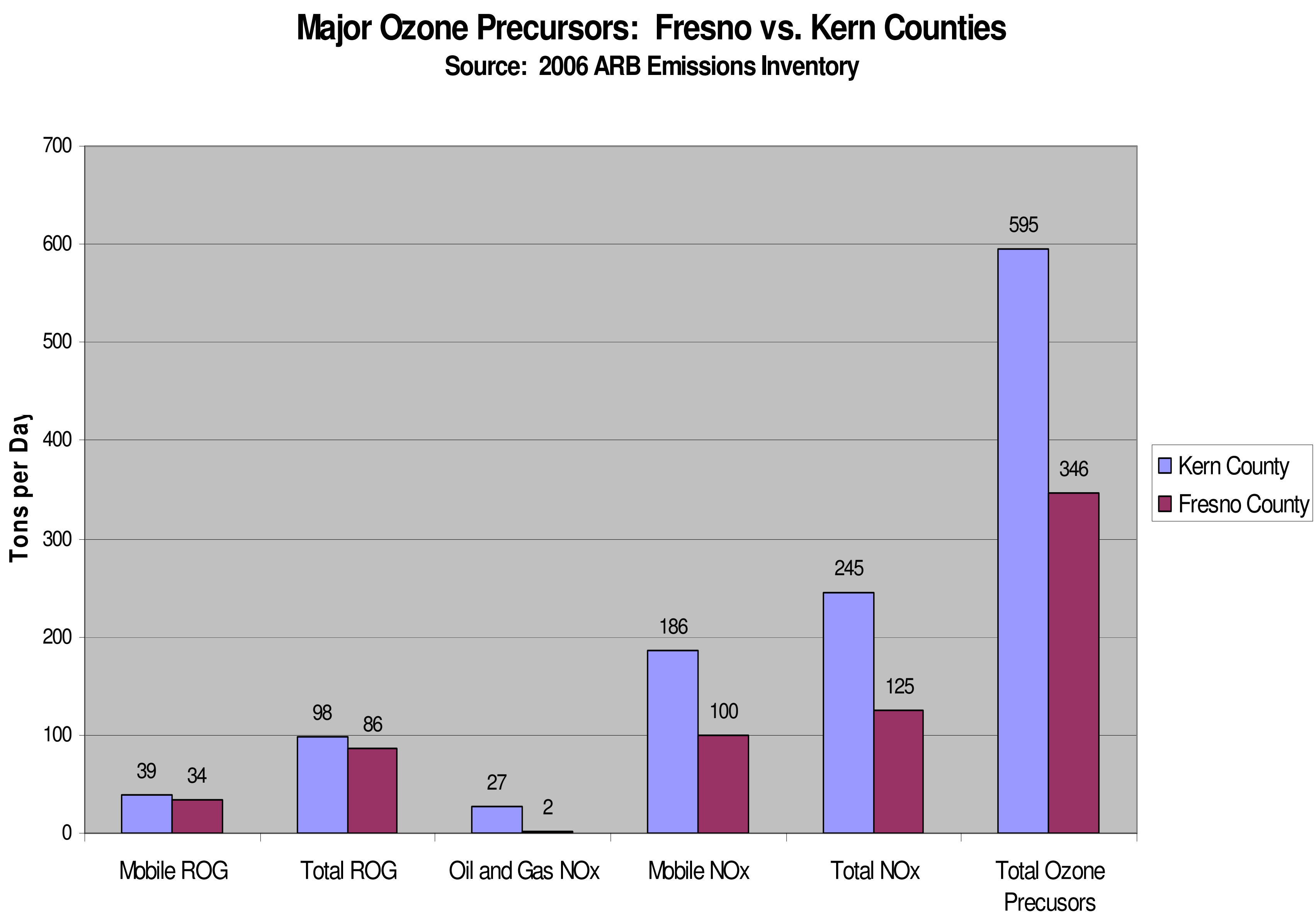

Major Ozone Precursors: Fresno vs. Kern Counties
Source: 2006 ARB Emissions Inventory
Tons per Day
700
600
500
400
300
200
100
0
39
34
98
86
27
2
186
100
245
125
595
346
Mobile ROG
Total ROG
Oil and Gas NOx
Mobile NOx
Total NOx
Total Ozone Precursors
Kern County
Fresno County

Figure 7

Example of Apparent Ban Effect in Fresno: November 18, 2006

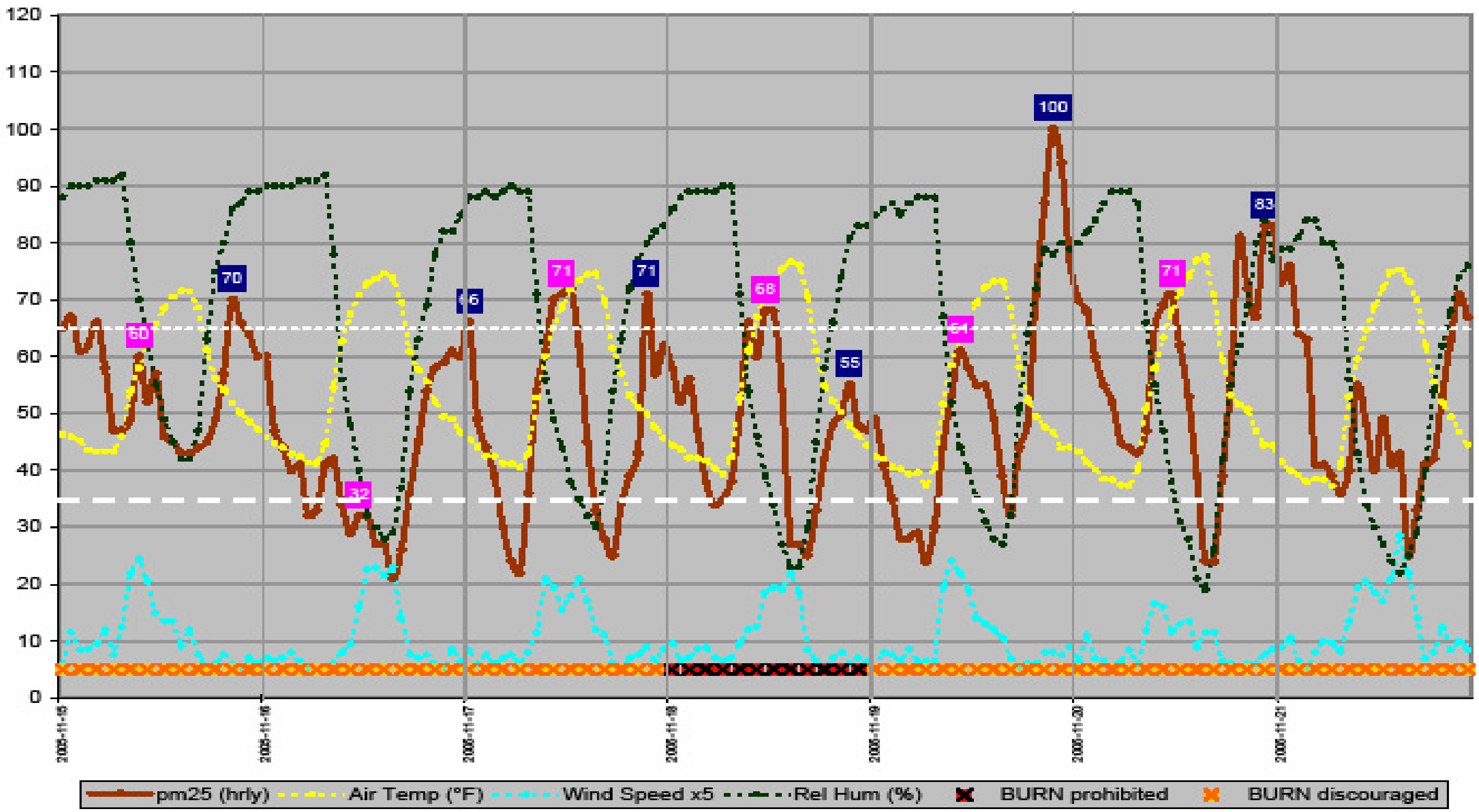


Figure 8

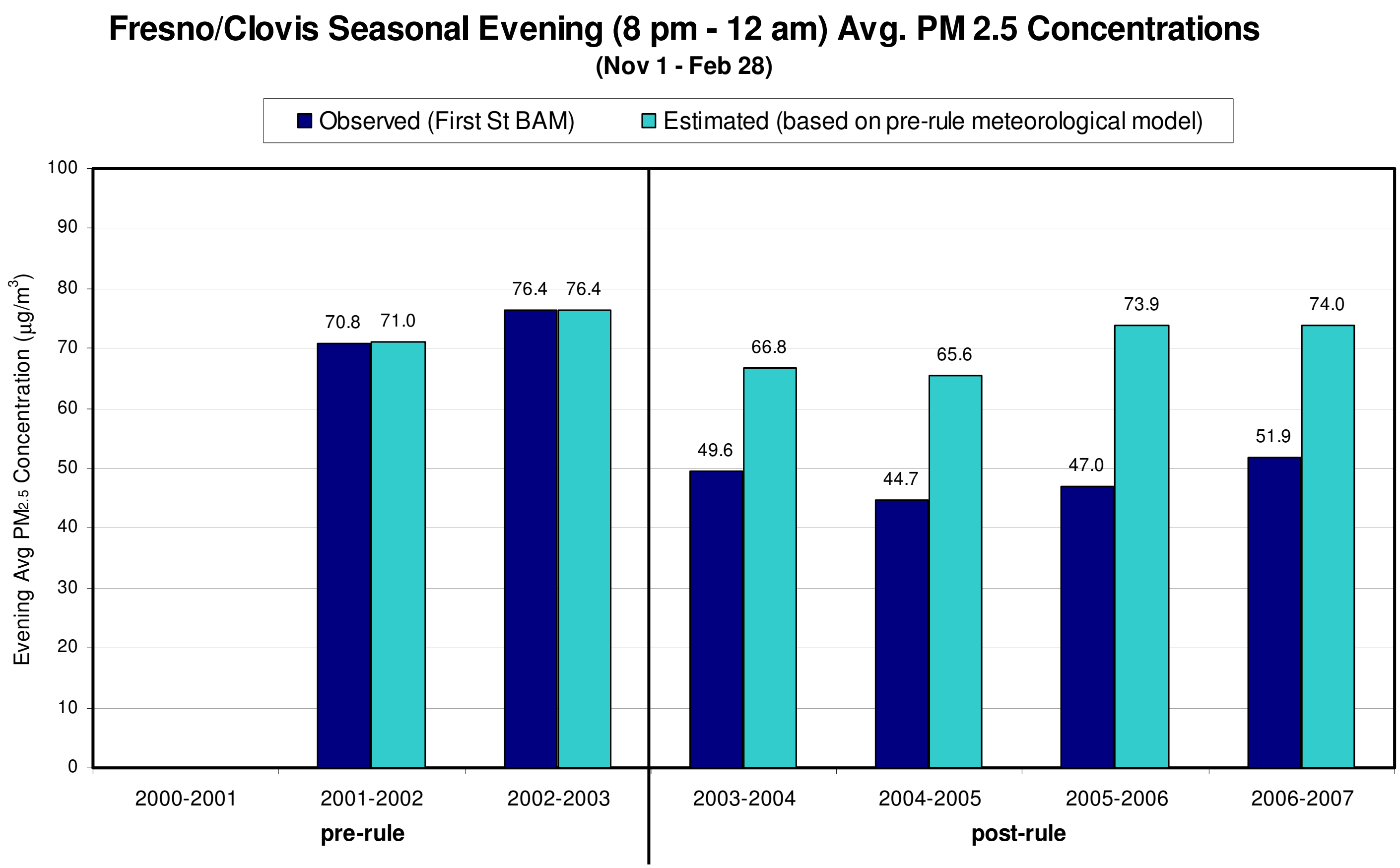

Fresno/Clovis Seasonal Evening (8 pm - 12 am) Avg. PM 2.5 Concentrations
(Nov 1 - Feb 28)
Observed (First St BAM)
Estimated (based on pre-rule meteorological model)
Evening Avg PM2.5 Concentration (µg/m3)
100
90
80
70
60
50
40
30
20
10
0
70.8
71.0
76.4
76.4
49.6
66.8
44.7
65.6
47.0
73.9
51.9
74.0
2000-2001
2001-2002
2002-2003
2003-2004
2004-2005
2005-2006
2006-2007
pre-rule
post-rule

Figure 9

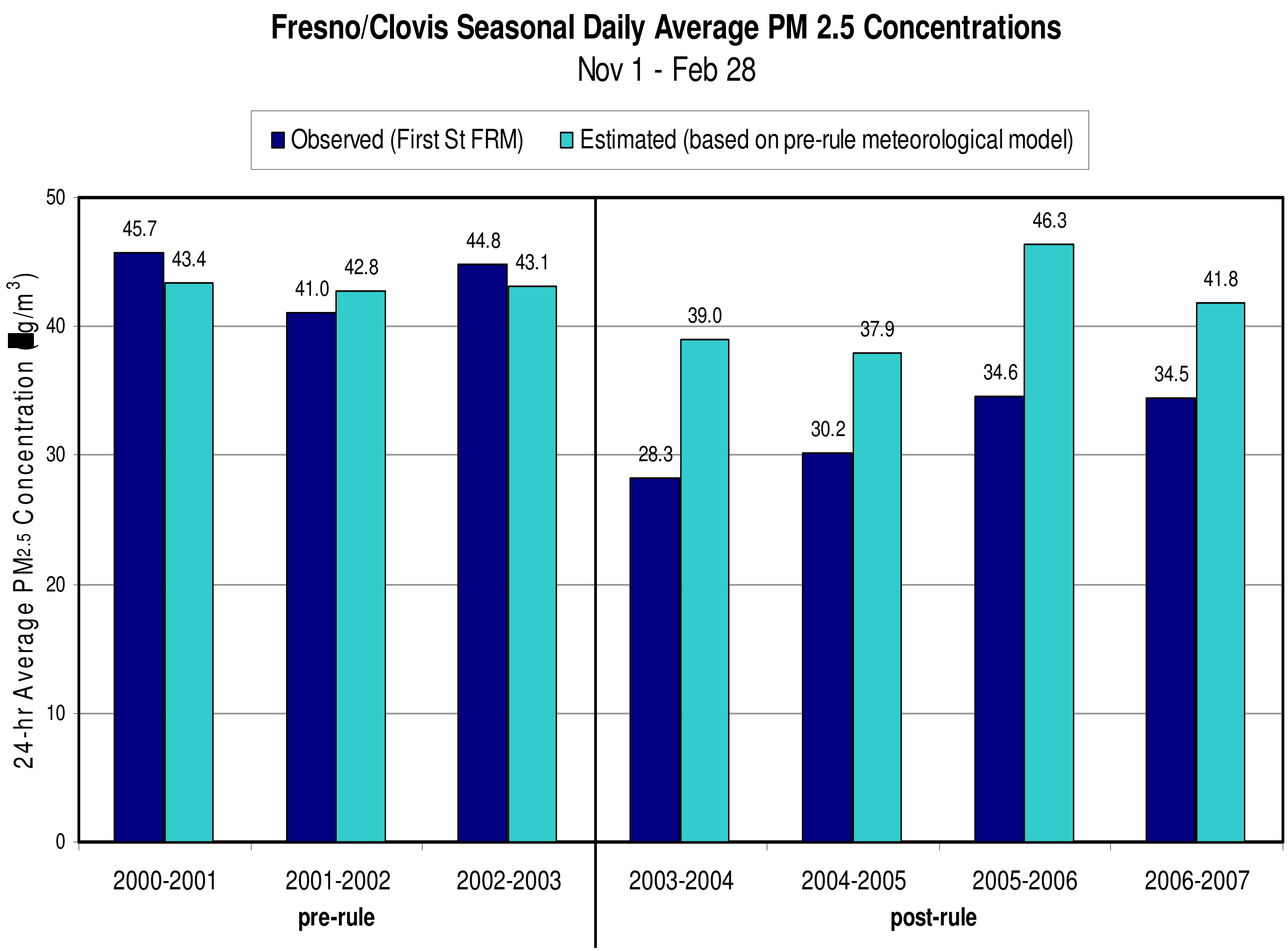

Fresno/Clovis Seasonal Daily Average PM 2.5 Concentrations
Nov 1 - Feb 28
Observed (First St FRM)
Estimated (based on pre-rule meteorological model)
24-hr Average PM2.5 Concentration (µg/m3)
0
10
20
30
40
50
45.7
43.4
41.0
42.8
44.8
43.1
28.3
39.0
30.2
37.9
34.6
46.3
34.5
41.8
2000-2001
2001-2002
2002-2003
2003-2004
2004-2005
2005-2006
2006-2007
pre-rule
post-rule

Figure 10

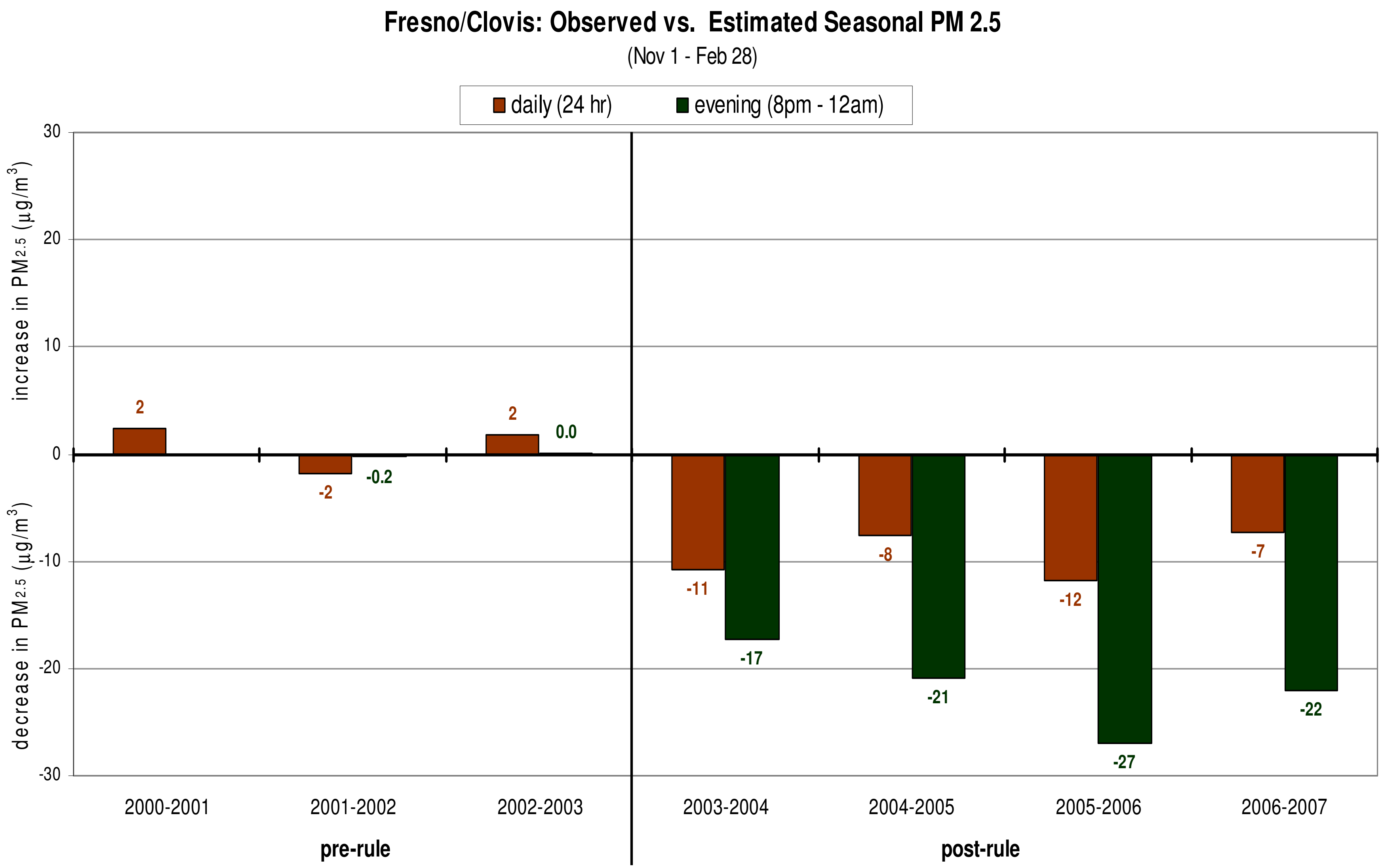

Fresno/Clovis: Observed vs. Estimated Seasonal PM 2.5
(Nov 1 - Feb 28)
daily (24 hr)
evening (8pm - 12am)
increase in PM2.5 (µg/m3)
decrease in PM2.5 (µg/m3)
30
20
10
0
-10
-20
-30
2
-2
-0.2
2
0.0
-11
-17
-8
-21
-12
-27
-7
-22
2000-2001
2001-2002
2002-2003
2003-2004
2004-2005
2005-2006
2006-2007
pre-rule
post-rule

Figure 11

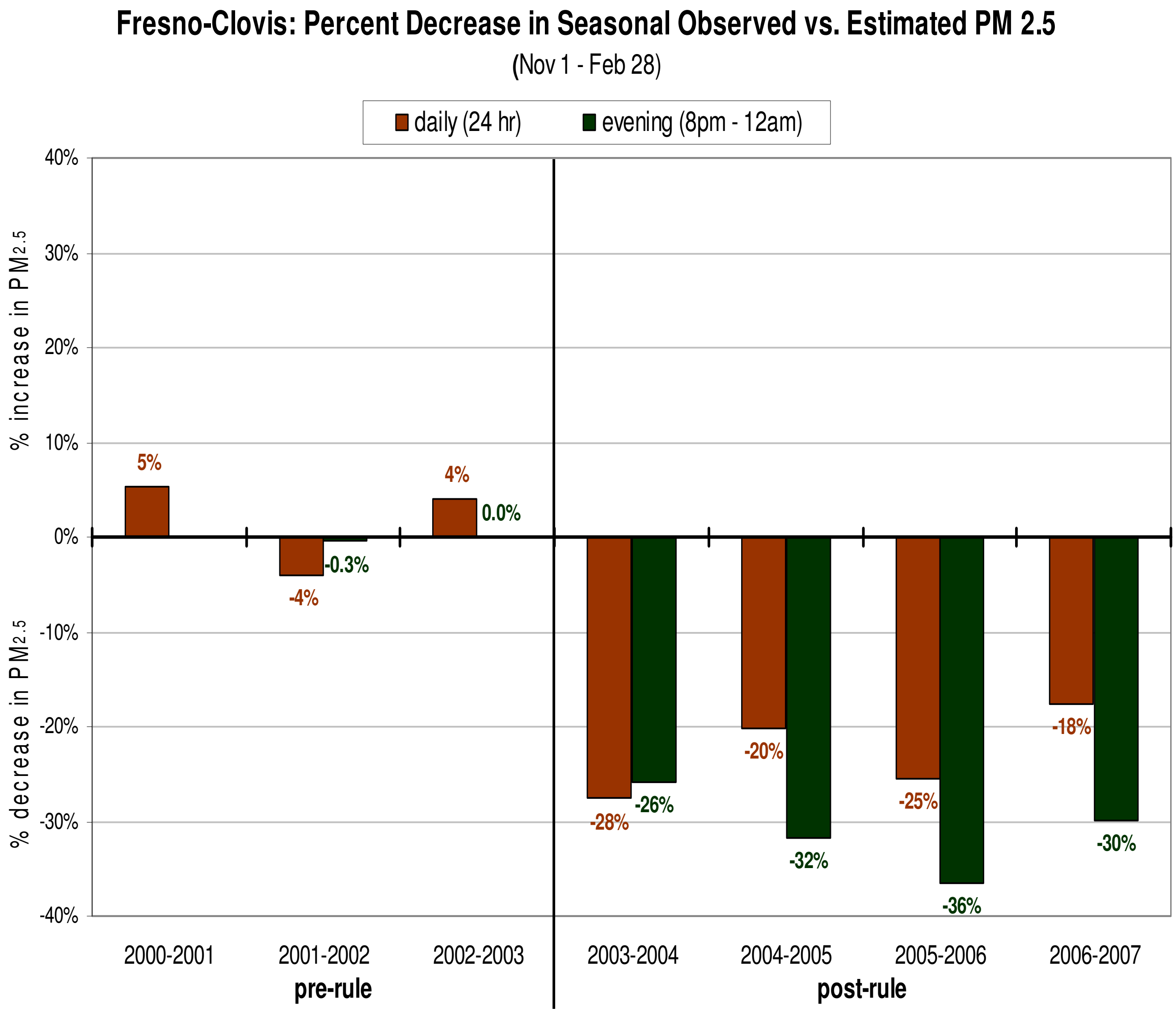

Fresno-Clovis: Percent Decrease in Seasonal Observed vs. Estimated PM 2.5
(Nov 1 - Feb 28)
daily (24 hr)
evening (8pm - 12am)
% increase in PM2.5
% decrease in PM2.5
40%
30%
20%
10%
0%
-10%
-20%
-30%
-40%
5%
-4%
-0.3%
4%
0.0%
-28%
-26%
-20%
-32%
-25%
-36%
-18%
-30%
2000-2001
2001-2002
2002-2003
2003-2004
2004-2005
2005-2006
2006-2007
pre-rule
post-rule

Figure 12

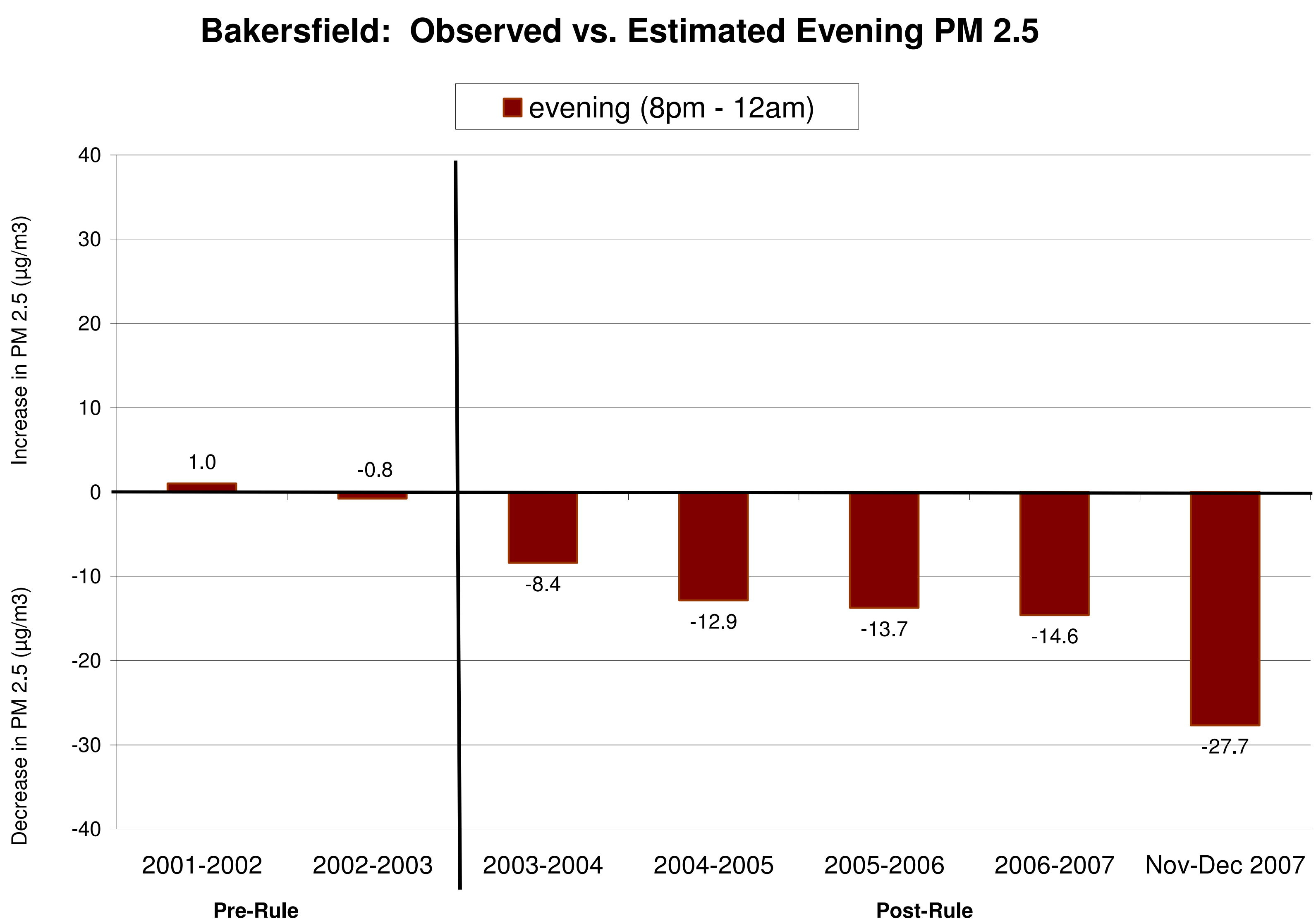

Bakersfield: Observed vs. Estimated Evening PM 2.5
evening (8pm - 12am)
Increase in PM 2.5 (µg/m3)
Decrease in PM 2.5 (µg/m3)
40
30
20
10
0
-10
-20
-30
-40
1.0
-0.8
-8.4
-12.9
-13.7
-14.6
-27.7
2001-2002
2002-2003
2003-2004
2004-2005
2005-2006
2006-2007
Nov-Dec 2007
Pre-Rule
Post-Rule

Figure 13

Bakersfield: Percentage Difference in Observed vs. Predicted PM 2.5

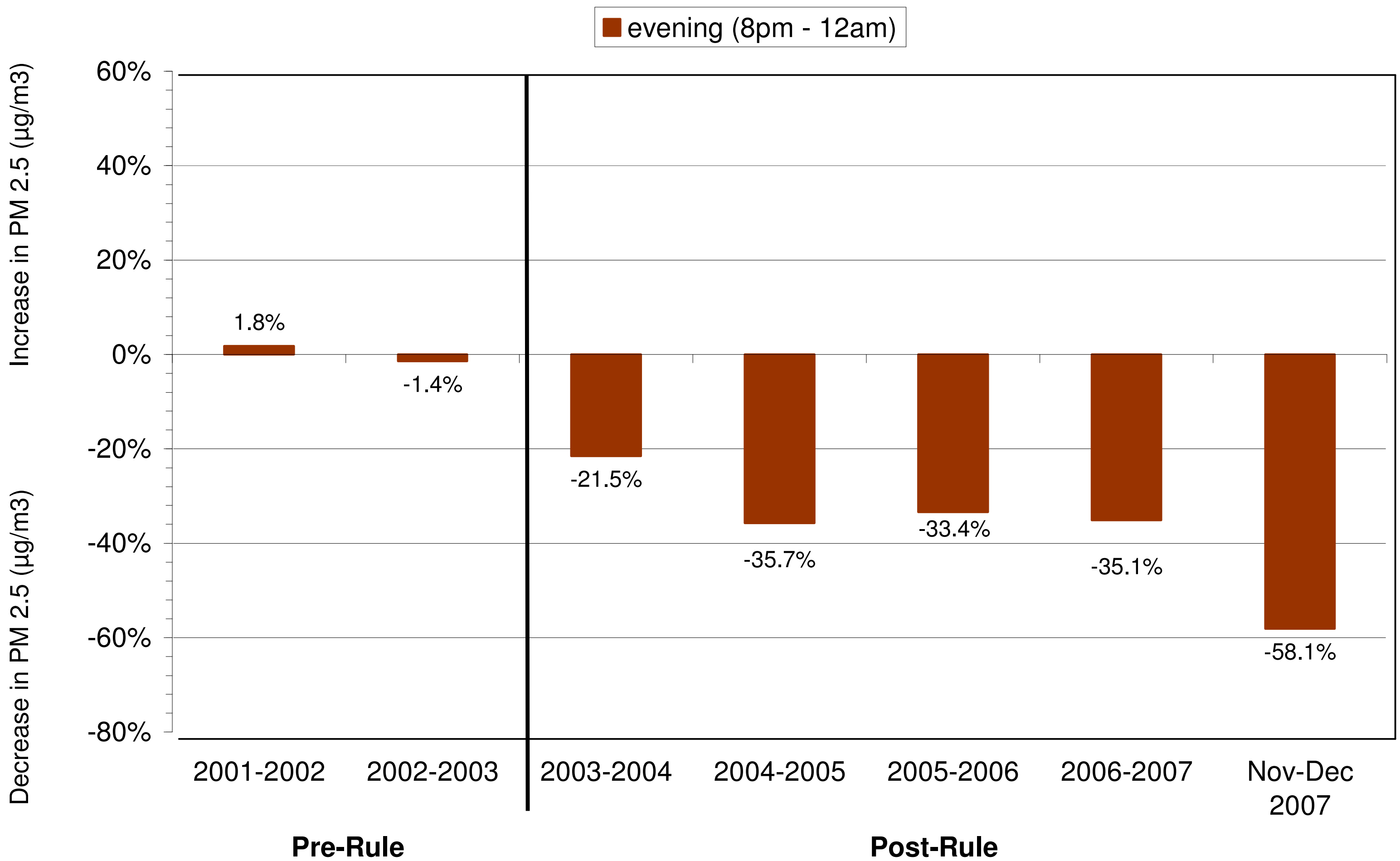


Table 2

2001 Incidence Results: Standard Run (Short-Term Cut points)

Fresno/Clovis						
Endpoint Group	Mean	Standard Deviation	Low Estimate	High Estimate	County Mean	County Standard Deviation
Asthma Exacerbation	3,046	1,480	1,566	4,526	4,893	2,377
Acute Myocardial Infarction	64	22	42	86	103	35
Emergency Room Visits, Respiratory	23	5	18	28	37	8
Hospital Admissions, Cardiovascular	15	3	12	18	24	5
Hospital Admissions, Respiratory	18	6	12	24	29	10
Work Loss Days	6,189	449	5,739	6,638	9,942	722
Acute Bronchitis	170	98	72	268	273	157
Acute Respiratory Symptoms	35,791	3,114	32,676	38,905	57,495	5,003
Mortality	54	19	35	73	87	30
Lower Respiratory Symptoms	1,276	362	914	1,638	2,050	581
Upper Respiratory Symptoms	977	381	596	1,358	1,569	612
Chronic Bronchitis	32	16	17	48	52	25

Table 2 (Cont.)

Bakersfield						
Endpoint Group	Mean	Standard Deviation	Low Estimate	High Estimate	County Mean	County Standard Deviation
Asthma Exacerbation	1,690	821	869	2,511	4,537	2,203
Acute Myocardial Infarction	34	12	23	46	92	31
Emergency Room Visits, Respiratory	13	3	10	16	34	8
Hospital Admissions, Cardiovascular	8	2	6	10	22	5
Hospital Admissions, Respiratory	9	3	6	13	25	9
Work Loss Days	3,505	254	3,251	3,759	9,409	682
Acute Bronchitis	89	51	38	140	240	137
Acute Respiratory Symptoms	20,184	1,752	18,432	21,935	54,184	4,703
Mortality	30	10	19	40	80	28
Lower Respiratory Symptoms	708	200	508	907	1,900	536
Upper Respiratory Symptoms	545	212	333	757	1,463	570
Chronic Bronchitis	17	8	9	25	46	22

Table 3

2002 Incidence Results: Standard Run (Short-Term Cut points)

Fresno/Clovis						
Endpoint Group	**Mean**	**Standard Deviation**	**Low Estimate**	**High Estimate**	**County Mean**	**County Standard Deviation**
Asthma Exacerbation	3,610	1,753	1,857	5,363	5,791	2,812
Acute Myocardial Infarction	77	26	52	103	124	41
Emergency Room Visits, Respiratory	27	6	21	34	44	10
Hospital Admissions, Cardiovascular	18	4	14	22	29	6
Hospital Admissions, Respiratory	22	7	14	29	35	12
Work Loss Days	7,538	547	6,991	8,084	12,091	877
Acute Bronchitis	194	110	84	304	311	177
Acute Respiratory Symptoms	43,634	3,790	39,844	47,425	69,994	6,080
Mortality	63	22	41	85	101	35
Lower Respiratory Symptoms	1,509	426	1,082	1,935	2,420	684
Upper Respiratory Symptoms	1,161	453	709	1,614	1,863	726
Chronic Bronchitis	38	18	20	56	61	29

Table 3 (Cont.)

Bakersfield						
Endpoint Group	**Mean**	**Standard Deviation**	**Low Estimate**	**High Estimate**	**County Mean**	**County Standard Deviation**
Asthma Exacerbation	2,020	981	1,039	3,001	5,369	2,608
Acute Myocardial Infarction	43	14	28	57	113	38
Emergency Room Visits, Respiratory	15	3	12	19	41	9
Hospital Admissions, Cardiovascular	10	2	8	12	26	6
Hospital Admissions, Respiratory	11	4	8	15	30	10
Work Loss Days	4,302	312	3,990	4,614	11,436	830
Acute Bronchitis	102	58	44	160	271	154
Acute Respiratory Symptoms	24,862	2,165	22,698	27,027	66,088	5,754
Mortality	35	12	23	48	94	33
Lower Respiratory Symptoms	852	242	610	1,094	2,264	643
Upper Respiratory Symptoms	652	254	398	906	1,732	675
Chronic Bronchitis	20	10	11	30	54	26

Table 4

2003 Incidence Results: Standard Run (Short-Term Cut points)

Fresno/Clovis						
Endpoint Group	**Mean**	**Standard Deviation**	**Low Estimate**	**High Estimate**	**County Mean**	**County Standard Deviation**
Asthma Exacerbation	3,006	1,461	1,545	4,468	4,818	2,342
Acute Myocardial Infarction	67	23	44	90	107	37
Emergency Room Visits, Respiratory	23	5	18	28	37	8
Hospital Admissions, Cardiovascular	16	3	12	19	25	5
Hospital Admissions, Respiratory	18	6	12	24	29	10
Work Loss Days	6,412	467	5,945	6,878	10,275	748
Acute Bronchitis	166	95	71	261	266	153
Acute Respiratory Symptoms	37,247	3,254	33,994	40,501	59,691	5,214
Mortality	54	19	36	73	87	30
Lower Respiratory Symptoms	1,277	365	912	1,642	2,046	585
Upper Respiratory Symptoms	970	378	592	1,348	1,554	606
Chronic Bronchitis	32	16	17	48	52	25

Table 4 (Cont.)

Bakersfield						
Endpoint Group	**Mean**	**Standard Deviation**	**Low Estimate**	**High Estimate**	**County Mean**	**County Standard Deviation**
Asthma Exacerbation	1,492	725	766	2,217	3,920	1,906
Acute Myocardial Infarction	32	11	21	43	85	29
Emergency Room Visits, Respiratory	11	3	9	14	30	7
Hospital Admissions, Cardiovascular	7	2	6	9	19	4
Hospital Admissions, Respiratory	8	3	5	11	22	8
Work Loss Days	3,245	236	3,009	3,481	8,528	621
Acute Bronchitis	81	46	34	127	212	122
Acute Respiratory Symptoms	18,817	1,647	17,170	20,464	49,453	4,328
Mortality	28	10	18	37	73	25
Lower Respiratory Symptoms	637	183	454	820	1,673	481
Upper Respiratory Symptoms	481	188	293	669	1,265	494
Chronic Bronchitis	16	8	8	24	42	20

Figure 14

Asthma Exacerbation Valuation: Bakersfield

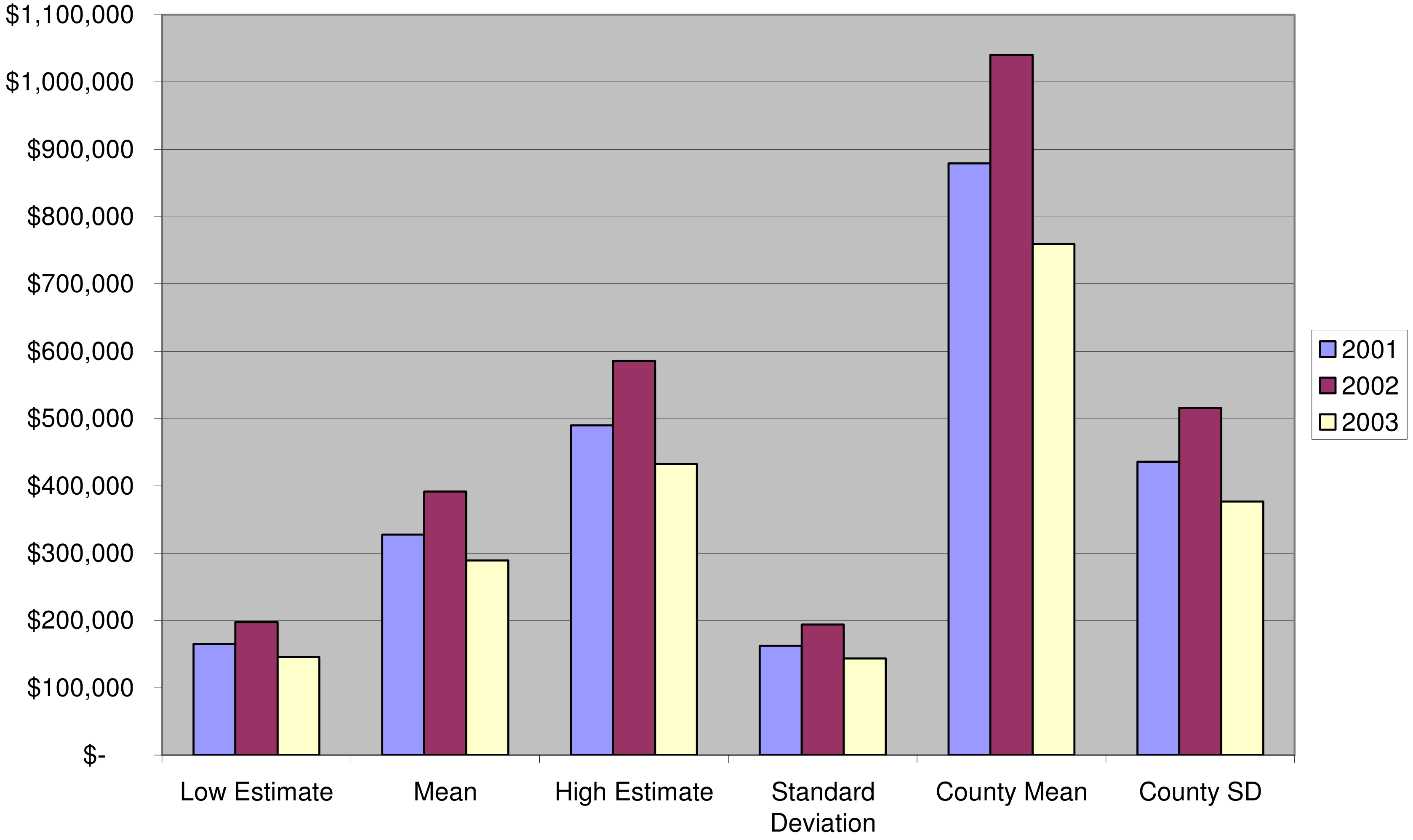


Figure 15

Asthma Exacerbation Valuation: Fresno/Clovis

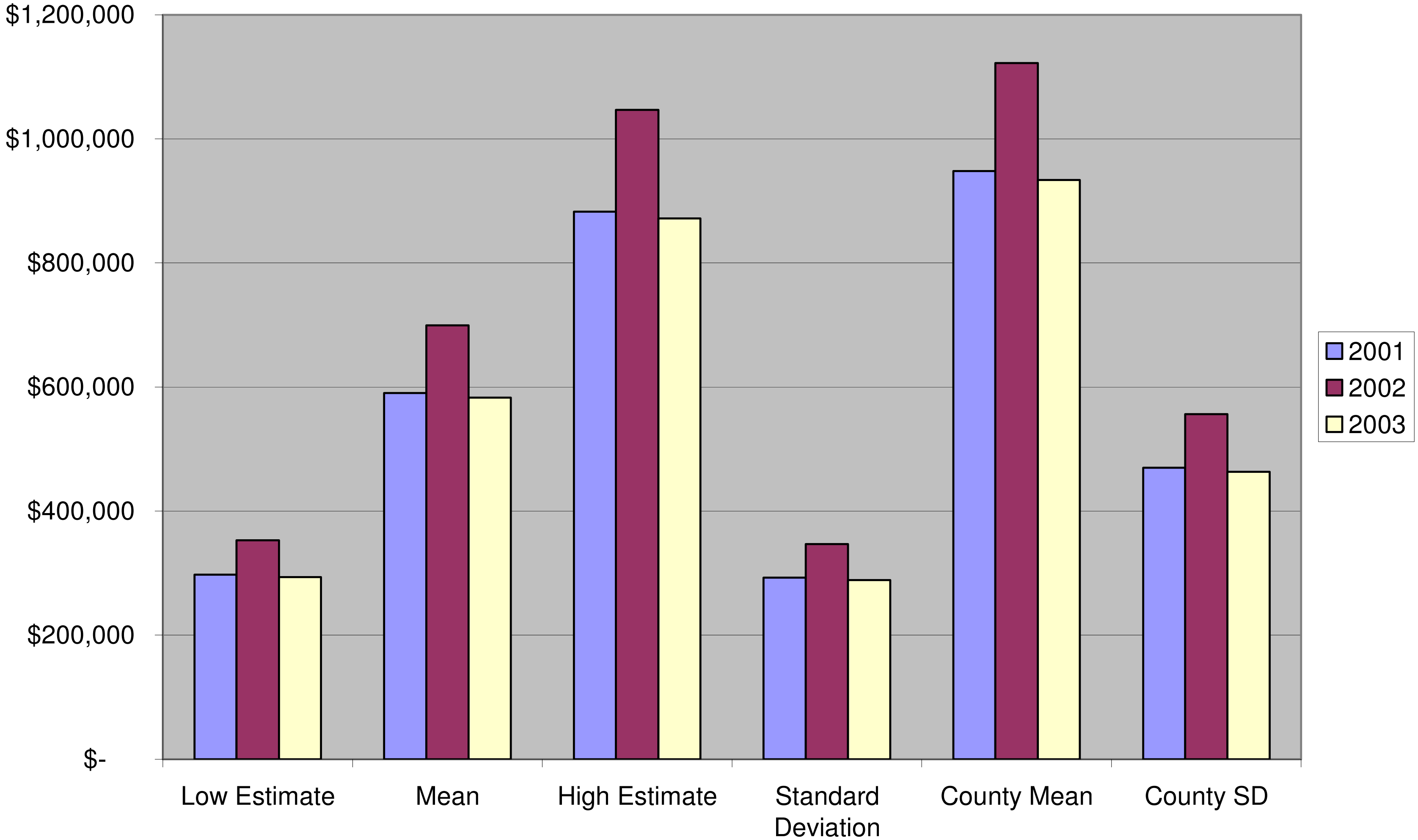


Figure 16

Acute Myocardial Infarction Valuation: Bakersfield

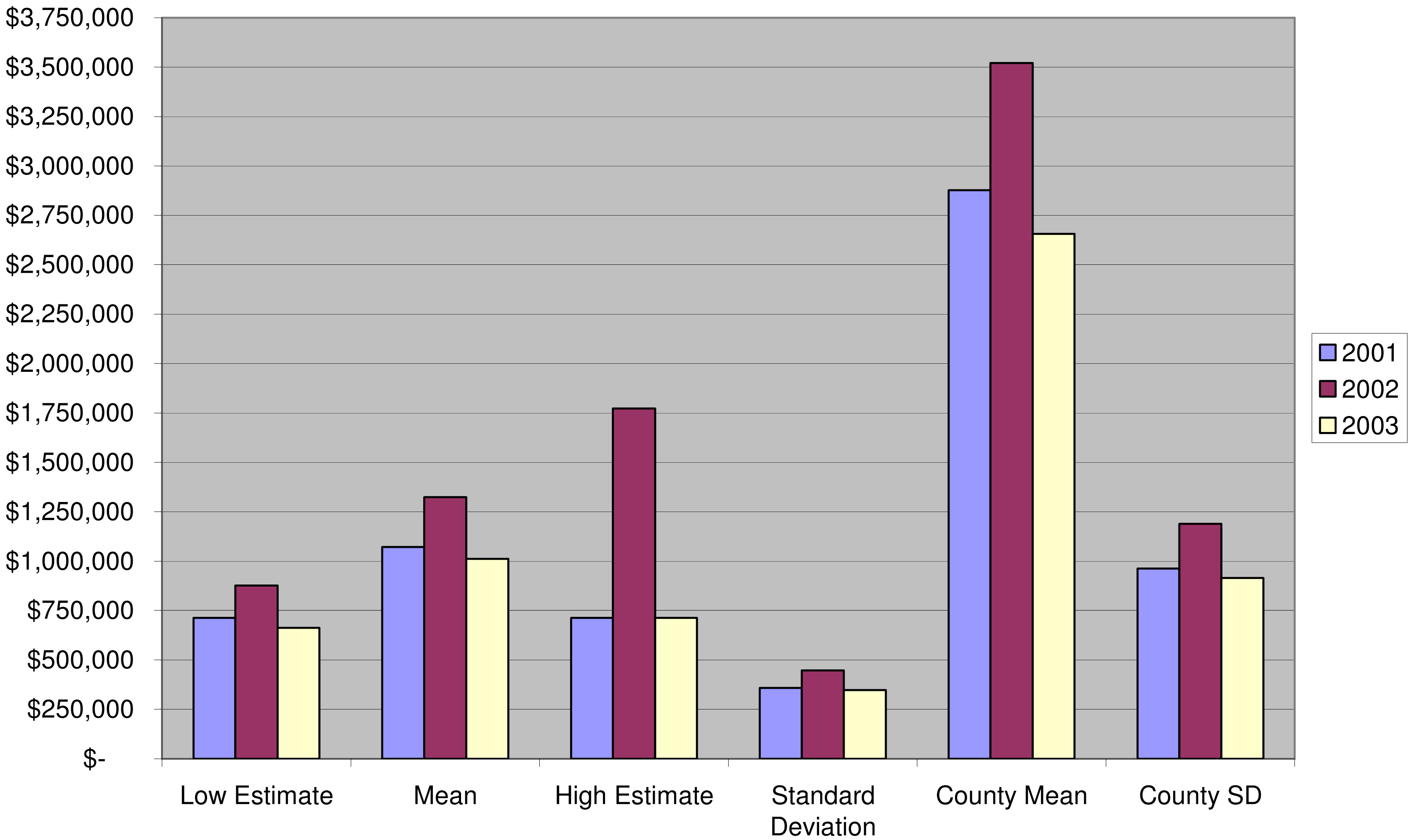


Figure 17

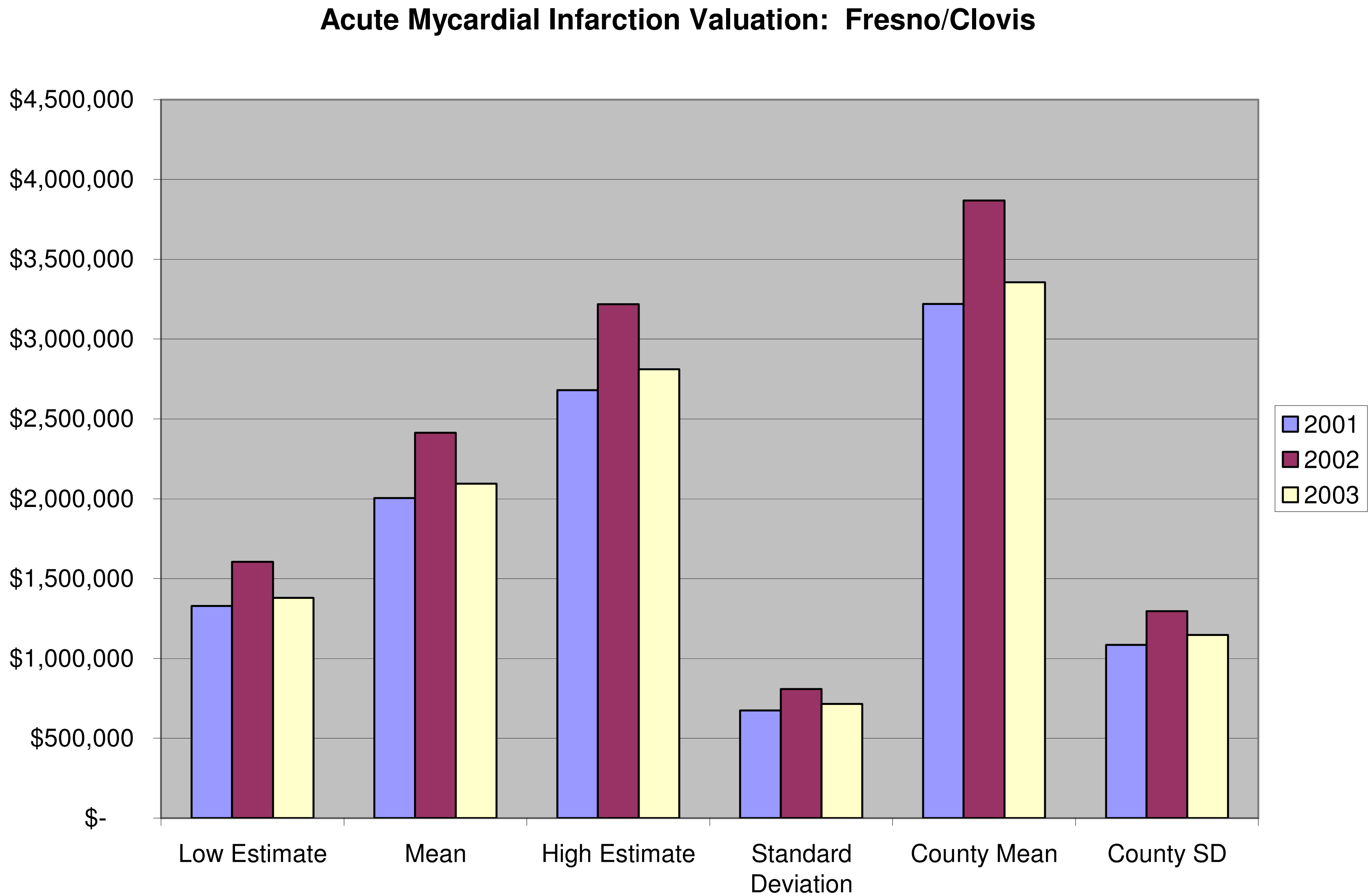

Acute Mycardial Infarction Valuation: Fresno/Clovis
$4,500,000
$4,000,000
$3,500,000
$3,000,000
$2,500,000
$2,000,000
$1,500,000
$1,000,000
$500,000
$-
Low Estimate
Mean
High Estimate
Standard Deviation
County Mean
County SD
2001
2002
2003

Figure 18

Respiratory Emergency Room Visits Valuation: Bakersfield

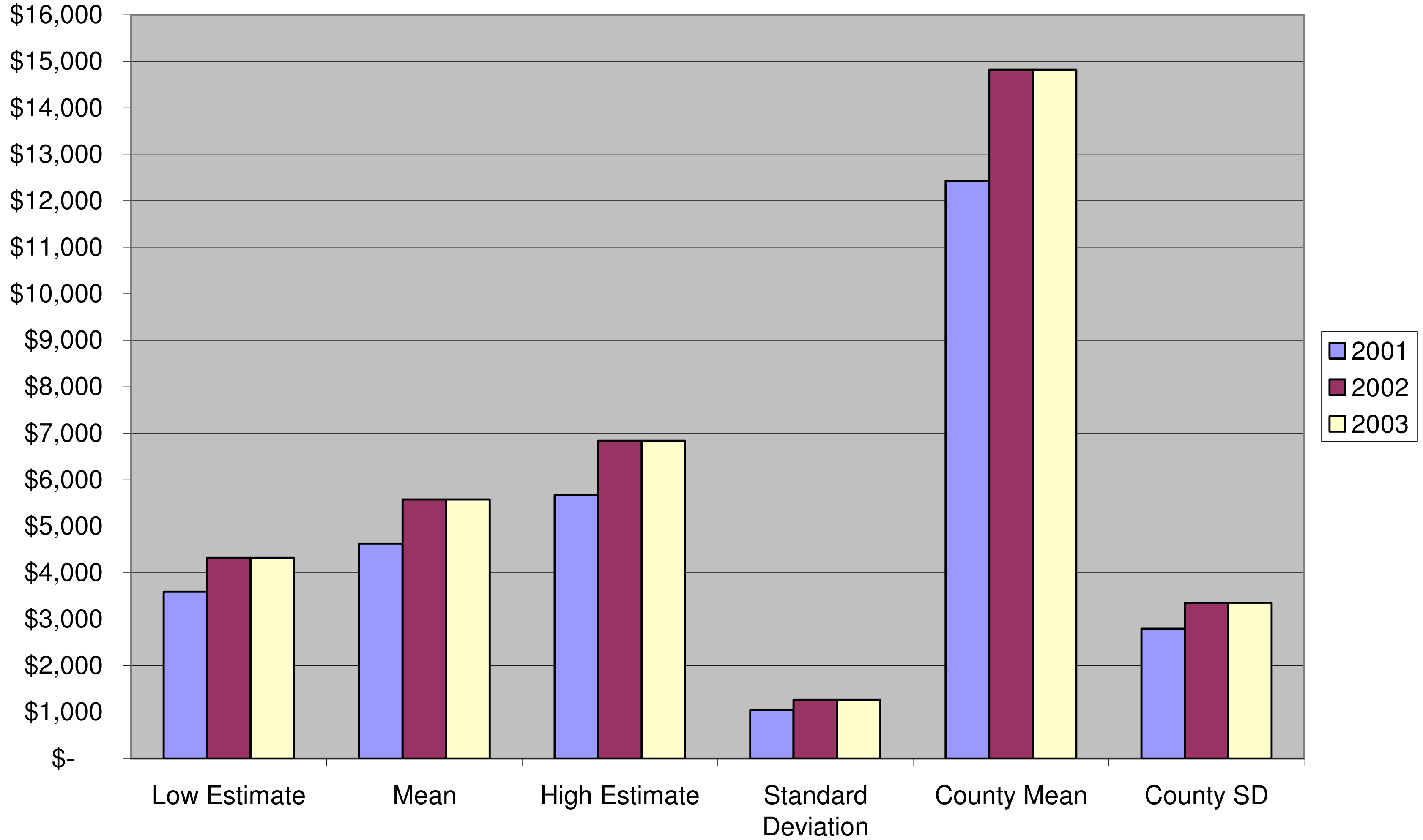


Figure 19

Respiratory Emergency Room Visits Valuation: Fresno/Clovis

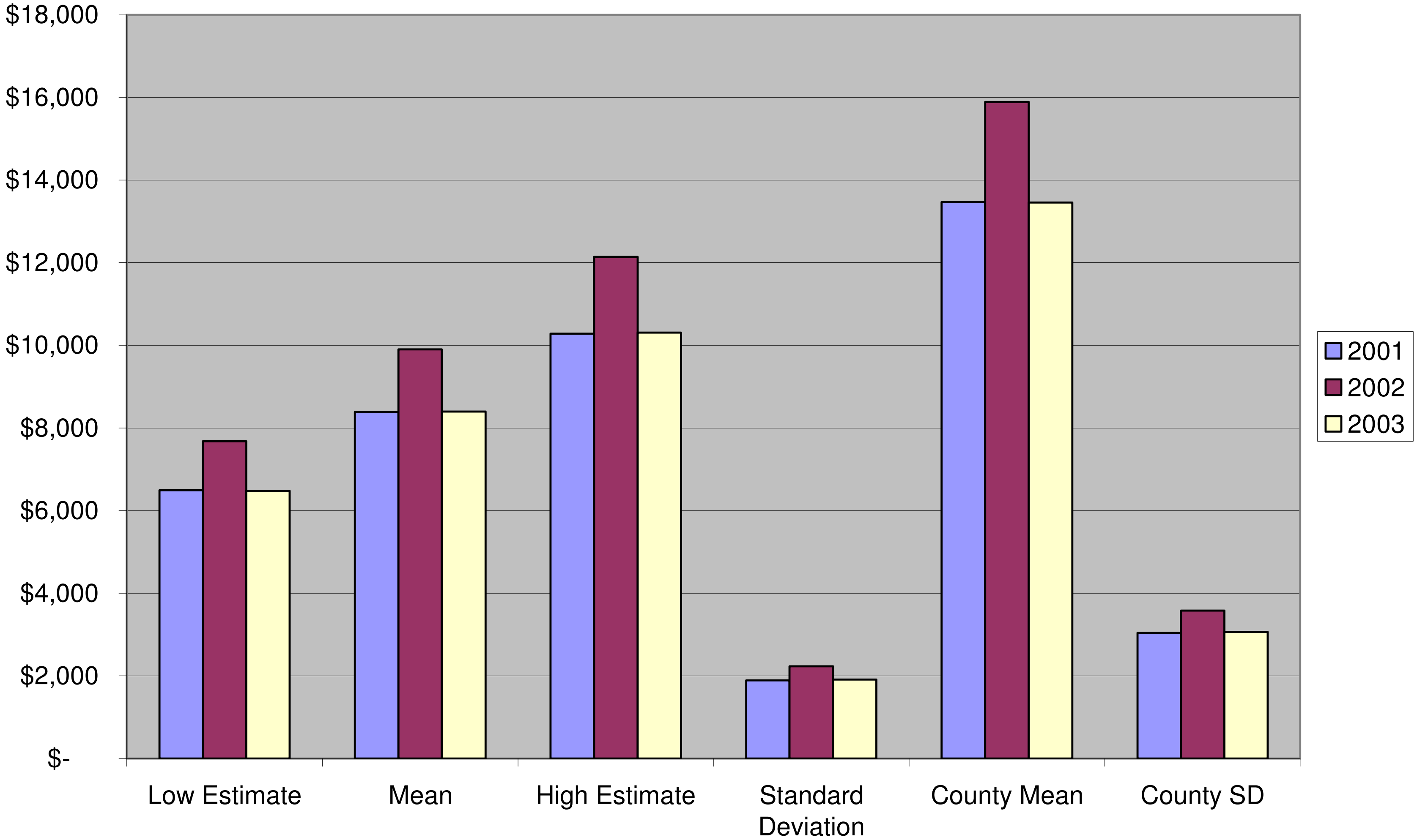


Figure 20

Cardiovascular Hospital Admissions Valulation: Bakersfield

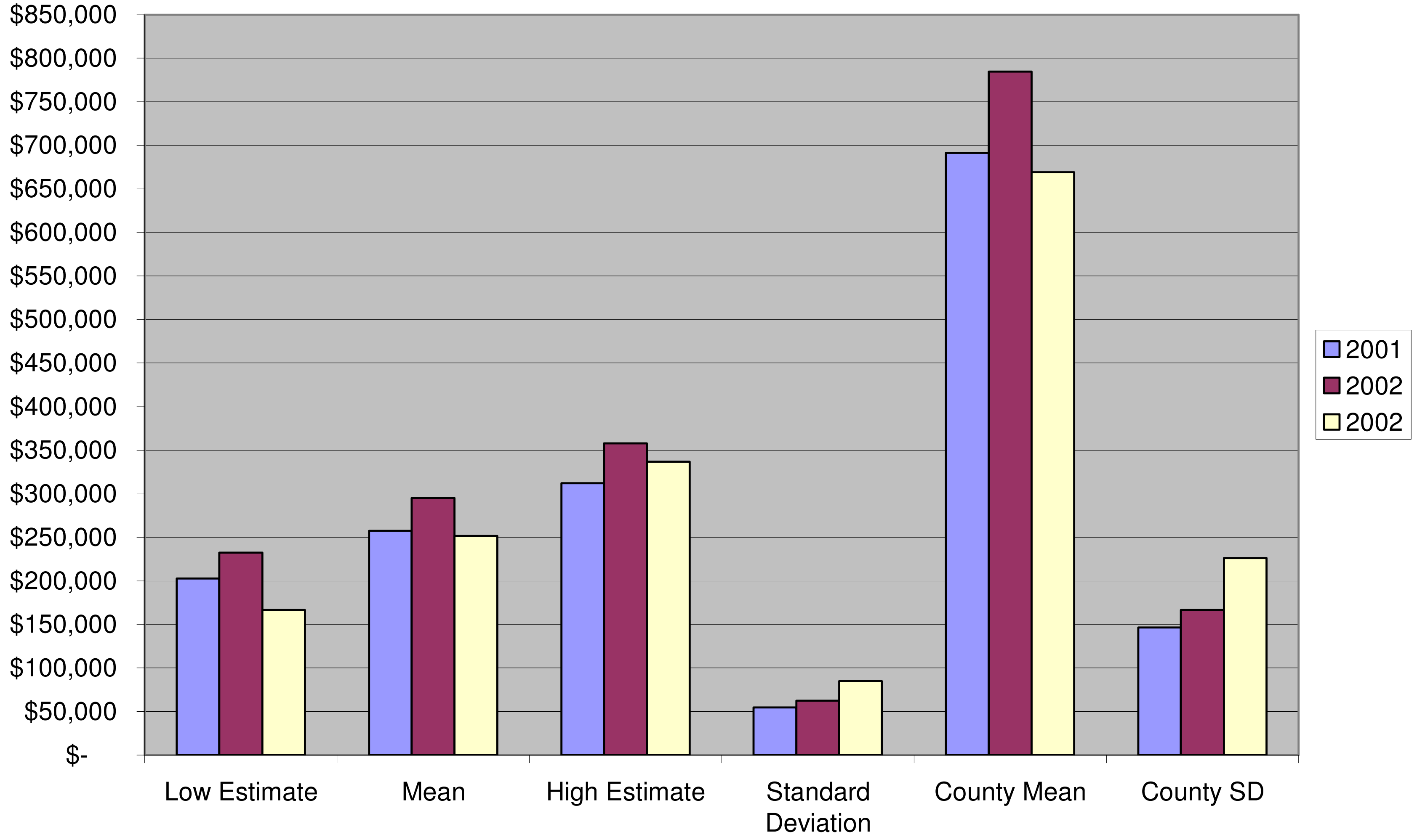


Figure 21

Cardiovascular Hospital Admissions Valuation: Fresno/Clovis

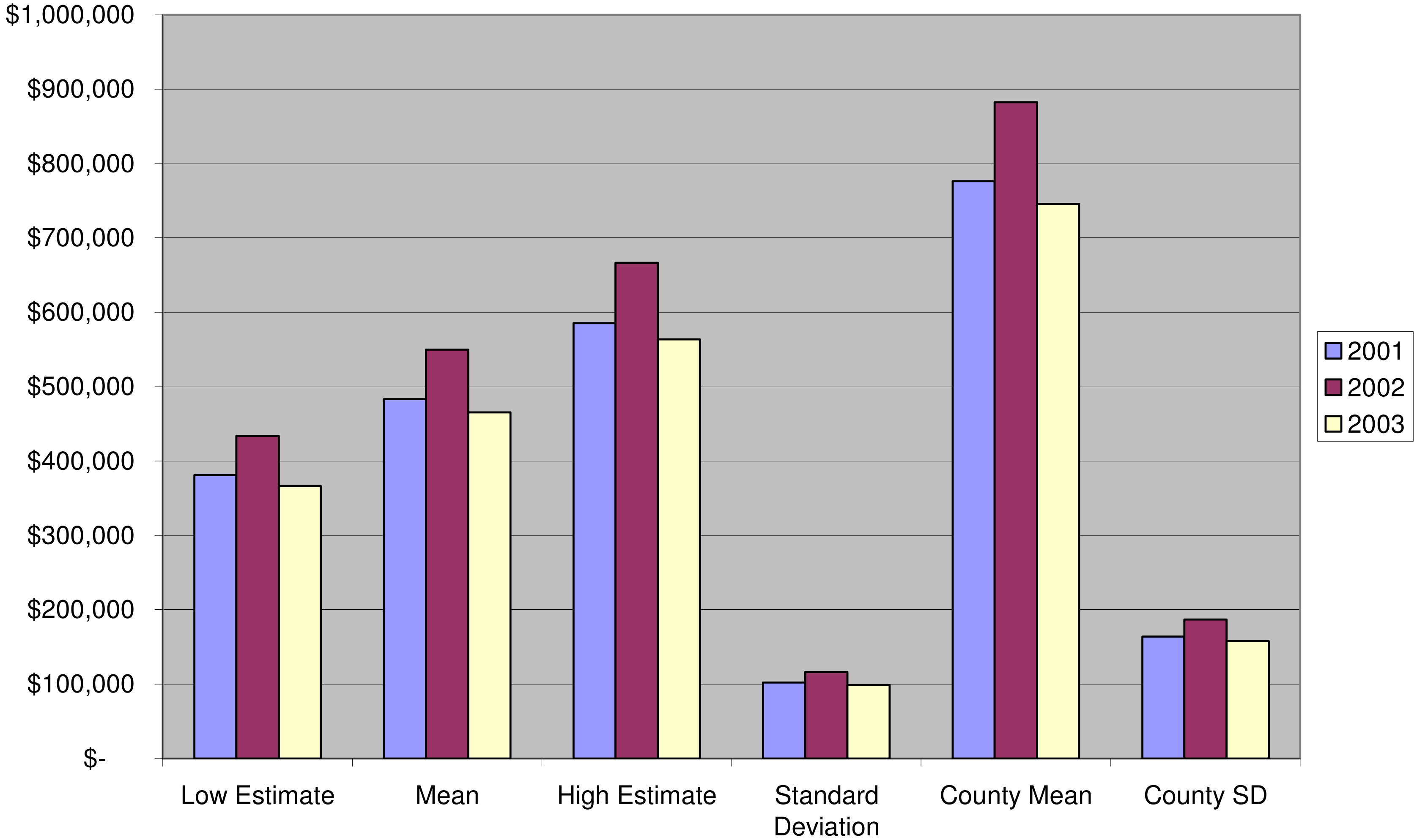


Figure 22

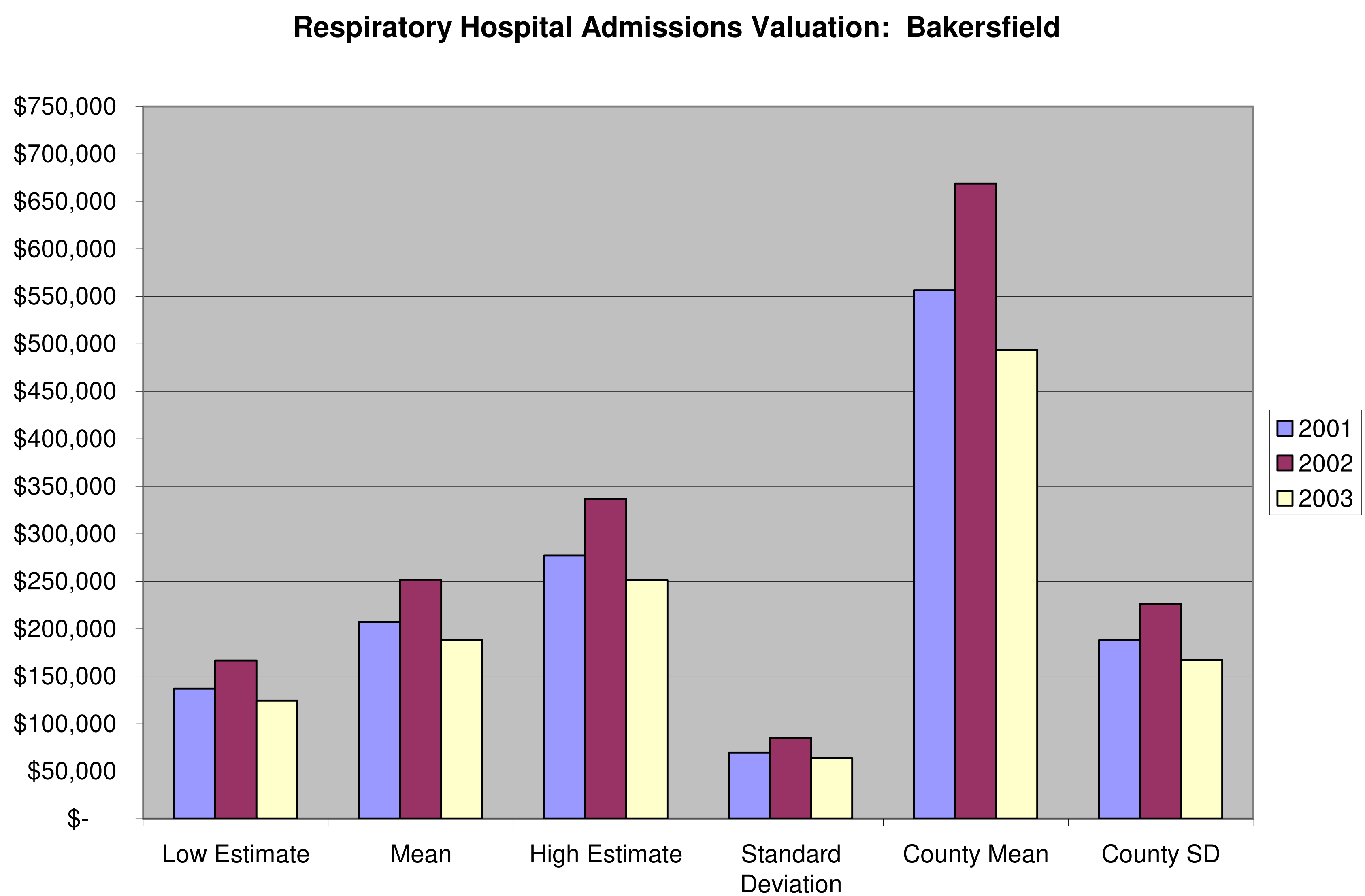

Respiratory Hospital Admissions Valuation: Bakersfield
$750,000
$700,000
$650,000
$600,000
$550,000
$500,000
$450,000
$400,000
$350,000
$300,000
$250,000
$200,000
$150,000
$100,000
$50,000
$-
Low Estimate
Mean
High Estimate
Standard Deviation
County Mean
County SD
2001
2002
2003

Figure 23

Respiratory Hospital Admissions Valuation: Fresno/Clovis

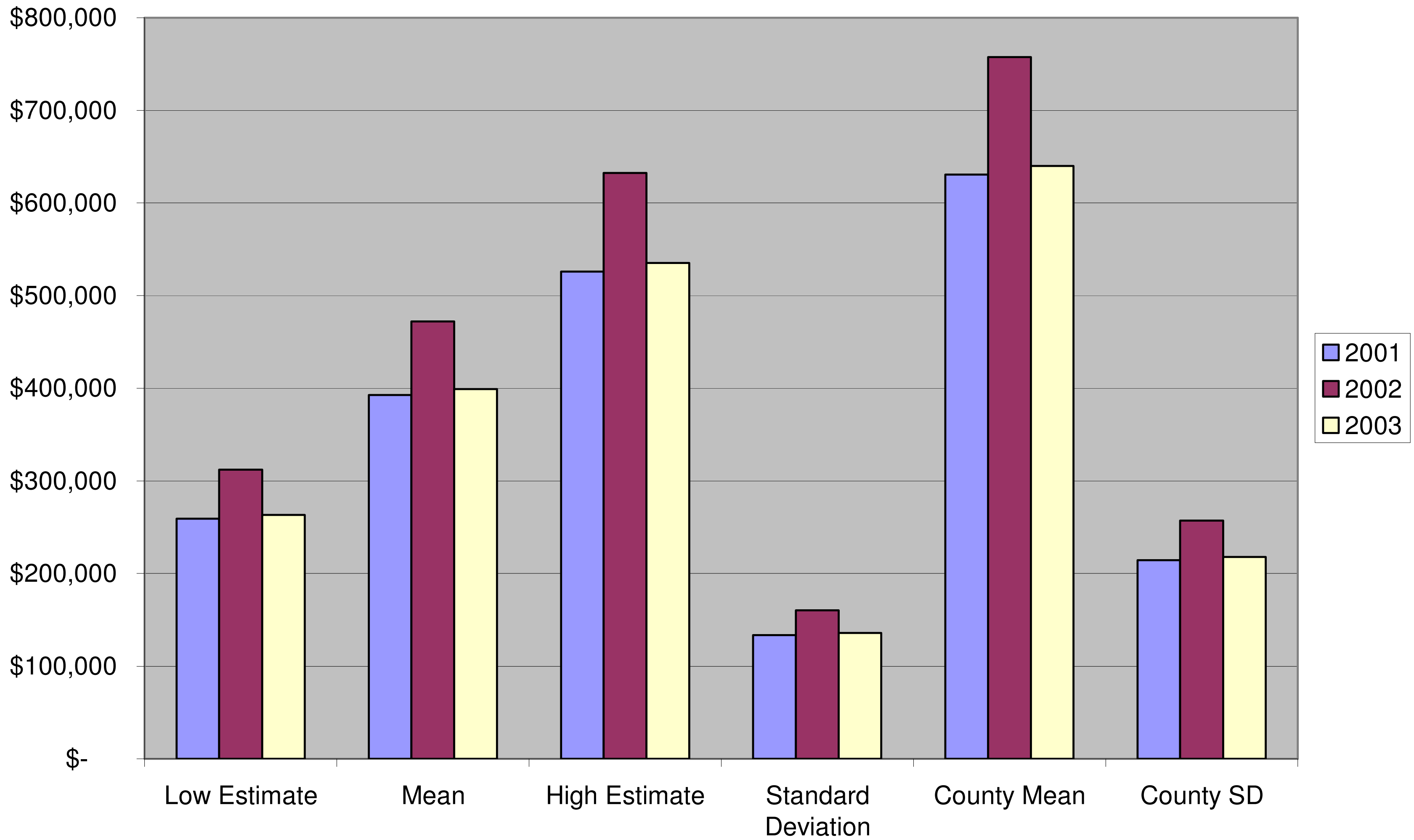


Figure 24

Work Loss Days Valuation: Bakersfield

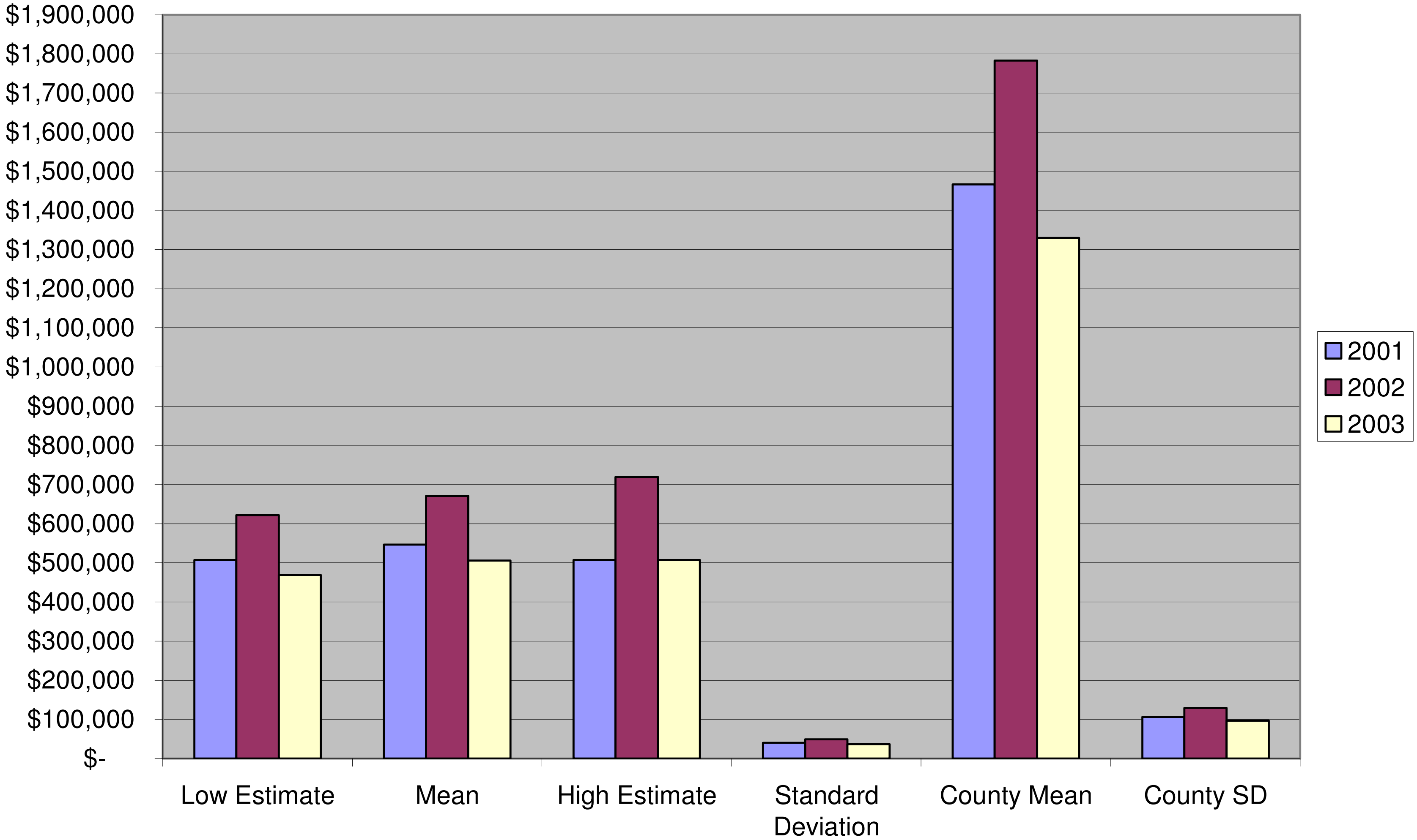


Figure 25

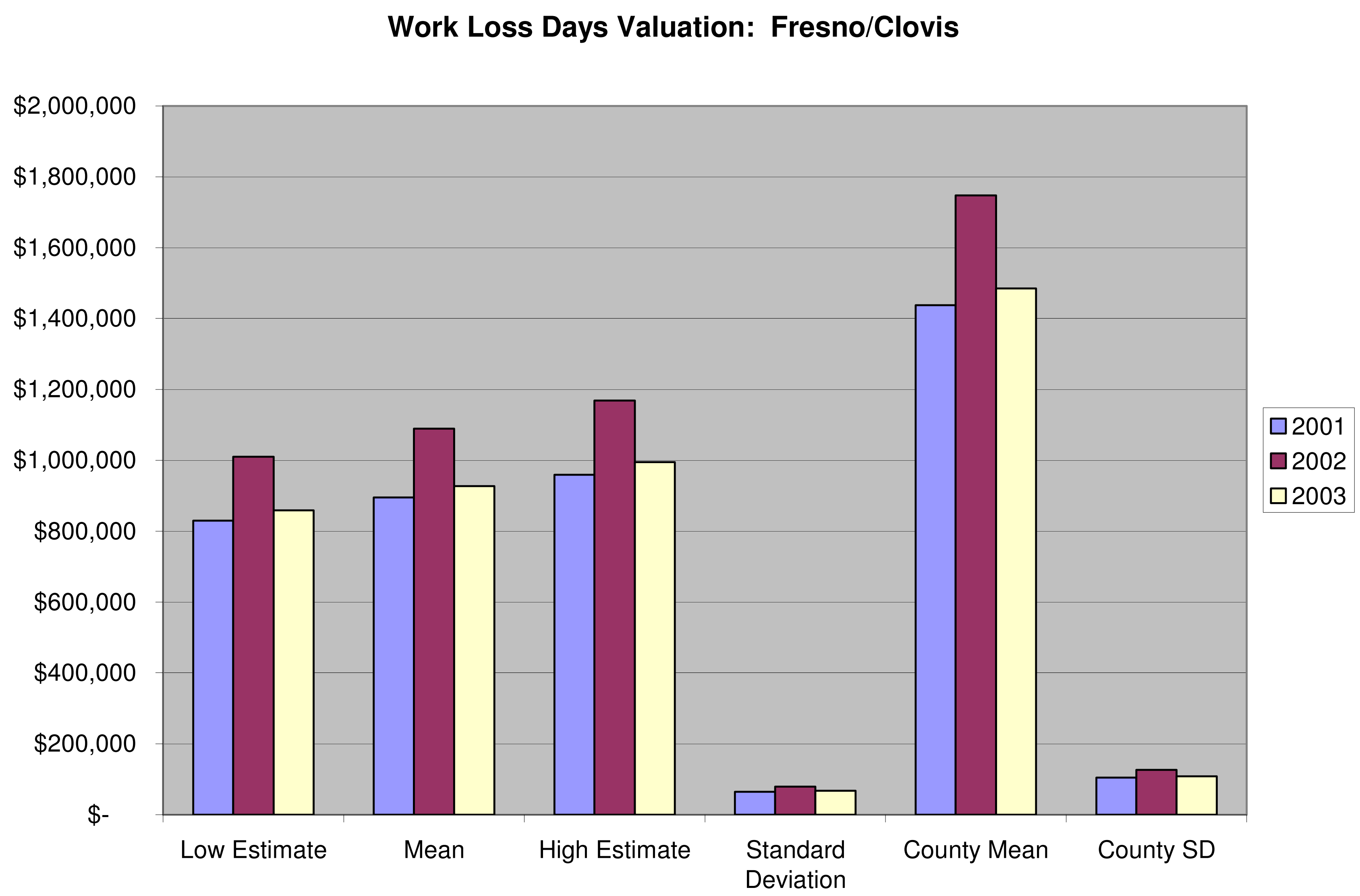

Work Loss Days Valuation: Fresno/Clovis
$2,000,000
$1,800,000
$1,600,000
$1,400,000
$1,200,000
$1,000,000
$800,000
$600,000
$400,000
$200,000
$-
Low Estimate
Mean
High Estimate
Standard Deviation
County Mean
County SD
2001
2002
2003

Figure 26

Acute Bronchitis Valuation: Bakersfield

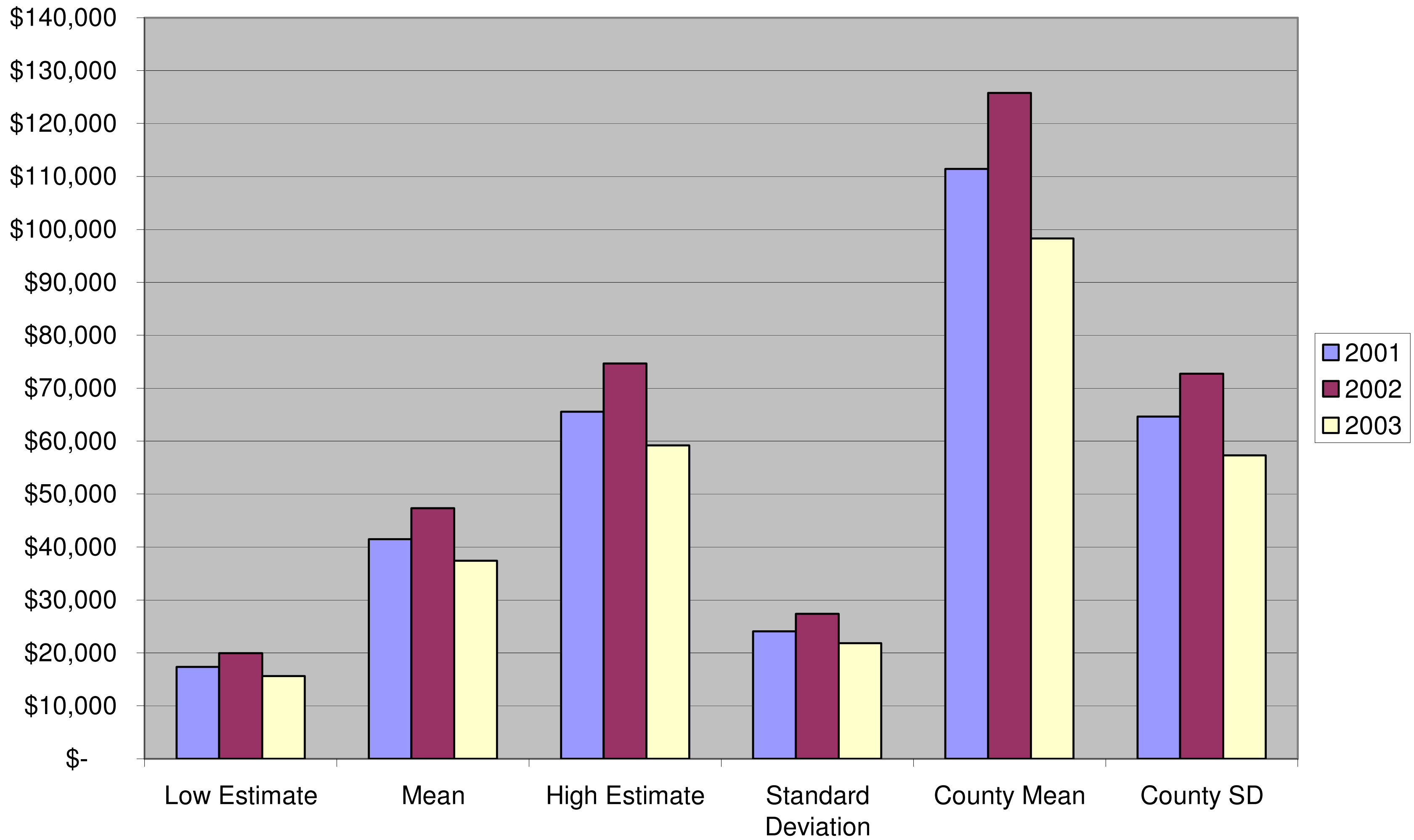


Figure 27

Acute Bronchitis Valuation: Fresno/Clovis

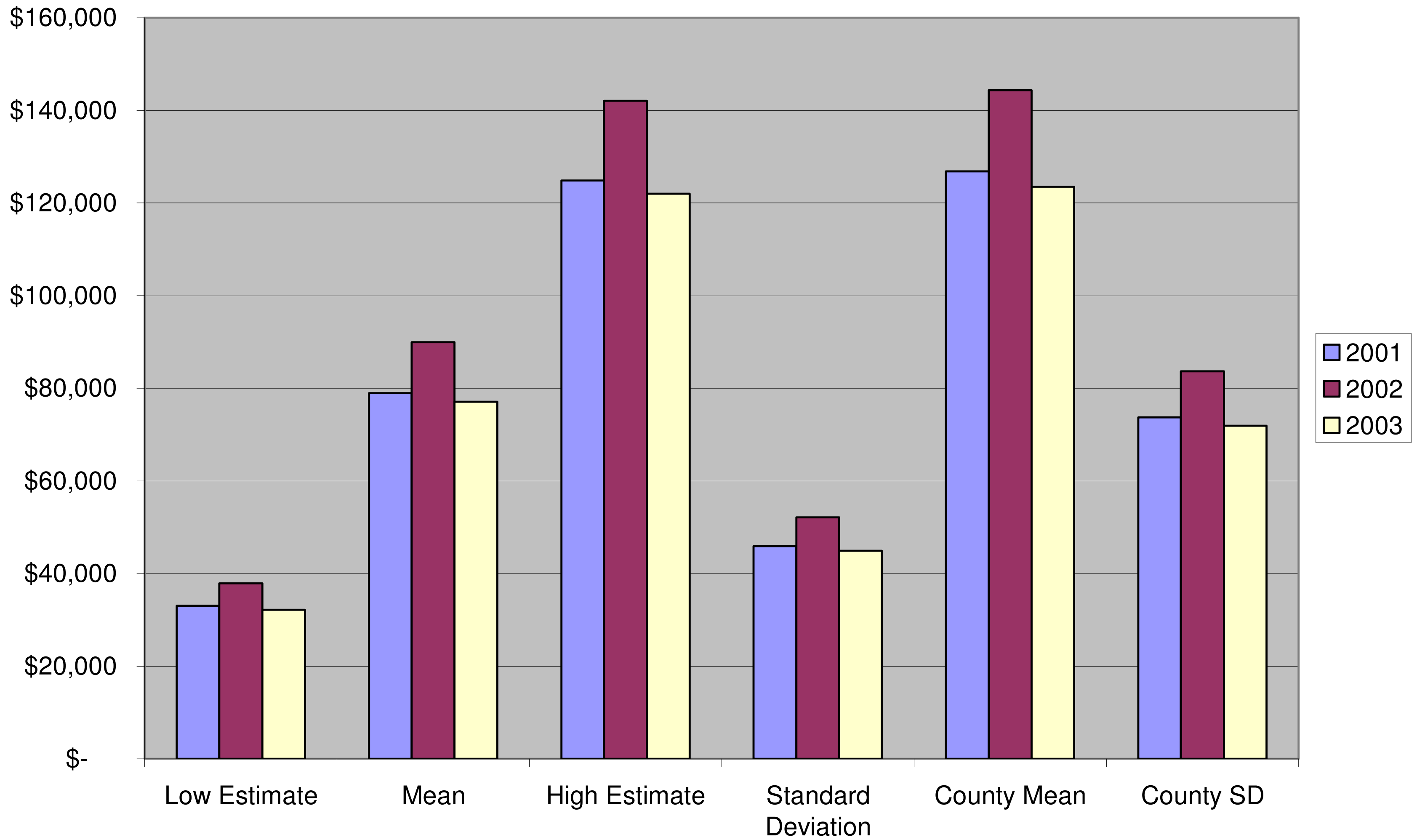


Figure 28

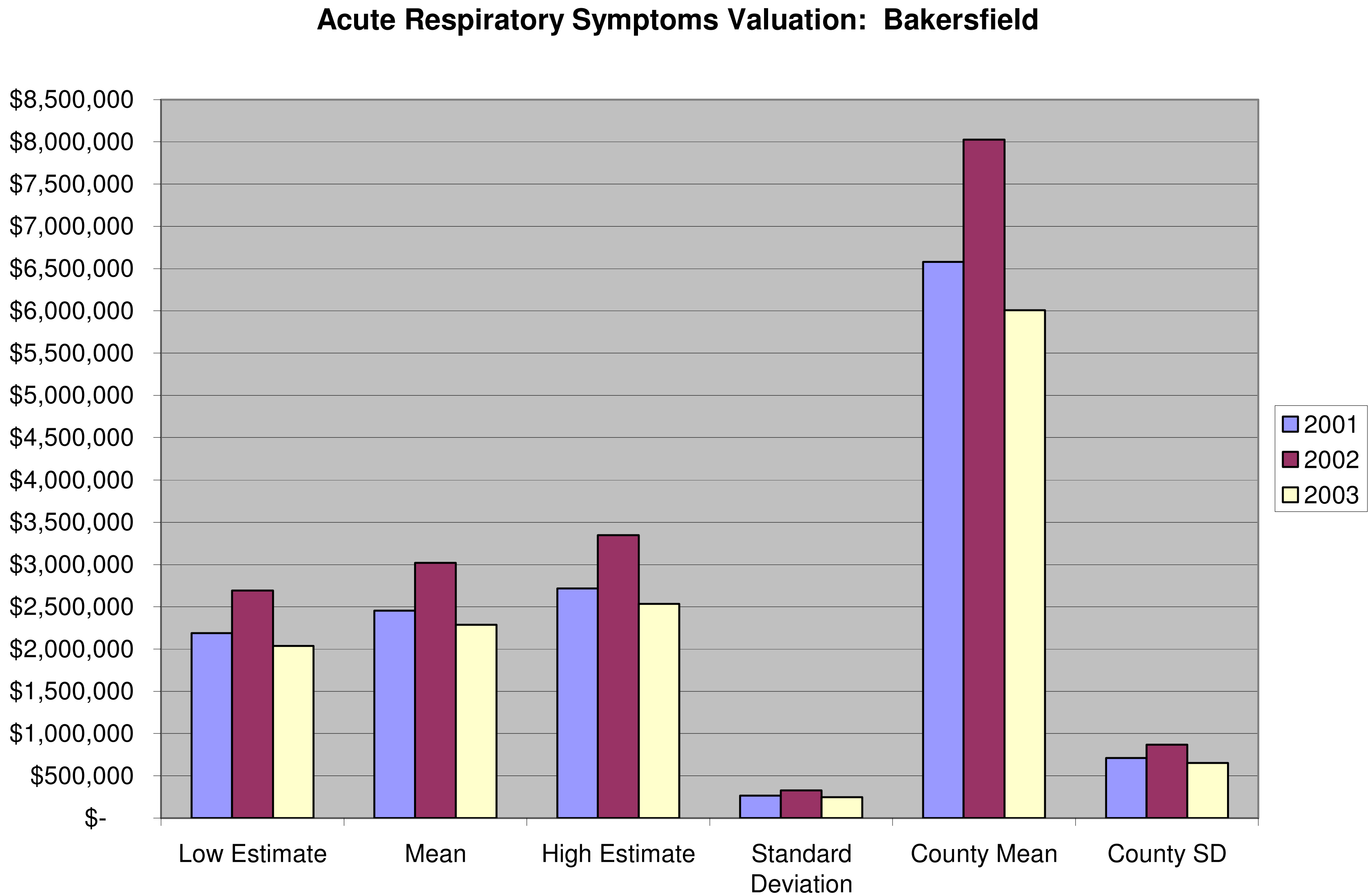

Acute Respiratory Symptoms Valuation: Bakersfield
$8,500,000
$8,000,000
$7,500,000
$7,000,000
$6,500,000
$6,000,000
$5,500,000
$5,000,000
$4,500,000
$4,000,000
$3,500,000
$3,000,000
$2,500,000
$2,000,000
$1,500,000
$1,000,000
$500,000
$-
Low Estimate
Mean
High Estimate
Standard Deviation
County Mean
County SD
2001
2002
2003

Figure 29

Acute Respiratory Symptoms Valuation: Fresno/Clovis

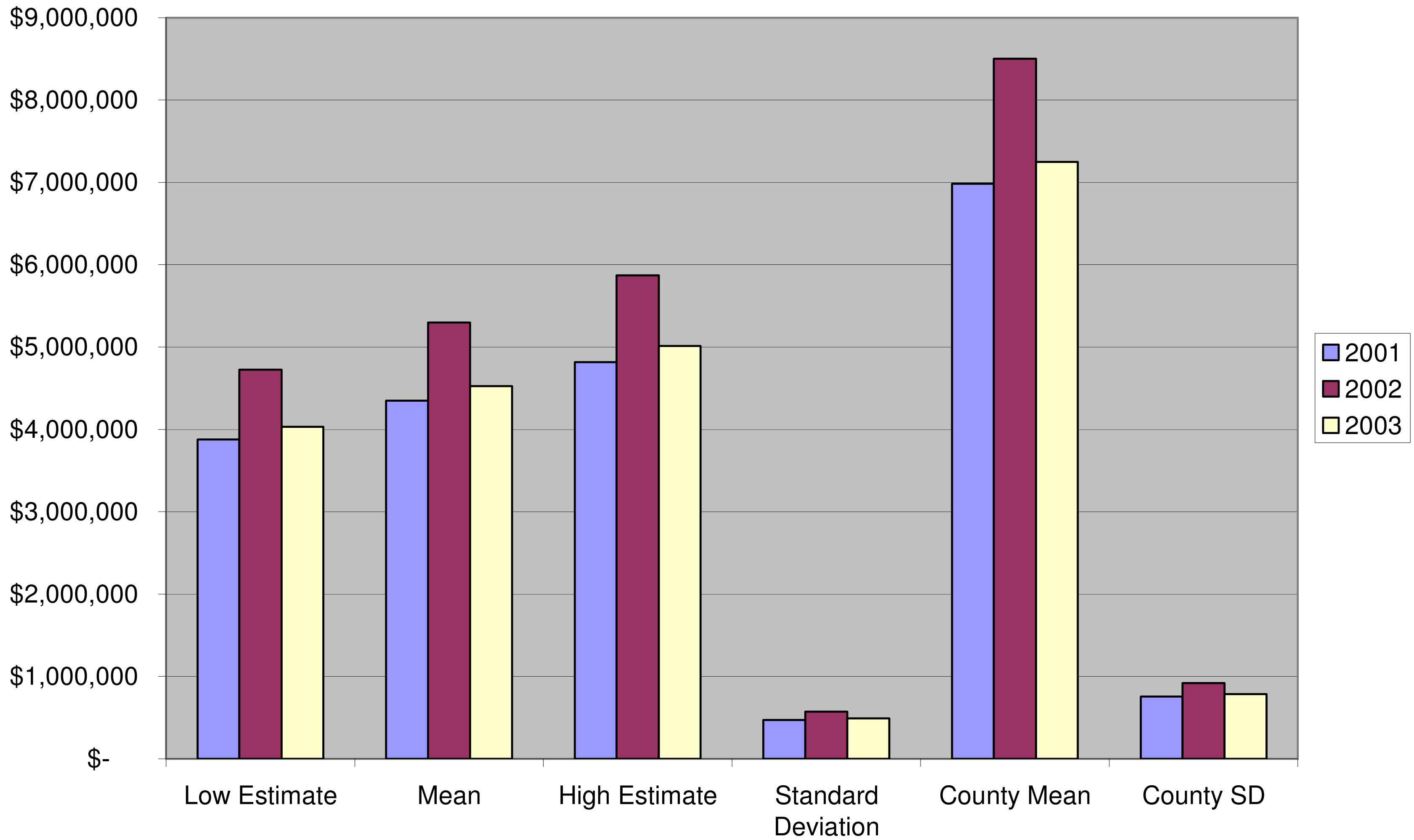


Figure 30

Lower Respiratory Symptoms Valuation: Bakersfield

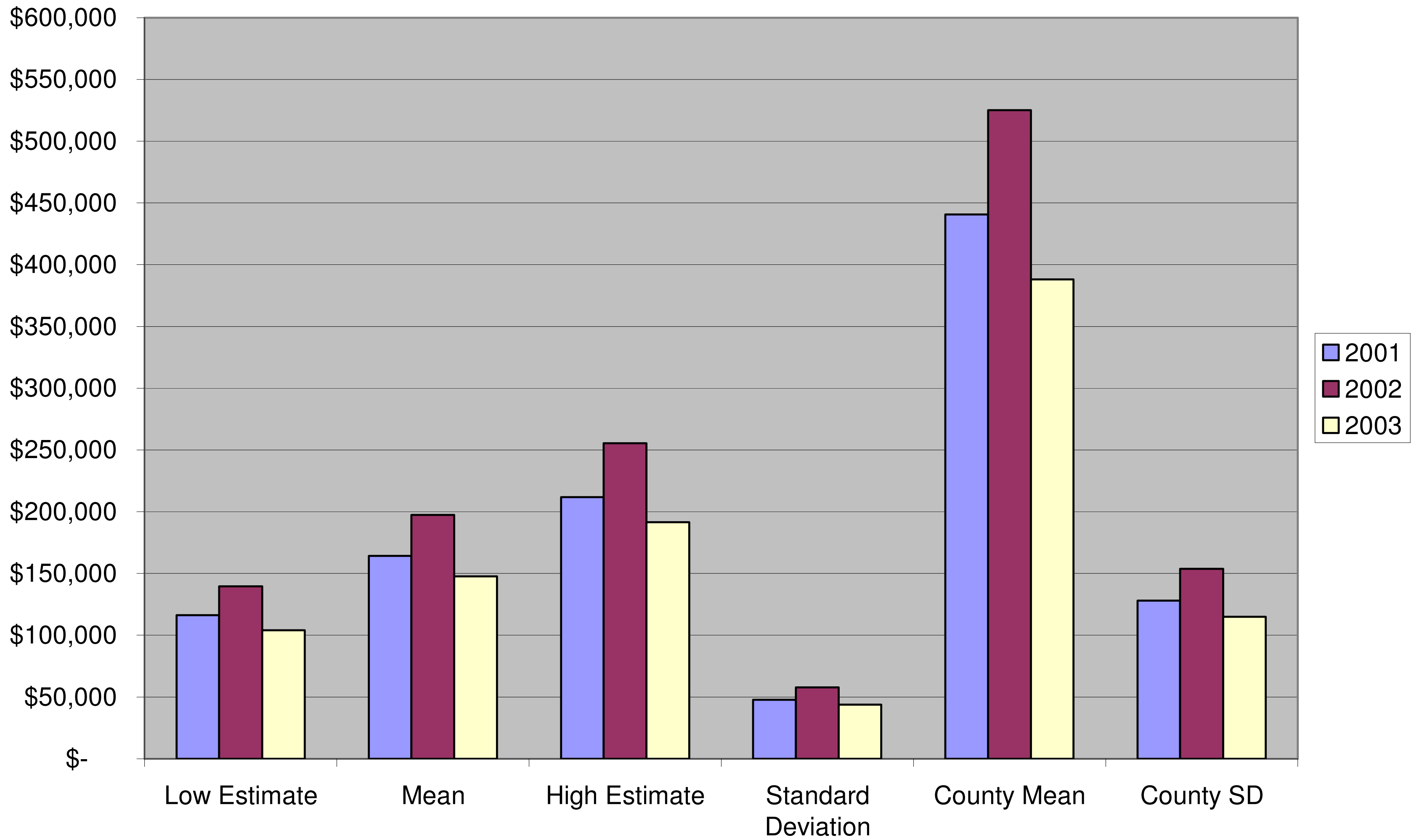


Figure 31

Lower Respiratory Symptoms Valuation: Fresno/Clovis

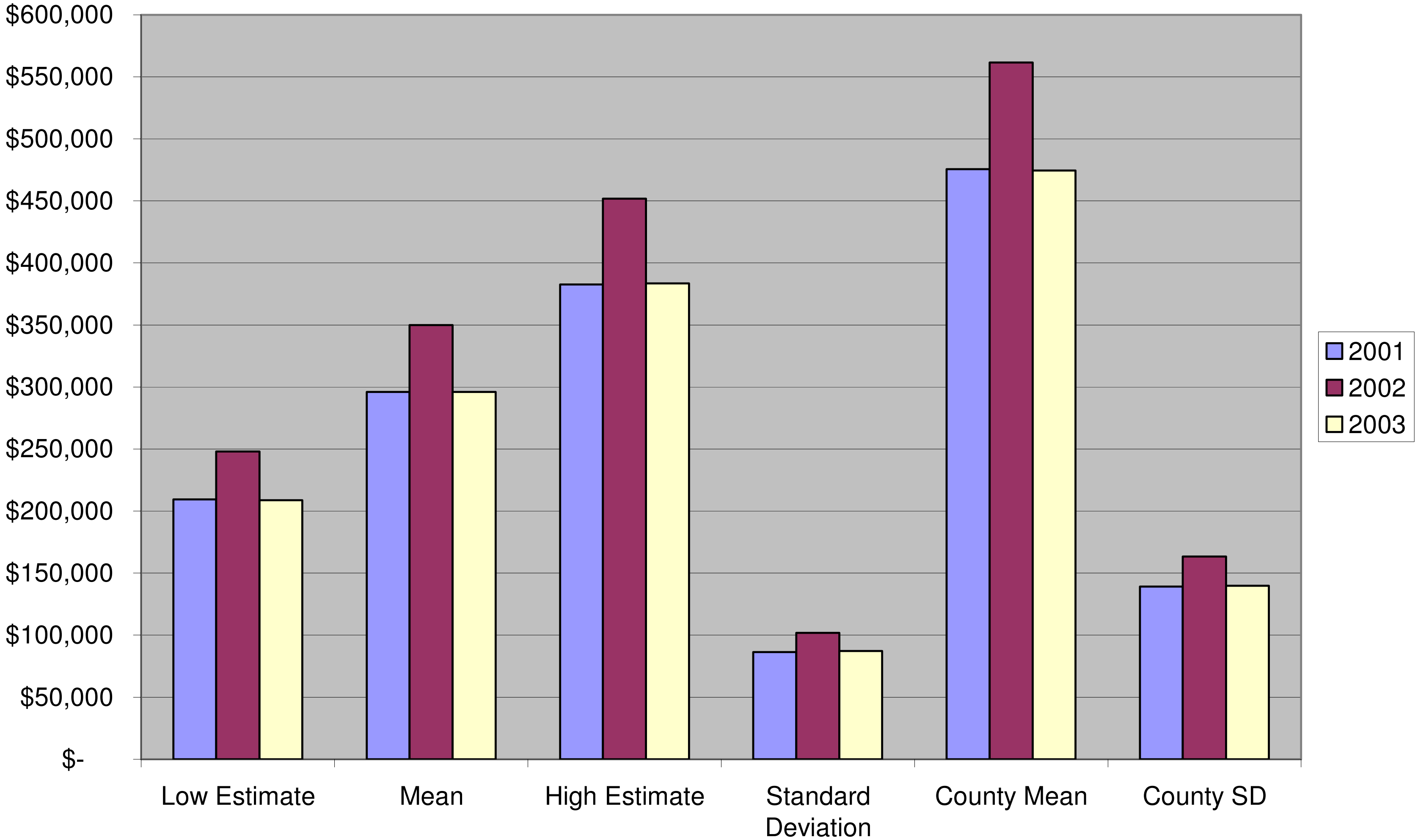


Figure 32

Upper Respiratory Symptoms Valuation: Bakersfield

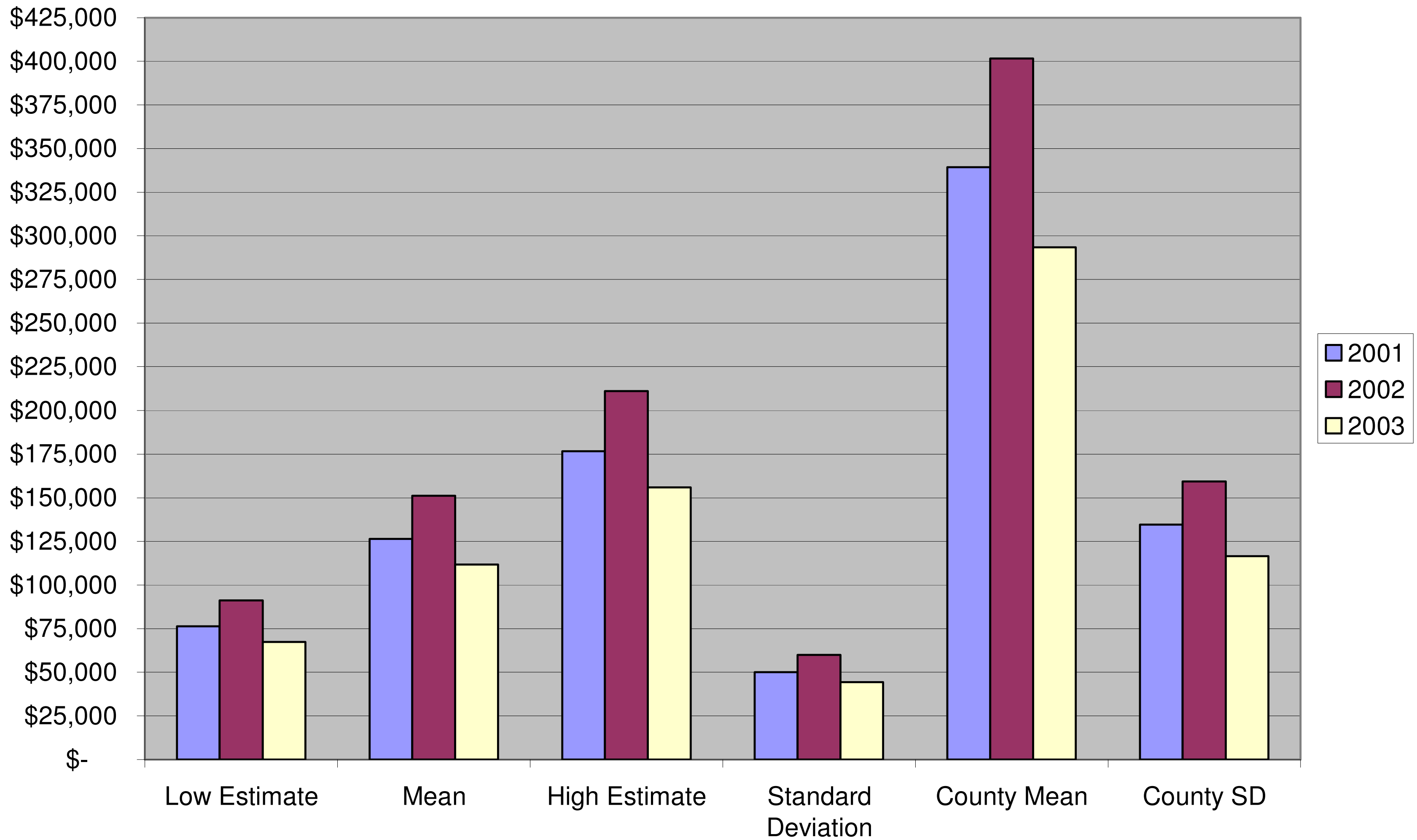


Figure 33

Upper Respiratory Symptoms Valuation: Fresno/Clovis

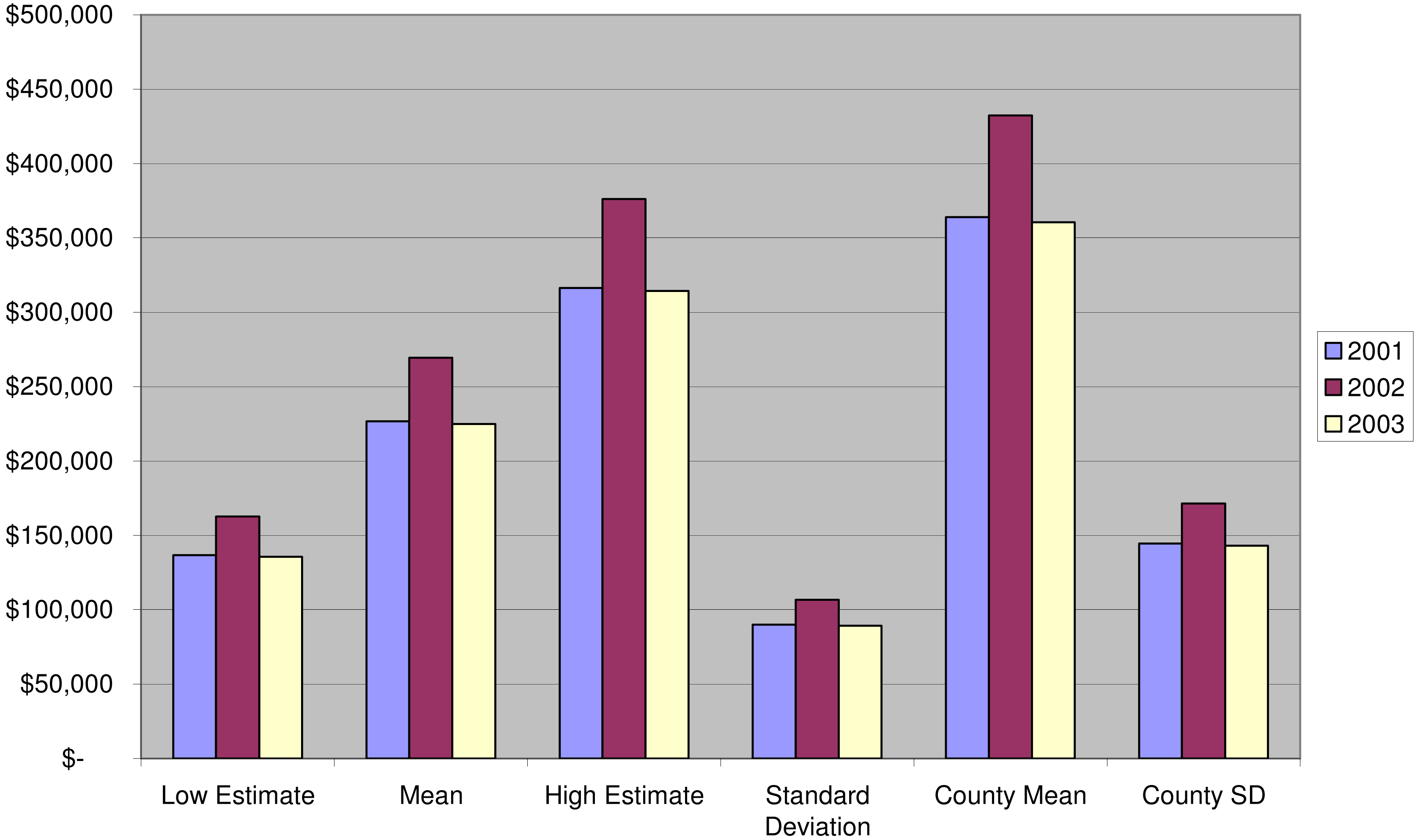


Figure 34

Chronic Bronchitis Valuation: Bakersfield

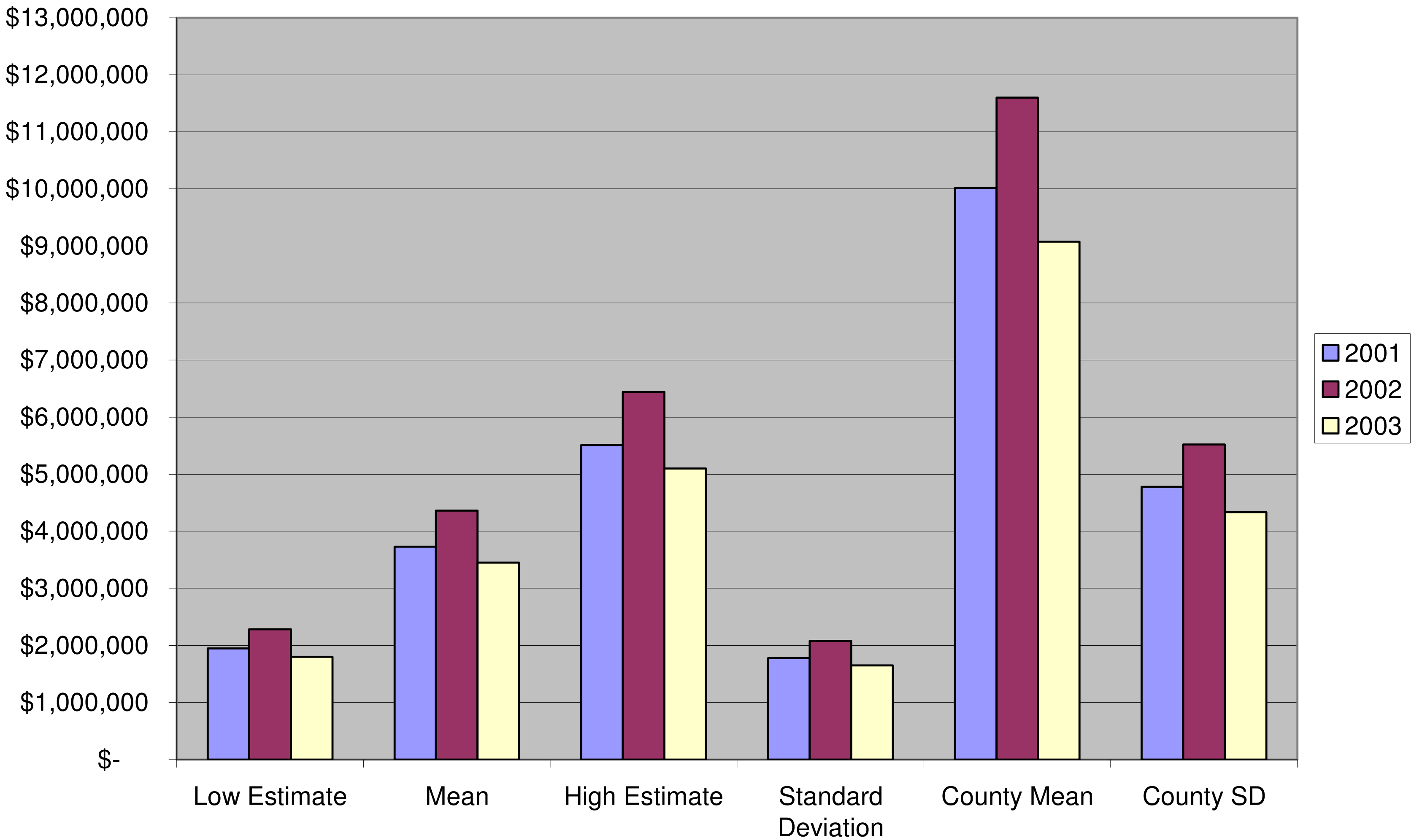


Figure 35

Chronic Bronchitis Valuation: Fresno/Clovis

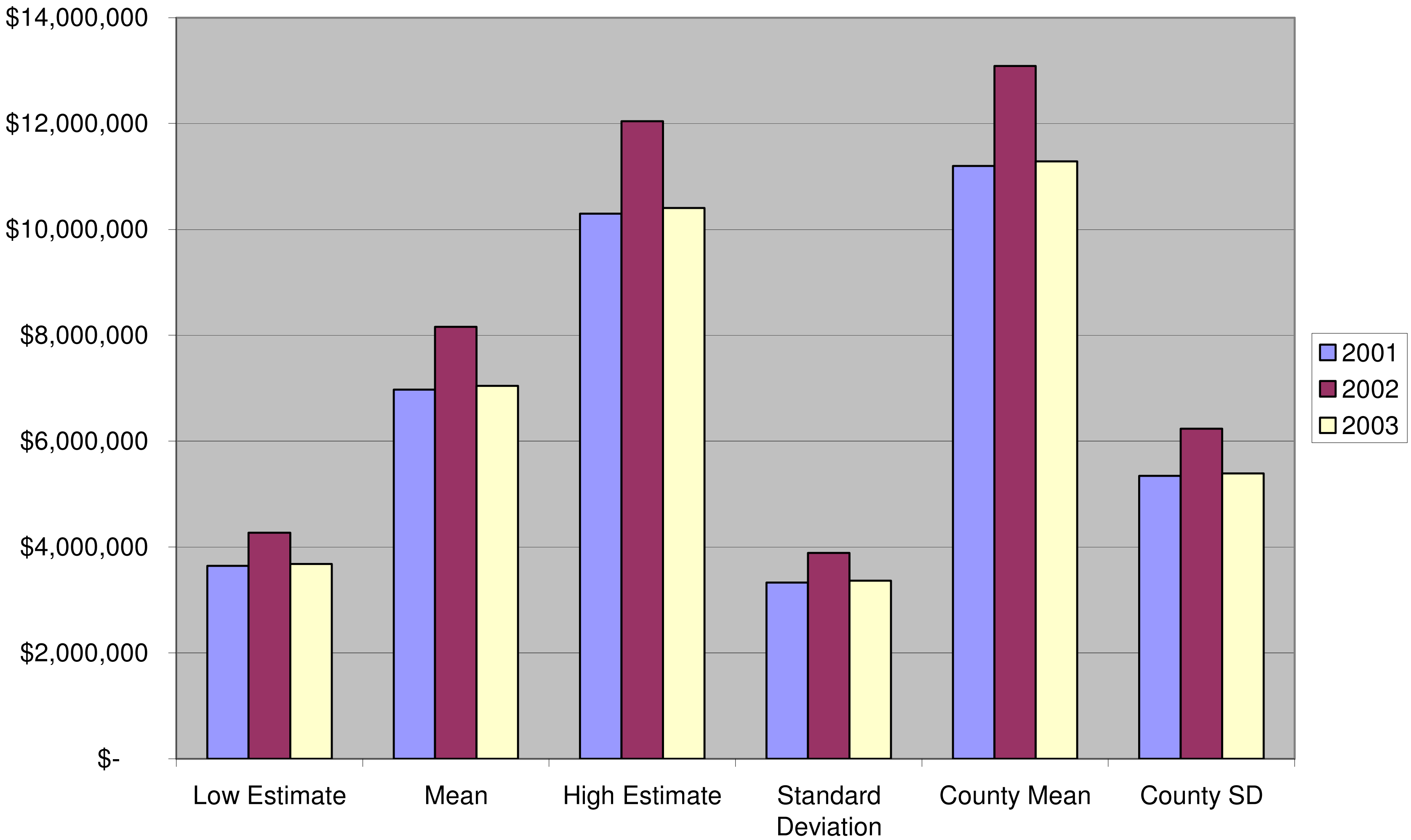


Figure 36

Estimated Annual Pre-Rule 4901 Excess Morbidity Costs for Bakersfield: 2001-2003

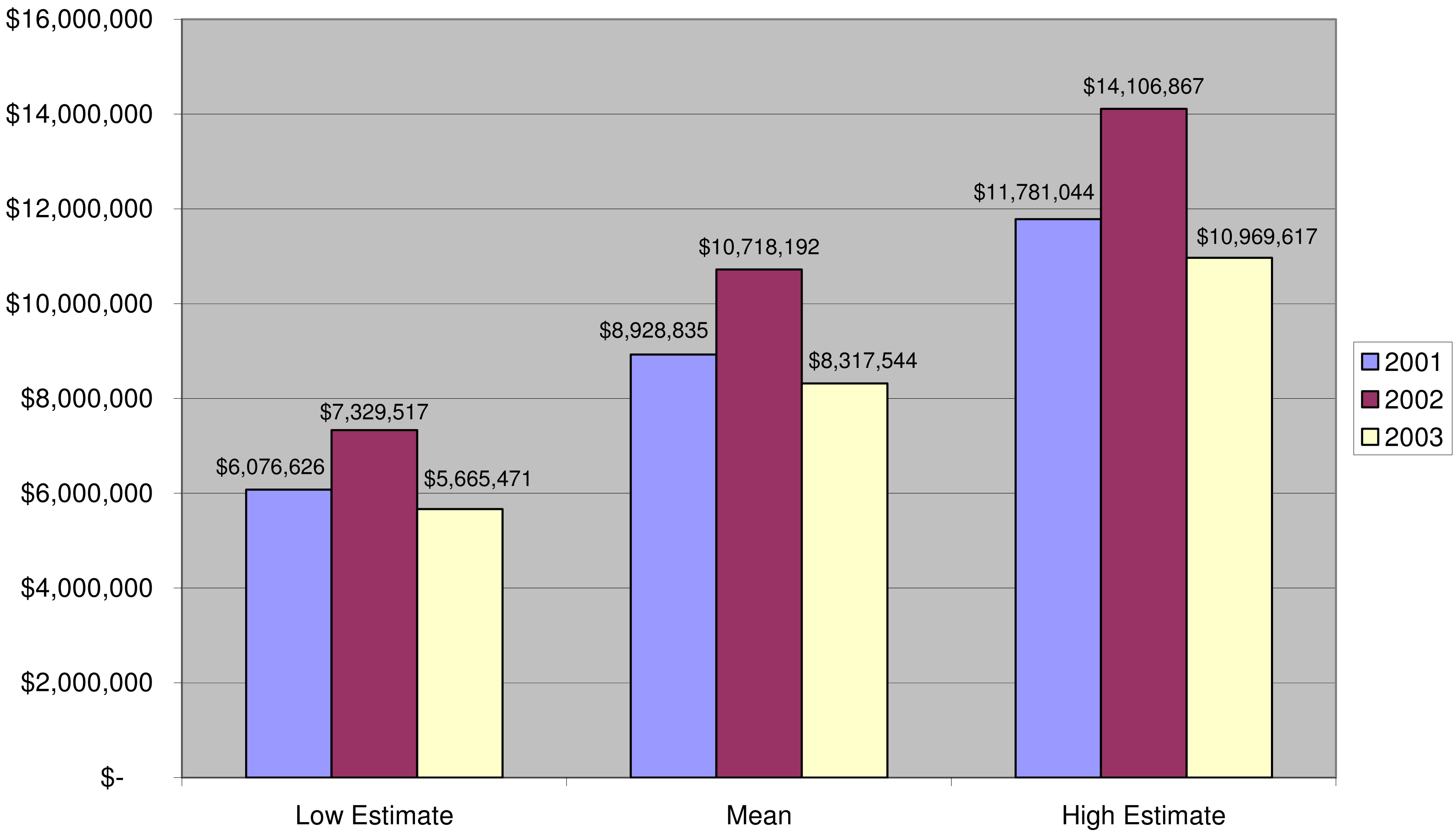


Figure 37

Estimated Annual Pre-Rule 4901 Excess Morbidity Costs for Fresno/Clovis: 2001-2003

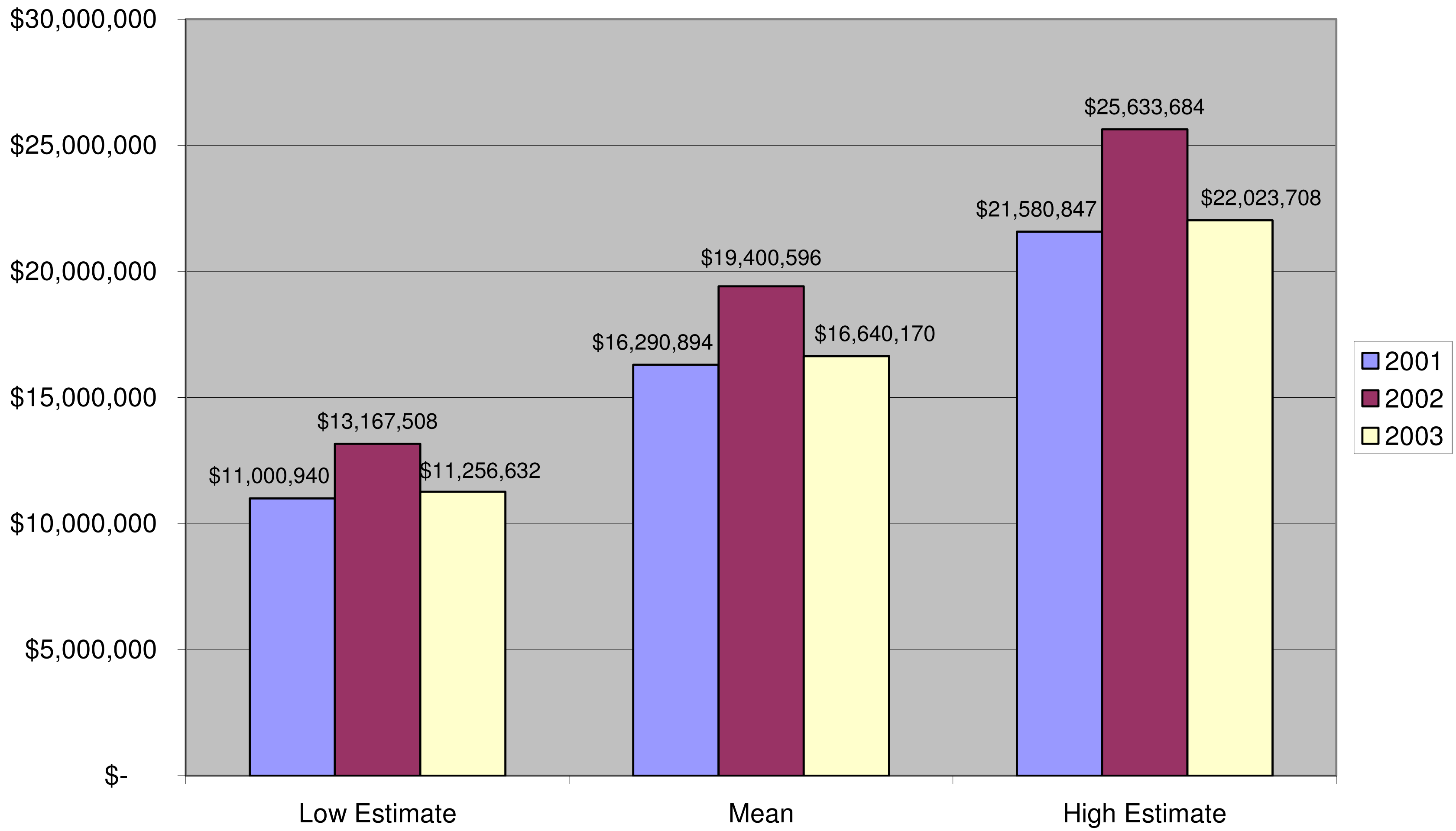


Figure 38

Estimated Annual Pre-Rule 4901 Excess Mortality Costs for Bakersfield: 2001-2003
(Excess Lives Lost in Parantheses)

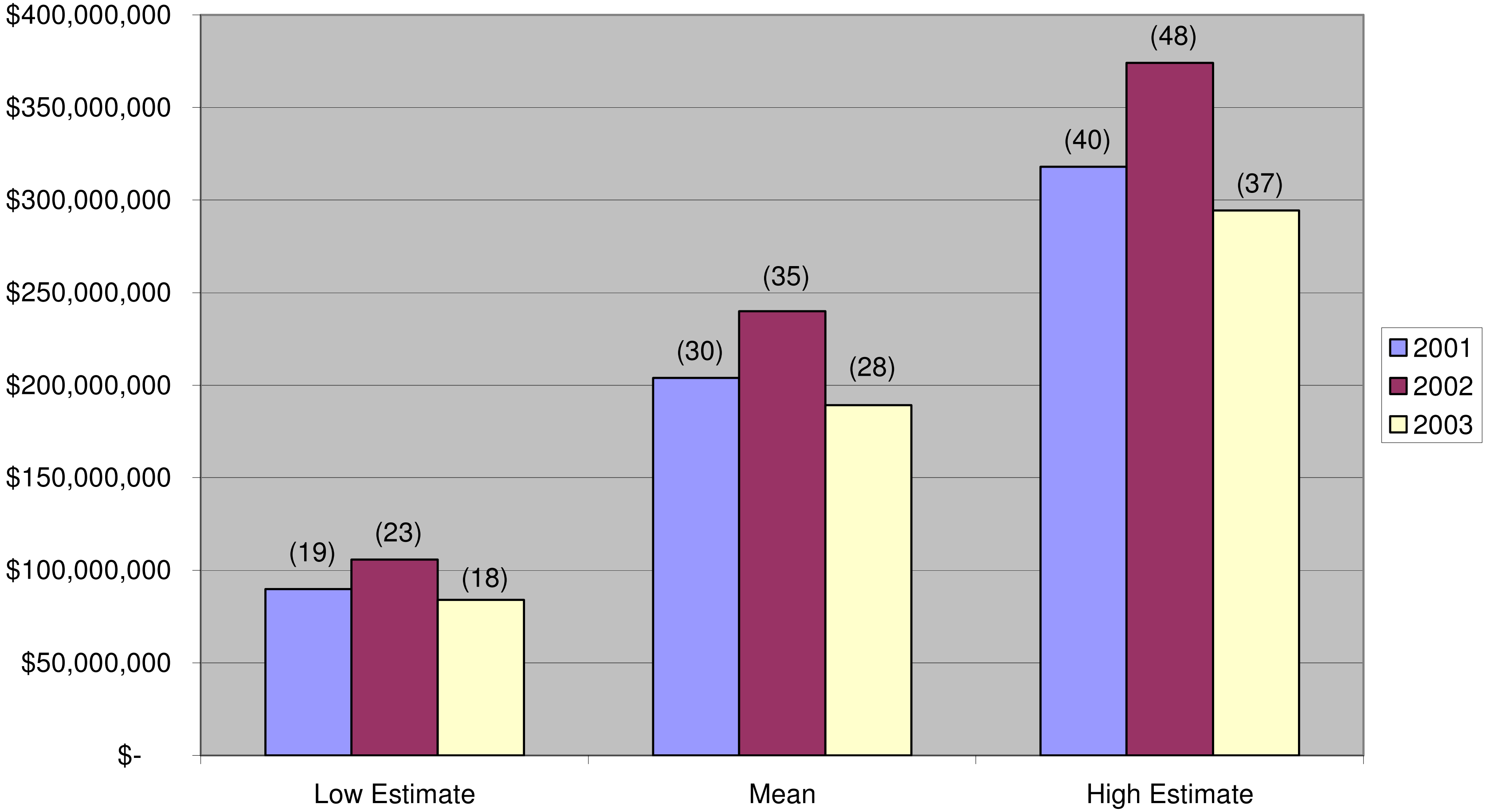


Figure 39

Estimated Annual Pre-Rule 4901 Excess Mortality Costs for Fresno/Clovis: 2001-2003
(Excess Lives Lost in Parantheses)