November 2009

Influence Analysis in Support of Characterizing Uncertainty in Human Health Benefits Analysis

Final Report

Prepared for

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SECTION 1
INTRODUCTION

The U.S. Environmental Protection Agency's Office of Air Quality Planning and Standards (USEPA OAQPS) prepares estimates of the benefits and costs of air quality regulations. OAQPS also assesses the sensitivity of the benefits and costs to uncertainties in the data and assumptions used for their analyses. As part of EPA's efforts to assess uncertainty, RTI and Lumina Decision Systems developed an influence and uncertainty analysis model for BenMAP (USEPA, 2008). BenMAP is a software package widely used at the U.S. EPA and elsewhere to estimate the benefits of improvements in air quality.

This document outlines the methods and results of the influence and uncertainty analysis of the BenMAP estimates of the benefits from air quality improvements. The BenMAP influence analysis focuses on a selection of important but uncertain parameters, functions, and input data used to calculate the human health benefits of reductions in $PM_{2.5}$. For health outcomes, the model examines mortality, acute myocardial infarction (AMI) and chronic bronchitis (CB). The results of this analysis may be used to guide decisions about how to prioritize future efforts to characterize these uncertainties and, where possible, reduce them.

The goals of the project were to identify those input parameters and assumptions that have the potential to be significant contributors to the uncertainty in the results of BenMAP, to compare the potential size of their contributions, and to identify those likely to make the largest contributions.

By influence analysis, we mean a graphic depiction of the model structure in the form of a hierarchy of influence diagrams. Each variable, including input assumptions, decisions, intermediate variables, and results, is depicted as a labeled node. Influence arrows between the nodes depict relationships where one variable influences another via a mathematical relationship in the underlying model.

By uncertainty analysis, we mean the process of comparing the effect of the uncertainty in each input variable on a result variable. Range sensitivity analysis is a method of uncertainty analysis that depicts the range of values in a result variable produced by changing each uncertain input from a low to high value, while leaving all the other inputs at a nominal or mid value. We will examine sensitivities by assessing plausible ranges on each input and computing deterministic measures of sensitivity to compare their effects on selected output variables.

The focus of this project was to conduct an uncertainty analysis of BenMAP as a tool to estimate the benefits of improvements in air quality. In order to keep the level of effort for the project within the resources available, the scope was defined to include the effects of uncertainty in the explicit inputs to BenMAP, including:

- Particulate matter under 2.5 microns ($PM_{2.5}$), and no other types of atmospheric pollutant.
- Annual average concentration of $PM_{2.5}$, ignoring any effects of short-term peak concentration except insofar as they affect annual averages.
- Improvement in air quality was specified in terms of current annual average concentration of $PM_{2.5}$ and a future, usually lower, concentration of $PM_{2.5}$ at a future date, typically 2020, and excluding any preceding variables or factors that might affect $PM_{2.5}$, such as changes in emissions, or climate, as modeled in CMAQ and other computer models.
- Spatial resolution was to cover the contiguous United States (excluding Alaska, Hawaii), in 36-kilometer grid squares, and no smaller regions such as counties.
- Affected population was by age range, ignoring effects of gender, race, socioeconomic status, or other differentiators.
- Effects of improved air quality are to be examined on reduction in mortality and two types of morbidity, CB and AMI, and no other end points, such as other diseases or visibility.
- Treatment of uncertainty was explored by defining a range of values for key parameters, and their effects on results while holding all other parameters at their mid values (range sensitivity analysis). Probabilistic treatment of uncertainties about input parameters using expert probability distributions and Monte Carlo analysis to propagate probabilistic uncertainties were explicitly beyond the scope of this project.

The rest of the report is structured as follows: Section 2 presents the approach taken for the sensitivity analysis, followed by a discussion of the uncertain parameters and functions in Section 3 and the influence diagrams associated with the model in Section 4. The results can be found in Section 5, followed by a discussion of the results and possible implications of the results for characterizing uncertainty in Section 6.

SECTION 2
APPROACH

2.1 Overview of Approach

The goals of the project are to identify those input parameters and assumptions that have the potential to be significant contributors to the uncertainty in the results of BenMAP, to compare the potential size of their contributions, and to identify those likely to make the largest contributions. This outline shows the steps involved in conducting the influence and uncertainty analysis, which are described in more detail below.

- Identify and classify the uncertainties
  - Develop an inventory of possible sources of uncertainty
  - Classify these sources in terms of source and type of uncertainty
  - Select which of these uncertainties should be treated quantitatively in the sensitivity analysis
  - Assess ranges of plausible values for selected parametric uncertainties and ranges of plausible alternative forms for model uncertainties
- Build simplified model and conduct sensitivity analysis
  - Develop influence diagrams to trace which sources of uncertainty have effects on which results
  - Develop a simplified or reduced-form model
  - Compare the simplified model with BenMAP for selected scenarios to validate and calibrate it.
  - Conduct sensitivity analysis using ranges to identify the relative importance of the uncertainty associated with different parameters and model assumptions on the results using various measures of sensitivity
- Provide the results and discussion of the results to EPA, so that EPA can use the information to assess which uncertainties are most important to investigate in more detail

2.2 Identify and Classify the Uncertainties

The first step is to identify and classify the sources of uncertainty in BenMAP. The team developed an inventory of sources of uncertainty by reviewing BenMAP, including its input files and documentation. Where BenMAP offers different functional forms, we identified an explicit source of uncertainty. Where it uses a particular functional form and some other functional form appeared reasonable, we identified that as an implicit model uncertainty. An exception is the

uncertainties in emissions and air quality whose explicit quantification is outside the scope of this study.

We classified each source of uncertainty according to its source and type, using the following categories:

2.2.1 Sources of Uncertainty

- **Explicit parameters** inside BenMAP, where BenMAP makes it easy to select a value as an input.
- **Input parameters** generated outside of BenMAP, such as emissions or population distribution.
- **Implicit parameters**, where BenMAP uses a single value, but there are other plausible values not offered as an explicit input to BenMAP.
- **Explicit model forms** selectable within BenMAP such as the functional form for concentration-response (CR) functions.
- **Implicit model forms** used in BenMAP where there are other plausible model forms not offered as an explicit input to BenMAP.

2.2.2 Types of Uncertainty

- Parameter uncertainty
  - **Measured:** Uncertainty in measured quantities due to measurement biases and limited sample size, for example, population estimate from past census, mortality data, willingness to pay (WTP) to avoid a health outcome or the estimate of beta in CR functions
  - **Forecast:** Uncertainty in forecasts based on expert judgment and/or extrapolation from past trends, for example, future population, Gross Domestic Product (GDP), or $PM_{2.5}$ concentrations.
  - **Values:** These are used to quantify outcomes such as avoided premature mortality and morbidity into dollars, for example, the value of a statistical life (VSL), the discount rate, or cost of illness (COI) estimates.
- Model uncertainty
  - **Functional form:** Due to explicit or implicit choice of functions, for example, CR functions or functional form for forecast of population growth.

2.3 Assess Ranges for Parameters and Alternative Functional Forms

After preparing a basic list of potential uncertainties, OAQPS organized a workshop to provide advice on additional sources of uncertainty, approaches to quantifying and evaluating uncertainty, and the range of values or functional forms that could be used in the analysis. The

workshop included experts from inside and outside EPA on the topics of population forecasting, monetary valuation of mortality and morbidity endpoints, and techniques for assessing uncertainty. Appendix A contains a memo summarizing the workshop. EPA staff with expertise on the health impacts of $PM_{2.5}$ and staff involved with estimating and forecasting baseline emissions and changes in ambient air quality were also consulted. The team also conducted limited literature reviews, although a full literature review to update the information currently in BenMAP was outside the scope of this project (see discussion in Section 6 on this topic).

After establishing the sources of uncertainty and classifying their source and type, we selected which to treat quantitatively in the sensitivity analysis. We included those parameters that appear to have significant uncertainty, those model uncertainties that are explicit in BenMAP, and a few implicit model uncertainties where we could identify a reasonable alternative to that assumed in BenMAP.

Next, a plausible range was selected for each uncertain parameter. The range for each parameter includes three values:

> **Mid value:** This is a central or nominal value used for initial analysis for comparison with BenMAP; usually the same values used for the BenMAP runs provided by EPA to calibrate the model. The values from BenMAP are not necessarily mean or median values, but in all cases the values are within the range we evaluate (between the low and high values). From a probabilistic perspective, the mid value might be the most likely (mode), mean, or median value. However, for most of the values we do not have information about the distribution, and we did not perform an explicit probabilistic assessment in this study.
>
> **Low value:** This is a low value that is plausible, but not the smallest conceivable value or minimum. If we had a distribution, the low value might be about the tenth percentile—a value such that someone with expertise on the topic would be surprised if the true value turned out to be smaller. Without a distribution, judgment was used to select values that seemed like plausible lower bounds.
>
> **High value:** This is a high value that is plausible, but not usually the largest conceivable value or maximum. From a probabilistic perspective, it might be about the ninetieth percentile—a value such that someone with expertise on the topic would be surprised if the true value turned out to be larger. Without a distribution, judgment was used to select values that seemed like plausible upper bounds.

For a few inputs, notably the mortality CR functions obtained from expert elicitation, we have their uncertainty assessed explicitly in the form of probability distributions (IEc, 2006). For those quantities, we chose 10^{th}, 50^{th} (median), and 90^{th} percentiles of those distributions as the low, mid, and high values for use in range sensitivity analysis. Assessing probability

distributions for other quantities and conducting a probabilistic sensitivity analysis was outside the scope of this project.

For model uncertainties, we compare the effects of two or more model formulations (functional forms).

2.4 Develop Influence Diagrams

The initial hierarchy of influence diagrams shows how uncertain input parameters and model form choices influence the resulting output variables, including avoided premature mortality and net benefits. To avoid creating a single diagram of overwhelming complexity, we organized the diagrams using Analytica modules into a hierarchy of diagrams, each focusing on a particular aspect of the model. Figure 2-1 provides an example of the hierarchy of diagrams. Section 4 presents and discusses the final influence diagrams.

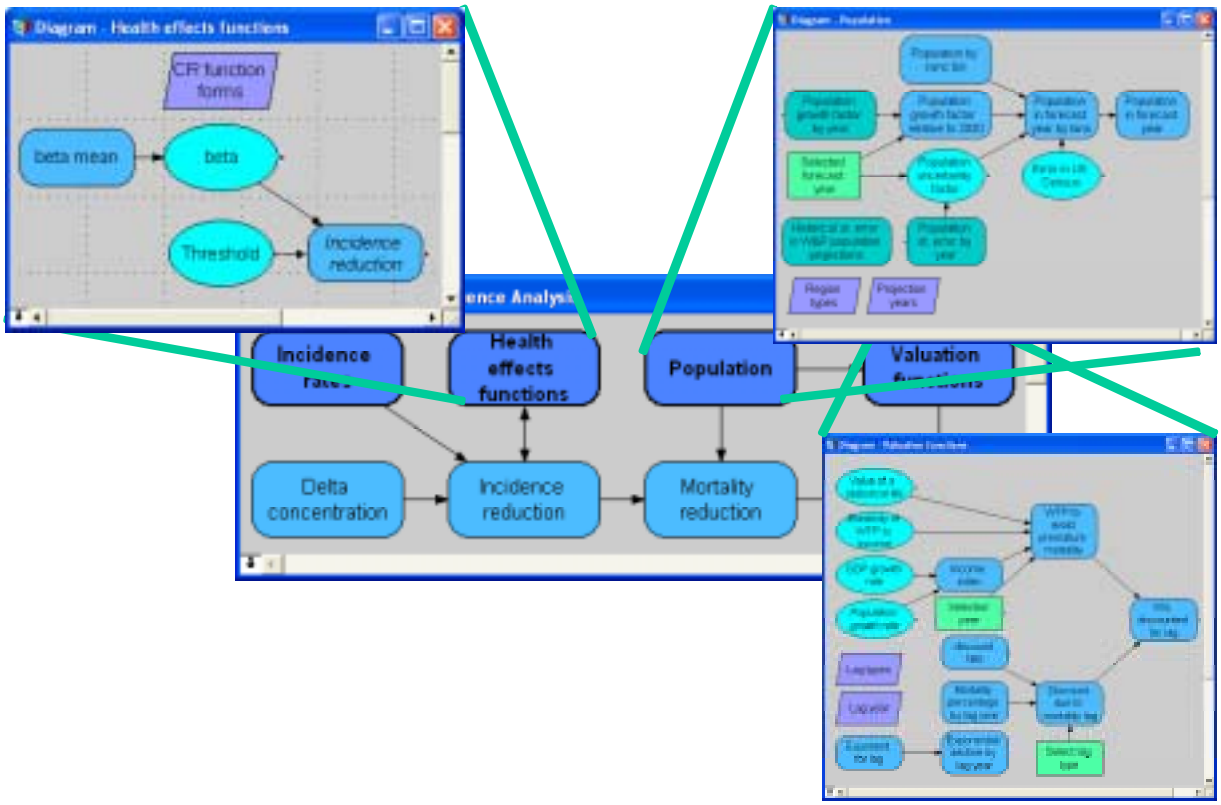


Figure 2-1. Hierarchical Influence Diagram Showing the Top Level Model and Three Selected Subdiagrams

2.5 Use of Analytica

Analytica is a general-purpose software environment for building, analyzing, and communicating quantitative models (*Analytica User Guide, Release 4.1*, Lumina Decision Systems, Inc. 2008. www.Lumina.com). We used Analytica to create the hierarchy of influence diagrams and to construct a simplified model of BenMAP that we used to conduct the sensitivity analysis described in this report. Analytica lets users draw in influence diagrams by creating and positioning nodes and drawing influence arrows to connect them. It provides a general mathematical modeling language that we used to construct the model. It also allows probabilistic modeling, defining variables with probability distributions, and using Monte Carlo or Latin hypercube sampling to propagate uncertainties through the model. Although full probabilistic analysis was outside the project scope, we did use the Monte Carlo facilities to obtained low, mid, and high values (as 10th, 50th, and 90th percentiles) for the slope (beta) of mortality concentration-response functions that had been assessed as a combination of probability distributions as the product of an elicitation of a set of twelve experts (IEc, 2006).

2.6 Develop a Simplified Model to Conduct Sensitivity Analysis and Compare to BenMAP

The next step was to build a model in Analytica based on the initial influence diagrams that corresponds to the components of a BenMAP benefits analysis but is simplified so that it can run rapidly enough to perform extensive sensitivity analysis. The reasons to build the simplified model include:

- BenMAP is too large and takes too long to compute to be able to perform a large number of runs to support extensive sensitivity and uncertainty analysis.
- Some kinds of sensitivity analysis require modification of the model structure, which is much easier on a simplified model. Comparing some kinds of model form uncertainty and assessing the imprecision introduced by aggregation are two examples.

Note that the simplified model is not a substitute for BenMAP. The simplified model could only be built and calibrated because BenMAP exists. The simplified model does not duplicate many of BenMAP's functions, including aggregating data into grid squares and generating maps of inputs and results.

The key simplification is to reduce the geographic aggregation from the 16,576 36km grid squares used for BenMAP runs, displayed in Figure 2-2, to a much smaller set of bins. The input grid square data includes the population for 2020, annual average concentration of $PM_{2.5}$ at baseline, planned reductions in emissions, and baseline-incidence data. We aggregate the

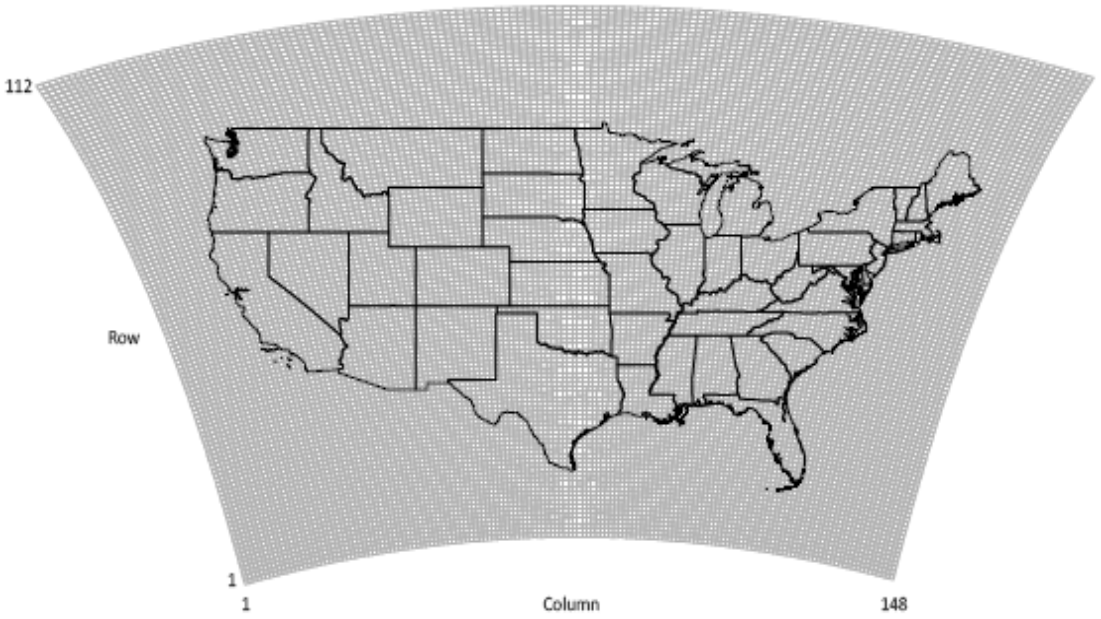


Figure 2-2. 36 km Grid Squares over the Contiguous United States

population from the grid squares into bins, with a bin for each base concentration from 0 to 1, 1 to 2, up to 15 to 16 micrograms/cubic meter of $PM_{2.5}$. In this way, we reduce the computational effort by a factor of about 1,000, from over 16,000 grid squares to just 16 bins. For each bin, we use the population-weighted average for the base concentration and the delta concentration in the simplified model.

2.6.1 Calibration to BenMAP

The Analytica version of the model approximates the results of BenMAP, but it does not match the results exactly due to its simplified representation and there may be some small differences in the implementation of algorithms in BenMAP. These cause modest differences in the estimated number of cases reduced (morbidity and mortality) and the total benefits. To increase the accuracy of the sensitivity analysis, we calibrated the Analytica model to selected results of BenMAP for both number of cases of mortality and morbidity and the value of those cases, for each of the CR functions. The calibration multiplies each Analytica result by a factor so that it produces identical results to the corresponding BenMAP runs, with two exceptions:

1. For Pope et al. (2002) CR function with threshold of 15 $\mu g/m^3$, the Analytica model generated zero cases, since the single grid square with base concentration above 15 µg/m3 (in Los Angeles at 15.05 µg/m3) was included in 15 µg/m3 bin, with a population-weighted average base concentration of 14.87 µg/m3, and so below the threshold.

2. For Expert K, who specified a likelihood of causality of 0.35, we used a mid value (50th percentile) of zero for beta, where BenMAP uses the mean value. Hence, in this case, the Analytica model produces zero mortality for mid (nominal) analysis, where BenMAP uses a small positive value for beta.

This calibration process substantially improves the correspondence of the results of the sensitivity analysis with what would be obtained were the sensitivity analysis to be carried out with full runs of BenMAP. The mid (central values) are identical (with the above exceptions). The ranges used in the range sensitivity analysis, as perturbations around this mid value, should be similar but not identical to what one would obtain if one performed these range sensitivity runs with BenMAP. Thus, the slight approximation remaining for the range sensitivity results will have negligible on the main conclusions of this study—to identify the relative importance of the various sources of uncertainty.

2.7 Analysis Strategy

We use two measures of sensitivity in comparing the effects of each uncertain input X on the output variable Y:

Elasticity: The percent change in Y for a one percent change in X.

Output range: The lower and upper values of the output corresponding to lower and upper value of input range, holding all other inputs at their nominal values. The standard tornado chart displays output ranges.

These measures of sensitivity focus on one uncertain input at a time, holding the others at their mid values. This makes the analysis fast and easy, but it ignores any possible interactions in the effects of two or more inputs on the outputs. We can rule out many interactions—or at least conclude that they are multiplicative (rather than additive)—just by inspecting the form of the equations, without having to run the model. However, there are some interactions that may be worth examining using the model, for example between the threshold and beta of CR functions. We will also examine one or two interactions between parameter uncertainties and functional form uncertainties, notably in the functional form of the CR functions.

SECTION 3
CLASSIFY UNCERTAINTIES AND QUANTIFY PARAMETER RANGES

3.1 Final List of Uncertainties

The first step in the process involved identifying a set of uncertain parameters and model assumptions. Table 3-1 lists the sources of uncertainty identified for potential inclusion in initial sensitivity analysis. In the first column, the potential source of uncertainty is categorized as either a BenMAP choice (selected by user from choices in BenMAP) or as a BenMAP default (defined in BenMAP, the user can sometimes import different data to change assumption). The next two columns identify the source and type of uncertainty using the categories defined in Section 2.2.

Table 3-1. List of Major Sources of Uncertainty in the BenMAP Model

Modeling Step	Uncertainty Source	Uncertainty Type	Current Formulation in BenMAP
CR FUNCTION AND ISSUES IN THE ESTIMATION OF ADVERSE HEALTH EFFECTS			
1 BenMAP choice	Functional form of the CR function	Model Uncertainty, Functional form	▪ Alternative functional forms are sometimes available to represent CR relationship including linear, log-linear, logistic, and Cox proportional hazard models
2 BenMAP choice	Threshold in the CR function	Parameter Uncertainty, Measured	▪ EPA estimates a point estimate threshold below which there is no change in incidence rate associated with change in air pollution concentration, e.g., for a log-linear CR model: ▪ $\Delta y=y_0\times[\exp(\beta\times(\max(PM_1,T)-\max(PM_0,T)))-1]$ where, T is the threshold
3 BenMAP default	Air quality metric in BenMAP CR functions	Parameter Uncertainty, Measured	▪ Air quality metrics are matched to the epi studies. For pre-loaded functions, these are already defined in BenMAP. ▪ For $PM_{2.5}$, EPA currently uses CR functions that use a quarterly average air quality concentration. BenMAP creates an annual average by averaging the 4 quarterly averages
4 BenMAP default	Extrapolation below PM concentration in study	Parameter Uncertainty, Extrapolate beyond range	▪ BenMAP does not require that PM concentrations be within the range of PM concentrations used in the epi studies
5 BenMAP default	Current exposure and cumulative exposure	Parameter Uncertainty, Measured	▪ BenMAP assumes a pulse of exposure to pollutants in the analysis year. The CR functions may apply to short-term exposure or long-term exposure. For epi-based mortality studies, EPA uses the long-term CR functions.

(continued)

Table 3-1. List of Major Sources of Uncertainty in the BenMAP Model (continued)

Modeling Step	Uncertainty Source	Uncertainty Type	Current Formulation in BenMAP
CR FUNCTION AND ISSUES IN THE ESTIMATION OF ADVERSE HEALTH EFFECTS			
6 BenMAP default	Equal toxicity of PM components	Parameter Uncertainty	▪ The functions in BenMAP assume equal toxicity for all $PM_{2.5}$ species. Assuming differential toxicity would require defining a new pollutant in BenMAP and obtaining air quality modeling or monitoring data for that species.
7 BenMAP choice	Mortality—Coefficient (β) in the CR function	Parameter Uncertainty, Measured	▪ EPA currently uses two epi studies for the relationship between exposure to PM and premature mortality over time (i.e., Pope et al., 2002; Laden et al., 2006). ▪ EPA also uses CR functions generated through an expert elicitation. Other studies are available.
8 BenMAP choice	CB—Coefficient (β) in the CR function	Parameter Uncertainty, Measured	▪ EPA currently uses two studies for the relationship between exposure to PM and developing CB over time (i.e., Abbey et al., 1993) ▪ Parameter of the CR function (b) was specific using a mean value and a standard error which can be used to form a normal distribution
9 BenMAP choice	AMI—Coefficient (β) in the CR function	Parameter Uncertainty, Measured	▪ EPA uses one study for the relationship between exposure to PM and AMI (i.e., Peters et al., 2001) ▪ Parameter of the CR function (b) was specific using a mean value and a standard error which can be used to form a normal distribution
10 BenMAP default	AMI—Parameter in the CR function	Parameter Uncertainty, Measured	▪ Only considers AMI's for individuals who do not die within 28 days. Because 6% of male and 8% of female hospitalized heart attack patients die within 28 days, the function includes a correction factor of 0.93 (on average) to estimate the number of non-fatal AMIs (Rosamond et al., 1999)
BASELINE INCIDENCE RATES AND PREVALENCE			
1 BenMAP default	Allocating baseline incidence to grid cells	Model Uncertainty, Aggregation	▪ Baseline incidence rates allocated to grid cells in BenMAP, not clear how
2 BenMAP default	Mortality Baseline Incidence Rates	Model Uncertainty, Functional form and aggregation	▪ Age, cause, and county-specific mortality rates were obtained from CDC for years 1996 through 1998 by county ▪ CDC's age groups include <1, 1–4, 5–9, 10–14, 15–19, 20–24, 25–34, 35–44, 45–54, 55–64, 65–74, 75–84, and 85+ ▪ Mortality rates are averaged across three years, assumes that rates are uniformly distributed across all ages in the reported age group

(continued)

Table 3-1. List of Major Sources of Uncertainty in the BenMAP Model (continued)

Modeling Step	Uncertainty Source	Uncertainty Type	Current Formulation in BenMAP
2 BenMAP default	Mortality Baseline Incidence Rates	Model Uncertainty, Functional form and aggregation	▪ Age, cause, and county-specific mortality rates were obtained from CDC for years 1996 through 1998 by county ▪ CDC's age groups include <1, 1–4, 5–9, 10–14, 15–19, 20–24, 25–34, 35–44, 45–54, 55–64, 65–74, 75–84, and 85+ ▪ Mortality rates are averaged across three years, assumes that rates are uniformly distributed across all ages in the reported age group
3 BenMAP default	Mortality—Year of baseline incidence	Parameter uncertainty, Measured	▪ Age, cause, and county-specific mortality rates were obtained from CDC for years 1996 through 1998 by county ▪ Mortality rates are averaged across three years
4 BenMAP choice	Mortality—Forecast baseline incidence rates	Parameter Uncertainty, Forecast	▪ Project CDC Wonder county and age-specific mortality rates for 1997 to future years using Census projections of national age-specific mortality rates from 1999 through 2050. Adjust county and age-specific 1997 CDC Wonder rate by ratio of Census projection for year Y to the estimated Census age-specific mortality rate for 1997 (1997 Census mortality rate estimated by regressing mortality rates from 1999–2008 on year). ▪ All segments of the population assumed to grow at same rate ▪ User chooses the forecast year
5 BenMAP default	AMI Baseline Incidence Rates	Model uncertainty, Parameter uncertainty	▪ AMI incidence rates are based on regional hospitalization rates and hence inherit uncertainties associated with those rates ▪ Hospitalization rates in 1999 were estimated for four regions based for 3 age groups (0-18, 18-46, 65+) using National Hospital Discharge Survey and population data.
6 BenMAP default	CB Baseline Incidence Rates	Parameter uncertainty	▪ For ages 27+, the incidence rate is 0.00378 (Abbey et al., 1993) ▪ No other age group or geographic breakdown is available
7 BenMAP default	CB Prevalence	Parameter uncertainty	▪ Age group specific prevalence estimates are 18-44 (0.0367), 45-64 (0.0505), 65+ (0.0587). For ages 18+, the prevalence is 0.0443
8 BenMAP default	Morbidity—Forecast baseline incidence and prevalence rates	Model uncertainty, Forecast	▪ BenMAP contains year 2000 only, no projections currently available

In December 2008, EPA sponsored a workshop to provide expert feedback on the uncertainties used in the analysis, additional sources of uncertainty, the reasons for uncertainty and variability in parameter values, and to provide advice on actual ranges of values or on sources of data to derive ranges. The workshop participants included both EPA staff and outside experts in the areas of population forecasting, mortality valuation, morbidity valuation and uncertainty analysis. After the workshop, additional discussions took place with EPA health scientists and air quality modelers. Appendix A provides more details on the workshop.

3.2 Quantify Ranges for Parameters

Following the workshop, we selected a set of uncertain parameters and model assumptions from the list in Table 3-1 for inclusion in the sensitivity analysis. For each parameter, we defined a range of values. Table 3-2 presents the range for each uncertain parameter. We selected ranges that represent plausible upper and lower bounds, but not necessarily extreme values. In addition, we selected mid values. The mid values do not necessarily represent the "middle" of the distribution, especially since we usually lack the information needed to determine what the distribution looks like. In most cases, the mid value will be consistent with the value from BenMAP for runs provided by EPA, which is provided in the last column.

3.3 Source for Range Recommendations

1. VSL:
   - Uncertainty in VSL estimates (calculated from an individual's WTP to reduce the risk of mortality by a given percent) are associated with the stated and revealed preference methods used to calculate VSL, the data, and the assumptions used to make the calculation. VSL is also believed to be characterized by variability due to preferences, baseline age and health, and other personal and social characteristics.
   - The range from $1,000,000 to $10,000,000 with a midpoint of $5,500,000 covers the range from most of the current studies and meta-analyses and was recommended by the experts who participated in the workshop. The midpoint represents the VSL that EPA Office of Air and Radiation used for benefits analysis between 2004 and 2009.
2. Elasticity of WTP with respect to income:
   - Uncertainty in the income elasticity of WTP come from the methods and data used to estimate the values. In addition, elasticity estimates usually come from cross-sectional data, but they are being used to represent change in elasticity over time.
   - The range comes from the BenMAP manual and was supported by the experts who participated in the workshop.

Table 3-2. Range Values for Uncertain Parameters

		Low	Mid	High	Value from BenMAP Run
1.	VSL	$1,000,000	$5,500,000	$10,000,000	$5,500,000
2.	Elasticity of WTP to income for mortality	0.2	0.40	1	0.40
3.	Discount rate	1%	3%	7%	3%, 7%
4.	Value of an avoided AMI, 3% discount rate	$11,000	$85,309	$372,000	Varies by age, years of treatment
5.	Value of an avoided case of CB, 3% discount on COI value	$11,000	$340,481	$1,749,539	$340,481
6.	Uncertainty in Census 2000, percent of baseline from BenMAP run	98%	100%	102%	100%
7.	Uncertainty in Census 2020 population forecast	90%	100%	110%	100%
8.	Threshold in mortality CR function	0	0	10ug/m^3	BenMAP runs used 0 and 10ug/m^3
9.	Beta for mortality CR function with a threshold of 10ug/m^3	Low	Mid	High	Different for each study and expert
10.	Beta for mortality CR function with no threshold	Low	Mid	High	Different for each study and expert
11.	Beta for CB CR function with no threshold	0.004993999	0.0137	0.02240599	0.0137
12.	Beta for AMI CR function with a threshold of 10ug/m^3	0.02130709	0.033201	0.04509491	0.033201
13.	Beta for AMI CR function with no threshold	0.012227397	0.024121	0.036015217	0.024121307
14.	Base mortality rate, percent of value in BenMAP	95%	100%	105%	100%
15.	Incidence rate for CB	0.067872271	0.378	0.798218895	0.378
16.	Incidence rate for AMI	0.1391	0.7747	1.6359	
17.	GDP growth rate	1.72%	2.34%	3.04%	
18.	Base $PM_{2.5}$ concentration, percent difference from BenMAP run	85%	100%	115%	100%
19.	Change in $PM_{2.5}$concentration, percent difference from BenMAP run	70%	100%	130%	100%

3. Discount rate: 3% and 7% are required for use in Federal regulatory analysis. The lower end of the range, 1%, was suggested because of the long time frame for the model forecasts.

4. Value of an avoided AMI, 3% discount rate:
   - Uncertainty in the distribution of values for an avoided AMI is associated with factors such as the lack of WTP values (BenMAP includes only COI values), the age of the studies, the difficulty defining the costs associated with a single AMI separate from other conditions, the impact of co-morbidities on cost, the cost of potential complications after the AMI, and similar issues.
   - The expert panel recommended a lower bound of one-half the COI and an upper bound of WTP plus COI. BenMAP currently uses only COI estimates for AMI's. The COI measures include estimates of direct medical costs and opportunity cost (lost earnings). In the absence of readily available estimates of WTP, we used the range from BenMAP studies for 5 year and 10 year length of costs discounted at 3% (Table H-5, USEPA, 2008).
     i. **Low:** one-half the lowest COI in Table H-5
     ii. **Mid:** the average COI in Table H-5 across all ages (not including 0-24 age group)
     iii. **High:** because there is not WTP value, the high end of the range was set at two times the highest COI in Table H-5

5. Value of an avoided case of CB, 3% discount rate:
   - The uncertainty associated with the value of an avoided case of CB comes from factors such as the age and sample of the existing WTP studies and other factors similar to AMI's.
   - The range of values was derived from the COI estimates from Table H-3 in the BenMAP User's Guide and the WTP formula in Section H.2.1.1 (USEPA, 2008).
     i. **Low:** the lowest COI value in Table H-3 (which is similar in magnitude to one-half the lowest COI for an AMI)
     ii. **Mid:** the median value of the WTP function in BenMAP
     iii. **High:** WTP value plus the highest COI value from Table H-3 (USEPA, 2008) for the 3% discount rate. WTP was calculated as follows:
        1. The formula for WTP in the BenMAP manual is WTP(x) = WTP(13)*exp(-beta(13-x)) (H.2.1.1 USEPA, 2008)
        2. x denotes severity and ranges from 1 to 12, where 1 is the least severe; beta is assumed to ~ N(0.18,0.0669). The WTP(13), the highest severity, come from Viscusi et al. (1991); estimates of the beta coefficient and standard error come from Krupnick and Cropper (1992).

3. Using beta=0.18-0.0669 and x=11 and the WTP(13) for the 90th percentile, the formula above is used to calculate the WTP(x) for the high value. The value of WTP thus obtained is $1,595,117.

6. Census estimate for 2000:

   - Uncertainty about national population estimate in 2000
   - A range of minus and plus 2% was specified based data from Census and population forecasts for future years. Population projections based on the 1990 Census include low, middle and high series estimates (U.S. Department of Commerce 1996). The difference between the high and low series in the projections for 1995 is less than .0001%. Comparing the 10-year projection of 2000 population to the population counted by the 2000 Census (U.S. Department of Commerce 2002), the difference between the actual 2000 Census and the middle series forecast for 2000 is about 2.4%. The calculations suggest that the uncertainty in the population estimate for 2000 is low and within a range of 2% of the actual estimate.

7. Population forecast for 2020 and distribution of population within the U.S.:

   - Uncertainty in the population forecast for 2020 comes from variety of sources including immigration trends, economic growth, the birth rate and the death rate. The share of the U.S. population in a particular county will depend on similar factors.
   - BenMAP uses the 2000 Census population estimate at the block group level that is aggregated and allocated to grid squares that match the air pollution data. The population forecast is based on county forecast data from Woods and Poole (2007) and then allocated to grid squares that match the air pollution data in BenMAP. The Woods and Poole forecast data uses a model that includes economic growth projections. The share of national population in each county based on the Woods and Poole data is used to allocate the 2000 Census estimate across counties. Confidence intervals reported by Woods and Poole are +/- 6.3% for metropolitan statistical areas and +/- 4.7% for states based on comparing 10-year forecasts with actual values. Uncertainty about whether people will move to areas of the country that are more or less polluted will potentially affect the benefit estimates.
   - To account for both the uncertainty in the 2020 forecast and the uncertainty in how the population will be spread out across counties, the 2020 population by grid square from BenMAP was adjusted +/- 10%.

8. Threshold in mortality CR function:

   - Guided by the expert elicitation and advice from EPA staff, the threshold for the PM/mortality CR function ranges from 0 (no threshold) to 10ug/m^3.

9. Beta for mortality CR function with a threshold of 10ug/m^3:

   - See Section 5.4 for details on calculating mid, low, and high values for beta for the different studies and experts.

10. Beta for mortality CR function with no threshold:
    - See Section 5.4 for details on calculating mid, low, and high values for beta for the different studies and experts.
11. Beta for CB CR function with no threshold:
    - Uncertainty in the beta arises from a lack of studies, possible regional variation, and other sources.
    - See Section 5.4 for details on calculating mid, low, and high values for beta for the different studies and experts.
    - Beta based on Abbey et al. (1993) using the mean of 0.0137 and a standard deviation of 0.00679645, the low and high are the 10^{th} and 90^{th} percentiles of the distribution (1.281 standard deviations from the man) and the mid value is the mean.
12. Beta for AMI CR function with a threshold of $10ug/m^3$:
    - Uncertainty in the beta arises from a lack of studies, possible regional variation, and other sources.
    - Beta based on Peters et al. (2001). Using the mean of 0.033201 and a standard deviation of 0.009284863, the low and high are the 10^{th} and 90^{th} percentiles of the distribution (1.281 standard deviations from the man) and the mid value is the mean.
13. Beta for AMI CR function with no threshold:
    - Uncertainty in the beta arises from a lack of studies, possible regional variation, and other sources.
    - Beta based on Peters et al. (2001). Using the mean of 0.024121307 and a standard deviation of 0.009284863, the low and high are the 10^{th} and 90^{th} percentiles of the distribution (1.281 standard deviations from the man) and the mid value is the mean.
14. Base mortality rate:
    - Uncertainty arises from possible errors in data collection and compilation, estimating rates for specific population sub-samples and averaging rates across sub-samples.
    - Assumed +/- 5% of base rate for mortality
15. Incidence rate for CB:
    - Uncertainty arises from lack of studies that estimate incidence rates.
    - BenMAP cites Abbey et al. (1993) and Abbey et al. (1995) as the source for the incidence rate values discussed in E.6.2 of the BenMAP manual (USEPA, 2008). We calculated the percentage change from low to mid to high using the range of AMI incidence rates and applied the percent difference to the mid estimate for CB.
        i. **Low:** 82% of the mid value

ii. **Mid:** consistent with the value from BenMAP run

iii. **High:** 111% of the mid value

16. Incidence rate for AMI
    - Uncertainty arises from lack of studies that estimate incidence rates.
    - Values come from Exhibit E-6 (which cites data from the 1999 National Hospital Discharge Survey and Rosamond et al. [1999]) in BenMAP manual (USEPA, 2008), we used highest and lowest values across regions and age groups (excluding 0-18)
17. GDP growth rate
    - Used forecasts from Table 20 (Macroeconomic Indicators) of the Annual Energy Outlook 2009 (DOE, 2009). The mid, low and high values were calculated based on the forecasts from the reference case, low and high economic growth cases, respectively. The compound annual average growth rate (CAGR) in GDP (real dollars) was computed over the period 2008 to 2020 for these three scenarios. These GDP numbers were used to adjust real income growth from the income growth projections in BenMAP up or down for the two ranges.
18. Base $PM_{2.5}$ concentration
    - Emissions and air quality forecasts were not part of the scope of this project. We assumed +/- 15% of base concentrations from BenMAP run to provide information on how uncertainty in the base concentrations might affect the range of outcomes.
19. Change in $PM_{2.5}$ concentration
    - Emissions and air quality forecasts were not part of the scope of this project. We assumed +/- 30% of base concentrations from BenMAP run to provide information on how uncertainty in the base concentrations might affect the range of outcomes.

3.4 Alternative Functional Forms

We used alternative functional form assumptions for:

- Lag structure for mortality valuation
- CR functions

SECTION 4
INFLUENCE DIAGRAMS

4.1 Introduction to Influence Diagrams

Influence diagrams trace how different sources of uncertainty affect different elements of the model and the final results. Figure 4-1 provides an illustrative influence diagram of a benefit-cost analysis with the variable node types used in Analytica influence diagrams labeled. (This example is purely to illustrate the notation, and not used in this analysis.) In this influence analysis, decisions (green rectangles) identify user options, such as choosing the base year for dollars or forecast year. Uncertain parameters (light blue ovals) identify variables on which we perform sensitivity analysis. The model is organized as a hierarchy of modules, each with its own diagram. Some variables affect variables in other modules. A node in italics (like *Year* in the submodule), is an *alias*, that is, a copy of a node whose original appears in another diagram, shown to clarify dependency relations.

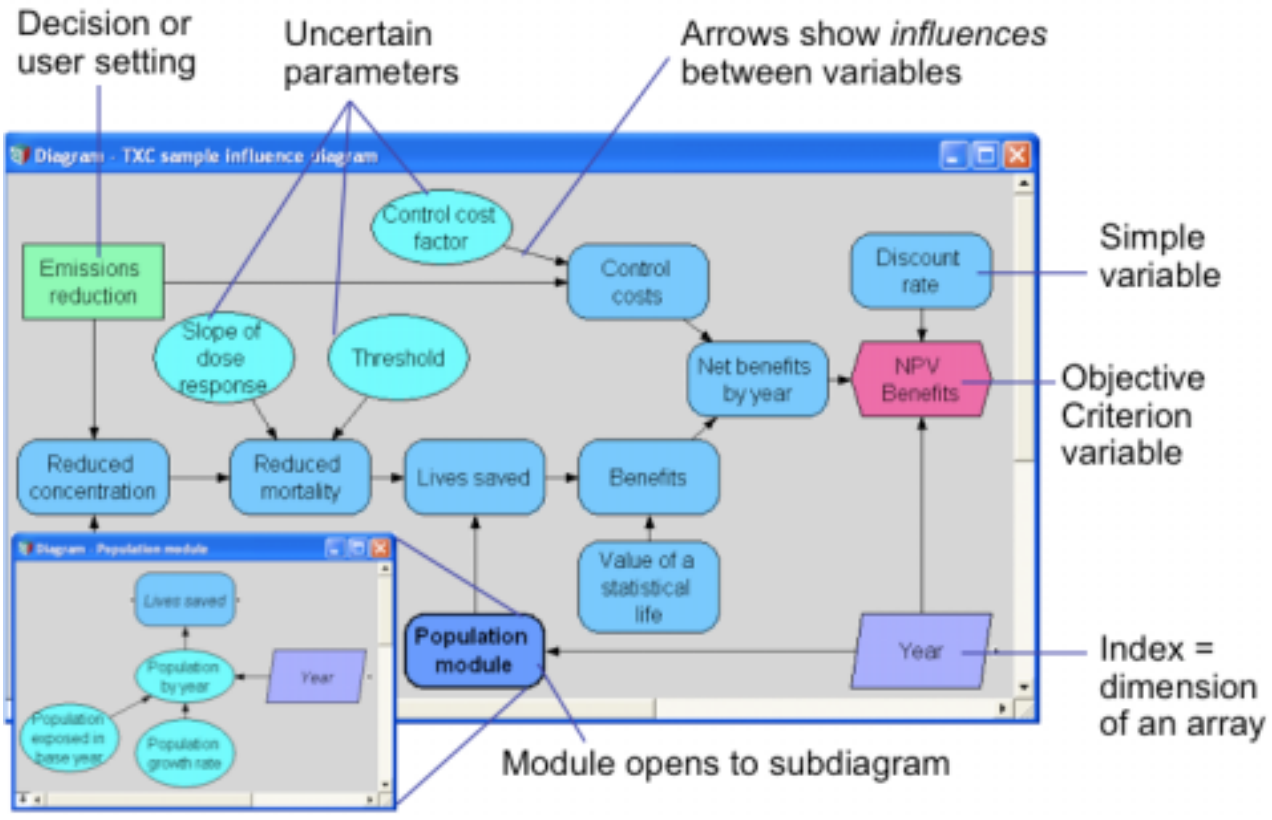


Figure 4-1. Illustrative Influence Diagram with Notation Defined

4.2 Influence Diagrams for Sensitivity Analysis

The top influence diagram, Figure 4-2, shows the key components in BenMAP as represented in Analytica. Each node with a thick outline represents a module containing an influence diagram shown in more detail below. The influence arrows show how one module or node affects another, and ultimately affects the final result, "Monetized benefits," shown as a red hexagon representing the final objective variable.

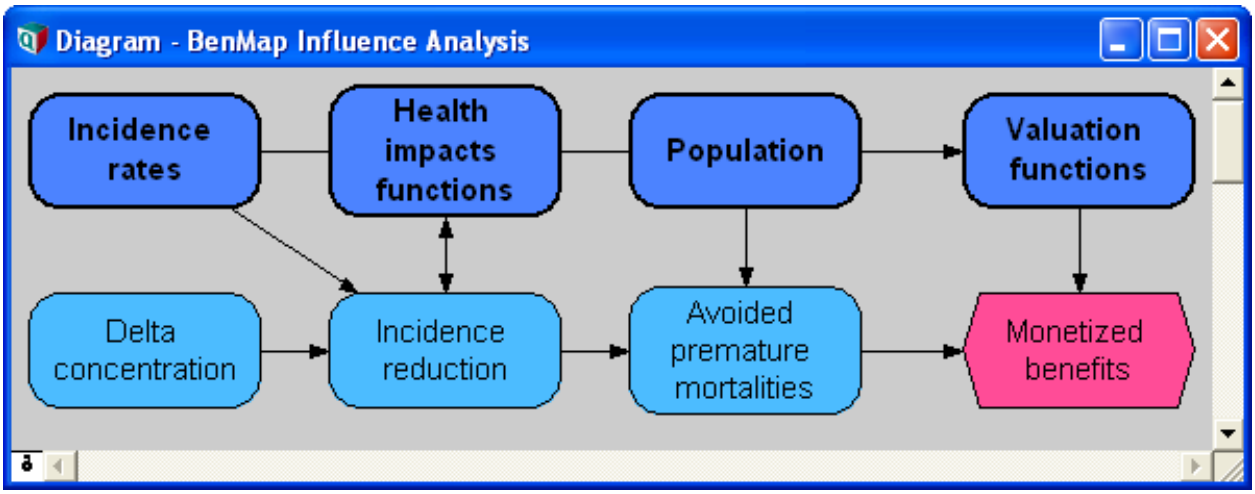


Figure 4-2. Top-Level Influence Diagram

The influence diagram for the $PM_{2.5}$ concentration, Figure 4-3, generates the base and delta concentration (change in concentration) in $PM_{2.5}$ for each concentration bin, using the base and delta for each bin computed from BenMAP inputs for each grid square, multiplied by an uncertain parameter with mid value 100% (the light blue oval nodes) to include uncertainty in these projections.

Figure 4-4 shows how the incidence rates are calculated. It is the submodule for "Incidence rates," the first module in the top row of Figure 4-2. This figure includes the key variables determining mortality by bin—that is, the mortality rate for each level of base concentration of $PM_{2.5}$. It also includes the incidence rate for morbidity endpoints CB and AMI.

Figure 4-5 shows the influence diagram for the CR functions. The green node "CR function data from epidemiological studies" contains the data defining those CR functions. We extract the threshold and beta (along with uncertainty expressed as standard deviations) from Table 5-1. This is combined with thresholds and betas from the expert elicitation distributions,

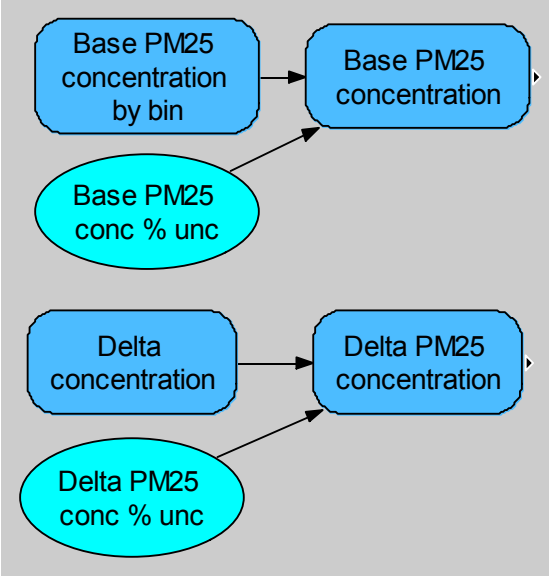


Figure 4-3. Influence Diagram for $PM_{2.5}$ Concentration

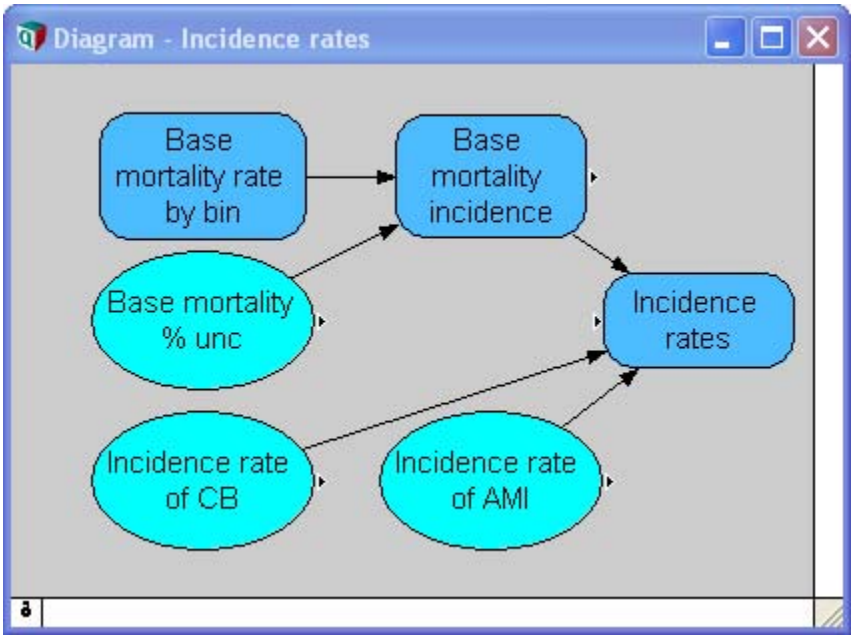


Figure 4-4. Influence Diagrams for Incidence Rates

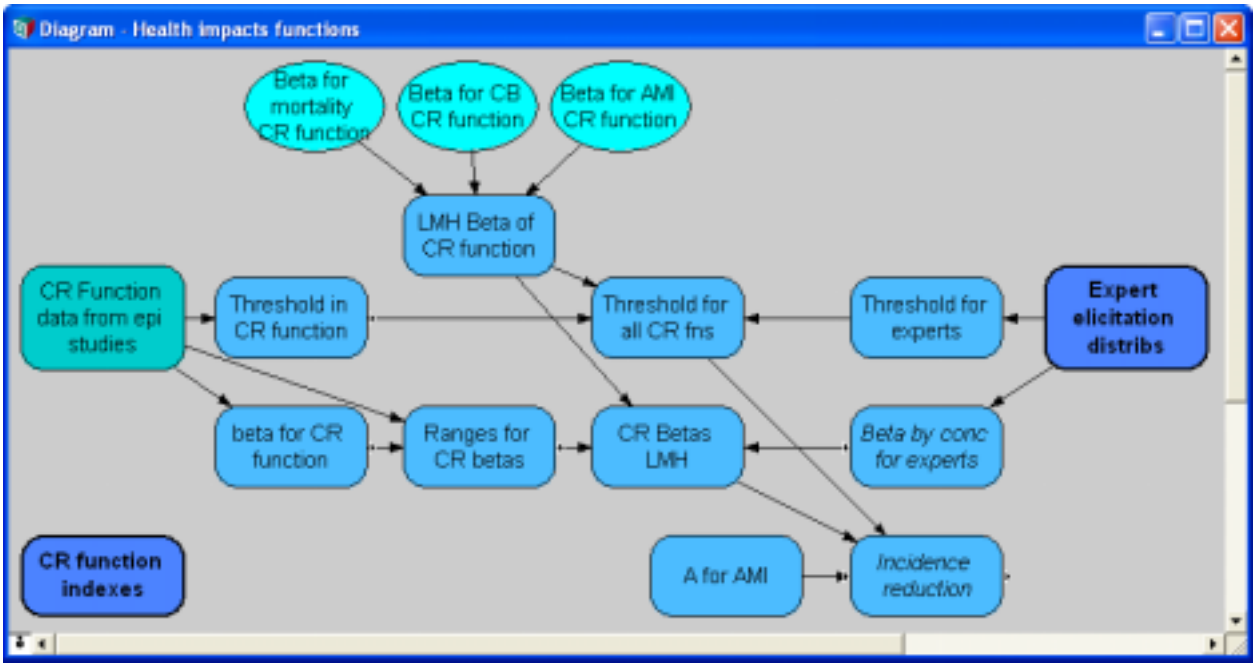


Figure 4-5. Influence Diagram for Health Impacts CR Functions

and low, mid and high betas for the CR function (the three ovals representing the three uncertain parameters used for sensitivity analysis: beta's for the mortality, CB, and AMI CR functions). Together the threshold and betas for all the CR functions feed into the incidence reduction node, also shown on the main Influence Diagram, Figure 4-2.

Figure 4-6 shows the influence diagram for the expert elicitation distributions, which feed into the "Incidence reduction" module in Figure 4-2. The EPA conducted an expert elicitation on the topic of the CR function for $PM_{2.5}$ and mortality (IEc, 2006). The data elicited from each expert was incorporated individually into the analysis. The turquoise node "Expert CR functions" contains the parameters defining the probability distributions obtained from experts for mortality CR functions for $PM_{2.5}$. The remaining nodes process these to generate probability distributions, to extract mid beta and threshold, combine segments for piecewise functions and compute low, mid, and high values for range sensitivity analysis as described below.

Figure 4-7 contains the influence diagram for the "Population" module in Figure 4-2. This module show how U.S. population in the forecast year (2020) is projected from population from the U.S. Census in 2000 and the projected increase to 2020. For this simplified analysis, it assumes the same percent growth in population for each concentration bin.

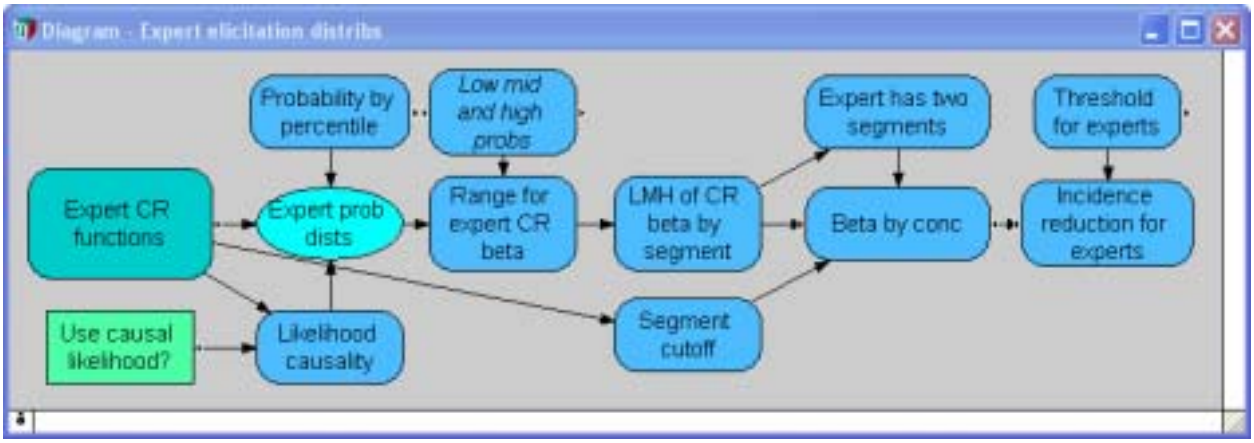


Figure 4-6. Influence Diagram for Expert Elicitation Distributions

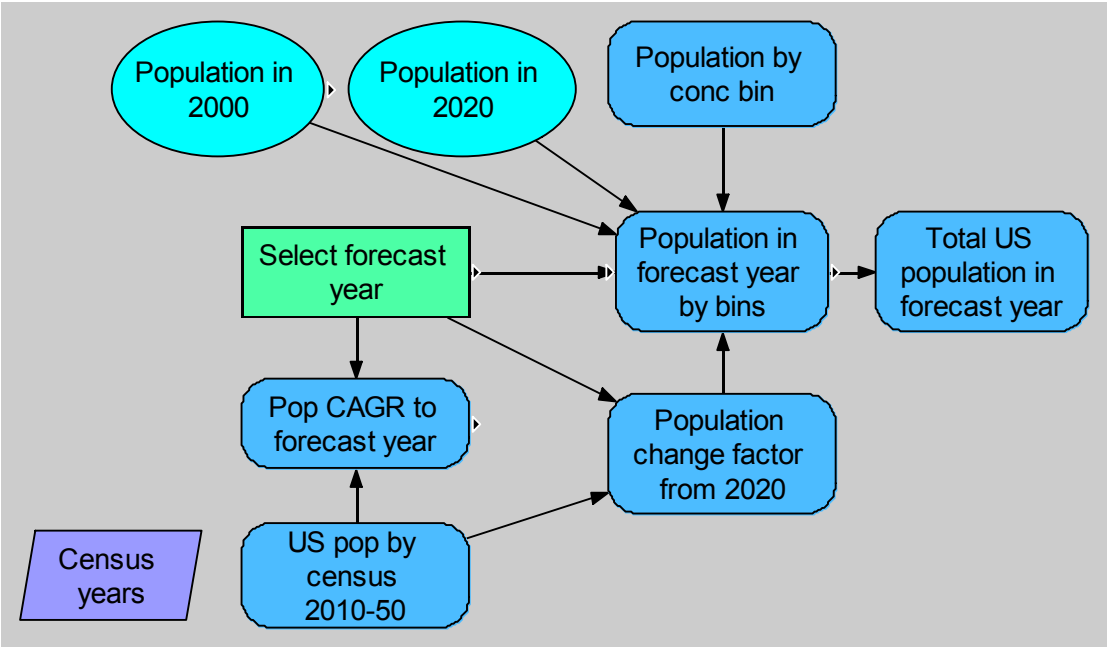


Figure 4-7. Influence Diagram for Population Projections

The influence diagram of valuation modules is presented in Figure 4-8, which feeds into the "Valuation functions" module in Figure 4-2. The diagram includes the key variables and modules used to compute the VSL, the value of avoiding a case of CB, and the value of avoiding an AMI for the forecast year adjusted for lags as necessary. The node "Value per case avoided by end point" combines the valuation of avoided mortality, CB and AMI.

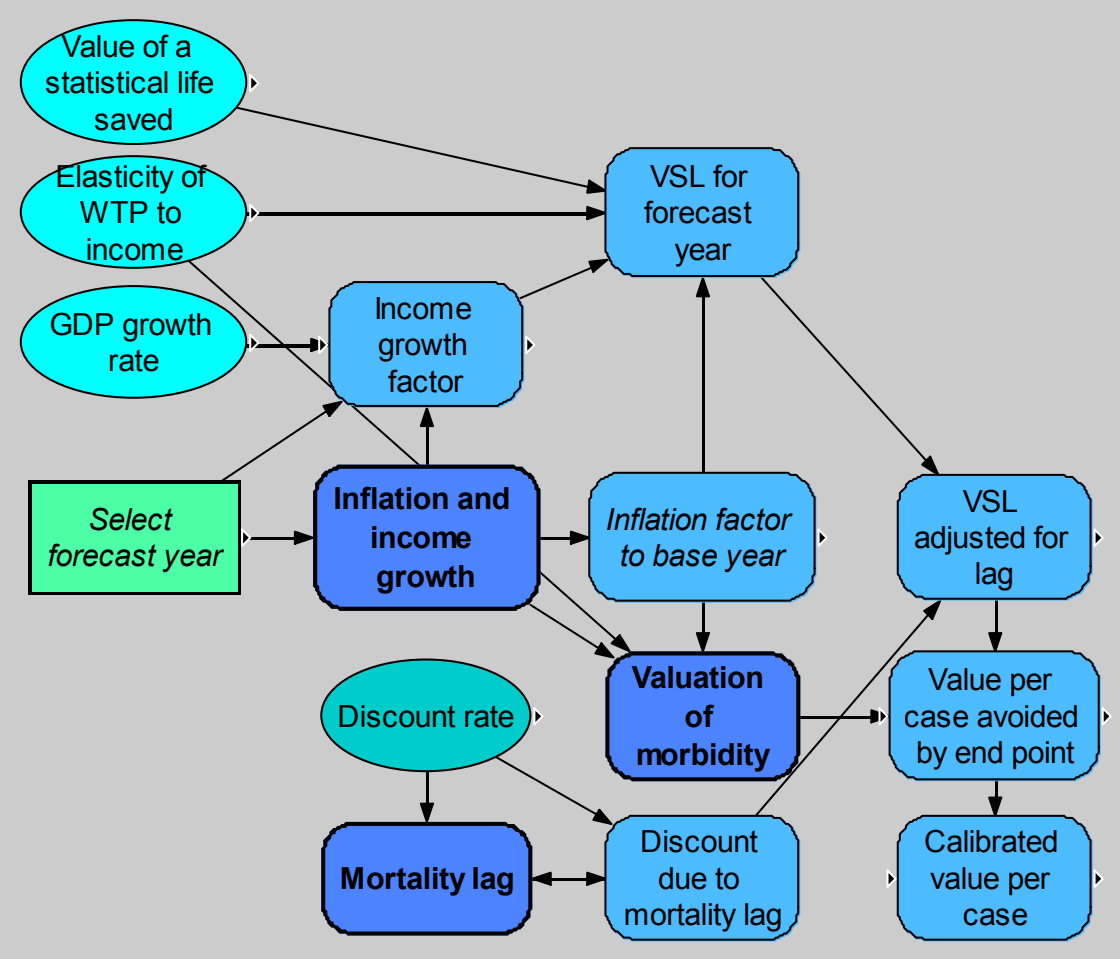


Figure 4-8. Influence Diagram for Valuation Modules

The diagram in Figure 4-8 includes three sub-modules for inflation and income growth, valuation of morbidity, and the mortality valuation lag. Figure 4-9 is the influence diagram for inflation and income growth, which calculates income growth to forecast year for mortality and CB, and the inflation factor to base currency year from standard EPA tables of income growth and inflation index. The income growth factor applies to the WTP functions for mortality and CB, but not to COI functions. It provides two income growth methods, one the same as BenMAP and the other on projections based on the ratio of GDP to population growth that allows us to use corresponding projections from the Annual Energy Outlook. The numbers below assume the BenMAP method, unless mentioned otherwise.

Figure 4-10 is the influence diagram for computing the value per case avoided of CB and AMI based on income effect on morbidity (if used) and an inflation factor to base year.

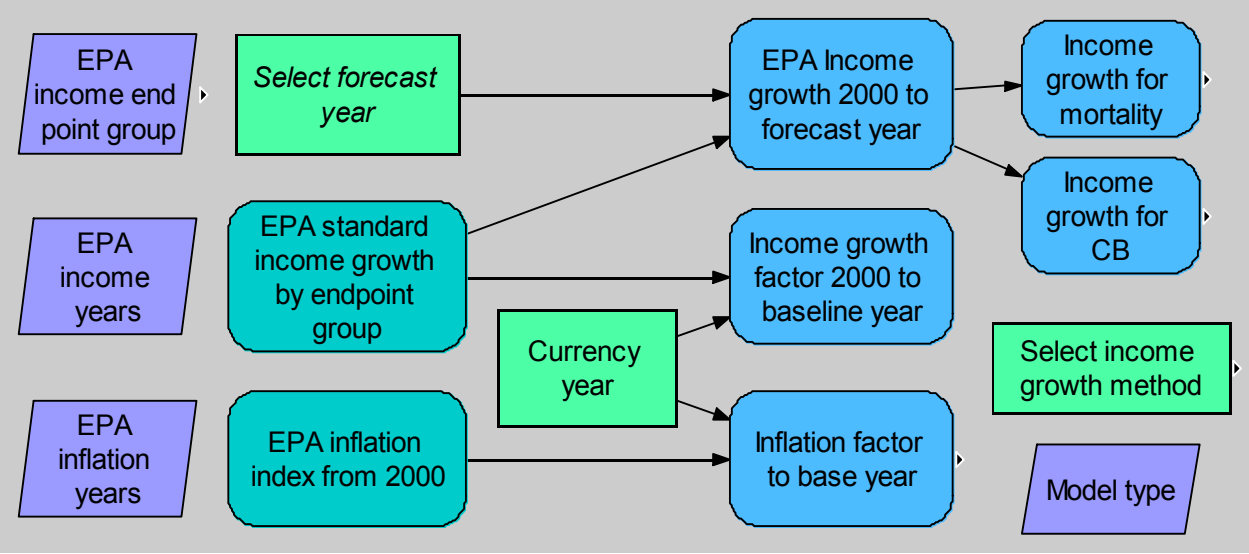


Figure 4-9. Influence Diagram for Inflation and Income Growth

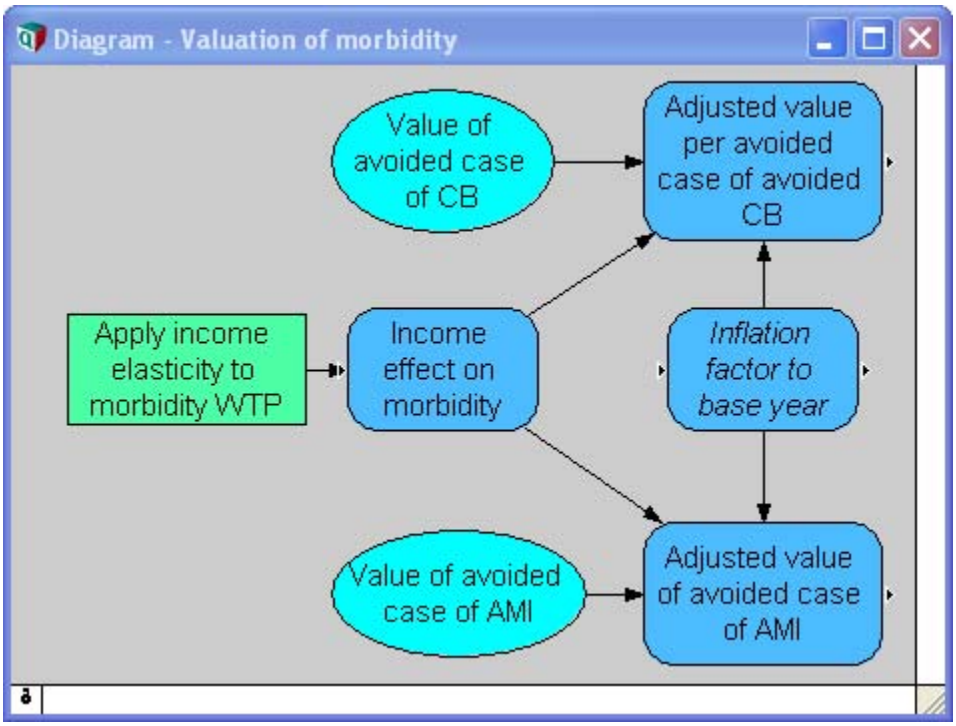


Figure 4-10. Influence Diagram for Value of Avoided Morbidity Endpoint

Figure 4-11, the influence diagram for mortality valuation lags, shows how the model calculates the effect of different assumptions about the mortality valuation lag structure. The mortality valuation lag structure defines the distribution of mortality across time based on different assumptions about the delay between exposure and its effect on mortality. The discount rate over time means that future mortality valuation is discounted when computing the present value at the time of exposure (or reduction in exposure due to improved air quality).

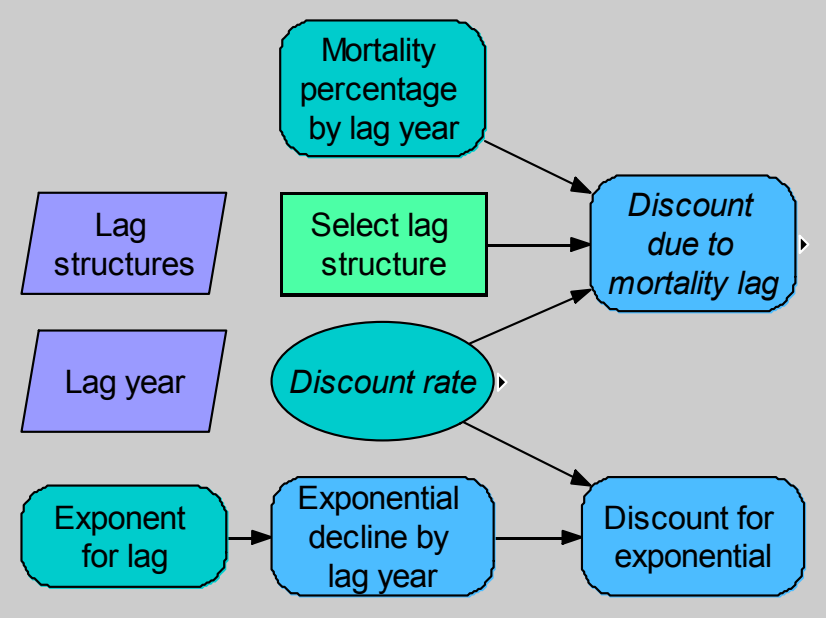


Figure 4-11. Influence Diagram for Mortality Valuation Lag

The different lag structures are presented in Figure 4-12. This chart shows the percentage of mortality that occurs in each of the 20 years following exposure for six lag structures. None or no lag means all mortality occurs in the year of exposure. 15-year means all deaths occur exactly 15 years after exposure. 20-year distributed means 20% of deaths occur in the year of exposure, 50% evenly distributed over years two to five, and 30% evenly distributed over the remaining 15 years.

BenMAP takes as an input the estimates or measurements of the current air quality and projections of improved air quality for a set of points or grid squares over the area of interest, in this case the contiguous United States. The air quality estimates and projections are produced by a series of models that project emissions, atmospheric transport, and air quality, which are depicted in the influence diagram in Figure 4-13. Most commonly, CMAQ provides the air quality projections to BenMAP. We provide this parent diagram, Figure 4-13, to show the context of the analysis.

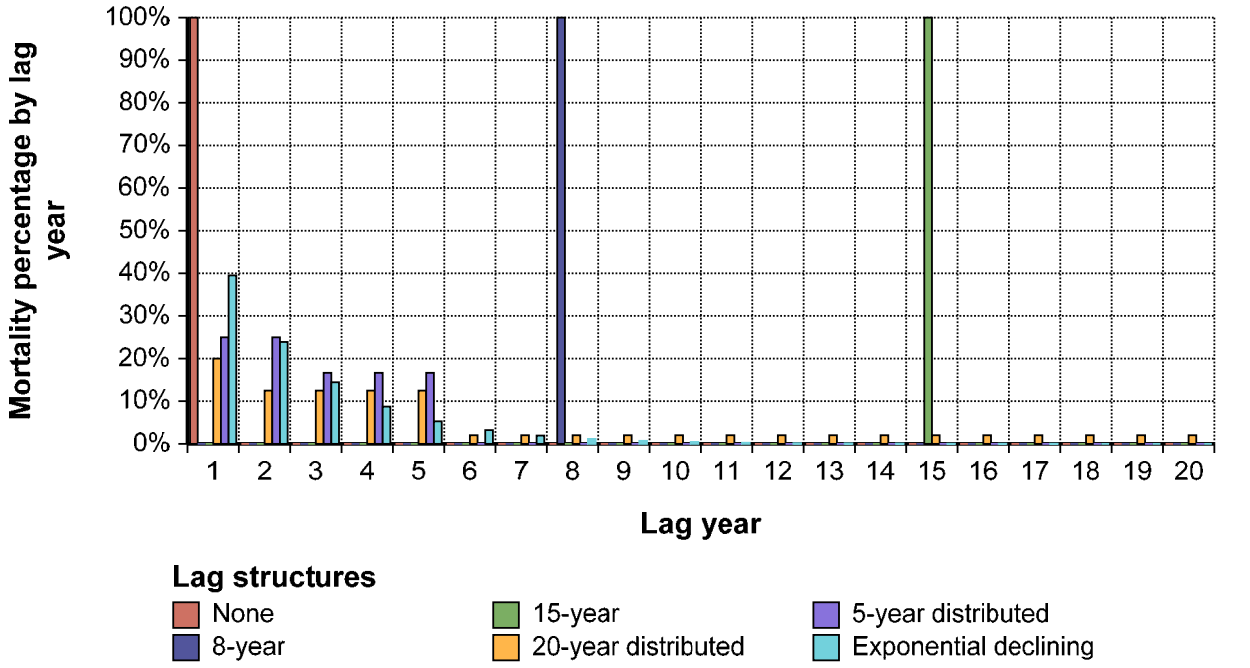


Figure 4-12. Mortality Lag

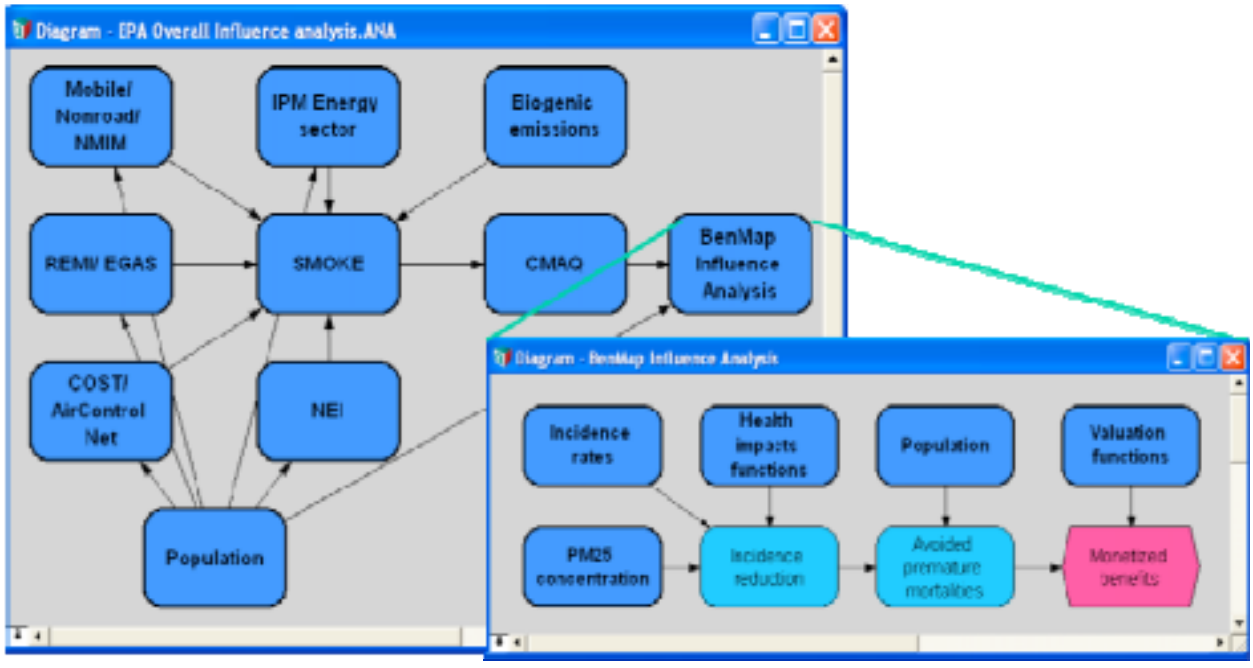


Figure 4-13. Influence Diagram for Air Quality

Analysis of the uncertainty in the air quality projections and the sources of uncertainty in those projections are outside the scope of this project. Accordingly, we selected an arbitrary range of uncertainties on the air quality—$PM_{2.5}$ concentrations—and improvements in air quality—delta reductions in $PM_{2.5}$ concentrations.

SECTION 5
RESULTS

5.1 Assumptions for Analysis

The sensitivity analysis results in this report are generated from the Analytica simplified version of the BenMAP model. They are calibrated to a specific run of BenMAP, so that the overall mortality and morbidity cases avoided, and the monetary benefits of those cases avoided exactly match the BenMAP run. See Section 5.4 for assumptions on the low, mid, and high values for each CR functions. Section 3 describes how the ranges for the other parameters were selected.

For simplicity, the primary results assume no mortality valuation lag—i.e., any mortality reduction is assumed to occur in the same year as the change in $PM_{2.5}$ concentration—except where we explicitly present the effects of other mortality valuation lag structures. The effects of discounting and mortality valuation lag change the benefits of mortality reduction by the given mortality valuation lag factor (shown in Figure 5-17). Accordingly, changing mortality valuation lag would not affect the relative width of range sensitivities that affect mortality.

5.2 Measures of Sensitivity Used in Analysis

We use two measures of sensitivity to compare the effects of each uncertain input X on the output variable Y:

- **Elasticity:** The percentage change in Y for a one percent change in X.
- **Range sensitivity:** The lower and upper values of the output corresponding to lower and upper value of input range, holding all other inputs at their nominal values. The standard tornado chart displays output ranges.

Most of our sensitivity results are based on range sensitivity, since, as its name implies, it is sensitive to the range of uncertainty (low to high) for each uncertain variable. However, elasticity does provide some interesting insights—it depends only on the mathematical structure of the model and the mid values of the inputs, but ignores their range of uncertainty. For a model

$$y = F(x),$$

the elasticity of y with respect to x is

$$\text{Elasticity}(y, x) = [F(x + dx) / (F(x)] / [(x + dx)/dx]$$

To provide some insight into this measure, consider these two examples:

Elasticity additive example

Total_benefits = Mortality_benefits + Morbidity_benefits

With values: $100M = $90M + $10M

Elasticity(Total_benefits, Mortality_benefits) = 90%

Elasticity(Total_benefits, Morbidity_benefits) = 10%

Thus, for a simple additive model, the elasticity of the result is equal to the value of each variable added as a percentage of the total.

Elasticity multiplicative example

This multiplicative example is a stylized model of the computation of mortality benefits, assuming a linear, no-threshold mortality function, with change in concentration (Delta_conc), slope (Beta_CR), and value of a statistical life (VSL):[1]

$$\text{Mortality\_benefits} = \text{Population} \times \text{Mortality\_rate} \times \text{Delta\_conc} \times \text{Beta\_CR} \times \text{VSL}$$

Elasticity(Mortality_benefits, Population) = 100%

Elasticity(Mortality_benefits, Mortality_rate) = 100%

Elasticity(Mortality_benefits, Delta_conc) = 100%

Elasticity(Mortality_benefits, Beta_CR) = 100%

Elasticity(Mortality_benefits, VSL) = 100%

The interesting point here is that for a purely multiplicative model, the elasticity of the product to each variable is 100%.

5.3 Elasticity Results

Figure 5-1 shows the elasticity of mortality to uncertain inputs, for the Pope et al. zero threshold CR function. The elasticity values were computed using the Analytica function Elasticity(Y, X). The function changes the value of X from x1 to x2 by multiplying it by

[1] BenMAP and the Analytica model actually use a log-linear mortality CR-function, not this simplified multiplicative form.

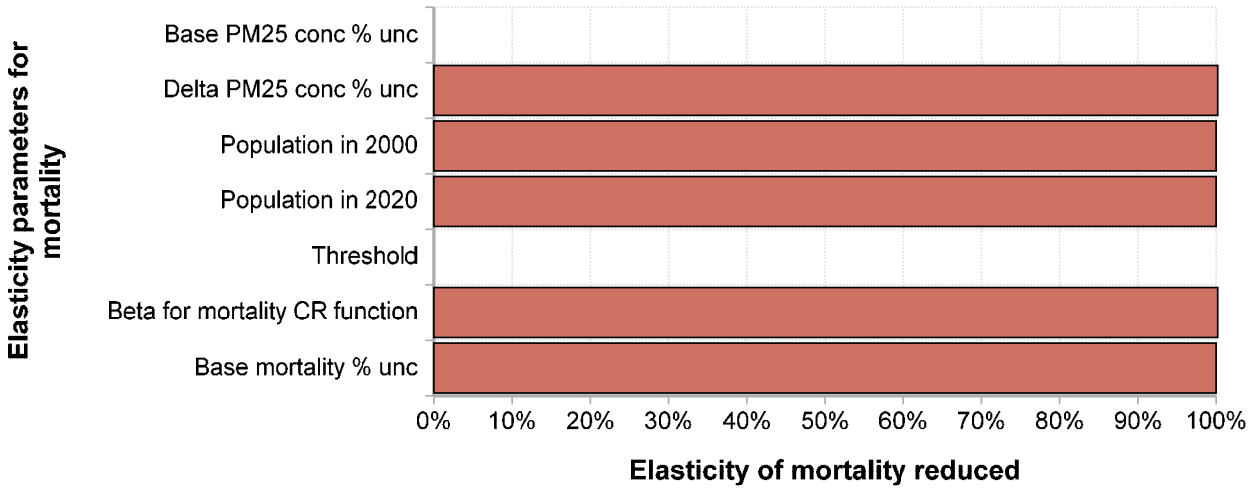


Figure 5-1. Elasticity of Mortality Parameters

$(1 + 10^{-8})$ and computes the resulting value of Y, changing from y1 to y2. It returns the ratio (y2 – y1)/(x2 – y1). Thus, it computes elasticity based on the mid values, ignoring the range on the parameters. The elasticity is 100% with respect to Delta $PM_{2.5}$ (reduction in PM concentration), population in 2000, population in 2020, beta for the mortality CR function, base mortality rate, and value of a statistical life suggests that the model is almost exactly purely multiplicative for these variables. (Note that the population in 2020 is actually a multiplier for growth from 2000 to 2020.) It is interesting also to see that the elasticity is zero with respect to the base $PM_{2.5}$ concentration and threshold.

Figure 5-2 shows the elasticity of total monetized benefits (including mortality and morbidity reduction) to each uncertain parameter, using the exponential declining lag structure. Again, elasticity with respect to Delta $PM_{2.5}$, population in 2000 and 2020 is still 100%, indicating that total benefits are directly proportional to these values. The elasticity to Beta on mortality function, base mortality, and value of a statistical life are 93%. These parameters are multiplicative factors for the benefits of mortality reduction, which is about 93% of the total benefits. The elasticity of the parameters for morbidity—betas, incidence rates, and WTP to avoid—are each about 2% for AMI and 5% for CB, adding up to 7% to account for the remaining total benefit. The GDP growth rate affects the income and hence VSL via the income elasticity. The discount rate has a negative elasticity because a higher discount rate reduces the benefits of reducing mortality given the exponential declining lag structure.

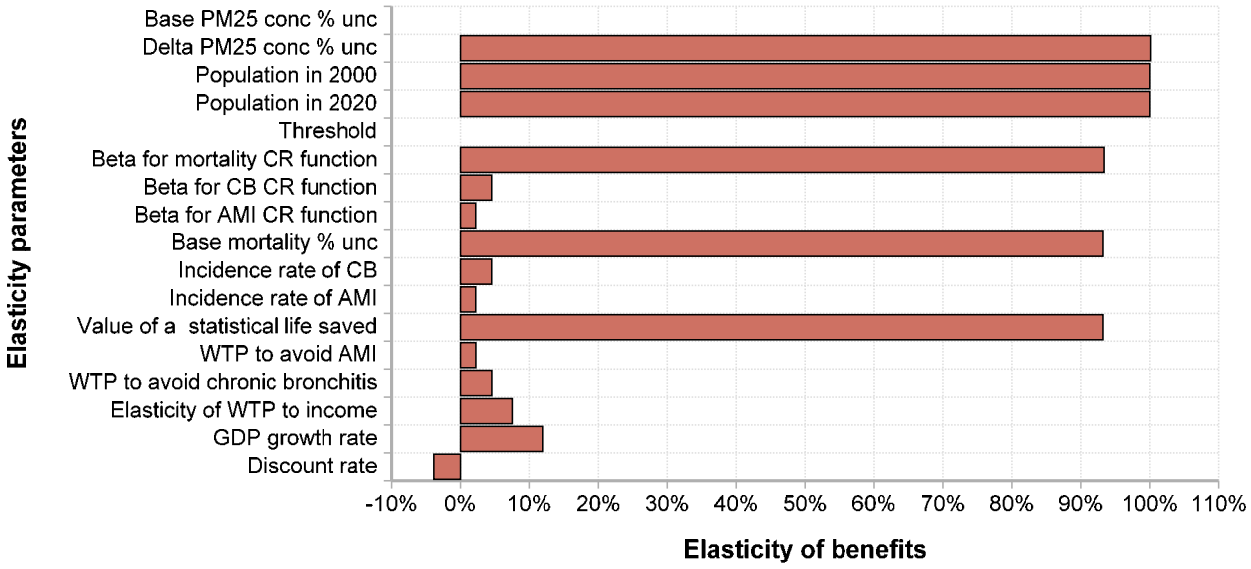


Figure 5-2. Elasticity of Total Monetized Benefits to Each Uncertain Parameter

5.4 Results for Different Concentration-Response Functions for Mortality and Morbidity

CR functions give the response to changes in mortality or morbidity as a function of changes in the atmospheric concentration of air pollution. In this project, we focus on particulate matter finer than 2.5 microns in diameter ($PM_{2.5}$). BenMAP uses a wide variety of CR functions. All use a log-linear function, some with and some without a threshold concentration below which $PM_{2.5}$ is assumed to have no health effect. For some cases, the choice of a threshold affects the beta slope, because the regression requires a higher slope to account for observed mortality when assuming a threshold below which there are no effects. These studies include several based on epidemiological studies, notably Pope et al. (2002) and Laden et al. (2006) for mortality CR functions, Abbey et al. (1993) for CB and Peters et al. (2001) for AMI. They also include probability distributions assessed by twelve experts, who remain anonymous and are identified by letters A through L. In this section, we describe the low, mid, and high values for each CR function for use in the range sensitivity analysis.

5.4.1 Ranges for Concentration-Response Functions from Published Epidemiological Studies for Mortality and Morbidity

Table 5-1 provides information on the range values from the published studies, including the end point, minimum age of population affected, threshold in $\mu g/m^3$, mean and standard deviation (SD) for beta parameter of the log-linear function of the CR functions from the epidemiological studies.

Table 5-1. Ranges for Epidemiological Studies

	Author	End point	Min age	Threshold	Beta mean	Beta SD
Pope et al 0	'Pope et al'	'Mortality'	30	0	5.82689m	2.157076m
Pope et al 7.5	'Pope et al'	'Mortality'	30	7.5	5.826891m	2.157076m
Pope et al 10	'Pope et al'	'Mortality'	30	10	6.56m	2.43m
Pope et al 12	'Pope et al'	'Mortality'	30	12	7.29m	2.7m
Pope et al 15	'Pope et al'	'Mortality'	30	15	8.75m	3.24m
Laden 0	'Laden'	'Mortality'	25	0	0.014842001	4.12m
Laden 10	'Laden'	'Mortality'	25	10	0.014842001	4.12m
CB 0	'CB'	'Chronic Bronchitis'	27	0	0.0137	6.796245m
CB 7.5	'CB'	'Chronic Bronchitis'	27	7.5	0.0137	6.796245m
AMI 0	'AMI'	'AMI'	18	0	0.024121307	9.284863m
AMI 7.5	'AMI'	'AMI'	18	7.5	0.033201	9.284863m

Note: The suffix "m" after a number means it is multiplied by 10^{-3}

We set the mid value for each beta equal to its mean. The low and high values are selected as the 10th percentile and 90th percentile of a normal distribution with specified mean and standard deviation—which are plus or minus 1.281 standard deviations from the mean.

Figure 5-3 shows the range (low, mid, and high) values for the CR functions for mortality and morbidity from selected epidemiological studies. The low (left of red bar) and high (right edge of green bar) values correspond to the 10th and 90th percentiles of the normal distributions estimated for the beta values, used for range sensitivity analysis.

5.4.2 Ranges from Expert Elicitations of Probability Distributions on CR Functions

In 2006, EPA commissioned a study to estimate CR functions for $PM_{2.5}$ from 12 experts. These estimates were elicited in the form of probability distributions (IEc, 2006). Table 5-2 from the Analytica model reproduces the value from Exhibit 3-9 "Summary of expert subjective uncertainty distributions for C-R coefficients" (page 3-30 IEc, 2006). Some experts (B, F, K, and L) assessed a piecewise log-linear function with two segments (pieces) and a different distribution on beta on each segment. The cutoff value is the $PM_{2.5}$ concentration (in ug/m^3) where the segments change from one to the other distribution. Where the expert specified a custom distribution, we fitted a continuous distribution to the specified minimum, 5th, 25th, 50th, 75th, 95th, and maximum points on each distribution using a piecewise cubic on the cumulative distribution (using Analytica's CumDist() function). The normal distributions were fitted to the 5th and 95th percentiles and the triangular fitted to min, median and max for distributions specified in those forms.

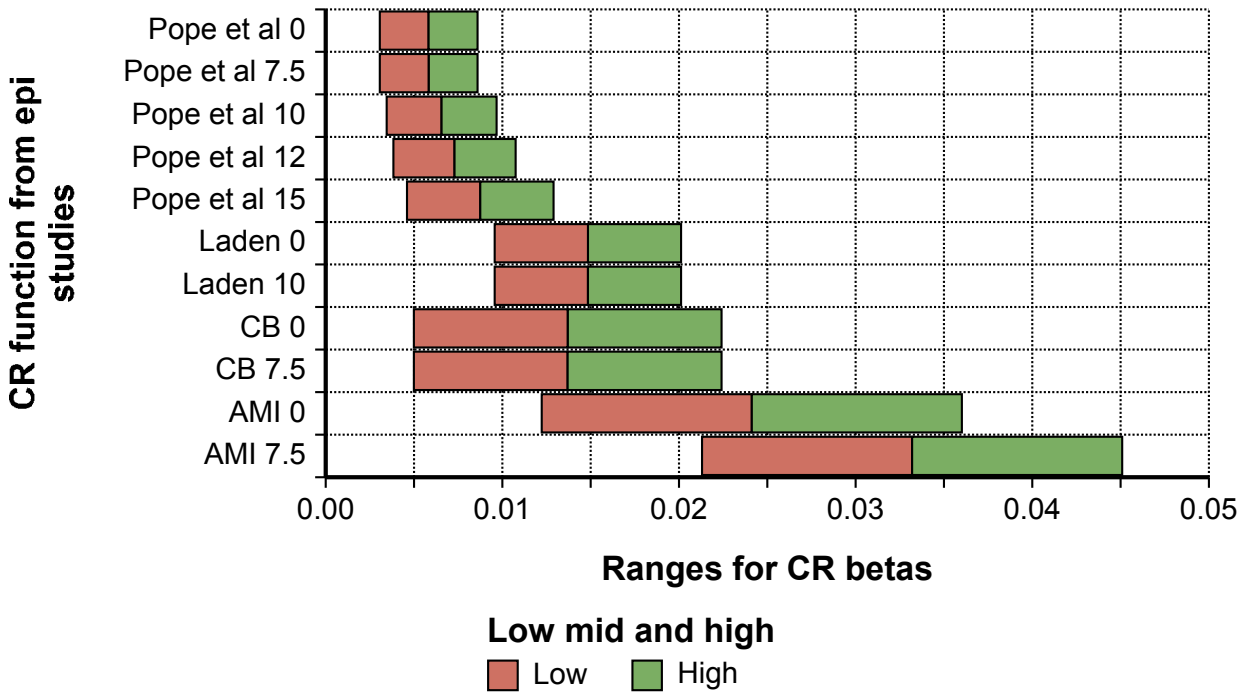


Figure 5-3. Ranges of Beta for CR Functions

In Table 5-2, "Prob causality" is the likelihood that each expert assigns to the hypothesis that human exposure to $PM_{2.5}$ in ranges up to 30 μg/m^3 causes significant mortality. "Includes causality**"** is "Y" or yes for experts that included this probability in their probability distributions.

For the other experts that did *not* include causality in the distributions they assessed, we treated the complement of the probability of causality as a probability mass that beta is zero, which we combined with the full distribution in the simulation. We used a Latin Hypercube sampling with 10,000 sample points to represent the combined distributions. We used these samples to estimate the 10th, 50th (median), and 90th percentile from these distributions, combining the continuous distribution with a probability of causality when not included in the original distribution assessment.

Only expert K expressed a belief that there might be a threshold, with a 50% chance that there is a threshold and 10% chance that it is greater than 5 μg/m^3. Accordingly for the range sensitivity, we set the low and mid value to 0 (which is the 10th and 50th percentile of the threshold distribution) and the high value (90th percentile) to 5 μg/m^3.

Table 5-2. Probability Distributions Elicited from Experts A through L

	Expert ID	Range	Cutoff	Distrib type	Min	5th %ile	25th %ile	50th %ile	75th %ile	95th %ile	Max	Includes causality	Prob causality	Threshold?
A	A		0	Normal	0	0.29	1.1	1.6	2.1	2.9	4	Y	0.95	N
B	B	4-10	4	Custom	0.01	0.1	0.2	1.2	2.1	2.6	2.8	N	0.98	N
B2	B	>10-30	10	Custom	0.1	0.2	0.5	1.2	2.1	2.6	2.8	N	0.98	N
C	C		0	Normal	0	0.4	0.9	1.2	1.5	2	4	Y	0.99	N
D	D		0	Triangular	0.1	0.35	0.66	0.9	1.1	1.4	1.6	N	0.95	N
E	E		0	Normal	0	1	1.6	2	2.4	3	5	N	0.99	N
F	F	4-7	4	Custom	0.37	0.58	0.73	0.93	1.1	1.4	1.7	Y	1	N
F2	F	>7-30	7	Custom	0.29	0.77	0.96	1.1	1.4	1.6	1.8	Y	1	N
G	G		0	Normal	0	0.7	0.88	1	1.1	1.3	1.5	N	0.7	N
H	H		0	Custom	0	0	0.4	0.7	1.3	2	3	Y	0.9	N
I	I		0	Normal	0.2	0.38	0.9	1.3	1.6	2.1	2.3	N	0.95	N
J	J		0	Weibull	0	0.15	0.53	0.9	1.3	2	3	Y	0.99	N
K	K	4-16µg/m3	4	Normal	0	0.1	0.28	0.4	0.52	0.7	0.8	N	0.35	Y
K2	K	>16-30µg/m3	16	Normal	0	0.1	0.45	0.7	0.95	1.3	1.5	N	0.35	Y
L	L	4-10	4	Custom	0	0.2	0.57	1	1.4	1.6	2.7	N	0.75	N
L2	L	>10-30µg/m3	10	Custom	0.02	0.2	0.57	1	1.4	1.6	2.7	N	0.99	N

Source: IEc, 2006.

Figure 5-4 shows the range (low, mid, high) values for the CR functions for mortality assessed by experts. For experts B, F, K, and L, there are two ranges since the experts assessed piecewise log-linear functions with two segments. The low (left of red bar) and high (right edge of green bar) values correspond to the 10th and 90th percentiles of the distributions assessed by each expert for the beta values, used for range sensitivity analysis. Expert K has a mid and low value of zero reflecting his or her likelihood of causality of only 0.35.

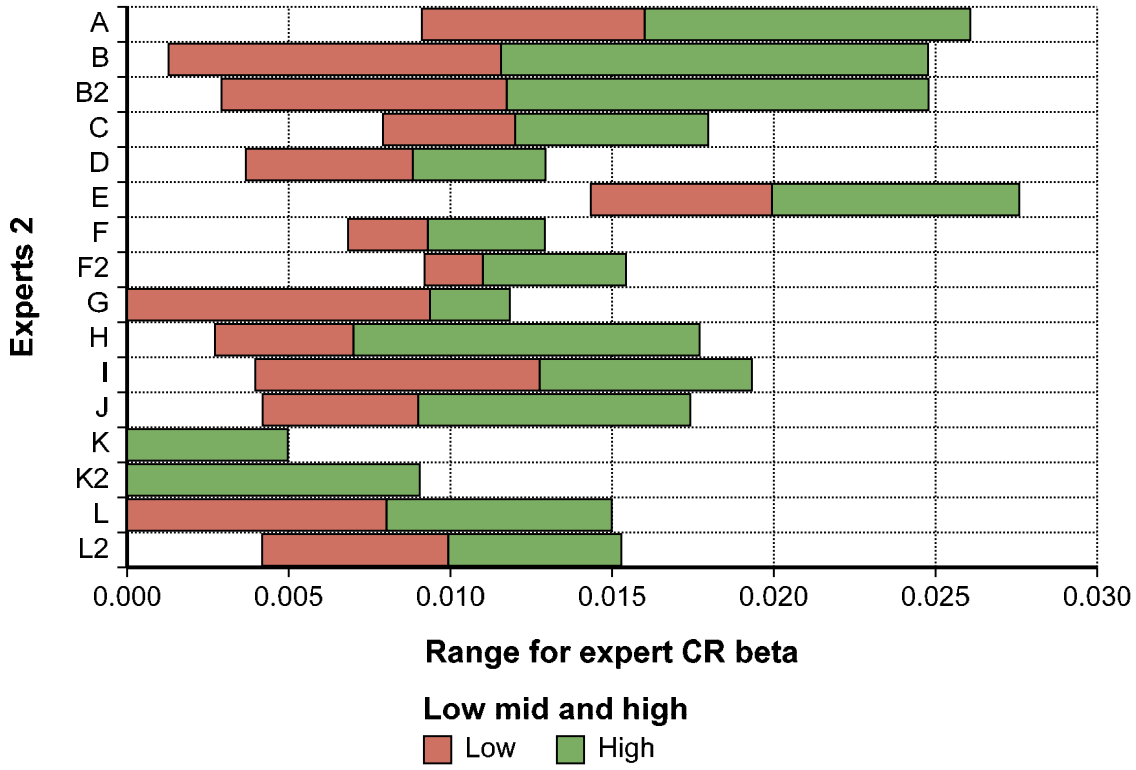


Figure 5-4. Ranges of Beta for CR functions from Experts A to L

Figure 5-5 provides a chart showing the range of cases of mortality or morbidity avoided for each CR function from the published epidemiological studies and from the expert elicitation. The chart includes epidemiological studies (Pope et al. and Laden et al.) and the twelve experts A to L. These ranges reflect the ranges in the beta of the CR functions shown previously. The numbers after Pope et al. and Laden et al. specify the threshold of $PM_{2.5}$ in $\mu g/m^3$. Low (left edge of red bar), mid (edge between red and green bar) and high (right edge of green bar) are the 10th, 50th, and 90th percentiles of probability distribution. For Pope et al. and Laden et al., these are distributions from the reported standard deviation of the estimates of beta. For the Experts A to L, these distributions are those estimated by the expert, as described above.

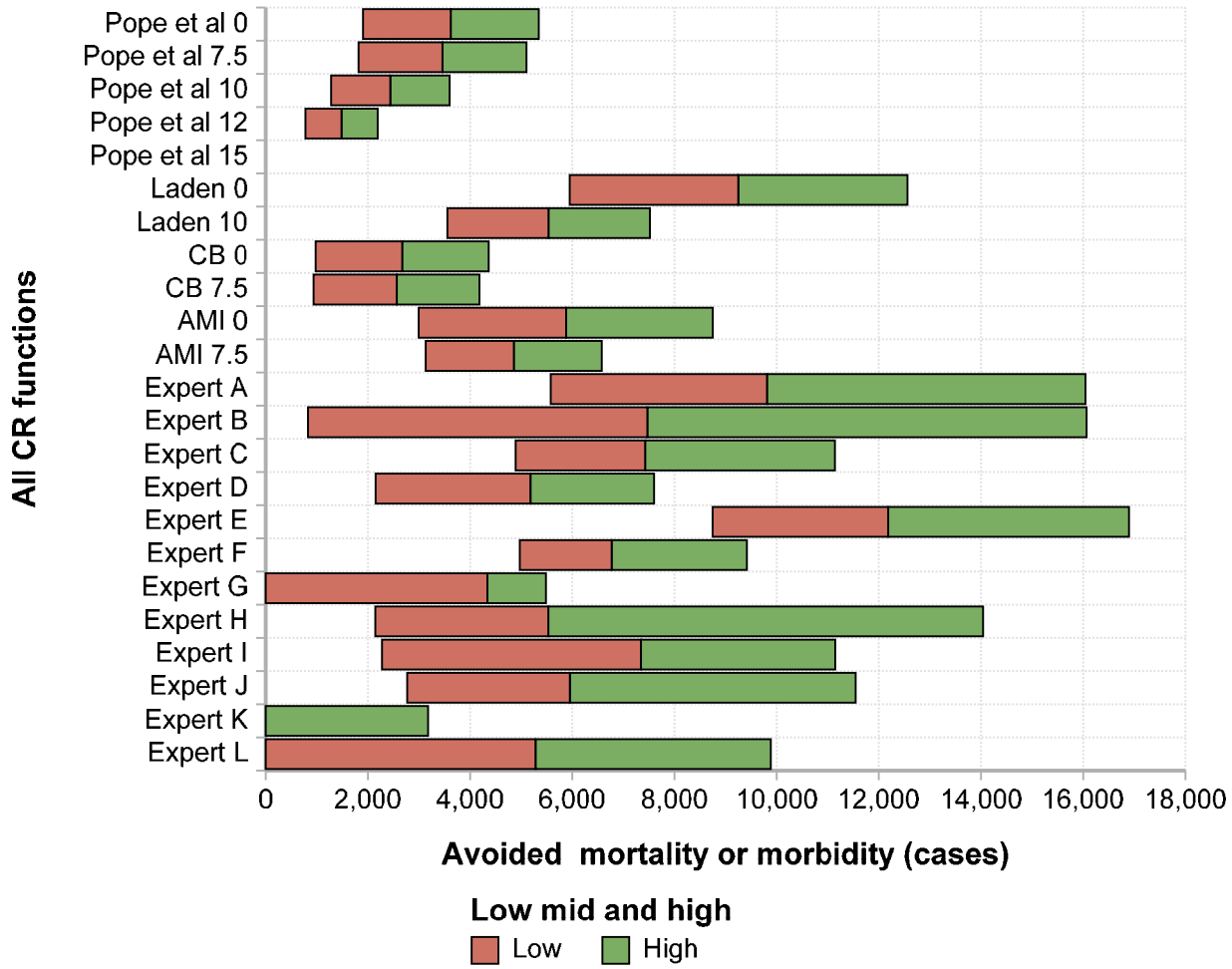


Figure 5-5. Range of Avoided Premature Mortalities and Morbidities (CB and AMI) for Low, Mid, and High Values for Each CR Function

Pope et al. 15 (with a threshold of 15 μg/m^3) has zero mortality and so zero reduction in mortality. BenMAP input data did not contain grid squares with current $PM_{2.5}$ concentration of greater than the threshold of 15 μg/m^3. Expert K assessed the likelihood of causality as only 0.35. So, the 10th and 50th percentiles of his or her distributions on beta of CR function are zero. Only the high value, the 90th percentile (right edge of green bar) is nonzero

Figure 5-6 shows the range of monetized benefits from reduced mortality or morbidity for each CR function. Each range (low, mid, and high value) corresponds with the low, mid, and high value for each CR function estimated as described above, holding all other parameters at their mid value. The mid values match the value from the BenMAP calibration run.

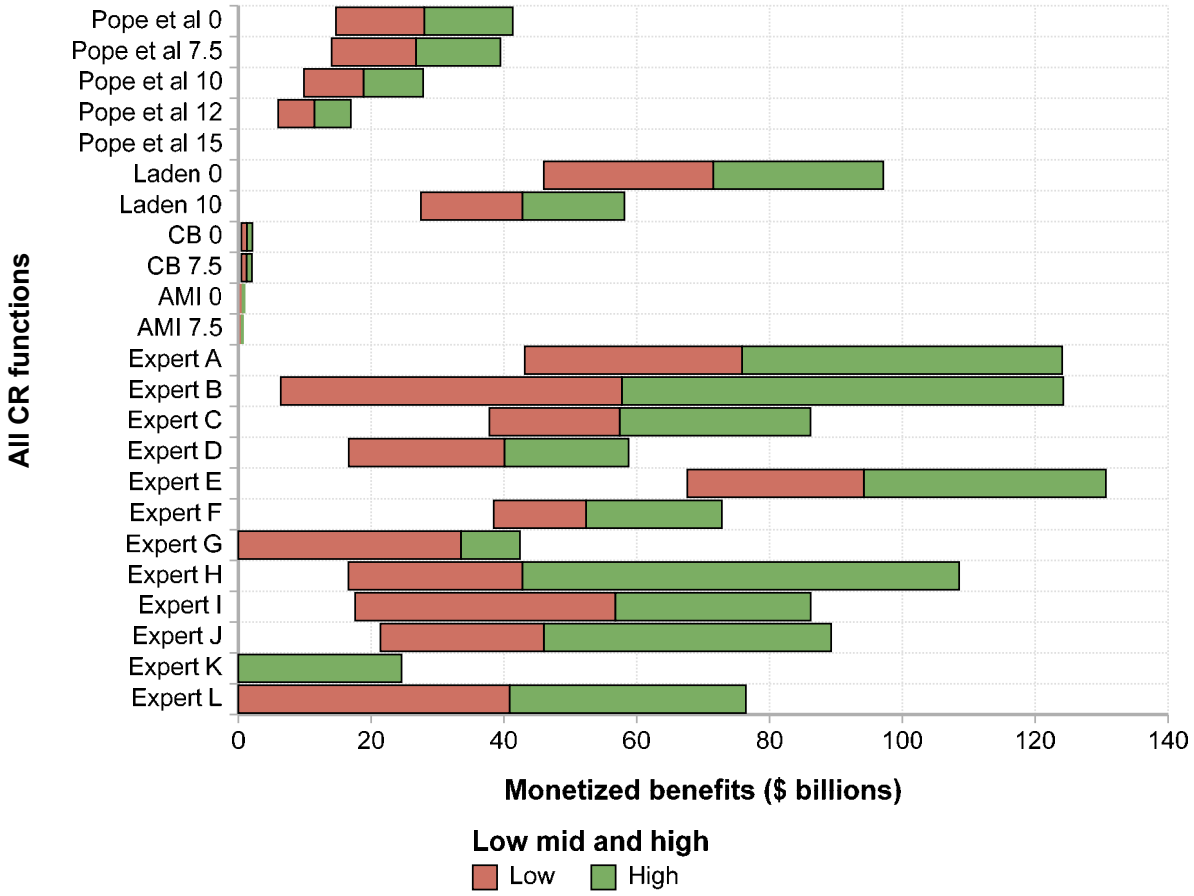


Figure 5-6. Range of Monetized Benefits for Low, Mid, and High Values for Each CR Function

Finally, Table 5-3 provides the number of cases of mortality or morbidity avoided with the low, mid, and high value for the beta from the CR function for each epidemiological study or expert, where the number after the name of the study or expert specifies the threshold.

Table 5-3. Number of Cases of Mortality or Morbidity Avoided Using the Low, Mid, and High Values for the Beta from the CR Function in Each Source

Source	Low	Mid	High
"Pope et al 0"	1,957	3,727	5,500
"Pope et al 7.5"	1,935	3,685	5,438
"Pope et al 10"	1,391	2,652	3,917
"Pope et al 12"	973	1,856	2,743
"Pope et al 15"	0	0	0
"Laden 0"	6,124	9,521	12,930
"Laden 10"	3,872	6,023	8,186
"CB 0"	961	2,631	4,290
"CB 7.5"	952	2,605	4,248
"AMI 0"	4,461	8,768	13,040
"AMI 7.5"	7,675	11,912	16,116
"Expert A"	5,837	10,268	16,791
"Expert B"	820	7,426	15,934
"Expert C"	5,065	7,691	11,541
"Expert D"	2,308	5,661	8,303
"Expert E"	9,212	12,820	17,786
"Expert F"	4,374	5,955	8,282
"Expert G"	0	5,992	7,582
"Expert H"	1,737	4,479	11,368
"Expert I"	2,503	8,173	12,434
"Expert J"	2,680	5,763	11,182
"Expert K"	0	0	3,191
"Expert L"	0	5,159	9,623

5.5 Range Sensitivity of Mortality Avoided Outcome

The following charts show the results of the range sensitivity analysis on avoided premature mortality. Each chart lists the uncertain parameters down the left axis. The width of each bar shows the effect of changing each parameter from its low value (left edge of red bar) to mid value and high value (right edge of blue bar). A wider bar means higher range sensitivity.

The range sensitivity results in Figure 5-7 use the Pope et al. zero threshold as the CR function for mortality. Delta $PM_{2.5}$ and beta have the largest range sensitivities. There is no sensitivity to changes in the base concentration or threshold, since this CR function assumes a fixed zero threshold. Figures 5-8a and 5-8b shows the range sensitivity for Pope et al. with a 10 and 12 ug/m^3 thresholds, respectively. Because of the threshold, the uncertainty in the base $PM_{2.5}$ concentration has a significant effect, larger even than the Delta $PM_{2.5}$ in this case, because it shifts population in some grid squares below the threshold for effects. Compared to the zero threshold case, the numbers of avoided premature mortalities is much lower.

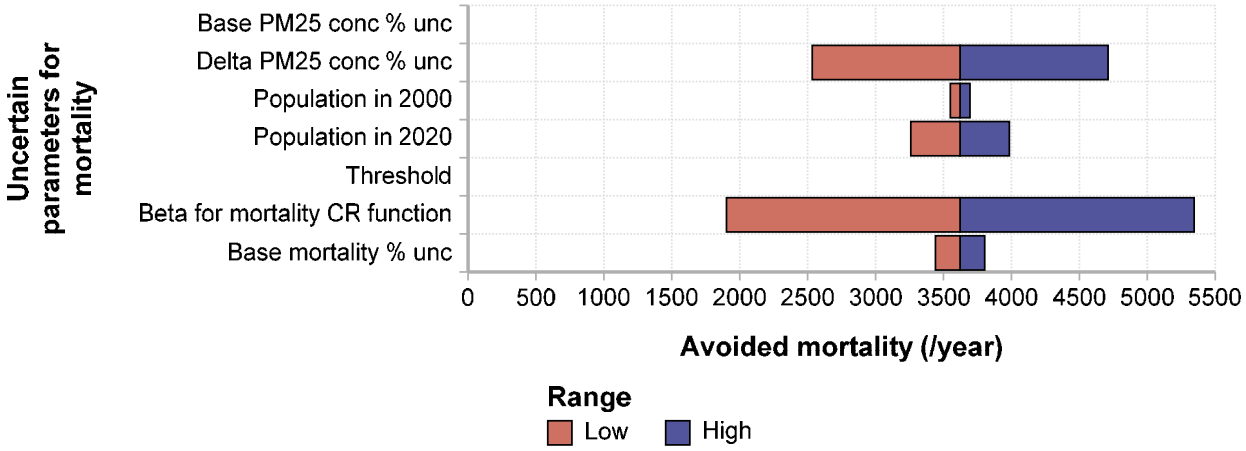


Figure 5-7. Range Sensitivity of Avoided Mortality for Pope et al. with Zero Threshold

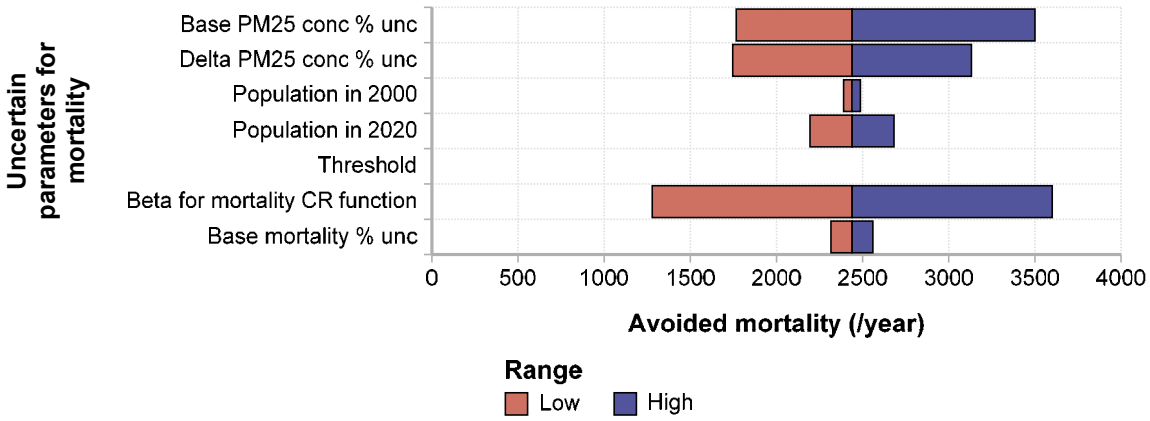


Figure 5-8a. Range Sensitivity of Avoided Mortality for Pope et al. with a 10 ug/m^3 Threshold

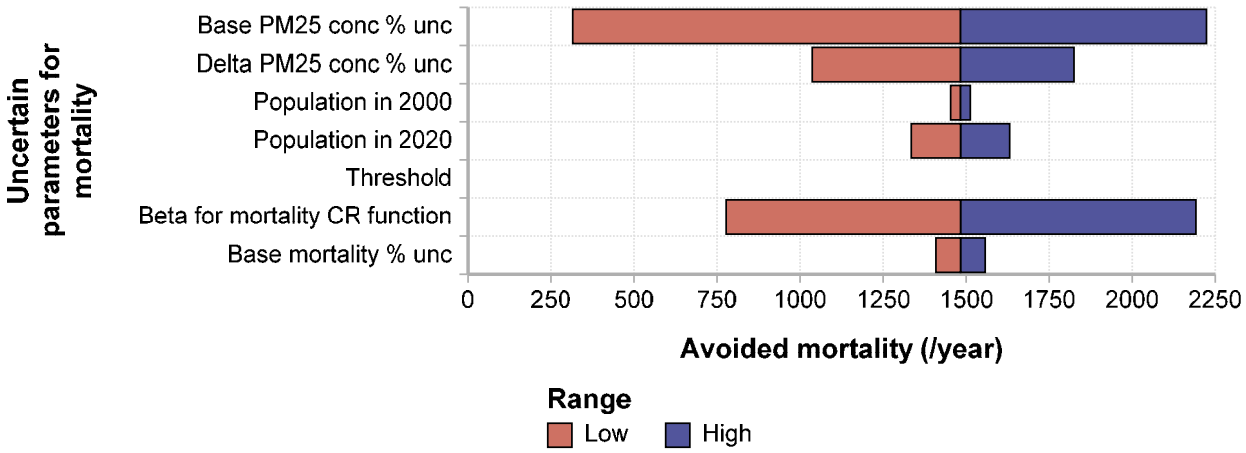


Figure 5-8b. Range Sensitivity of Avoided Mortality for Pope et al. with a 12 ug/m^3 Threshold

Figure 5-9 shows the range sensitivity of avoided mortality for Laden et al. with zero threshold. The sensitivity is similar to that for Pope et al. for zero threshold in terms of relative size of range sensitivities. Again there is no effect of Base $PM_{2.5}$.

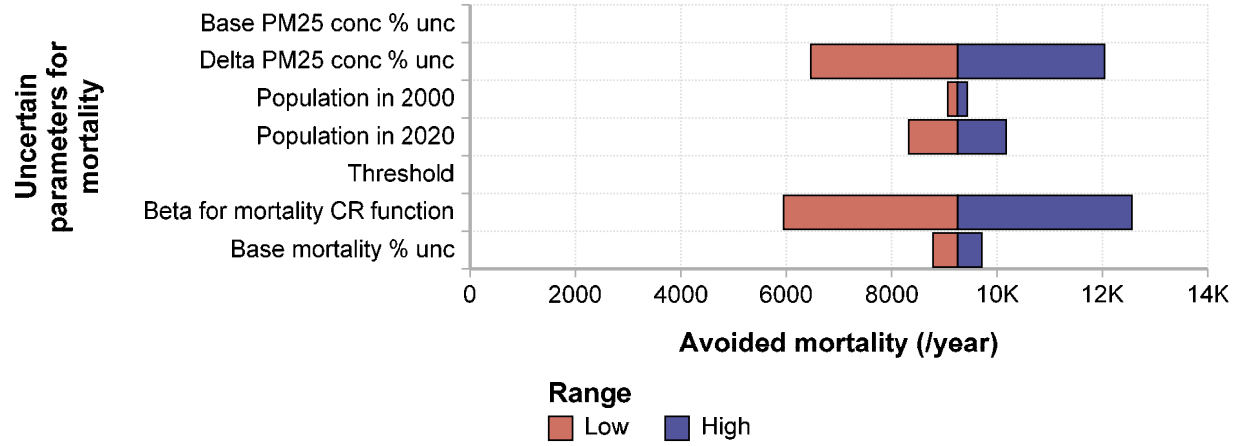


Figure 5-9. Range Sensitivity of Avoided Mortality for Laden et al. with Zero Threshold

Figure 5-10 shows the range sensitivity if we select a different Pope et al. CR function assuming a mid threshold of 7.5 µg/m^3. Thus, there is range sensitivity to threshold, with a high threshold (blue) of 10 µg/m^3 leading to lower cases avoided, and a low threshold (red) 0 increasing the cases avoided.

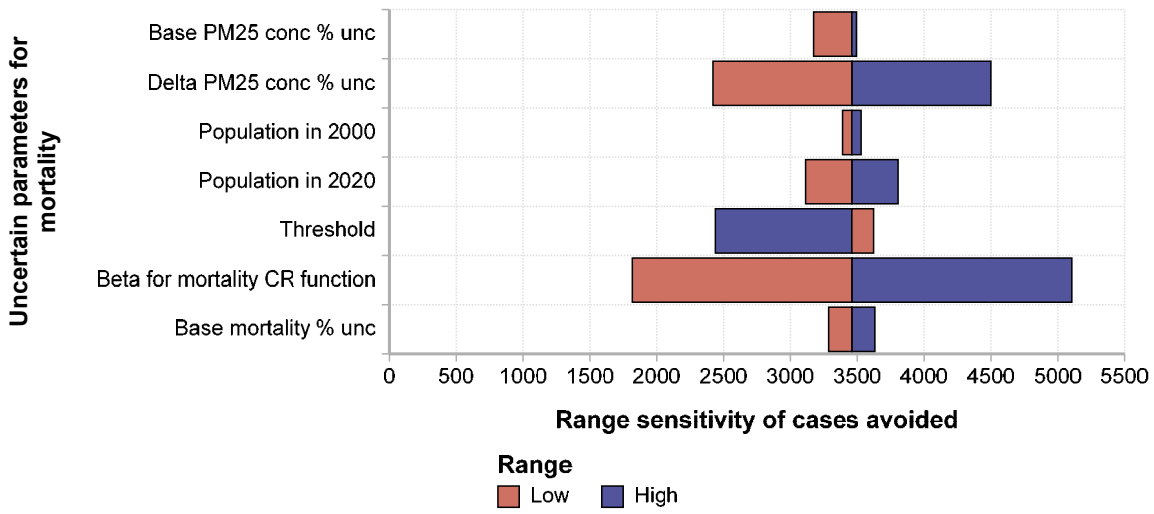


Figure 5-10. Range Sensitivity of Avoided Mortality for Pope et al. with Mid Threshold of 7.5 µg/m^3

Range sensitivity of avoided mortality for Laden et al. with 10 ug/m^3 threshold, Figure 5-11, is similar to that for Pope et al. for high thresholds. Range sensitivity of Base $PM_{2.5}$ is close to that for Beta.

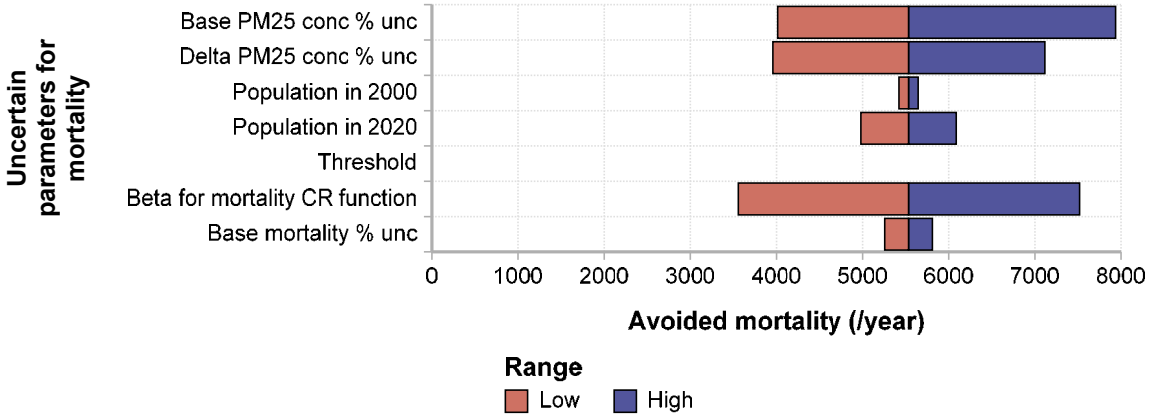


Figure 5-11. Range Sensitivity of Avoided Mortality for Laden et al. with 10 ug/m^3 Threshold

5.6 Range Sensitivity for Total Monetized Benefits Outcome

Figure 5-12 shows the range sensitivity of total monetized benefits to the full range of uncertain parameters for Pope et al. with zero threshold as the mid value. The zero threshold means no range sensitivity to Base $PM_{2.5}$ concentration. In this case, a higher threshold (based on the Pope et al. CR function adjusted for the higher threshold) leads to lower monetized benefits. The largest range sensitivity is the statistical value of a life, followed by Beta for mortality CR function, and then Delta $PM_{2.5}$ concentration. All the other range sensitivities are significantly smaller, with the value of an avoided case of CB being the largest. The discount rate has no effect because we are assuming no mortality valuation lag.

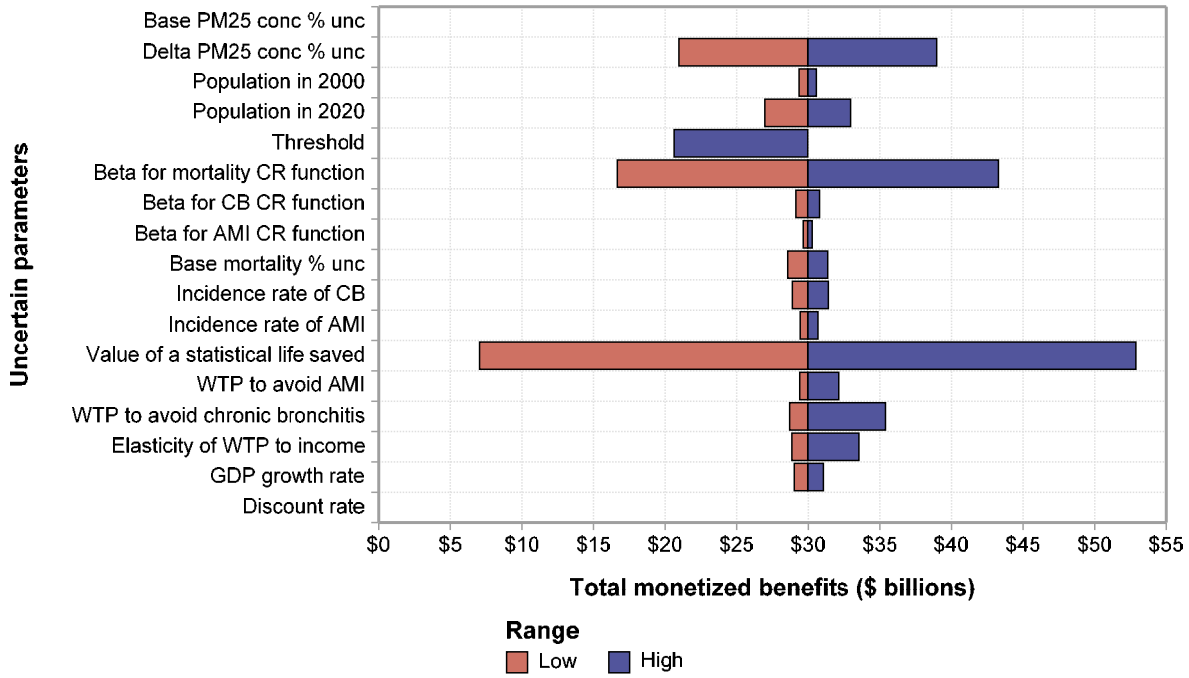


Figure 5-12. Range Sensitivity of Total Monetized Benefits to the Full Range of Uncertain Parameters for Pope et al. with Zero Threshold as the Mid Value

Figure 5-13, like the previous one, assumes the Pope et al. zero threshold CR function. The only difference is that we selected an exponential declining mortality valuation lag structure. This means that the results are slightly sensitive to the discount rate.

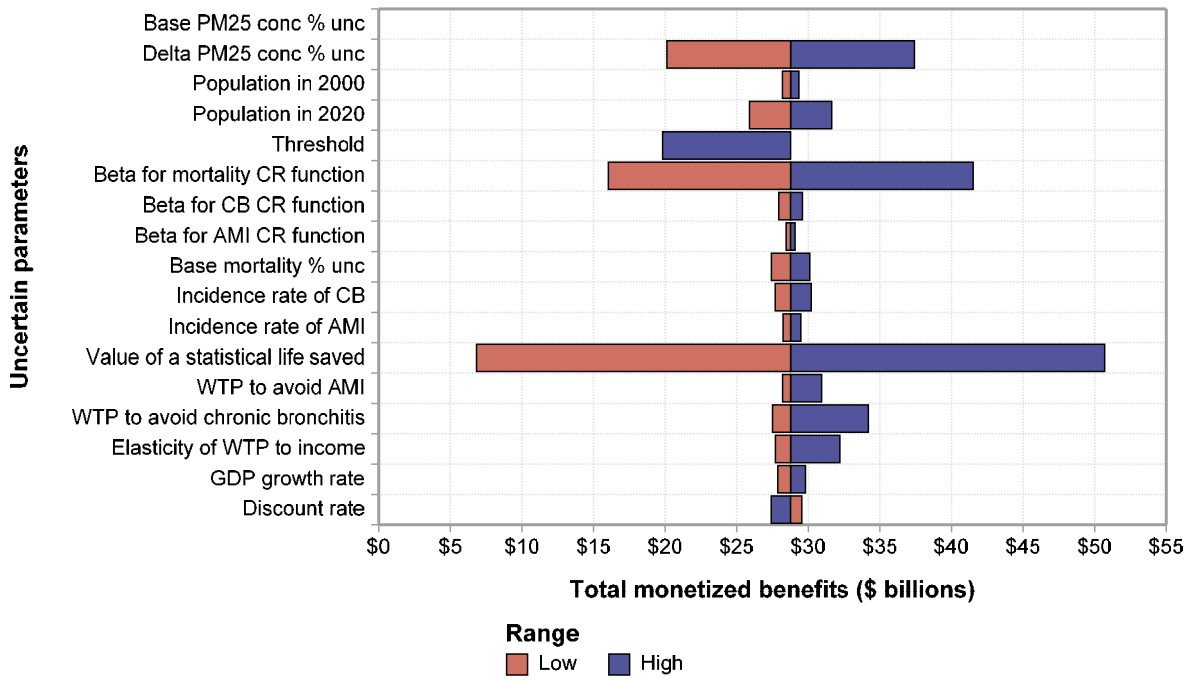


Figure 5-13. Range Sensitivity of Total Monetized Benefits to the Full Range of Uncertain Parameters for Pope et al. with Zero Threshold as the Mid Value with an Exponential Declining Mortality Valuation lag Structure

Figure 5-14 uses the Laden et al. zero threshold as the mid mortality function. It changes to the Laden et al. 10 threshold with high threshold. The relative sizes of the range sensitivities is identical to the previous chart using Pope et al. mortality function, but the absolute values are more than twice as large—$70 billion instead of $29 billion for mid values.

The final two range sensitivity charts are for experts E and K, who assessed the largest and smallest, respectively, of the mid values for the beta of the mortality CR functions. The chart in Figure 5-15 shows range sensitivities using Expert E. There is no sensitivity to threshold or Base $PM_{2.5}$, since Expert E has no threshold. The mid total benefits are $96 billion. Otherwise the pattern of the relative sizes of the range sensitivities is similar to Pope and Laden et al. CR functions. Figure 5-16 shows range sensitivities using Expert K. The mid value is only $2 billion per year, which is the benefits of reducing morbidity only, since Expert K's mid value (median) for the CR beta is zero. The zero mortality reduction leads to zero range sensitivity for VSL. For the high value of beta, the total benefits exceed $26 billion.

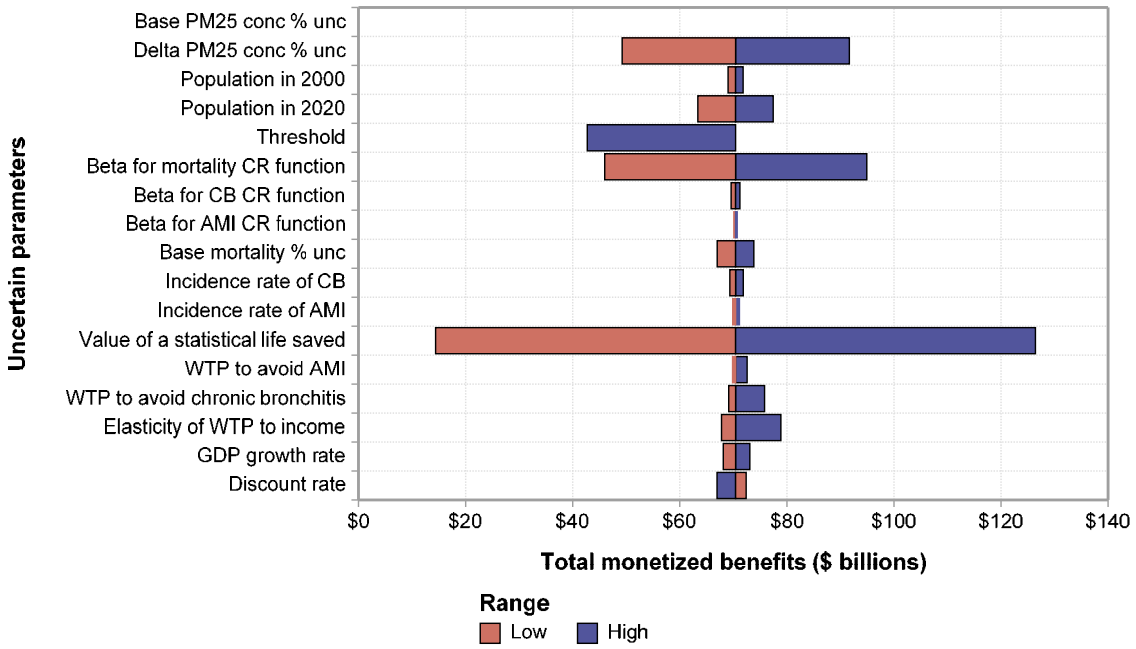


Figure 5-14. Range Sensitivity of Total Monetized Benefits to the Full Range of Uncertain Parameters for Laden et al. Zero Threshold as the Mid Value

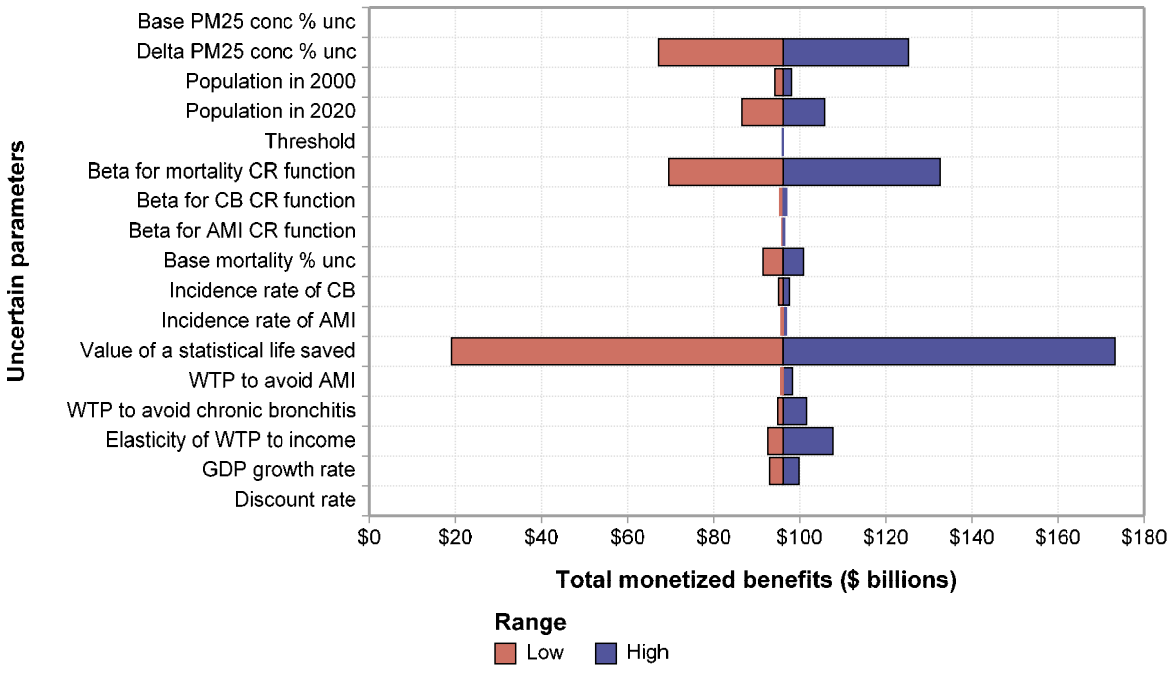


Figure 5-15. Range Sensitivity of Total Monetized Benefits to the Full Range of Uncertain Parameters for Expert E

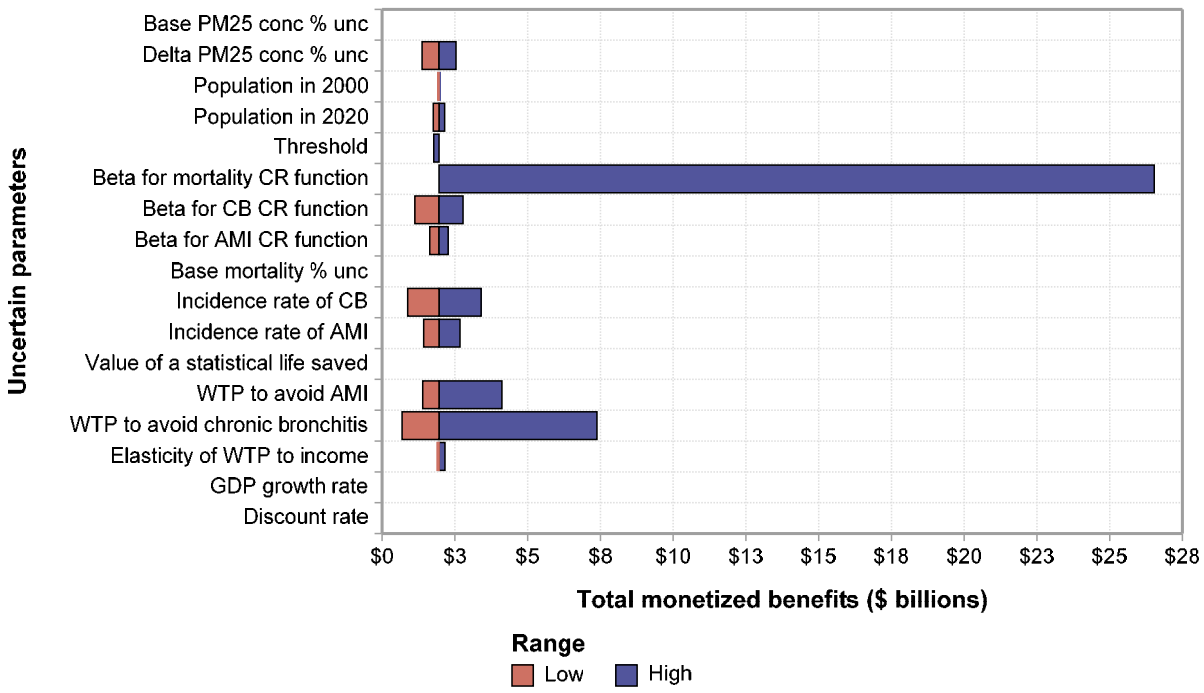


Figure 5-16. Range Sensitivity of Total Monetized Benefits to the Full Range of Uncertain Parameters for Expert K

Finally, uncertainty about the valuation lag structure for mortality has an impact on the outcomes. Figure 5-17 presents the impact on the total outcome of different assumptions about the valuation lag structure and about the discount rate. Figure 5-18 shows the range sensitivity of total monetized benefits to different discount rate assumptions for each lag structure. This graph is for Pope et al. with no threshold. The high discount rate (7%) at left of blue bar gives lower benefits, and low discount rate (1%) at right of red bar gives higher benefits.

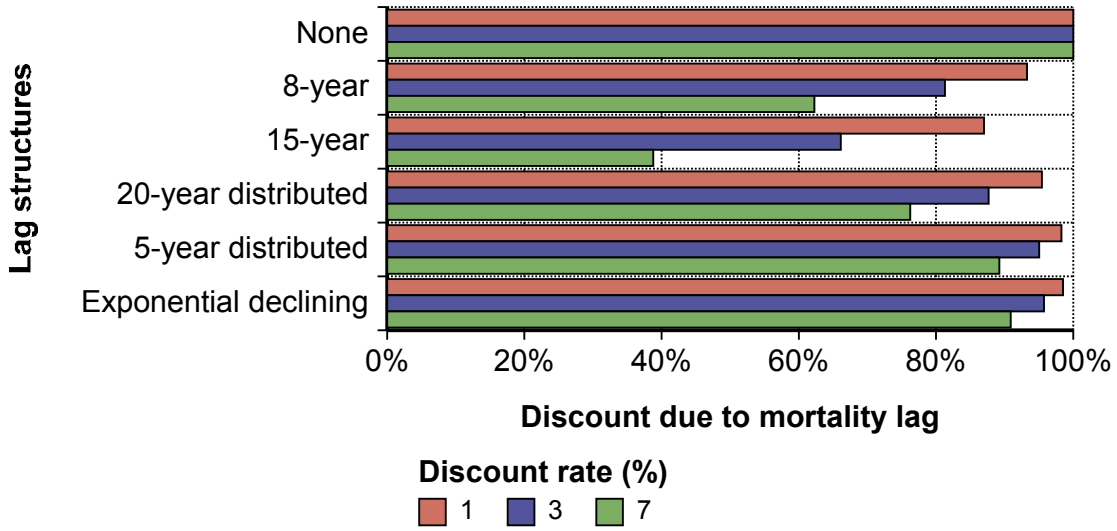


Figure 5-17. Discount by Lag Structure

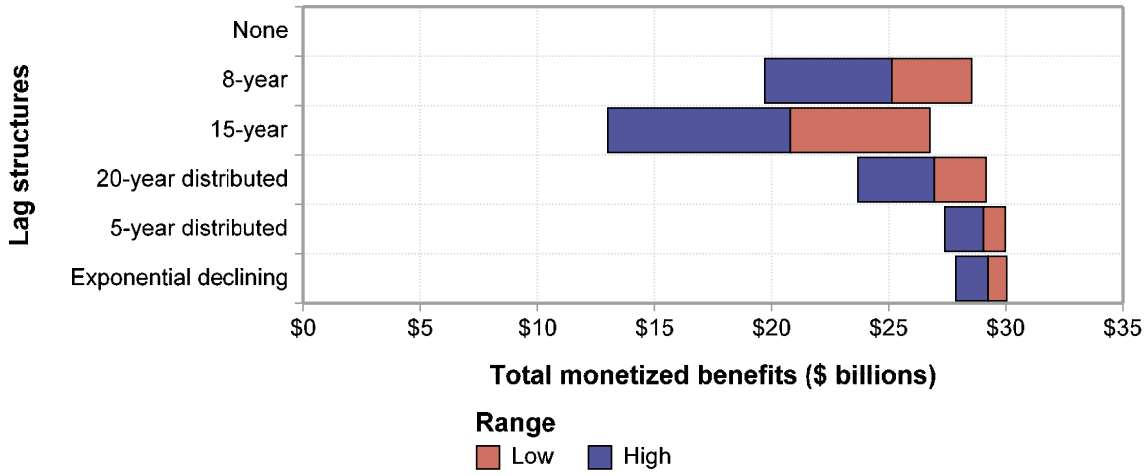


Figure 5-18. Range Sensitivity of Total Monetized Benefits to Discount Rate Assumptions for Different Mortality Valuation lag Structures

SECTION 6
DISCUSSION AND POSSIBLE NEXT STEPS

6.1 Discussion of Model Results

This report presents the results from our initial sensitivity analysis of the benefits from air quality regulations as estimated by BenMAP. The study examined the sources of uncertainty, the possible range of uncertainty for selected sources, the role and influence of the parameters or functions, and the sensitivity of the final benefit estimates to the different sources of uncertainty all in the simplified Analytica version of the BenMAP model. Here we discuss the results of the sensitivity analysis and suggestions for potentially useful next steps to explore the role of uncertainty on benefit estimation.

- Comparing the results from the different mortality CR functions, the differences between the functions are larger than the uncertainty of individual CR-functions. In other words, the uncertainty inherent in choosing a CR-function has more impact on results (mortality reduction or total benefits) than the uncertainty within each CR-function captured by its range sensitivity.

- The elasticity analysis finds that the uncertain parameters delta $PM_{2.5}$ concentration, the beta for the mortality CR function, population in 2000 and 2020, base mortality rates, and VSL all affect the total mortality reduction in an almost purely multiplicative fashion (Figure 5-1). Hence, the relative sizes of the range sensitivities (ratios of their widths) of these parameters are similar for each expert. Hence, most of the key results below on the relative range sensitivity are the same for all mortality CR-functions even if the mid points—mortality avoided and total net benefits—differ significantly from one expert to another (excepting Expert K because his mid estimate has zero mortality due to low probability of causation).

- In all cases (again, except Expert K), the parameter with largest range sensitivity is the VSL.

- For most of the results from the different mortality CR functions, the beta for mortality has the second largest range sensitivity analysis.

- The range sensitivity to delta $PM_{2.5}$, the reduction in concentration of $PM_{2.5}$, is the third largest, and in some cases (experts E and F) comparable to the range sensitivity for the morality CR function beta. Examination of the uncertainty inherent in projections of air quality and improvements in air quality was beyond the scope of this project, so we assumed a plus or minus 30% change in this variable to illustrate the possible effects of uncertainty on the results. Again it is not surprising that this quantity has a high sensitivity.

- Among the quantities with lower range sensitivity, the most sensitive include
  - Population in 2020—i.e., uncertainty in population projections and the distribution of the population across the country. Migration and immigration ranked high as sources of uncertainty in the population forecasts and population distribution because of the difficulty in predicting movements of people and the difficulty in forecasting economic activity many years into the future according to experts consulted for the project.
  - The value of an avoided case of CB, which is highly uncertain at present. The value of avoiding an AMI is also highly uncertain and if WTP studies existed for AMI's, AMI's might exhibit larger and more influential range sensitivity.
  - Elasticity of WTP to income.
- Discount rate is sensitive when using mortality valuation lag structures, especially those with longer average lag—and irrelevant with no mortality lag. It is a policy variable usually set by the government for purposes of public policy analysis (typically at 3% or 7% per year) rather than a quantity subject to empirical study. So, it is not clear that further study of this issue would be of value.

6.1.1 Comments on the Uncertainty Analysis Methods

The development of the influence diagrams in Section 4 provided an intuitive depiction of how the uncertain parameters combine and affect the results of interest. These diagrams reflect the actual Analytica model used for the numerical sensitivity analyses. In some cases, these diagrams include variables that are needed for the sensitivity analysis, but perhaps do not add clarity about the influence from a purely qualitative perspective. In support of transparency of our methods, we chose to display diagrams that reflect all the variables in the underlying quantitative model.

Creating a simplified version of a complex model, such as BenMAP, provides a depiction of its essentials, but we did not attempt to reproduce all the computations in BenMAP, which we felt would detract from clarity and add unhelpful complexity.

The diagrams in Section 4 also do not include the model elements involved in processing and aggregating the 36-km grid square data to the concentration bins, calibrating to BenMAP results, and performing the sensitivity analysis since they do not add clarity to the representation of the essentials of the benefits analysis. All these are available in the Analytica model for those that are interested.

We developed the extremely simple model with 16 concentration bins to make sure that the model would run fast, enabling us to do a wide variety of sensitivity runs. At the end of the project, we also did some tests using the full 36 km grid square data in Analytica. It turns out that

it takes about 1 to 5 seconds for the full analysis, which is faster than BenMAP by 2 or 3 orders of magnitude. We suspect this may be partly due to Analytica's high-speed algorithms for dealing with large arrays, but we would need to do more extensive analysis of both models to discover the full reasons. This opens the possibility of doing sensitivity or Monte Carlo analysis of BenMAP at the full 36-km level of detail using the Analytica model in a future study if needed.

6.2 Potential Next Steps

Below we discuss potential next steps based on the results from this uncertainty analysis. Based on research conducted by EPA and others, some of the largest sources of uncertainty are not good candidates for additional work. EPA has already devoted considerable resources to characterizing the uncertainty in the CR function for mortality, one of the most influential sources of uncertainty. Additional expert elicitation does not seem warranted without more and more conclusive empirical evidence. A similar conclusion applies to VSL. VSL is also much studied, and it is not clear that further study would lead to any significant reduction in its uncertainty.

6.2.1 Update Studies to Support Morbidity Valuation

Additional work on morbidity outcomes may offer important data for BenMAP. Without additional epidemiology studies, WTP values and updated studies, it is difficult to know whether the sensitivity analysis captures the full range of values. The range sensitivity to WTP to avoid CB is large ($77K to $1.6 million). The magnitude of the COI component is very small compared to the WTP. This highlights the importance of incorporating WTP into morbidity valuation. The CB WTP studies are both old and should be updated. Other morbidity endpoints, such as AMIs, have not been the subject of WTP studies. It may be worthwhile reviewing recent literature and investing in new studies to obtain updated estimates of COI and/or WTP for all health effects. The income elasticity of WTP is another parameter that could use additional research.

In general, much of the valuation data in the current version of BenMAP is potentially out-of-date, especially with changes over the last decade or two in healthcare and in methods used to estimate WTP and COI. Thus, there are both (i) uncertainties in the data itself and (ii) in applying them. An example of the former in context of COI would be that newer estimates may reflect the advent of newer technologies that result in shorter hospital stays and lower severity of illnesses. Also, individuals may be more educated and thus may undertake better preventive and follow-up care. On the other hand, overall increased costs of health care may lead to increased

estimates of COI. True COI estimates for different illnesses in recent years may be smaller than those in the studies found in BenMAP or they may be larger.

Uncertainties that stem from applying older estimates can also arise since current circumstances may be completely different from those of the studies. For example, the age composition (both current and projected) of highly polluted areas may be different from the ones that were used in the studies underlying BenMAP. This might create uncertainties associated with applying estimates to demographic groups that are different from the ones included in the study. For example, an older population will be at a higher risk to certain diseases and also experience more severe symptoms.

The current version of the influence model creates "bins" based on pollution concentrations. One way to assess the sensitivity of results to different demographic groups might be to "bin" by demographic characteristics.

6.2.2 More Detailed Mortality Valuation Estimates

Ideally, WTP and COI estimates would be more tailored to specific populations. For example costs should reflect more regional differences in healthcare utilization. Patients with co-morbidities may have different costs than otherwise healthy individuals who develop CB. Trajectories of costs for different outcomes should reflect common complications or sequela, health conditions that arise after an injury or disease.

6.2.3 Framework to Jointly Consider Multiple Health Endpoints

BenMAP incorporates information on incidence rates, COI and WTP from studies considering each health endpoint separately rather than in conjunction with other co-morbidities. This has two implications. First of all, there may be biased estimates due to confounding factors. Also, the general framework and associated assumptions differ across these studies. A review of recent literature to consider studies exploring multiple endpoints (for example, work being conducted by Cameron and DeShazo on WTP that incorporates multiple outcomes) might provide ideas.

6.2.4 Add Additional Outcomes and Expand Application to Other Pollutants

This study looked at only mortality, CB and AMI. Incorporating other outcomes, both health and non-health (such as visibility) would complete the sensitivity analysis. Expansion of the uncertainty analysis to cover some of these additional benefits would require extensions of the benefits model beyond BenMAP.

The results presented in this report arise from a particular air quality scenario (the 2006 PM RIA 15/35 option). Application of the model to alternative pollutants, such as ozone, additional regulatory scenarios for PM or to different species of PM were all suggested as possible topics for exploration that would provide some evidence on how far the results from one specific scenario can be generalized to other pollutants or air quality regulations.

6.2.5 Expanding Scope of the Uncertainty Analysis to Include Air Quality

The project scope imposed limitations on the study of uncertainties by excluding uncertainty in the base concentration and delta concentration in $PM_{2.5}$. These concentrations are estimated and projected by a variety of emissions and air quality models, including CMAQ, as we briefly showed in Figure 4-13. An explicit uncertainty analysis of the air quality models would be a significant effort, probably larger than the uncertainty analysis of BenMAP undertaken here, due to the greater complexity of the emissions and atmospheric transport models. In the absence of careful analysis of the uncertainty in the air quality estimates, we chose ranges for these quantities, plus or minus 15% for the base concentration, and plus or minus 30% for the deltas. The range sensitivity showed low sensitivity to the base concentration for non-threshold CR functions and range sensitivity to the delta was usually third the largest (beta on the mortality CR function and VSL).

A more thorough uncertainty analysis of benefits would require a more careful assessment of the ranges for the base and delta concentrations—based on analysis of uncertainty in projections using a simplified model of the air quality models, using an approach similar to that conducted here for BenMAP. It should also include uncertainty analysis based on comparison of air quality projections with actual observations, something that is not directly possible for benefits calculations.

6.2.6 Investigate Cost Uncertainty

The study does not address the costs of improving air quality. Explicit treatment of costs would require uncertainty analysis of the emissions models used to generate emissions inventories used by CMAQ. The addition of economic costs would require uncertainty analysis of the costs of reduced emissions.

6.2.7 A More Comprehensive Treatment of Uncertainties

This project focused on range sensitivity analysis, varying each of the uncertain parameters one at a time while leaving the other parameters fixed at their mid values. This approach does not assess the overall uncertainty in the results from the combined effects of all the uncertainties. One approach would be to examine the results when you set all parameters to

their low values—or all to their high values. This "Murphy's law" approach assumes that "everything that can go wrong does go wrong"—i.e., all parameters are at their "worst" level simultaneously. Conversely, everything goes right—all parameters are at their best level simultaneously. But the chance of all parameters being at one extreme simultaneously is vanishingly small: Given the 17 parameters (in the analysis here), if we assumed that the low value is the 10th percentile, the chance of all 17 being at or less than their low value simultaneously (or all at their high value) assuming independence would be 10^{-17}. Hence, the resulting range would be implausibly wide. It is for this reason we did not perform and do not recommend this approach.

A second limitation of the project scope was the exclusion of a probabilistic analysis. A full probabilistic analysis using Monte Carlo simulation would be the best approach to examine the combined effect of the multiple uncertainties on results. This approach would require an explicit probability distribution be assessed for each parameter—as they already were for the CR-mortality functions by experts A through L. It would also require interdependencies between parameters to be modeled. If EPA desires to obtain a more complete uncertainty analysis, we would strongly recommend this approach.

6.2.8 Large Changes in Population, Migration and Immigration

Looking back on past immigration or internal migration patterns might provide bounds on the possible size of large immigration or migration events. One could develop scenarios that resulted in large movements of population or increased/decreased immigration in response to very low probability events that have a large impact (hurricanes, droughts, changes in climate, political instability).

6.2.9 Additions to Analytica Model

As discussed in this report, the Analytica model is a simplified version of BenMAP. Further work to add more of the complexity from BenMAP into the Analytica model and using the full 16,000 points rather than bins removes some assumptions and increases the range of problems that can be assessed with the simplified model.

SECTION 7
REFERENCES

Abbey, D. E., F. Petersen, P. K. Mills and W. L. Beeson. 1993. Long-Term Ambient Concentrations of Total Suspended Particulates, Ozone, and Sulfur Dioxide and Respiratory Symptoms in a Nonsmoking Population. Archives of Environmental Health. Vol. 48 (1): 33-46.

Abbey, D. E., B. L. Hwang, R. J. Burchette, T. Vancuren and P. K. Mills. 1995. Estimated long-term ambient concentrations of PM10 and development of respiratory symptoms in a nonsmoking population. Arch Environ Health. Vol. 50 (2): 139-52.

Industrial Economics, Inc. (IEc), 2006. *Expanded Expert Judgment Assessment of the Concentration-Response Relationship Between* $PM_{2.5}$ *Exposure and Mortality*. Prepared for the U.S. EPA, Office of Air Quality Planning and Standards, September.

Krupnick, A. J. and M. L. Cropper. 1992. The Effect of Information On Health Risk Valuations. Journal of Risk and Uncertainty. Vol. 5 (1): 29-48.

Laden, F., J. Schwartz, F. E. Speizer and D. W. Dockery. 2006. Reduction in Fine Particulate Air Pollution and Mortality: Extended follow-up of the Harvard Six Cities Study. Am J Respir Crit Care Med. Vol. 173 (6): 667-72.

Peters, A., D. W. Dockery, J. E. Muller and M. A. Mittleman. 2001. Increased particulate air pollution and the triggering of myocardial infarction. Circulation. Vol. 103 (23): 2810-5. http://www.circulationaha.org/cgi/content/full/103/23/2810.

Pope, C. A., 3rd, R. T. Burnett, M. J. Thun, E. E. Calle, D. Krewski, K. Ito and G. D. Thurston. 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. Jama. Vol. 287 (9): 1132-41.

Rosamond, W., G. Broda, E. Kawalec, S. Rywik, A. Pajak, L. Cooper and L. Chambless. 1999. Comparison of medical care and survival of hospitalized patients with acute myocardial infarction in Poland and the United States. Am J Cardiol. Vol. 83 (8): 1180-5.

U.S. Department of Commerce, Economics and Statistics Administration, Bureau of the Census. February 1996. CURRENT POPULATION REPORTS Population Projections of the United States by Age, Sex, Race, and Hispanic Origin: 1995 to 2050, P25-1130.

U.S. Department of Commerce, Economics and Statistics Administration, Bureau of the Census. July 2002. U.S. Summary: 2000, Census 2000 Profile, C2KPROF/00-US.

U.S. Department of Energy, Department of Energy (DOE). March 2009. Macroeconomic Indicators**,** Projection Tables (Table 20), Updated Annual Energy Outlook 2009 Reference Case Service Report,. Report #:DOE/EIA-0383(2009). http://www.eia.doe.gov/oiaf/aeo/index.html.

U.S. Environmental Protection Agency (EPA). September 2008. BenMAP User's Manual. Office of Air Quality Planning and Standards Research Triangle Park, NC.

Viscusi, W. K., W. A. Magat and J. Huber. 1991. Pricing Environmental Health Risks—Survey Assessments of Risk—Risk and Risk—Dollar Trade-Offs For Chronic Bronchitis. Journal of Environmental Economics and Management. Vol. 21 (1): 32-51.

Woods & Poole Economics Inc. 2007. Complete Demographic Database. Washington, DC. http://www.woodsandpoole.com/index.php.

APPENDIX A
EXPERT WORKSHOP

RTI INTERNATIONAL | Memorandum

TO: Amy Lamson (Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency)

FROM: Carol Mansfield (RTI International)
Amir Moktari (RTI International)
Paramita Sinha (RTI International)
Max Henrion (Lumina Decisions Systems)

DATE: February 13, 2009

SUBJECT: Influence and Uncertainty Analysis of Human Health Benefits Estimates: Capturing Uncertainty in Input Data and Uncertainty Introduced in BenMAP Modeling Workshop

On December 15 and 16, 2008, the Office of Air Quality Planning and Standards (OAQPS) of the U.S. Environmental Protection Agency (EPA) held an expert workshop to solicit input on their planned influence analysis of the human health benefits of reductions in particulate matter (PM). The meeting was held at the OAQPS office in Research Triangle Park, North Carolina.

OAQPS is developing a model to conduct an influence analysis on the uncertain parameters, functions, and input data used to calculate the benefits of reductions in PM using BenMAP, the software program OAQPS uses to estimate economic benefits for many regulatory analyses. The model will be used to help OAQPS identify the degree to which uncertainty about key parameters and functional forms affects the benefits analysis. Long term, this analysis will help prioritize future research and provide a template for conducting influence analyses on other benefit assessments. The influence analysis will use Analytica software to create a simplified representation of BenMAP's calculations.

The workshop focused on uncertainty in population forecasts, valuation of mortality, and valuation of acute myocardial infarctions (AMIs) and chronic bronchitis in BenMAP. Outside experts were asked for input on the sources of uncertainty, structure of the influence analysis model, and the range of values that OAQPS should consider.

Specifically, the goals of the workshop were to

- Ensure important sources of uncertainty were not omitted, focusing first on the population data and forecasts and valuation techniques and estimates;
- evaluate the simplified model OAQPS is creating to conduct the influence analysis;
- solicit appropriate range data and distributions for uncertainty parameters and alternative functional form assumptions for model uncertainty to use in the sensitivity analysis; and

- solicit input on the methodology for the sensitivity analysis.

Before the workshop, OAQPS and RTI International identified a set of experts on population forecasting, morbidity and mortality valuation, and uncertainty analysis to participate in the workshop. OAQPS also indentified EPA staff to be included. Appendix A provides a list of the participants. The participants were e-mailed a guide that provided the goals of the workshop, an agenda, background information, and several tables that listed the sources of uncertainty related to population forecasting, mortality valuation, and morbidity valuation identified before the workshop. The Participants Guide is included in Appendix B.

1. Overview

The 1.5 day meeting was divided into seven sessions. The first three sessions included an introduction by Amy Lamson (EPA), an overview of BenMAP by Neal Fann (EPA), and an overview of the simplified Analytica model proposed for the influence analysis by Max Henrion (Lumina Decision Systems). The next three sessions each focused on a different topic, including population forecasting, valuation of mortality, and valuation of morbidity. For each discussion, Max Henrion presented the sources of uncertainty identified by the planning team before the workshop and how they fit into the Analytica model. After the presentation, the workshop participants spent 5 minutes thinking about the topic and additional sources of uncertainty. After 5 minutes, the participants at each table discussed their thoughts on sources of uncertainty with each other. This discussion was followed by a group discussion where each table reported sources of uncertainty they identified, and Ken Elstein (EPA) summarized the discussion on a computer linked to an overhead projector. Next, each participant spent time thinking about whether each source of uncertainty could be quantified, the possible range of values or functions that could be used in the influence analysis, and any comments on the uncertainty. Again, after the individual brainstorming, the participants at each table discussed their ideas and then each table reported back to the whole group. The group also discussed areas of agreement and disagreement, which were captured by Ken Elstein. The final session started with a review of the Analytica model by Max Henrion followed by a group discussion on the approach to the current influence analysis and on ways to model the uncertainty in BenMAP.

2. Session 2: Overview of BenMAP

Neal Fann presented an overview of BenMAP (slides in Appendix C). The main steps in BenMAP can be summarized as follows:

- Step 1: Use studies to find relative risk estimates that show the relationship between pollutant concentration and the health effect. Find the incremental change in the health outcome based on a unit change in concentration (β) with standard error.
  - Note: BenMAP does not model population exposure, assuming all exposure occurs where the population resides.
  - Note: For some functions, EPA includes threshold-adjusted functions in BenMAP that refit the data for the threshold model from the original nonthreshold model (in the original epidemiology study).
- Step 2: Apply the health impact function from Step 1 to the incremental air quality improvement for the population and background incidence rate in each air quality grid square to estimate the change in health outputs.
  - Note: BenMAP includes preloaded national-level health data and applies it to a smaller-scale area such as the grid size associated with the air quality data (typically 12 km square or 36 km square). If local-scale data is available, it can be loaded into BenMAP.
  - Note: County-level population is mapped to the air quality grid squares before being imported into BenMAP using a program called Popgrid.
- Step 3: Value health outcome using willingness to pay (WTP) or cost of illness (COI) estimates by multiplying the change in health incidence by WTP or COI. In BenMAP, a distribution of health outcome incidence and a distribution of WTP or COI are created, and random draws from both distributions create the distribution of total benefits.

3. Session 3: Overview of Simple Analytica Model of BenMAP

Max Henrion presented an overview of the simple model of BenMAP he has created using Analytica software (slides in Appendix C). The objectives for the model are to (1) identify sources of uncertainty in BenMAP, (2) visualize how the sources of uncertainty affect the results using an influence diagram, (3) assess the range of values of key uncertainties, and (4) compare their relative contributions to the results using sensitivity analysis. The simplified Analytica model will be calibrated to BenMAP by comparing the output of the simplified model at different steps with runs of BenMAP.

BenMAP is a complex program with a lengthy running time for large-scale analyses, and conducting an extensive influence or sensitivity analysis with BenMAP would be time consuming. With a simplified model of BenMAP, we can conduct initial influence analysis to identify parameters or functional form assumptions that have the biggest impact on the outcomes of the benefits analysis, including both health incidence and monetary benefits. The simplified model allows us to test parameters over a wide range of values without requiring excessive

resources. Analytica provides a flexible and transparent format for the analysis. Max Henrion presented an example using tornado graphs to show sensitivity of the simplified model to different sources of uncertainty based on fabricated data.

To reduce the size of the data set and the complexity of the Analytica model, the air quality grid squares were aggregated into 16 bins based on initial ambient air quality concentration. We also evaluated sensitivity to the level of aggregation (e.g., instead of 16 bins we can use a smaller number of bins). More concentration bins means more detail and decreasing aggregation. A variety of aggregation issues can be addressed, including spatial and temporal, over age groups and across endpoints.

The participants discussed some of the assumptions used to create the Analytica model and pointed out some differences between the way BenMAP treats certain aspects of the model and the way the preliminary Analytica model does. For example, uncertainty varies depending on the control strategy. The control strategy that generated data used for this example is a more urban-focused control strategy. A different control strategy might have a different level of uncertainty if it is a more regional approach. With the binning approach, one may lose the ability to consider the geographic impact of applying policy changes. To address these concerns, the Analytica model will need to be tested using several control strategies and different assumptions about bin size and then calibrated to BenMAP.

The following changes in terminology were requested:

- Use “avoided premature mortalities” instead of “lives saved”
- Use “value of a statistical life” instead of “value of statistical life saved”
- Use “concentration-response” instead of “dose-response”
- Use “health impact function” instead of “health effects function”
- Use “monetized benefits” instead of “benefits” (unless referring generically to incidence reduction and monetized benefits)
- Use “total monetized benefits” instead of “net present value of benefits” (because we generally do not evaluate streams of benefits)
- Use “cessation lag” instead of “VSL adjusted for lag” (because we adjust the total mortality benefits, not the VSL specifically)

4. Session 4: Population

Max Henrion started the session with a presentation on how population enters the Analytica model (Appendix C). The experts were asked to think about additional sources of uncertainty not captured in the current model and for their judgment on the ranges for uncertain parameters. For

the influence analysis, we want plausible low, mid, and high values or perhaps the 10th percentile, median, and 90th percentile.

Much of the discussion centered on the factors that affect the accuracy of the Census population forecasts. The Census forecasts population at the national level and does not use an economic model to support the forecasts. Migration and immigration emerged as two factors that the Census projections may not capture well. BenMAP uses Woods and Poole to project the population data at the county level, and this dataset does include an economic component to its forecasts.

The group also discussed uncertainty introduced through the assignment of the population forecasts to the air quality grid squares. The air quality grid squares are at a finer resolution than the underlying health data. The Census data capture where people live, but people do not typically remain in one location throughout the day. The finer the resolution, the more likely that exposure will be misclassified if the population travels between grid squares during the day. A higher level of aggregation might be preferable. Participants suggested a case study (e.g., assign a population based on land use categories or check the sensitivity of one grid cell by assigning all of the population to a single grid square, such as the grid square with the highest PM2.5 concentration in the area).

The participants also discussed other measures of sensitivity. Experts were concerned that by defining ranges we would actually introduce another source of uncertainty. If the range is unknown, it may be more appropriate to use elasticity rather than range since a range can be misleading if one end is a low-probability event.

Discrete events that result in large-scale population and migration shifts within the United States (e.g., Hurricane Katrina) were discussed. Scenario analysis could be used to address the impact of discrete events. The importance of uncertainty in population forecasts after 2030 was thought to be most important for climate change and other policies where the benefits may not occur in the near future. Scenario analysis may be the way to address the uncertainty of population forecasts over a longer time period.

Recommendations

Overall, the population expert and others in the group felt that, although uncertainties related to population forecasting were certainly worth exploring, population uncertainties are perhaps not as large as other uncertainties in the model. For the influence analysis, the Census low, medium, and high forecasts were thought to provide a good range. For allocating population to counties, the Woods and Poole confidence intervals were thought to provide a good range.

5. Session 5: Premature Mortality Valuation

The session started with an overview from Max Henrion on how the estimates of premature mortality and the value of reducing the risk of premature mortality (mortality valuation) are generated in the simplified Analytica model of BenMAP (slides in Appendix C). Mortality valuation is often referred to in the economics literature as the value of a statistical life or the VSL, but it is really the value of reducing the risk of premature mortality. EPA uses a single VSL function (a normal distribution with a mean of $5.5 million) that does not vary across people (e.g., demographics, health status, or cause of death). Because exposure in a particular year will cause premature deaths in the future, the monetized benefits are discounted to account for the cessation lag, typically over 5 years to 20 years.

There was a lively debate on whether VSL should be treated as a policy decision, rather than an uncertain empirical value. VSL measures the value of a reduction in mortality risk to an individual. VSL is internally consistent within the utilitarian framework, which is the framework for benefit-cost analysis. Some argued that policy makers should use alternative VSL frameworks (e.g., social choice, altruism, revealed preference for government programs). The current VSL estimates do not value the distribution of risk within the population (e.g., environmental justice issues).

The discussion identified a number of factors that influence both the degree of uncertainty (in the strict sense of the word) associated with VSL estimates and the variability in VSL across individuals or over time as individuals age or wealth increases. Personal characteristics that may cause VSL to vary across individuals include age, health status, income or wealth, number of children, differing preferences over the characteristics of the risk (voluntary, unknown, dread factor), cultural factors, and wealth.

VSL values have been estimated using both revealed preference (RP) studies and stated preference (SP) studies. The RP studies mostly look at the trade-off between wages and job risk. The population in RP studies (healthy, working-age adults) and the type of risks differs (mostly sudden death from a workplace accident or homicide) from populations susceptible to premature mortality from PM exposure, which, on average, will be older and less healthy). SP studies are more likely to value risks similar to those associated with PM exposure such as the risk of chronic illnesses like cancer or other chronic diseases. Most SP studies survey the general population and include older adults and individuals with compromised health status. One suggestion from the participants was to use VSL studies that match more closely the type of risk posed by exposure to PM and to compare the range of SP and RP studies. Finally, WTP can be elicited for risk of death in the future. WTP for risk of death in the future could replace the

assumed lag structure currently used for benefits analysis, which could be described as somewhat ad hoc based on several interpretations of the epidemiology data.

Participants discussed the income elasticity of VSL and thought, in general, that it was not likely to be a large source of uncertainty. However, there were questions about using cross-sectional estimates of income elasticity to estimate elasticity over time.

Recommendations

Everyone recognizes the importance of the VSL in calculating the total benefits of a reduction in PM. For the influence analysis, the range of $1 million to $10 million was supported by most participants, although a lower bound of $700,000 could also be considered. If we use the range from SP studies, it may be more like $1 million to $3 million.

6. Session 6: Morbidity Valuation

The session on morbidity valuation focused on chronic bronchitis and AMI. Max Henrion discussed how the incidence and value of the diseases enter the Analytica model (slides in Appendix C).

The participants discussed the general issue of WTP estimates and COI estimates. Theoretical differences in the costs captured by each measure and how to avoid double-counting were discussed. We are unaware of WTP estimates for AMIs, and the WTP estimates for chronic bronchitis are from SP studies with known problems, including the age of the studies, the small and unrepresentative sample, and advances in SP methodology since the studies were conducted. In addition, the studies compared risk/risk trade-offs with risk/dollar trade-offs and concluded the risk/risk trade-offs were more stable. The COI estimates were also thought to be dated. Medical costs, technology, and public awareness of diseases and treatments have all changed significantly over time.

Some questions raised by the participants related to the health and epidemiology literature. The severity of PM-related AMIs and chronic bronchitis are not known, which complicates the task of deciding which WTP or COI estimates are appropriate. Participants suggested that the model consider several disease trajectories with different cost implications. Another source of uncertainty relates to sequelae resulting from PM-related AMIs and chronic bronchitis, costs beyond the hospital stay, costs to unpaid caregivers, and long-term impacts on life expectancy and quality of life. Assumptions about the duration of the illnesses and the proper discount rate were raised. A number of sources for uncertainty and variability came up in the discussion, including regional and urban/rural variation in medical costs, gender, age, and health status.

Finally, the group also discussed the best methods for pooling the results from several studies for morbidity endpoints.

Recommendations

For AMIs, the participants thought that we should search for more recent COI estimates to get a better sense of the range of possible costs and use all the available studies to create the range of values. Several studies have shown that WTP tends to be a factor of 2 larger than COI for the same health endpoint, and those studies together with WTP studies for related diseases could be compared to COI. Wage losses for individuals under age 27 and over 65 should be included in the range.

For chronic bronchitis, participants suggested we use the WTP values for most severe and least severe in the range. They also suggested that COI estimates be incorporated.

For both morbidity endpoints, the suggested range was ½ COI in existing BenMAP studies (if newer estimates cannot be found) to the top end of COI + WTP + adjustments for sequelae costs and other excluded categories.

7. Session 7: Discussion and Recommendations on Approach to Influence and Uncertainty Analysis

In the final session, Max Henrion reviewed the simplified BenMAP model being developed using Analytica software for the influence analysis (slides in Appendix C, revised influence diagrams in Appendix D). The discussion focused on the approach being proposed for the influence analysis and solicited comments and suggestions from the workshop participants.

The influence analysis will start by creating a Tornado diagram. For each parameter or functional form assumption, the model is run using the range of possible values for the parameter or functional form holding all the other parameters at their mean value. The Tornado diagram stacks the range of total benefits associated with the range of the parameter value (or functional form assumptions) from the parameters and functional form assumptions that generate the largest range in total benefit estimates down to the smallest.

The Tornado diagram does not account for interactions between parameters or between parameters and functional form assumptions. There was a discussion about how to handle interactions. One suggestion by several participants was to use probabilistic sensitivity analysis measures such as rank correlations and regression measures. However, one participant felt strongly that we should not make any assumptions about probability distributions where we did

not have information about the distribution. Instead, it was suggested that a response surface using Latin hyper-cube points could be created.

Recommendations

The list of recommendations summarizes a variety of perspectives and does not represent a consensus on the part of the participants.

- Conduct analysis both using Tornado diagram and allowing for interactions.
- Conduct comparisons between the results of the simplified Analytica model of the BenMAP model and runs from BenMAP itself to make sure the Analytica model will provide results that mimic the results that would have been achieved using BenMAP itself.
- Identify parameters and functional form assumptions that have the largest impact on the outcomes of interest (monetary benefits and health incidence). Explore these sources in more detail.
- Explore the sensitivity of both the monetary value of benefits and the incidence of the health endpoints, since both are important to people.
- After influence analysis identifies potentially influential parameters and functional form assumptions, EPA will assess the level of resources that might be needed to reduce the uncertainty.
- Use two or three different control scenarios to generate reductions in concentrations. Whether the reductions are local or regional, or just an overall percentage reduction, may affect the relative importance of the parameters.

The discussion also included ideas on how to refine the simplified model:

- Initially, the model assumes that the entire exposed population in each base concentration bin experiences the same reduction in PM2.5 concentration levels (averaged over the reductions for all grid squares in that bin). Later, if time permits, we could expand the bins into a bin array with a second dimension of concentration reductions for each of the concentration bins and see if this reduces the aggregation uncertainty. Therefore, each bin would include grid squares with the same baseline concentration and the same reduction in concentration.
- The model does not differentiate among population segments (i.e., race, ethnicity, or gender). Initially, the model uses an average across age groups, but this will be refined for the final analysis.

Appendix A : Participant List

Soad Benromdhane, OAQPS, HEID
Lillian Bradley, OAQPS, HEID
Linda Chappell, OAQPS, AQAD
Ken Davidson, OTAQ
Chris Dockins, OPEI, NCEE
Ken Elstein, ORD
Ron Evans, OAQPS, HEID
Neal Fann, OAQPS, HEID
Chris Frey, NCSU
Charlie Fulcher, OAQPS, HEID
Beth Hassett-Sipple, OAQPS, HEID
Brian Heninger, OPEI, NCEE
Max Henrion, Lumina
Bob Hetes, ORD, NHEERL
Bryan Hubbell, OAQPS, HEID
Alan Krupnick, RFF, econ
Amy Lamson, OAQPS, HEID
John Langstaff, OAQPS, HEID
Carol Mansfield, RTI
Amir Mokhtari, RTI
Ellen Post, Abt
Pradeep Rajan, OAQPS, HEID
Harvey Richmond, OAQPS, HEID
Paramita Sinha, RTI
Laura Taylor, NCSU, econ
Scott Voorhees, OAQPS, HEID
Paul Voss, UNC
Darryl Weatherhead, OAQPS, HEID

Appendix B : Participant Guide

Influence and Uncertainty Analysis of Human Health Benefits Estimates: Capturing Uncertainty in Input Data and Uncertainty Introduced in BenMAP Modeling

Participants Guide

U.S. Environmental Protection Agency
Research Triangle Park, NC
December 15–16, 2008

Dear Participant,

On behalf of the U.S. EPA, I would like to welcome you to the workshop. EPA's Office of Air Quality Planning and Standards organized this meeting to solicit your input on our planned influence analysis of the human health benefits of reductions in PM. A 2002 National Academy of Sciences report recommended that EPA conduct an Influence Analysis to improve uncertainty characterization in our benefits analyses and to identify the modeling elements and assumptions that have the largest influence on the human health benefits results. We will present a preliminary model for influence analysis focusing on the valuation of human health benefits associated with mortality and AMIs estimated using BenMAP. As we develop our approach, we want outside advice from experts like you on the sources of uncertainty, structure of the influence analysis model, and the range of values we should consider. The results of this analysis will help to prioritize future efforts to reduce uncertainty. We also plan to take the results of this report to EPA's Science Advisory Board sometime next year.

We have set three main goals for this workshop:

Desired Goals

1. Ensure we have not left out any important sources of uncertainty focusing first on the population data and forecasts and valuation techniques and estimates.
2. Evaluate the simplified model we are creating to conduct the influence analysis
3. Solicit appropriate range data and distributions for uncertain parameters and alternative functional form assumptions for model uncertainty to use in the sensitivity analysis
4. Solicit input on the methodology for the sensitivity analysis

Desired Outcomes

1. Comprehensive list of uncertainties in benefits analysis arising from population data/forecasts and from valuation approach.
2. Confirmation that simplified influence analysis model of BenMAP is accurate and complete
3. Appropriate range data and/or distributions to use in the sensitivity analysis
4. Enhanced understanding of the benefits analysis process and assumptions by participants
5. Methods for incorporating uncertainties into the sensitivity analysis

Your active participation is crucial to achieving these goals.

Please take a few minutes to familiarize yourself with this Participants' Guide, paying particular note to the "Meeting Principles" and "Lists of Uncertainties." If there is anything we can do to improve the workshop, do not hesitate to let me or the facilitator know. Thank you for your interest and participation in this workshop.

Sincerely,

Amy Lamson
Air Benefits and Cost Group
Office of Air Quality Planning and Standards
U.S. Environmental Protection Agency

Agenda for

Influence and Uncertainty Analysis of Human Health Benefits Estimates: Capturing uncertainty in input data and uncertainty introduced in BenMAP modeling
Classroom C112 in EPA Main Building, EPA RTP Campus
(109 T.W. Alexander Drive, RTP N.C. 27711)

Day 1: Monday, December 15th
Registration (8:30am to 9:00am)
Session 1 (9:00am to 9:30am): Welcome and Introductions—Amy Lamson, OAQPS

Session 2 (9:30am to 10:15am): Introduction to benefits and BenMAP—Neal Fann, OAQPS

Break (10:15am to 10:30am)

Session 3 (10:30am to 12.00pm): Overview of the simplified influence analysis model and project strategy—Max Henrion, Lumina Decision Systems

Lunch (12:00pm to 12:45pm): EPA cafeteria (on your own)

Session 4 (12:45pm to 2:45pm): Population estimates
12:45pm to 1:00pm: Identified sources of uncertainty in population estimates and uncertainty introduced by BenMAP modeling assumptions—Max Henrion, Lumina Decision Systems
1:00pm to 2:45pm: Discussion on current population estimates in BenMAP

- 5min Quiet brainstorming on the following questions:
  - Are there additional sources of uncertainty in population forecasts or introduced by BenMAP's use of the population data?
  - Do you think this will have big impact on benefits results?
- 15min Report out and discussion
- 10min Quiet brainstorming on the following questions:
  - Can/should this source of uncertainty be modeled quantitatively in the influence analysis?
  - What range of values should we use for these parameters or where can we get the range (i.e., from a study or existing data)?
  - Are there other functional forms or modeling approaches that make sense for this component of the model or what would be a good source for this information?
- 30min Small group discussion
  - Where do we agree and where do we disagree?

- 45min Report out and discussion

Break (2:45pm to 3:00pm)

Session 5 (3:00pm to 5:15pm): Valuation of mortality reduction
3:00pm to 3:30pm: Identified sources of uncertainty in valuation of mortality and uncertainty introduced by BenMAP modeling assumptions—Max Henrion, Lumina Decision Systems

- 3:30pm to 5:15pm: Discussion on valuation of mortality reduction
  - 5min Quiet brainstorming on the following questions:
    - Are there additional sources of uncertainty in valuation of mortality reductions or introduced by BenMAP's use of valuation studies?
    - Do you think this will have big impact on benefits results?
  - 15min Report out and discussion
  - 10min Quiet brainstorming on the following questions:
    - Can/should this source of uncertainty be modeled quantitatively in the influence analysis?
    - What range of values should we use for these parameters or where can we get the range (i.e., from a study or existing data)?
    - Are there other functional forms or modeling approaches that make sense for this component of the model or what would be a good source for this information?
  - 30min Small group discussion
    - Where do we agree and where do we disagree?
  - 45min Report out and discussion

Wrap-up (5:15 to 5:30)
Dinner with group 6:30pm (optional, otherwise on your own) Please let Carol Mansfield know if you are interested in the group dinner

Day 2: Tuesday, December 16th

Welcome (8:30am to 8:45am): Introduction, recap from Day 1—Amy Lamson, OAQPS

Session 6 (8:45am to 10:45am): Valuation of morbidity reduction

8:45am to 9:00am: Identified sources of uncertainty in valuation of mortality and morbidity reduction and uncertainty introduced by BenMAP modeling assumptions—Max Henrion, Lumina Decision Systems

- 9:00am to 10:00am: Discussion on valuation of morbidity reduction
    - 5min Quiet brainstorming on the following questions:
        - Are there additional sources of uncertainty in morbidity valuation or introduced by BenMAP's use of the morbidity valuation models?
        - Do you think this will have big impact on benefits results?
    - 15min Report out and discussion
    - 10min Quiet brainstorming on the following questions:
        - Can/should this source of uncertainty be modeled quantitatively in the influence analysis?
        - What range of values should we use for these parameters or where can we get the range (i.e., from a study or existing data)?
        - Are there other functional forms or modeling approaches that make sense for this component of the model or what would be a good source for this information?
    - 30min Small group discussion
        - Where do we agree and where do we disagree?

Break (10:00am to 10:15am)

- 10:15am to 10:45am: Discussion on valuation of morbidity reduction, con't
    - 30min Report out and discussion

Session 7 (10:45am to 12:20pm): Discussion and Recommendations on Approach to influence and uncertainty analysis—Max Henrion, Lumina Decision Systems

Closing (12:20 to 12:30) Wrap-up and Next Steps

Meeting Principles

1. **Everyone shares the responsibility for making the meeting a success**: This meeting is a true collaboration between all attendees, including the organizers and facilitators. Your active participation is critical. If you have an idea for a discussion topic or process suggestion, please share it orally and/or in writing through a posted note. If you have a criticism, please balance it with a solution.

2. **Stay on topic**: Start from the "big picture" before moving into details. Jumping to details prematurely can consume a lot of time on a topic that the group may later decide is unnecessary. A "Parking Lot" is available to post ideas/comments to ensure that they are addressed at the appropriate time.

3. **Listen and understand**: All participants bring to this meeting diverse experiences, ideas, knowledge, and perspectives. Inquire of others to understand their views before advocating your own.

4. **Be transparent:** Our assumption is that all participants are coming to this meeting with the intent of making the workshop more effective. Those with individual needs/concerns should make them known to the group so we can develop innovative approaches to meet all needs.

5. **First brainstorm, then critique**: The most creative ideas emerge when participants can build upon each other's suggestions. Often the seemingly wildest ideas stimulate true innovation. Avoid premature critiquing that can unintentionally shut down the creative process.

6. **Provide everyone an equal opportunity to speak**: Part of our diversity includes variations in how we prefer to express ourselves. Freely offer your perspectives in whatever way is most comfortable for you, and allow others the opportunity to express theirs.

7. **Commit to being fully present**: Please turn off cell phones, or put them on vibrate; put away the PDAs and Blackberrys. You can always check them during breaks.

Background Information

For more information regarding the model and type of analysis to be discussed during the workshop, please consult the following websites.

- Benefits analysis
  - OAQPS Economic Guidelines (1999): http://www.epa.gov/ttn/ecas/econdata/Rmanual2/0.0.html
  - EPA Guidelines for Preparing Economic Analyses: http://yosemite.epa.gov/ee/epa/eed.nsf/webpages/Guidelines.html#download

- EPA benefits analysis for PM
  - Regulatory Impact Analysis for Particle Pollution NAAQS (2006): http://www.epa.gov/ttn/ecas/ria.html
  - PM Benefits chapter: http://www.epa.gov/ttn/ecas/regdata/RIAs/Chapter%205—Benefits.pdf
  - PM Sensitivity analyses: http://www.epa.gov/ttn/ecas/regdata/RIAs/Appendix%20J—Additional%20Benefits%20Sensitivity%20Analyses.pdf

- BenMAP model
  - General Introduction: http://www.epa.gov/air/benmap/
  - Download version 3.0: http://www.epa.gov/air/benmap/download.html
  - BenMAP Manual: http://www.epa.gov/air/benmap/models/BenMapManualSept08.pdf
  - BenMAP Manual Appendices: http://www.epa.gov/air/benmap/models/BenMAPappendicesSept08.pdf

Table 1. List of Major Sources of Uncertainty (Parametric and Model) for Mortality in Different Simulation Steps of the BenMAP Model

BenMAP choice: Selected by user from choices in BenMAP
BenMAP default: Defined in BenMAP, user can sometimes import different data to change assumption
Input: Generated outside BenMAP

Modeling Step	Uncertainty Source	Uncertainty Type	Current Mortality Formulation in BenMAP
Population Data			
BenMAP choice	Selection of forecast year	Parameter Uncertainty, Forecast	▪ BenMAP allows the user to select the analysis year. Many recent analyses use 2020.
BenMAP default	Estimating population levels in non-census years—Population levels between 2000 and 2030	Parameter Uncertainty, Forecast	▪ Using county-level population scale factors based on, e.g., $age_{4\text{-}9,g,t}=age_{4\text{-}9,g,2000}\times age_{4\text{-}9,county,t}/age_{4\text{-}9,county,2000}$ For the g^{th} population grid cell and for $2000<t<2030$. Population forecasts for future years through 2030 based on a study by Woods and Poole (2007).
Input	Estimating population levels in non-census years—Population levels after 2030	Model Uncertainty, Forecast	▪ Even if user imports a new population dataset, it must be imported through Popgrid, which has this assumption built in ▪ Linear extrapolation after 2030,e.g., $age_{4\text{-}9,g,2035}=age_{4\text{-}9,g,2030}+5\times(age_{4\text{-}9,2030}-age_{4\text{-}9,2029})$
Input	Population distribution within an age group	Model Uncertainty, Functional form	▪ Uniformly distributed *within* each age group, e.g., $age_{3\text{-}12} = ½ \times age_{1\text{-}4} + age_{5\text{-}9} + 3/5 \times age_{10\text{-}14}$
Input	Forecasts of population from Woods and Poole	Parameter Uncertainty, Forecast	▪ Woods and Poole forecasts population based on projected economic conditions (county economies linked), natural increase, and migration due to economy at the county level (confidence intervals reported by Woods and Poole ±6.3%for metropolitan statistical areas and ±4.7%for states)
Input	Assigning population data to grid squares	Model Uncertainty, Functional form	▪ Popgrid (a separate program) assigns 2000 Census block data to grid squares for 304 race/ethnicity/gender/age groups, including population growth weights.

(continued)

Table 1. List of Major Sources of Uncertainty (Parametric and Model) for Mortality in Different Simulation Steps of the BenMAP Model (continued

Modeling Step	Uncertainty Source	Uncertainty Type	Current Mortality Formulation in BenMAP
Valuation			
BenMAP choice	VSL estimate	Parameter Uncertainty, Measured	▪ Uses mean for Value of Statistical Life (VSL) of $5.5 million (2000$), with range from $1 million to $10 million. ▪ Alternative distributions for the mean and range can be used.
BenMAP choice	Income elasticity of WTP	Parameter Uncertainty, Measured	▪ Income elasticity estimates for VSL from literature, mean of 0.40, lower bound 0.08 and upper bound 1.
Input	Income growth per person	Parameter Uncertainty, Forecast	▪ Standard & Poor's projections of future changes in Gross Domestic Product (GDP) occurring after the year 2010 ▪ Divide the projected change in GDP by the Woods & Poole projected change in total US population to produce an estimate of the future GDP per capita
Input	Lag structure in mortality	Model uncertainty, Functional form	▪ EPA considers alternative lag structures for PM-related pre-mature mortality (a) no lag effect (b) 8-year: incidences all occur in the 8th year following year of change in exposure (c) 15-year: incidences all occur in the 15th year following year of change in exposure (d) Alternative segments: 20% of incidence occur in the 1st year, 50% in years 2 to 5, and 30% in years 6 to 20 (e) 5-year distributed: 50% of incidences occur in years 1 and 2 and 50% in years 2 to 5 ▪ Exponential: incidences occur at an exponentially declining rate following year of change in exposure

(continued)

Table 1. List of Major Sources of Uncertainty (Parametric and Model) for Mortality in Different Simulation Steps of the BenMAP Model (continued

Modeling Step	Uncertainty Source	Uncertainty Type	Current Mortality Formulation in BenMAP
Valuation (continued			
BenMAP default	Income elasticity and income growth adjustment to WTP	Model Uncertainty, Functional form	$\varepsilon = \frac{\frac{\Delta WTP}{WTP}}{\frac{\Delta I}{I}} = \frac{(WTP_2 - WTP_1)*(I_2 + I_1)}{(I_2 - I_1)*(WTP_2 + WTP_1)}$ ▪ $\varepsilon I_2 WTP_2 + \varepsilon I_2 WTP_1 - \varepsilon I_1 WTP_2 - \varepsilon I_1 WTP_1 = I_2 WTP_2 + I_1 WTP_2 - I_2 WTP_1 - I_1 WTP_1$ $WTP_2 * (\varepsilon I_2 - \varepsilon I_1 - I_2 - I_1) = WTP_1 * (\varepsilon I_1 - \varepsilon I_2 - I_1 - I_2)$ $WTP_2 = WTP_1 * \frac{\varepsilon I_1 - \varepsilon I_2 - I_2 - I_1}{\varepsilon I_2 - \varepsilon I_1 - I_2 - I_1}$
BenMAP default	Choice of baseline currency year for GDP and WTP	Parameter Uncertainty, Measured	▪ BenMAP uses year 2000 baseline
BenMAP default	Conversion of WTP and GDP to real dollars	Parameter Uncertainty, Measured	▪ BenMAP has inflation indices for all goods, medical costs and wages using year 2000 baseline
BenMAP choice	Discount rate	Parameter Uncertainty, Measured	▪ EPA discounts benefits that occur after the analysis year at 3% and 7% ▪ Applies when there is a lag between exposure and mortality
C-R Function and Issues in the Estimation of Adverse Health Effects			
BenMAP choice	Functional form of the C-R function	Model Uncertainty, Functional form	▪ Alternative functional forms are sometimes available to represent C-R relationship including linear, log-linear, logistic, and Cox proportional hazard models

(continued)

Table 1. List of Major Sources of Uncertainty (Parametric and Model) for Mortality in Different Simulation Steps of the BenMAP Model (continued

Modeling Step	Uncertainty Source	Uncertainty Type	Current Mortality Formulation in BenMAP
C-R Function and Issues in the Estimation of Adverse Health Effects (continued)			
BenMAP choice	PM Coefficient (β) in the C-R function	Parameter Uncertainty, Measured	▪ Each mortality study including expert opinion assumes a distribution representing uncertainty in β value and a mean value. Example distributions include normal, weibull, and triangular
BenMAP choice	Threshold in the C-R function	Parameter Uncertainty, Measured	▪ EPA estimates a point estimate threshold below which there is no change in incidence rate associated with change in air pollution concentration, e.g., for a log-linear C-R model: $\Delta y=y_0\times[\exp(\beta\times(\max(PM_1,T)-\max(PM_0,T)))-1]$ Where, T is the threshold
BenMAP choice	Select air quality metric in BenMAP to match metric in epi study	Parameter Uncertainty, Measured	For PM2.5, EPA currently uses C-R functions that use a quarterly average air quality concentration. BenMAP creates an annual average by averaging the 4 quarterly averages; quarterly averages are average of daily 8 hour average.
BenMAP choice	Conversion of air quality metrics reported in epi studies to common metric	Parameter Uncertainty, Measured	Currently only done for ozone, not PM
BenMAP default	Extrapolation beyond PM concentration in study	Parameter Uncertainty, Extrapolate beyond range	BenMAP makes no adjustment if PM levels resulting from regulation are outside the range of PM levels from the study
BenMAP choice	Current exposure and cumulative exposure	Parameter Uncertainty, Measured	Studies do not account for effect current exposure versus cumulative exposure for current and lagged mortality
BenMAP default	Differential toxicity of PM components	Parameter Uncertainty, Measured	Assumes equal toxicity, no mechanism in BenMAP for adjusting this assumption

(continued)

Table 1. List of Major Sources of Uncertainty (Parametric and Model) for Mortality in Different Simulation Steps of the BenMAP Model (continued

Modeling Step	Uncertainty Source	Uncertainty Type	Current Mortality Formulation in BenMAP
Incidence Rates			
BenMAP choice	Mortality Baseline Incidence Rates	Model Uncertainty, Functional form and aggregation	▪ Age, cause, and county-specific mortality rates were obtained from CDC for years 1996 through 1998 by county ▪ CDC's age groups include <1, 1–4, 5–9, 10–14, 15–19, 20–24, 25–34, 35–44, 45–54, 55–64, 65–74, 75–84, and 85+ ▪ Mortality rates are averaged across three years ▪ It is assumed that rates are uniformly distributed across all ages in the reported age group
BenMAP choice	Choice of incidence baseline year	Parameter uncertainty, Measured	▪ Age, cause, and county-specific mortality rates were obtained from CDC for years 1996 through 1998 by county ▪ Mortality rates are averaged across three years
BenMAP default	Forecast baseline incidence rates	Parameter Uncertainty, Forecast	▪ Project CDC Wonder county and age-specific mortality rates for 1997 to future years using Census projections of national age-specific mortality rates from 1999 through 2050. Adjust county and age-specific 1997 CDC Wonder rate by ratio of Census projection for year Y to the estimated Census age-specific mortality rate for 1997 (1997 Census mortality rate estimated by regressing mortality rates from 1999–2008 on year). ▪ All segments of the population assumed to grow at same rate
Input	Assigning baseline incidence to grid cells	Model Uncertainty, Aggregation	▪ Baseline incidence rates assigned to grid cells in BenMAP, not clear how
Air Pollution and Exposure Estimation Algorithm			
BenMAP choice	Assigning air pollution data to grid-cell population data, monitoring values versus actual exposure	Model Uncertainty, Aggregation	▪ People living within a particular air pollution model grid-cell experience the same air pollution levels

(continued)

Table 1. List of Major Sources of Uncertainty (Parametric and Model) for Mortality in Different Simulation Steps of the BenMAP Model (continued

Modeling Step	Uncertainty Source	Uncertainty Type	Current Mortality Formulation in BenMAP
Air Pollution and Exposure Estimation Algorithm (continued)			
BenMAP choice	Size of air quality grid cell/CMAQ grid cell size	Parameter Uncertainty, Measured	▪ Select grid cell size based on air quality inputs, typically36km, 12 km, or smaller grid cell size
BenMAP choice	Monitor Rollbacks in BenMAP (in analysis of regulation, all monitors are assumed to meet the previous standard even if models forecast that they will not)	Model Uncertainty, Functional form	▪ Percentage rollback: monitor observations rolled back by a fixed percentage for values over defined background level ▪ Incremental rollback: monitors observations rolled back by a fixed increment for values over defined background level ▪ Rollback to standard: set values to determine if monitor in attainment, monitors not in attainment rolled back to attainment levels using one of several methods
Input	Monitor rollbacks to standard prior to BenMAP	Model Uncertainty, Functional form	▪ Monitor rollbacks conducted using air quality modeling data prior to importing the data into BenMAP
Input	Air Quality Modeling for baseline and control strategy	Parameter Uncertainty, Forecast	▪ Various changes in emissions assumptions, inventories, growth, spatial allocation, control strategy, baselines, spatial and temporal distributions, etc.
Unquantified and non-monetized benefits			
	WTP to avoid pain and suffering from the illness leading to death (not just the death itself)		
	Pain and suffering by family/friends (WTP by family and friends to prevent an individual's illness)		

Values for Sensitivity Analysis: Population Estimates **Reviewer Name:_____**

1	**Estimating population levels in non-census years—Population levels between 2000 and 2030**		
	BenMAP default, Parameter Uncertainty, Forecast		
	Analyze Quantitatively?	Minimum & Maximum Values or Source for Values; Functional Forms	Comments
2	**Estimating population levels in non-census years—Population levels after 2030**		
	Input, Model Uncertainty, Forecast		
	Analyze Quantitatively?	Alternative Functional Forms or Sources for Alternative Functions	Comments
3	**Population distribution within an age group**		
	Input, Model Uncertainty, Functional form		
	Analyze Quantitatively?	Alternative Functional Forms or Sources for Alternative Functions	Comments

4	**Forecasts of population from Woods and Poole**		
	Input, Parameter Uncertainty, Forecast		
	Analyze Quantitatively?	Minimum & Maximum Values or Source for Values	Comments
5	**Assigning population data to grid squares**		
	Input, Model Uncertainty, Functional form		
	Analyze Quantitatively?	Alternative Functional Forms or Sources for Alternative Functions	Comments
6	**Selection of forecast year**		
	BenMAP choice, Parameter Uncertainty, Forecast		
	Analyze Quantitatively?	Minimum & Maximum Values or Source for Values	Comments

7

Analyze Quantitatively?	Minimum & Maximum Values or Source for Values	Comments

8

Analyze Quantitatively?	Minimum & Maximum Values or Source for Values	Comments

9

Analyze Quantitatively?	Minimum & Maximum Values or Source for Values	Comments

Values for Sensitivity Analysis: Mortality Valuation **Reviewer Name:_____**

1 VSL estimate

BenMAP choice, Parameter Uncertainty, Measured

Analyze Quantitatively?	Minimum & Maximum Values or Source for Values; Functional Forms	Comments

2 Income elasticity of WTP

BenMAP choice, Parameter Uncertainty, Measured

Analyze Quantitatively?	Alternative Functional Forms or Sources for Alternative Functions	Comments

3 Income growth per person

Input, Parameter Uncertainty, Forecast

Analyze Quantitatively?	Alternative Functional Forms or Sources for Alternative Functions	Comments

4 Lag structure in mortality

Input, Model Uncertainty, Functional form

Analyze Quantitatively?	Minimum & Maximum Values or Source for Values	Comments

5 Income elasticity and income growth adjustment to WTP

BenMAP default, Model Uncertainty, Functional form

Analyze Quantitatively?	Alternative Functional Forms or Sources for Alternative Functions	Comments

6 Choice of baseline currency year for GDP and WTP

BenMAP default, Parameter Uncertainty, Measured

Analyze Quantitatively?	Minimum & Maximum Values or Source for Values	Comments

7 Conversion of WTP and GDP to real dollars

BenMAP default, Parameter Uncertainty, Measured

Analyze Quantitatively?	Minimum & Maximum Values or Source for Values	Comments

8 Discount rate

BenMAP choice, Parameter Uncertainty, Measured

Analyze Quantitatively?	Minimum & Maximum Values or Source for Values	Comments

9

Analyze Quantitatively?	Minimum & Maximum Values or Source for Values	Comments

10

Analyze Quantitatively?	Alternative Functional Forms or Sources for Alternative Functions	Comments

11

Analyze Quantitatively?	Minimum & Maximum Values or Source for Values	Comments

12

Analyze Quantitatively?	Minimum & Maximum Values or Source for Values	Comments

13

Analyze Quantitatively?	Minimum & Maximum Values or Source for Values	Comments

Appendix C: Slides for Sessions 2 through 7

Approaches to influence diagrams and sensitivity analysis for BenMAP

Max Henrion
Lumina Decision Systems
Los Gatos, CA

Carol Mansfield and Amir Mokhtari
RTI International
Research Triangle Park, NC

USA EPA,
Research Triangle Park, NC

15th December 2008

Lumina DECISION SYSTEMS

RTI INTERNATIONAL

Session 3: Overview of the simplified influence analysis model and project strategy

Max Henrion

Lumina Decision Systems
Los Gatos, CA

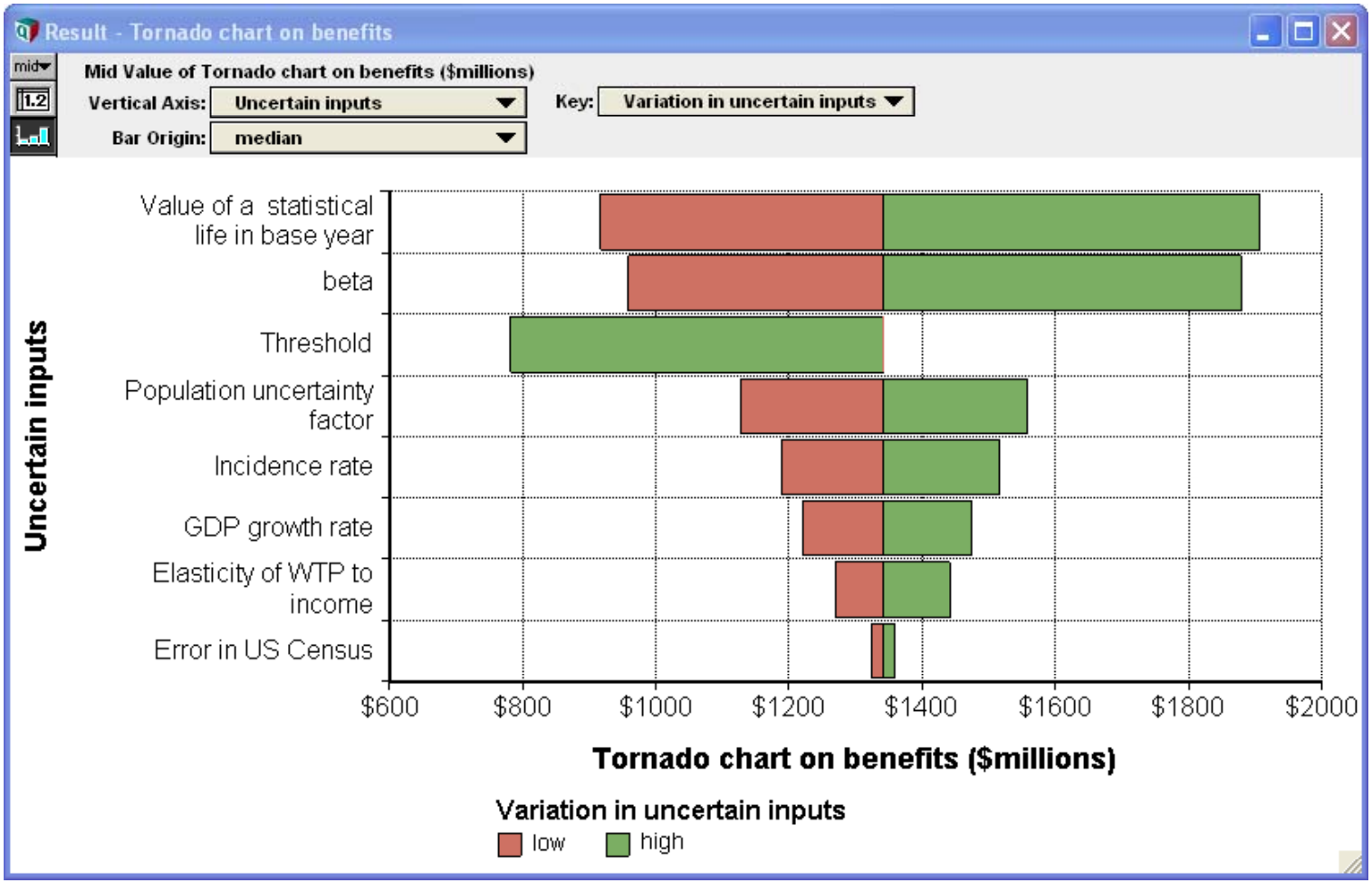
Objectives of the project

- To identify the sources of uncertainty in the assessment of benefits from improvements in air quality using BenMAP
- To visualize how the sources of uncertainty affect the results using influence diagrams
- To assess the range of values of key uncertainties
- To compare their relative contributions to the results using sensitivity analysis
- To identify which uncertainties are most in need of more careful characterization

Overview of strawman proposal for the approach

- Identify and classify the uncertainties and their effects
  - Develop an inventory of possible sources of uncertainty
  - Classify these sources in terms of source and type of uncertainty
  - Develop influence diagrams to visualize their effects on benefits
- Build model and conduct sensitivity analysis
  - Develop a simplified or reduced-form model
  - Assess ranges of plausible values for parametric uncertainties, and ranged of plausible alternative forms for model uncertainties
  - Conduct sensitivity analysis to identify their relative importance on results using various measures of sensitivity
- Compare the simplified model with BenMAP for selected scenarios to validate and calibrate it.
- Make recommendations on which uncertainties are most important to characterize in more detail and how

Example tornado diagram for sensitivity analysis



Any numbers and charts are purely illustrative.

Classifying sources of uncertainty

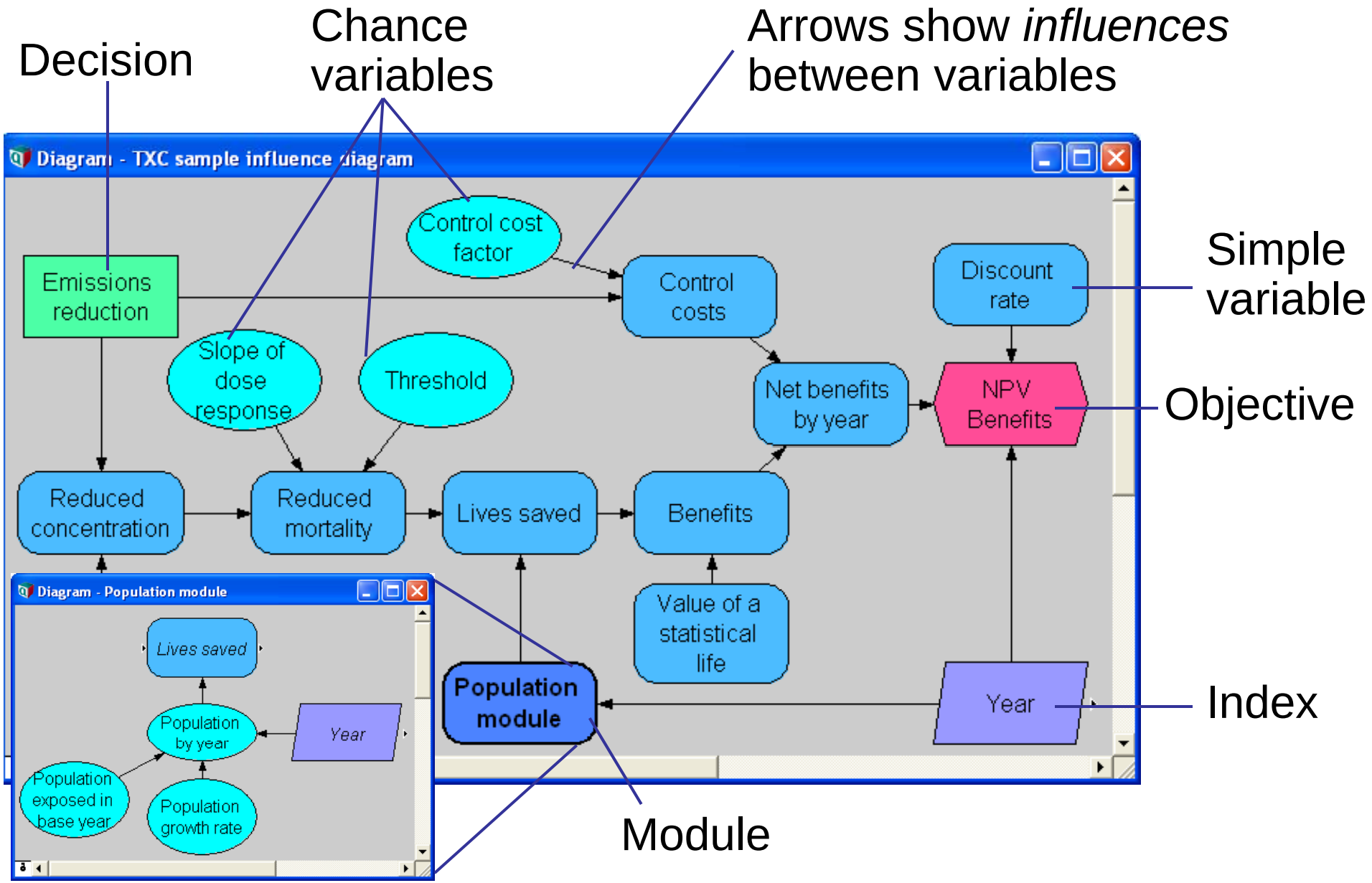
- **Uncertainties or assumptions within BenMAP**:
  - **Choice**: user can select value or option – e.g. forecast year for analysis, discount rate
  - **Input**: from input files – e.g. population projections
  - **Default**: method not easily modifiable
  - **Omitted**: issue not included in model – e.g. WTP to avoid pain and suffering, separate from mortality

- **Uncertainties that precede BenMAP** – such as:
  - Inputs and assumptions in emissions and air transport models, such as CMAQ,
  - air quality measurements
  - population projections, such as from Woods & Poole, BEA, and US Census, by country, aggregated to 30km grid by PopGrid
  - We examine the uncertainty in these inputs to BenMAP
  - But analysis of their sources of uncertainty is out of scope of this project.

Classifying types of uncertainty

- **Parameter uncertainties**
  - **Measured** (estimated) current or past values – e.g. population in recent census, current income levels, or incidence rates
  - **Forecast** or projection of future values – e.g. future population or income
  - **User choices** - e.g. year for analysis
  - **Policy variables** – e.g. discount rate, VSL(?)
- **Model uncertainties**
  - **Functional form** – e.g. for concentration-response function, or mortality lag from exposure
  - **Aggregation** – e.g. population from counties to 30km grid

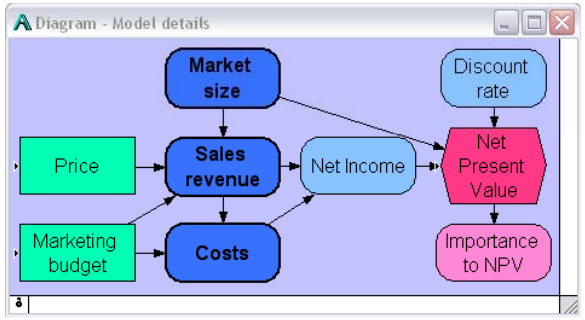
What is an influence diagram?

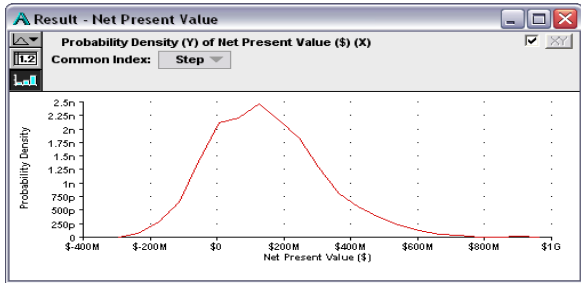


What is Analytica?

Analytica is a visual tool for building and deploying analytic applications. It offers:

- **Transparency:** Visual influence diagrams make models easier to create, understand, and audit.
- **Flexibility:** Intelligent Arrays™ make it easy to build and extend multi-dimensional models (data cubes)
- **Scalability:** Hierarchical modules, Intelligent Arrays, and ultra-compact code let you manage and run models much larger than is practical with spreadsheets.
- **Risk analysis:** Integrated Monte Carlo simulation enables fast evaluation of risk and uncertainty

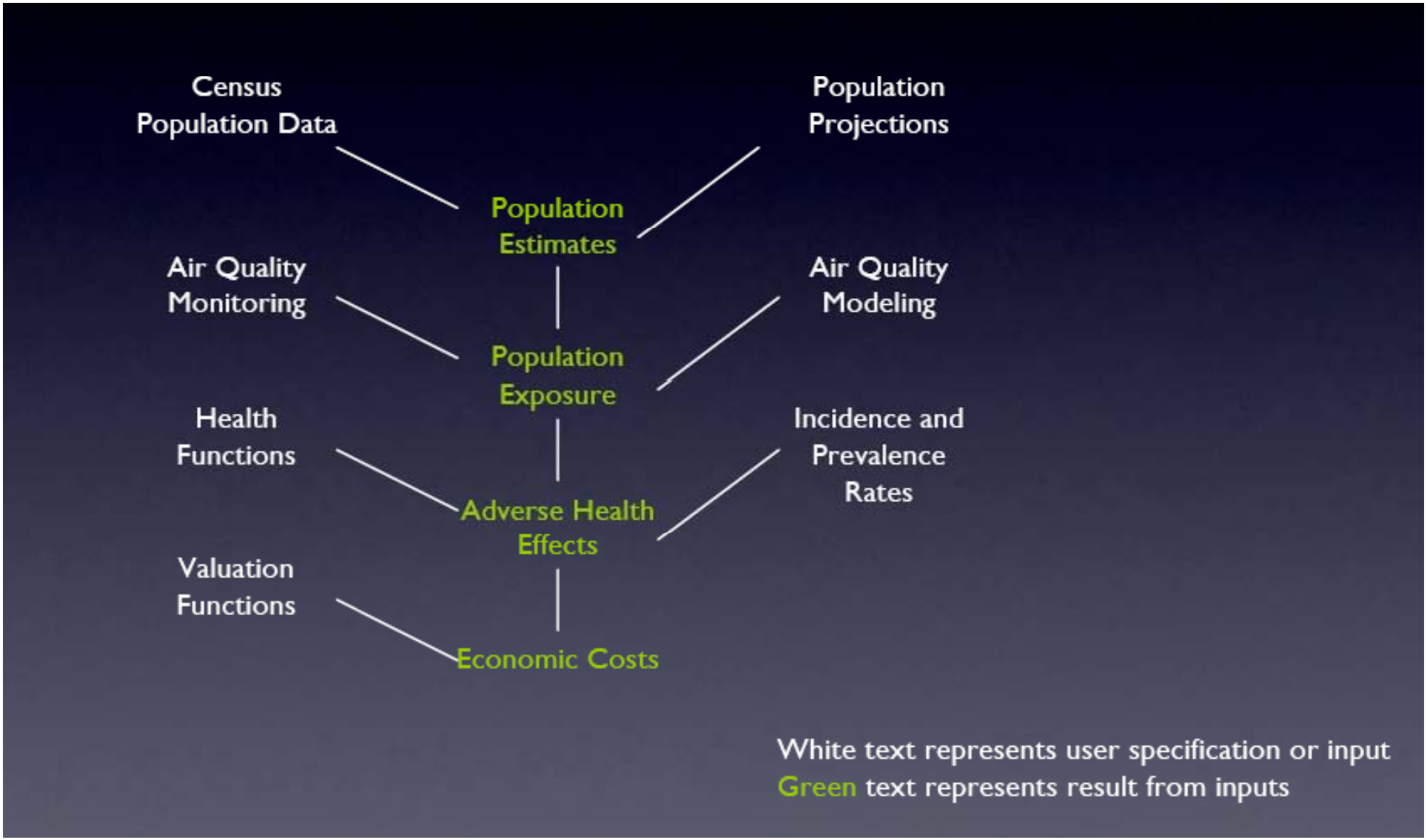




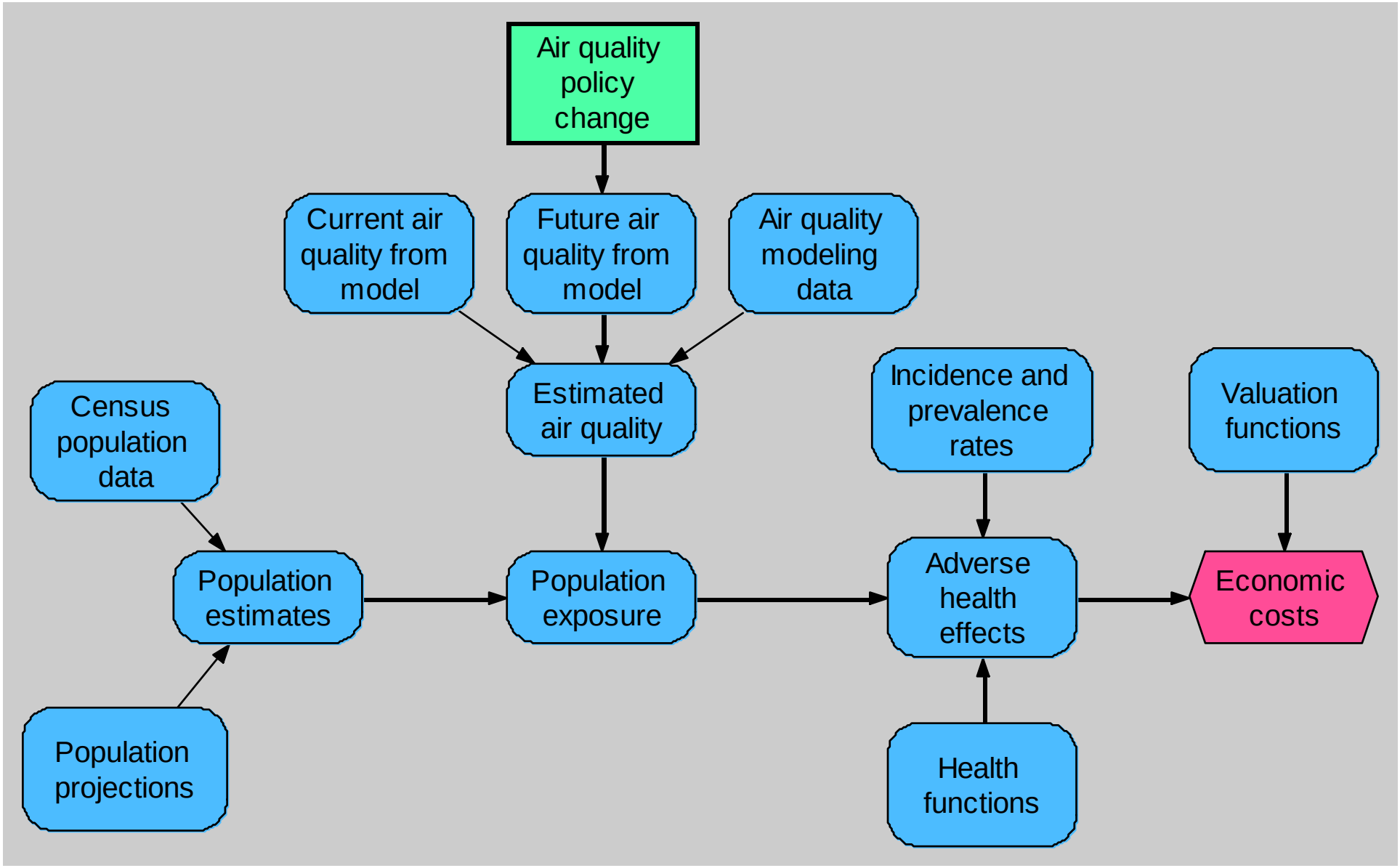
"Everything that's wrong with the common PC spreadsheet is fixed in Analytica", *PC Week*

Overview of BenMAP elements

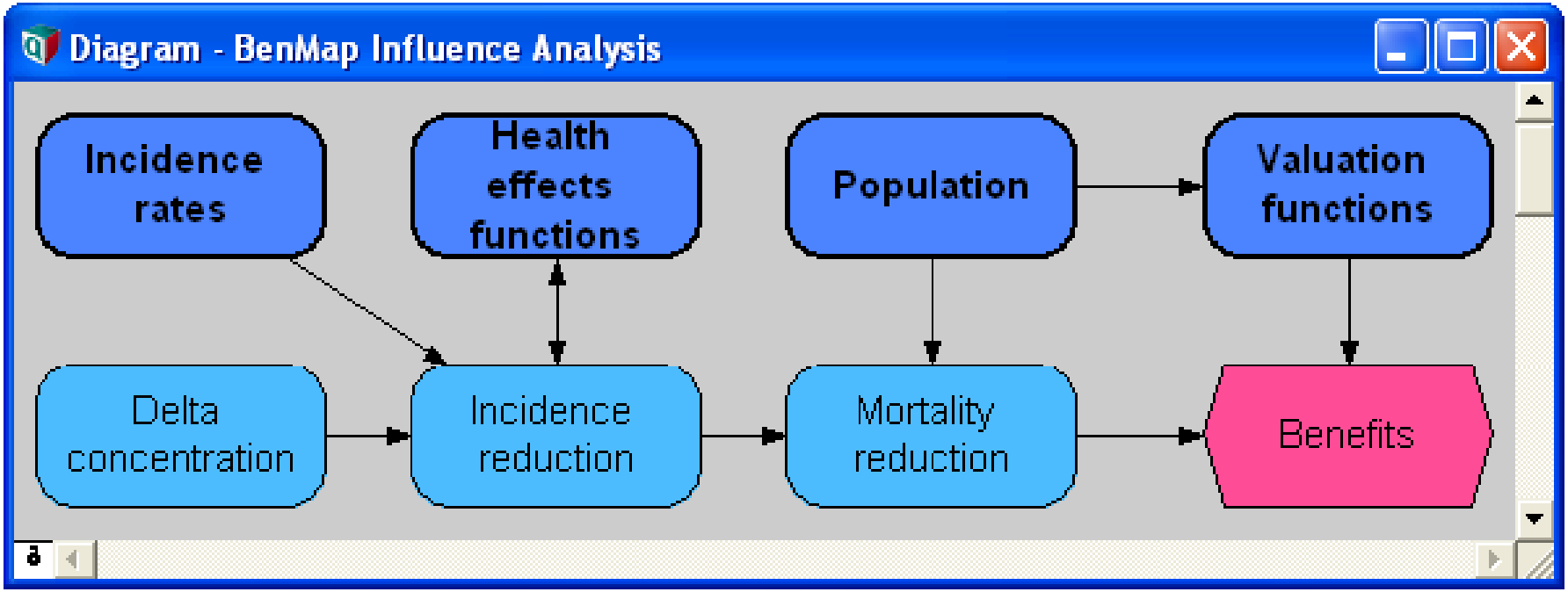
from BenMAP User Guide



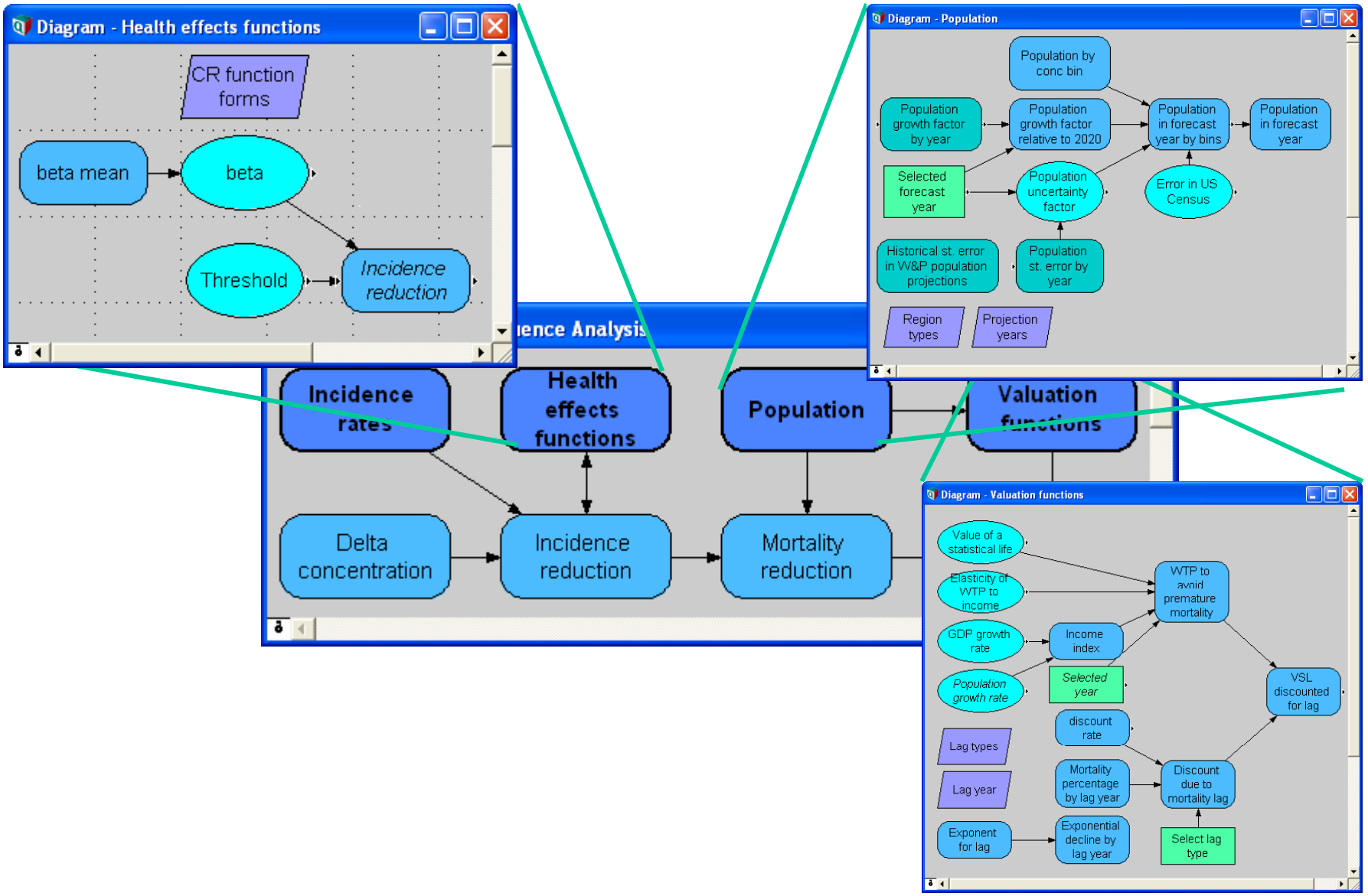
Influence diagram of BenMAP structure



Top level influence diagram: From strawman model



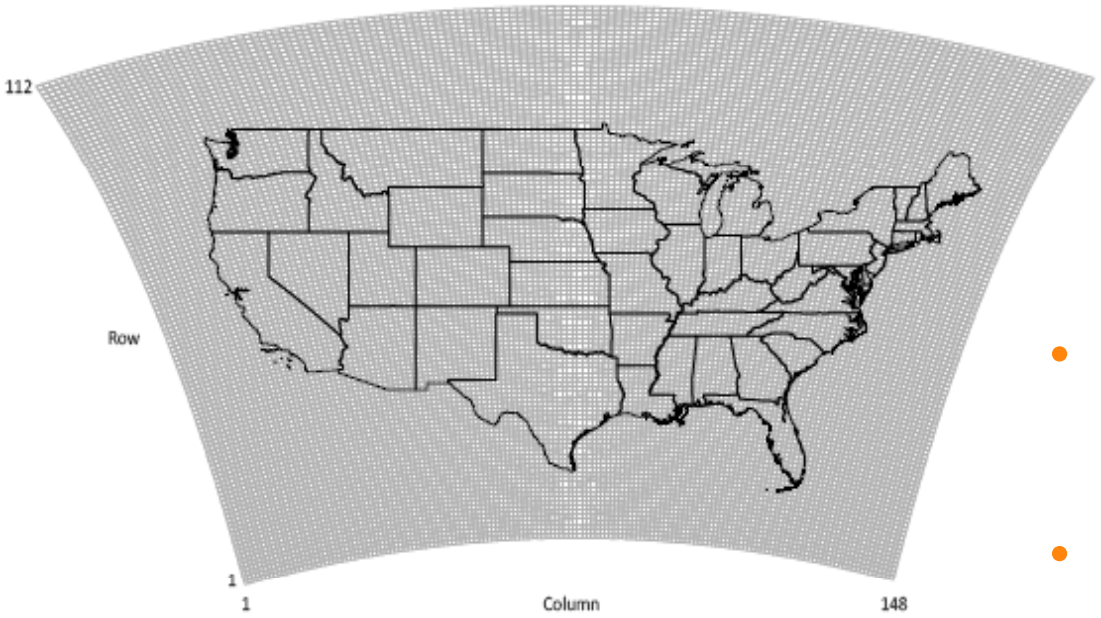
Influence diagrams for selected submodules



Why create a simplified model of BenMAP?

- BenMAP is too large and takes too long to perform a large number of runs for sensitivity analysis or Monte Carlo.
- For some kinds of uncertainty analysis, you need to modify model structure to handle dependencies appopriately.
- To explore the effects of alternative functional forms or aggregation, it's a lot easier to do on a simplified model
- Note: The simplified model is not a substitute for BenMAP: It could only be built because BenMAP exists and is available to calibrate it. It does not do mapping or analysis by grid square.

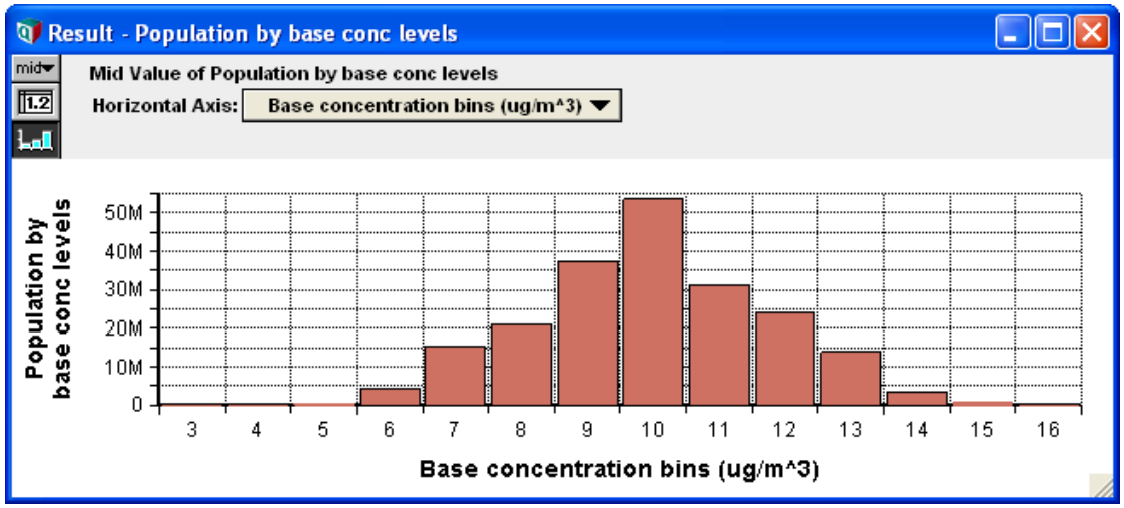
Binning grid square data to simplify the analysis



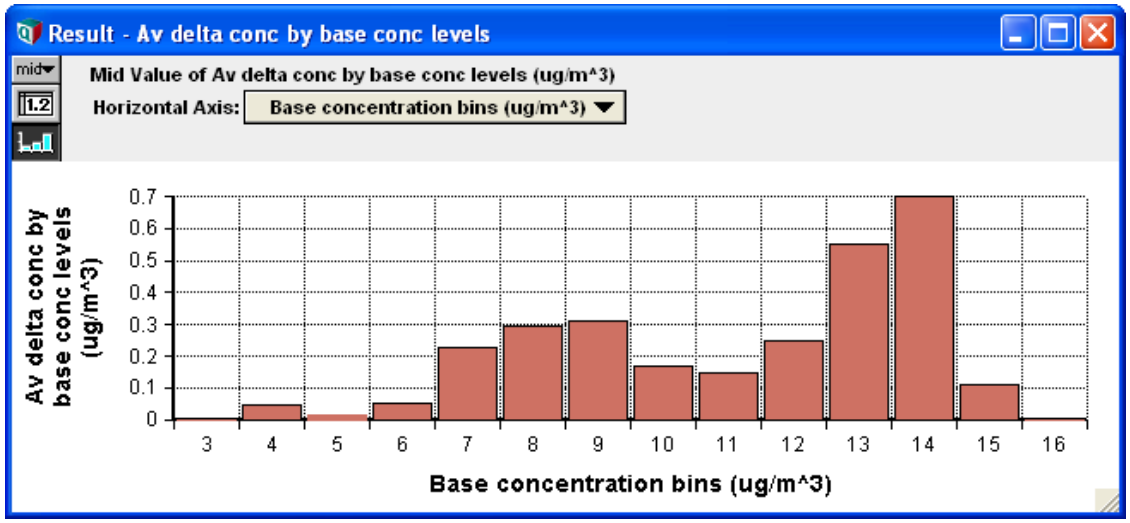
- We import data sets by 36km grid squares:
  - Population
  - Current PM2.5 concentration
  - Delta concentration w control
- We aggregate the grid square data into bins by base concentration levels
- This simplifies from 16,576 grid squares to about 16 bins - a factor of ~ 1000 times smaller

Results of binning

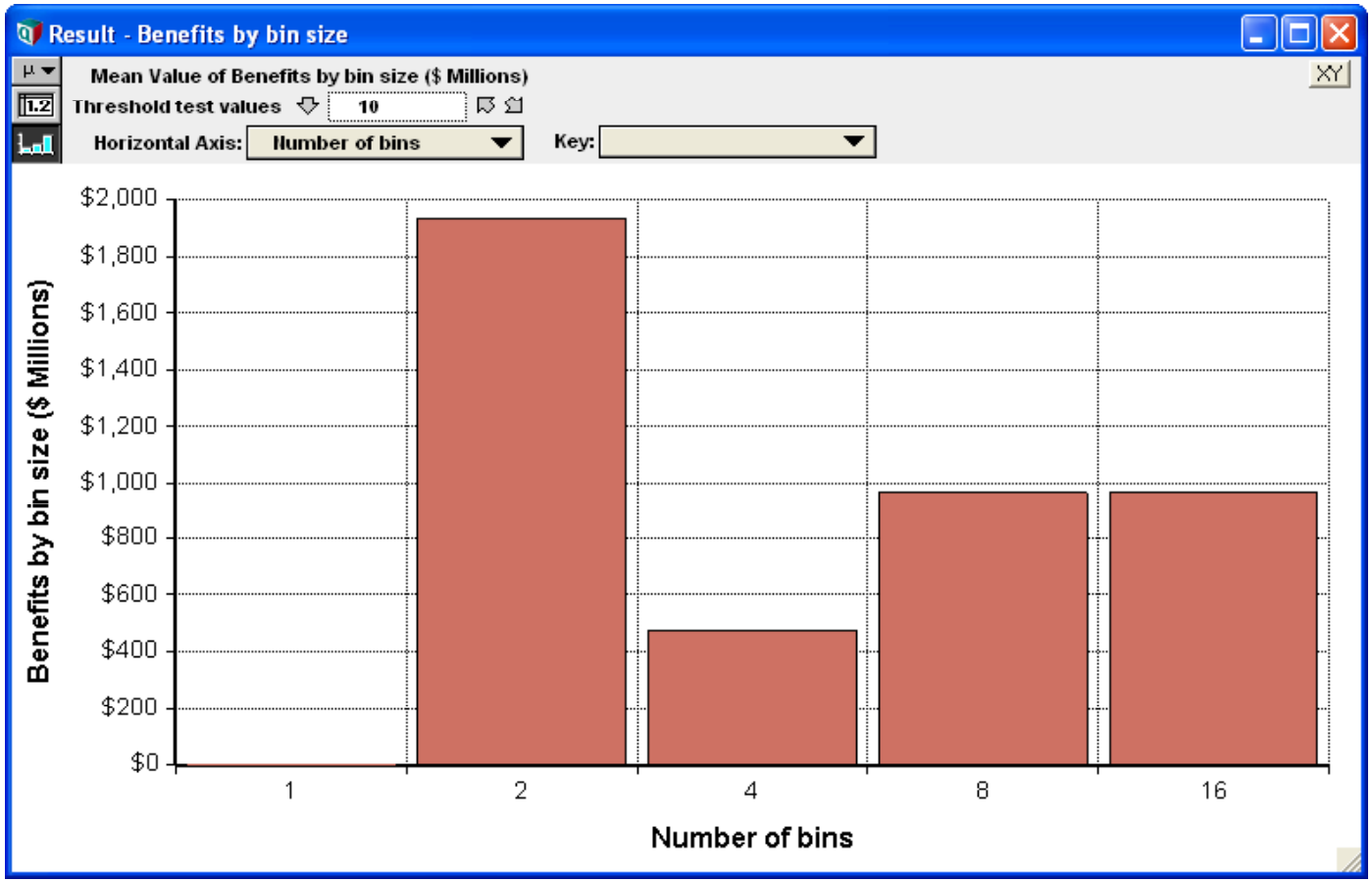
Population by base concentration bins



Delta conc. by base conc. bins

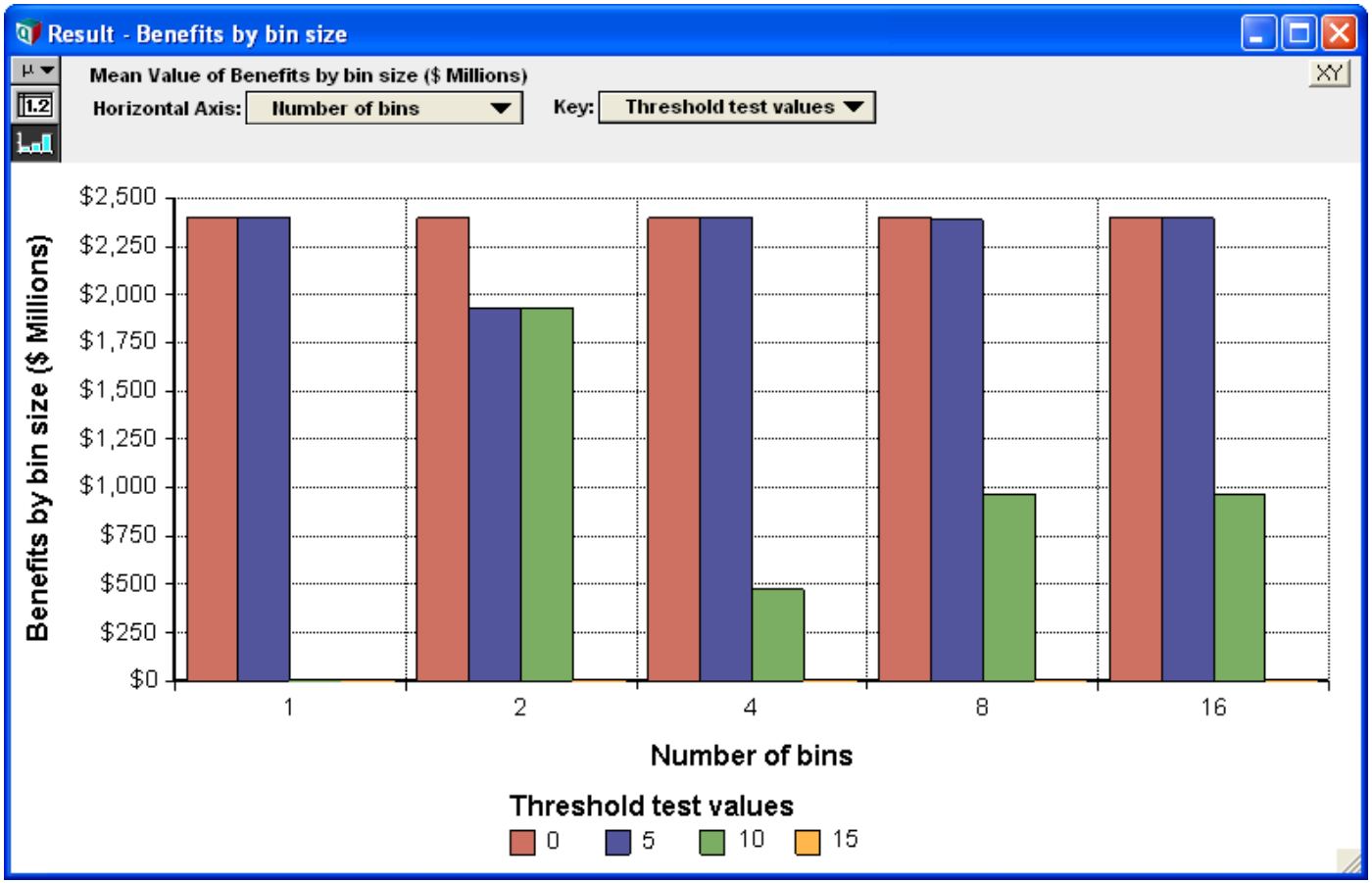


Sensitivity to the level of aggregation: By number of bins



More concentration bins means more detail, and decreasing aggregation.

Sensitivity to the level of aggregation: By number of bins



The sensitivity to aggregation level depends on the threshold of C-R function. For zero threshold, number of bins has no effect on results. (*Illustrative numbers only*.)

Where are we in this process? And what are we hoping to get from this workshop?

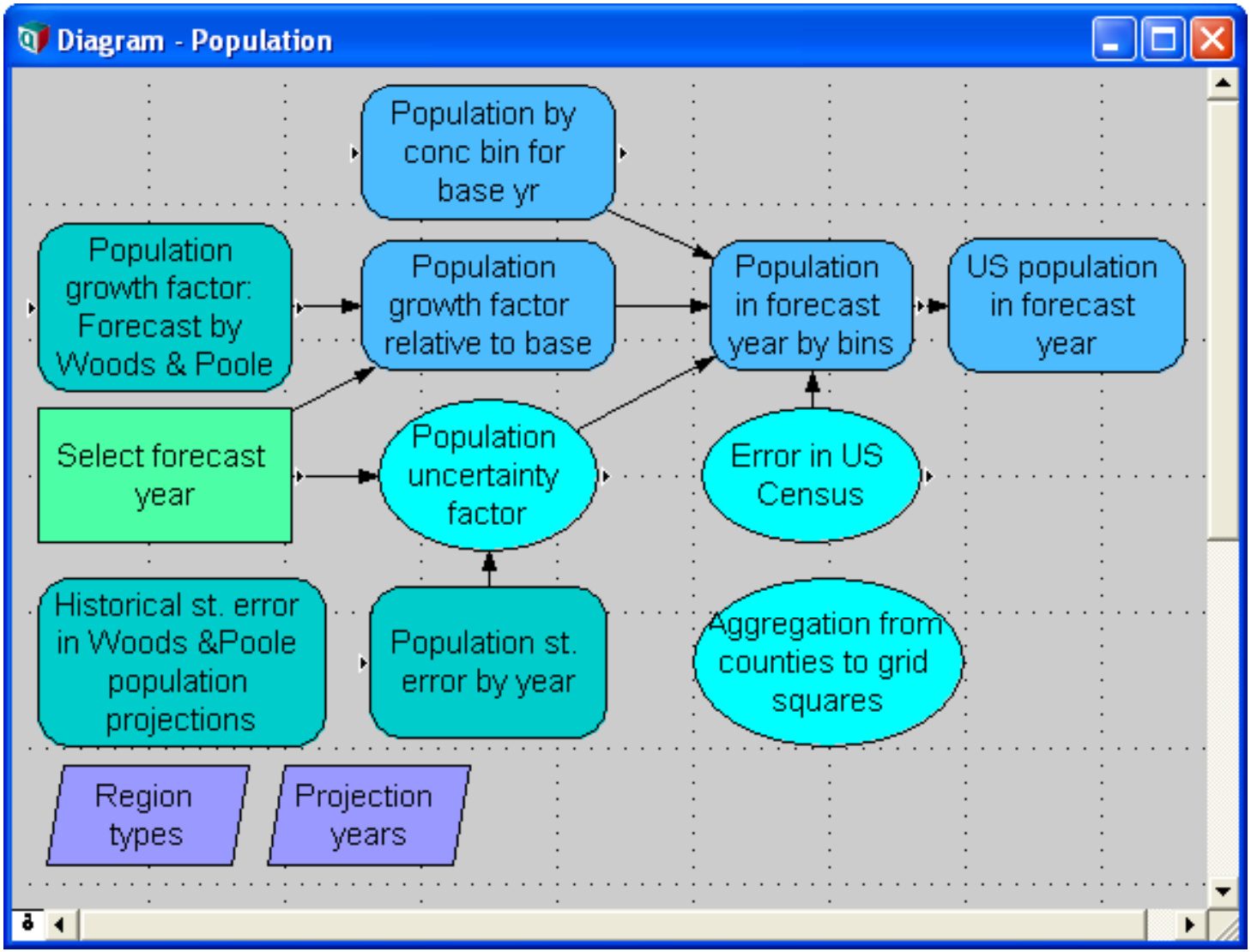
- We have an initial inventory of sources of uncertainty: We request your help to identify ones we've missed, and to review how they're classified and characterized
- We have developed strawman influence diagrams, for your comments.
- We have an initial simplified model capable of illustrative sensitivity analysis. We seek advice on how to refine it.
- Ranges of parameter values: We request your help in providing plausible ranges, or suggesting how to obtain them.
- Model form and aggregation uncertainties
- We would like your advice on the strawman proposed process for sensitivity analysis

Session 4:
Population Estimates:
Identified sources of uncertainty in population estimates and uncertainty introduced by BenMAP modeling assumptions

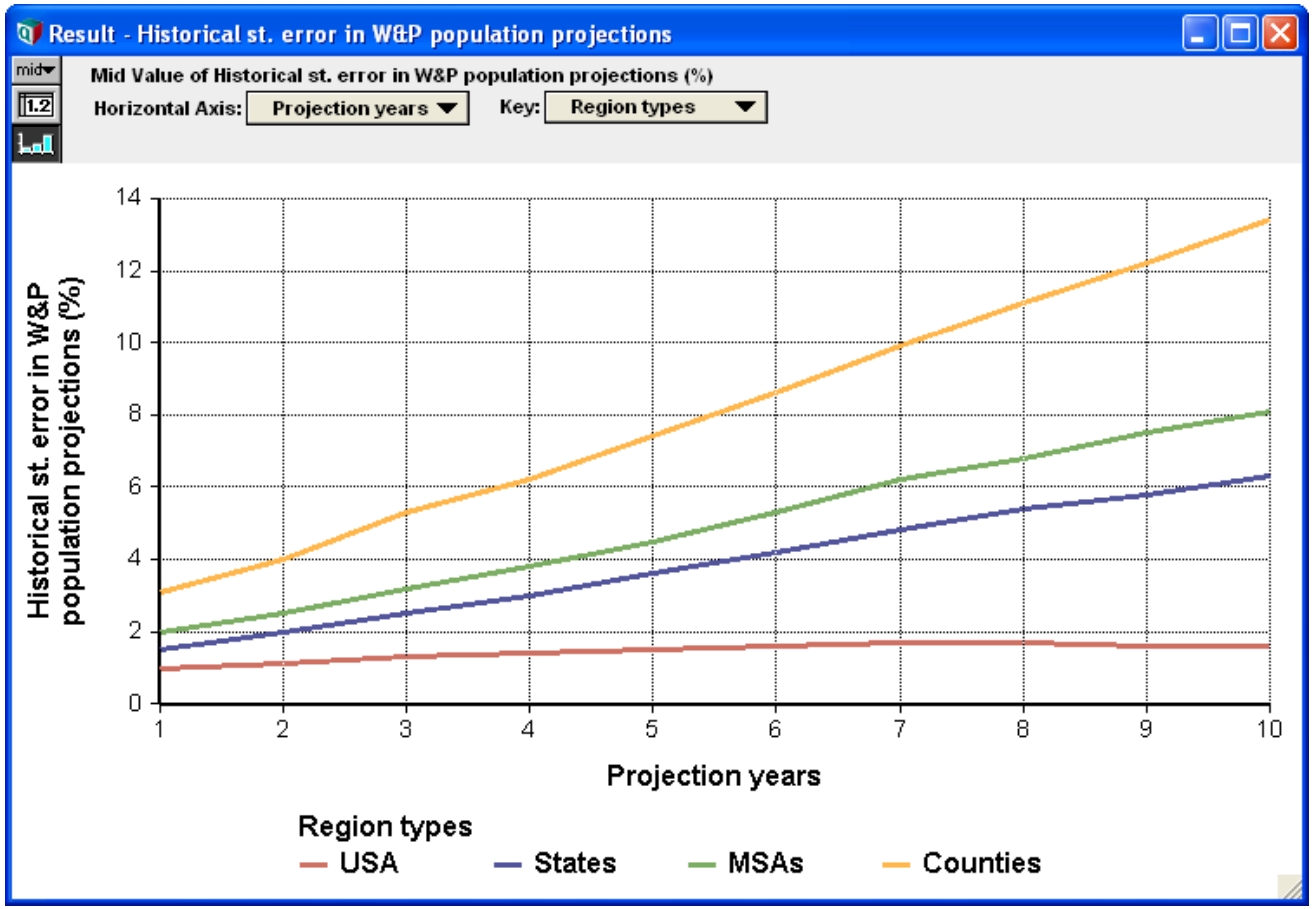
Max Henrion

Lumina Decision Systems
Los Gatos, CA

Draft influence diagram for population projections



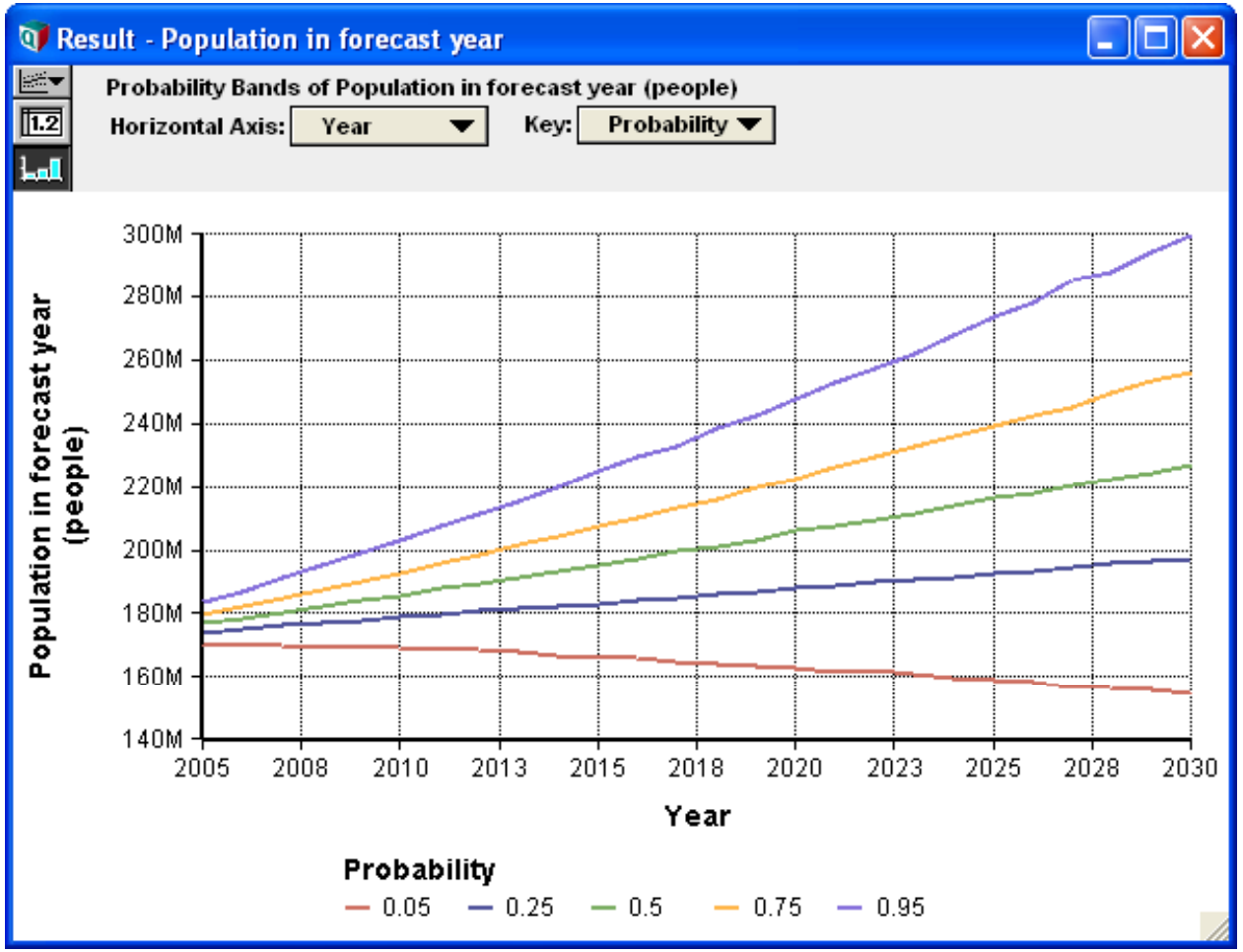
Retrospective accuracy of population projections



Standard deviation error percent for Woods & Poole projections of population compared against census data.

From 2008 Technical Description of Woods & Poole projections, table on page 20.

How should we estimate uncertainty in US population projections?



(age group 30 to 99)

Ranges for uncertain parameters

- We want plausible low, mid, and high values
  - not theoretically possible extreme min and max.
- Think of them as 10th percentile, median and 90th percentile
  - although, we're not looking for expert probability distributions for now.
- We'd like your estimates for the ranges
  - Or suggestions about how to obtain them
- For functional form, what set of functions should be considered?
- How can we estimate aggregation uncertainties?
  - e.g. population from county to grid sqares

Session 4: Discussion on population estimates

5min: Quiet brainstorming on these questions:

- Are there additional sources of uncertainty in population forecasts or introduced by BenMAP's use of the population data?
- Do you think this will have big impact on benefits results?

15min: Report out and discussion

10min: Quiet brainstorming on these questions:

- Can/should this source of uncertainty be modeled quantitatively in the influence analysis?
- What range of values should we use for these parameters or where can we get the range (i.e., from a study or existing data)?
- Are there other functional forms or modeling approaches that make sense for this component of the model or what would be a good source for this information?

30min Small group discussion

- Where do we agree and where do we disagree?

45min Report out and discussion

Session 5: Valuation of mortality reduction

Identified sources of uncertainty in valuation of mortality introduced by BenMAP

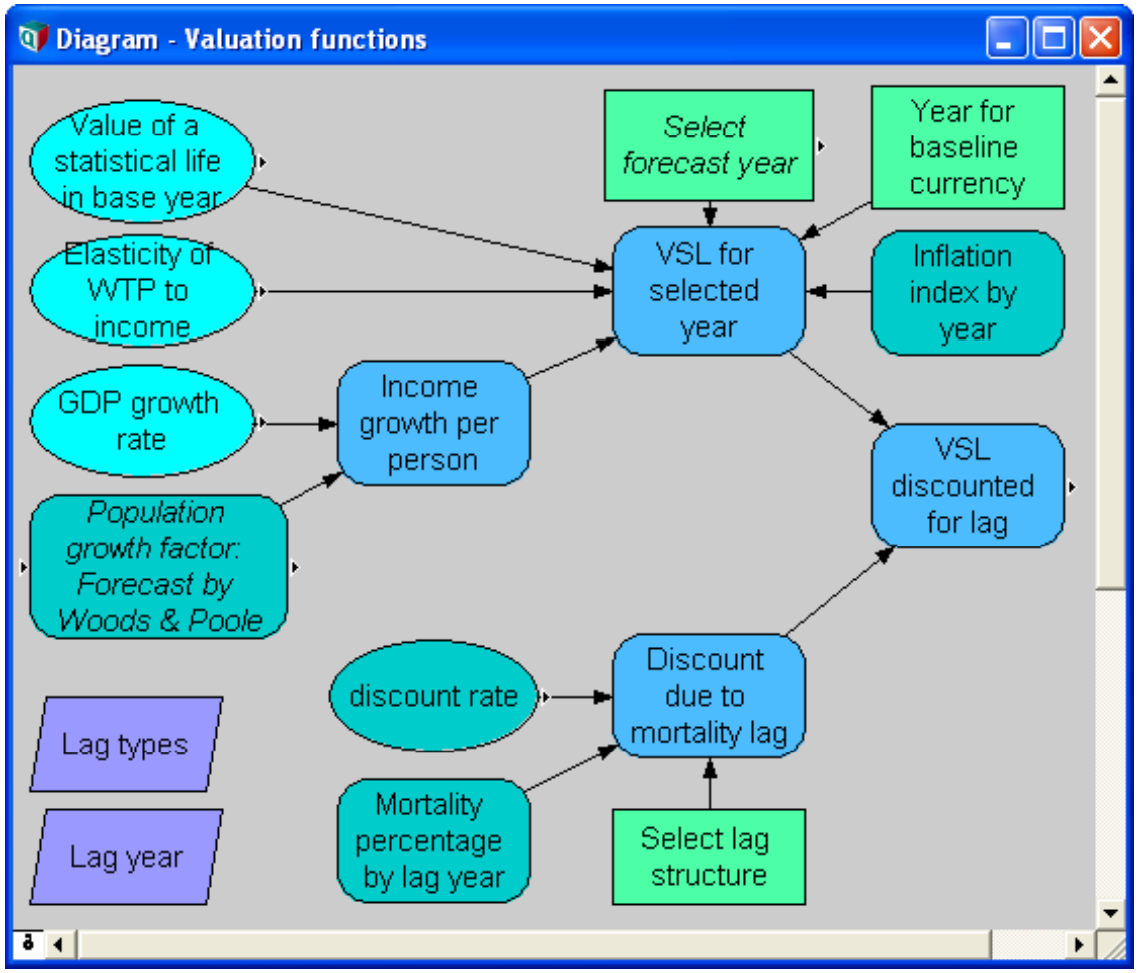
Max Henrion

Lumina Decision Systems
Los Gatos, CA

Valuation influence diagram

Draft influence diagram for Valuation of statistical lives saved, includes

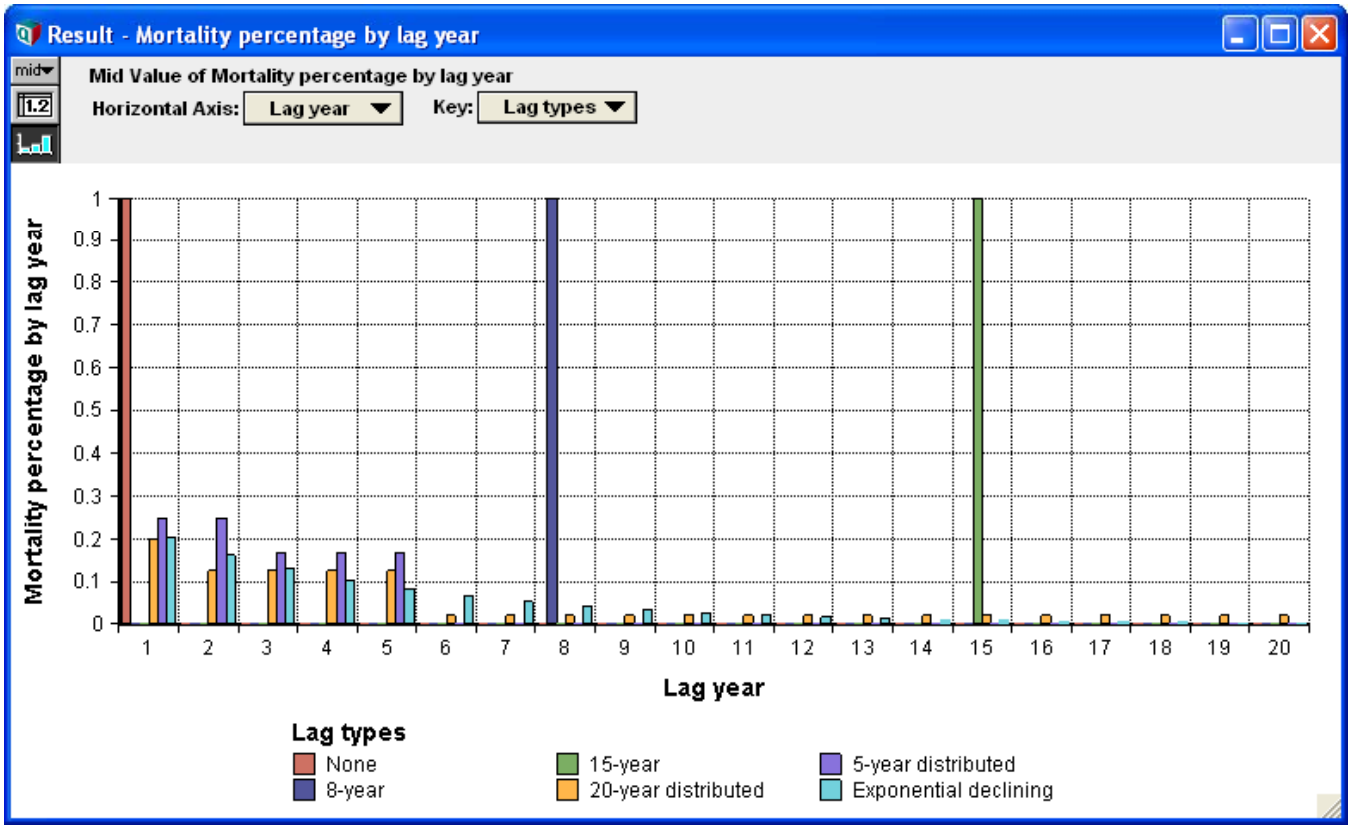
- Value of a statistical life
- Elasticity of WTP to income
- Income index
  - GDP growth rate
  - Population growth rate
- Select forecast year
- Inflation index and baseline currency year
- Discount due to mortality lag and lag structure



Mortality lag structures

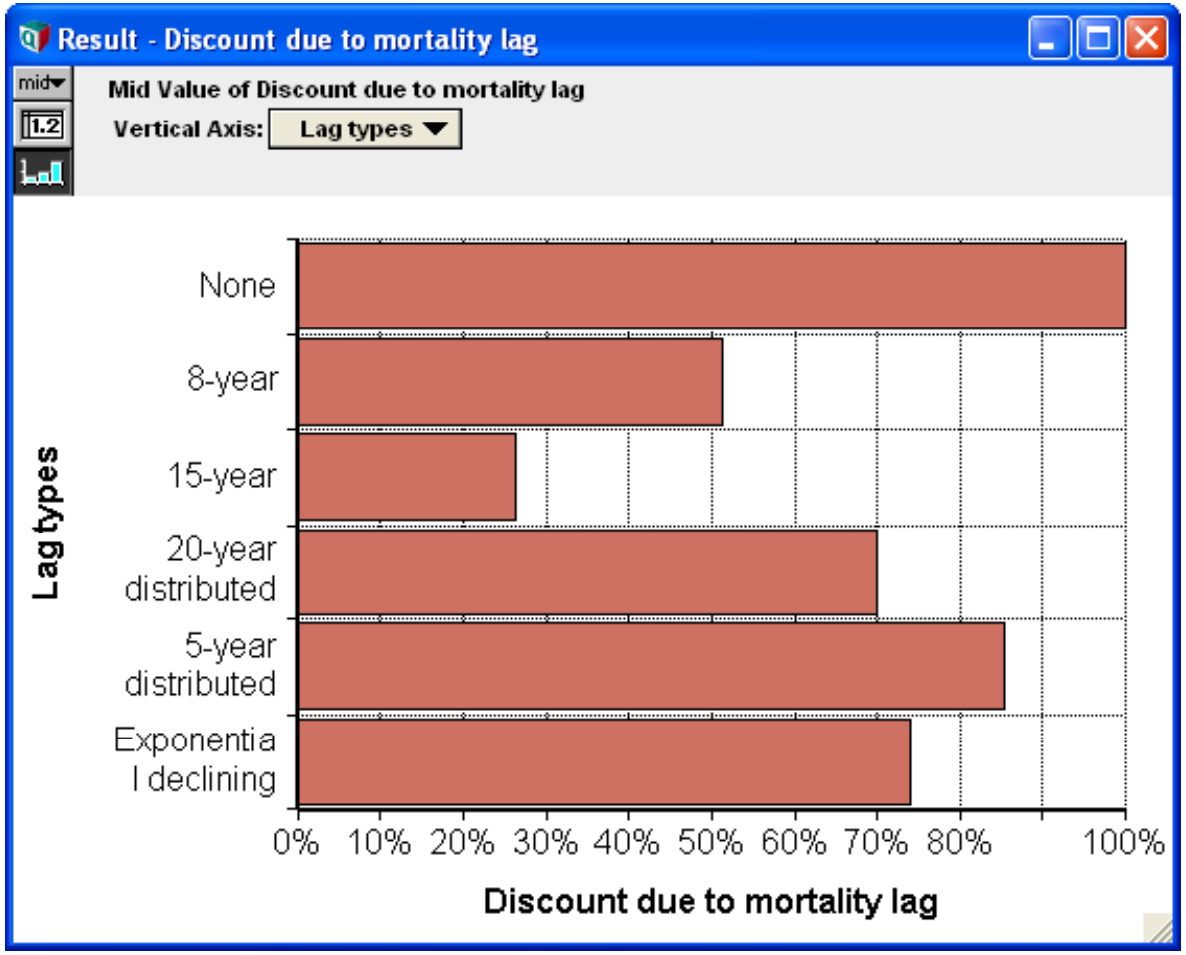
Six lag types representing model uncertainty about lag between exposure and mortality:

- None (no lagg in mortality)
- 8-year: All deaths happen 8 years after exposure
- 15-year: All deaths happen 15 years after exposure
- 20-year distributed:
- 5-year distributed:
- Exponential declining over 20 years

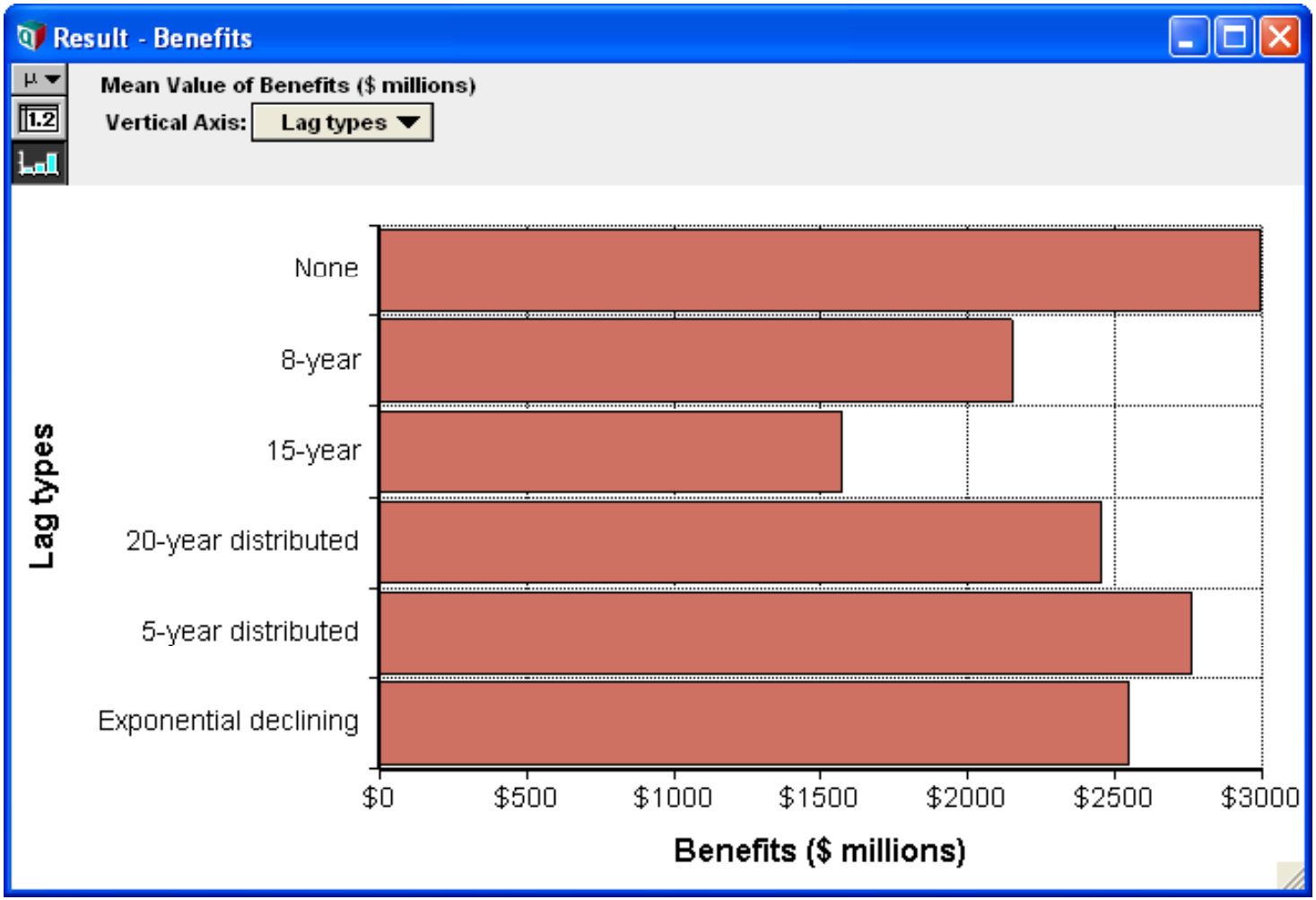


Mortality lag structure

- Using an annual discount rate, we convert each lag structure into a corresponding total discount rate on benefits



Effect of lag type on benefits



Ranges for uncertain parameters

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  - e.g. population from county to grid sqares

Session 5: Discussion on valuation of mortality reduction

5min Quiet brainstorming on:

- Are there additional sources of uncertainty in valuation of mortality reductions or introduced by BenMAP's use of valuation studies?
- Do you think these will have big impact on benefits results?

15min Report out and discussion

10min Quiet brainstorming on:

- Can/should this source of uncertainty be modeled quantitatively in the influence analysis?
- What range of values should we use for these parameters or where can we get the range (i.e., from a study or existing data)?
- Are there other functional forms or modeling approaches that make sense for this component of the model or what would be a good source for this information?

30min Small group discussion

- Where do we agree and where do we disagree?

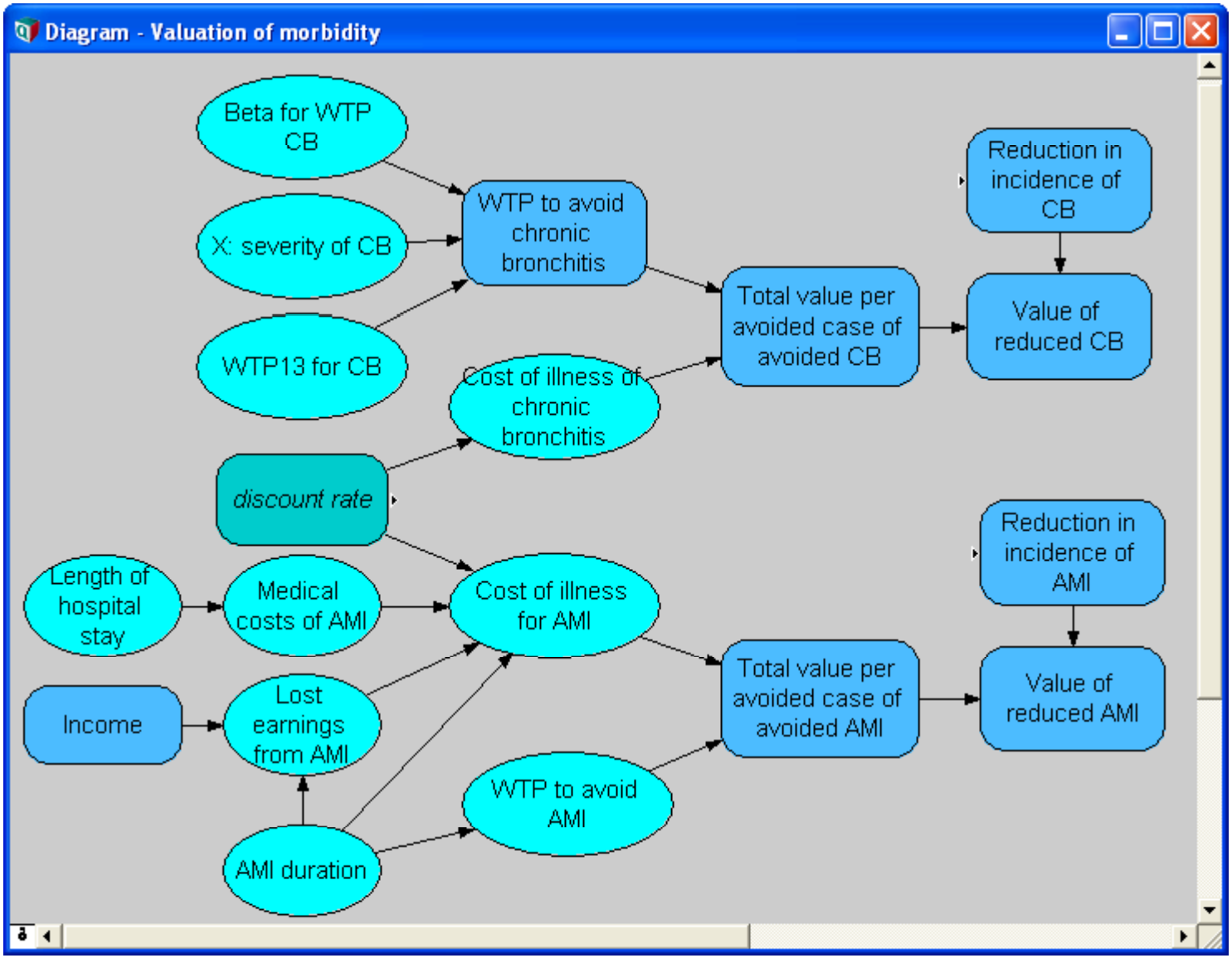
45min Report out and discussion

5:15 to 5:30: Wrap-up

Session 6: Valuation of morbidity reduction

Identified sources of uncertainty in valuation of morbidity introduced by BenMAP

Valuation of morbidity



Session 6: Discussion on valuation of morbidity reduction

5min Quiet brainstorming on:

- Are there additional sources of uncertainty in valuation of mortality reductions or introduced by BenMAP's use of valuation studies?
- Do you think these will have big impact on benefits results?

15min Report out and discussion

10min Quiet brainstorming on:

- Can/should this source of uncertainty be modeled quantitatively in the influence analysis?
- What range of values should we use for these parameters or where can we get the range (i.e., from a study or existing data)?
- Are there other functional forms or modeling approaches that make sense for this component of the model or what would be a good source for this information?

30min Small group discussion

- Where do we agree and where do we disagree?

15 mins Break (10:00am to 10:15am)

30min Report out and discussion

Session 7:
Discussion and Recommendations on Approach to influence and uncertainty analysis

Max Henrion

Lumina Decision Systems

Objectives of the project:
Recap

- To identify the sources of uncertainty in the assessment of benefits from improvements in air quality using BenMAP
- To visualize how the sources of uncertainty affect the results using influence diagrams
- To assess the range of values of key uncertainties
- To compare their relative contributions to the results using sensitivity analysis
- To identify which uncertainties are most in need of more careful characterization

Overview of proposed approach:
Recap

- Identify and classify the uncertainties and their effects
  - Develop an inventory of possible sources of uncertainty
  - Classify these sources in terms of source and type of uncertainty
  - Develop influence diagrams to visualize their effects on benefits
- Build model and conduct sensitivity analysis
  - Develop a simplified or reduced-form model
  - Assess ranges of plausible values for parametric uncertainties, and ranged of plausible alternative forms for model uncertainties
  - Conduct sensitivity analysis to identify their relative importance on results using various measures of sensitivity
- Compare the simplified model with BenMAP for selected scenarios to validate and calibrate it.
- Make recommendations on which uncertainties are most important to characterize in more detail and how

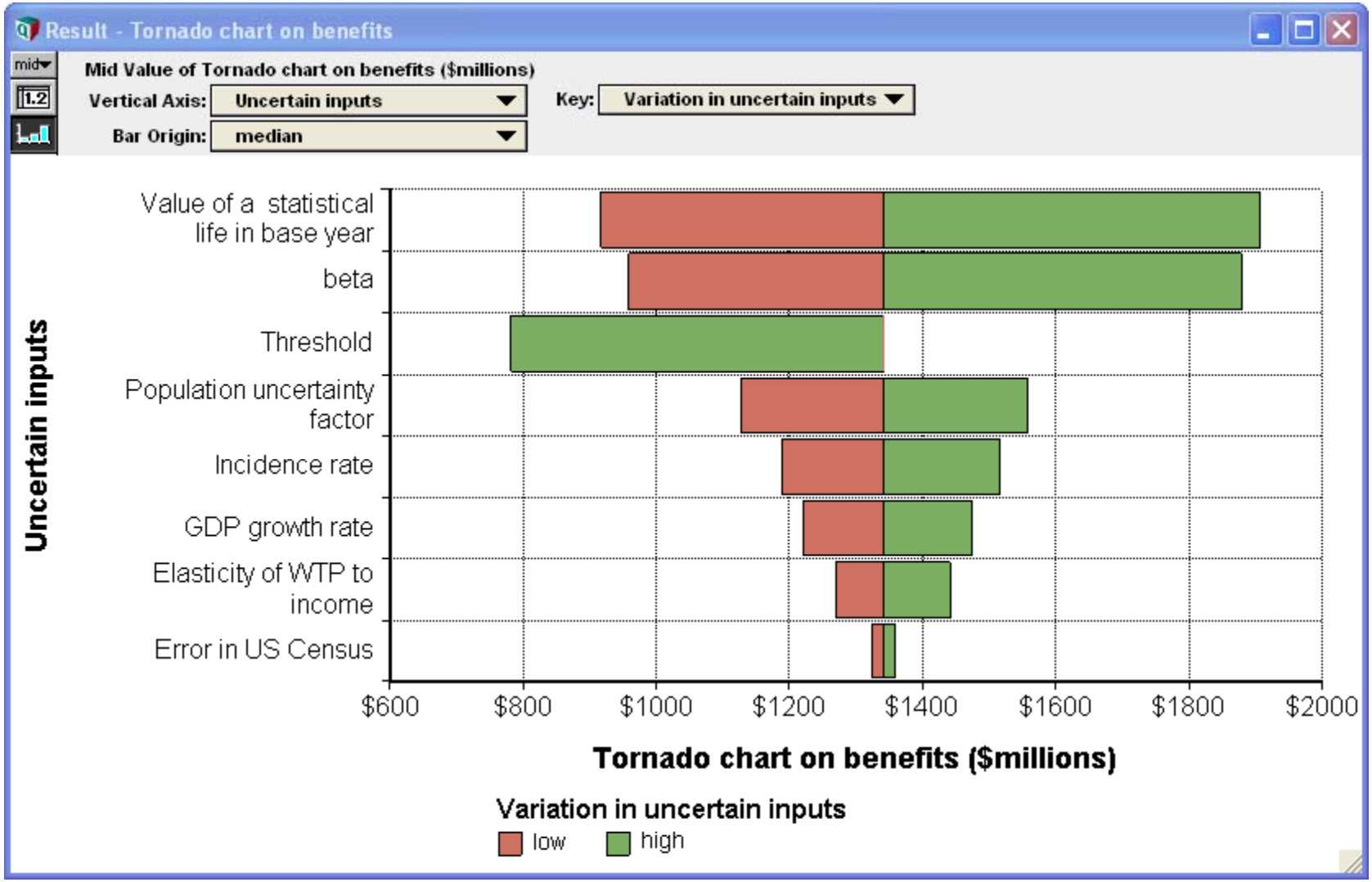
Refining the simplified model

- **Concentration reductions**
  - Initially, we assume that each all exposed population in each base concentration bin experiences the same reduction in PM2.5 concentration levels (averaged over the reductions for all grid squares in that bin)
  - Later, if time we could expand it to a bin array with a second dimension of concentration reductions for each concentration bin, and see if this reduces the aggregation uncertainty.
- **Population segments**
  - Initially, the model ignores population segments (sum over age groups, ethnic groups, and gender).
  - This is only relevant for CR-functions that are disaggregated by segment (currently, only morbidity not mortality functions.
  - Later, if time, we might add a dimension of segments to the bins, with separate population growth rates and incidence rates by segment.

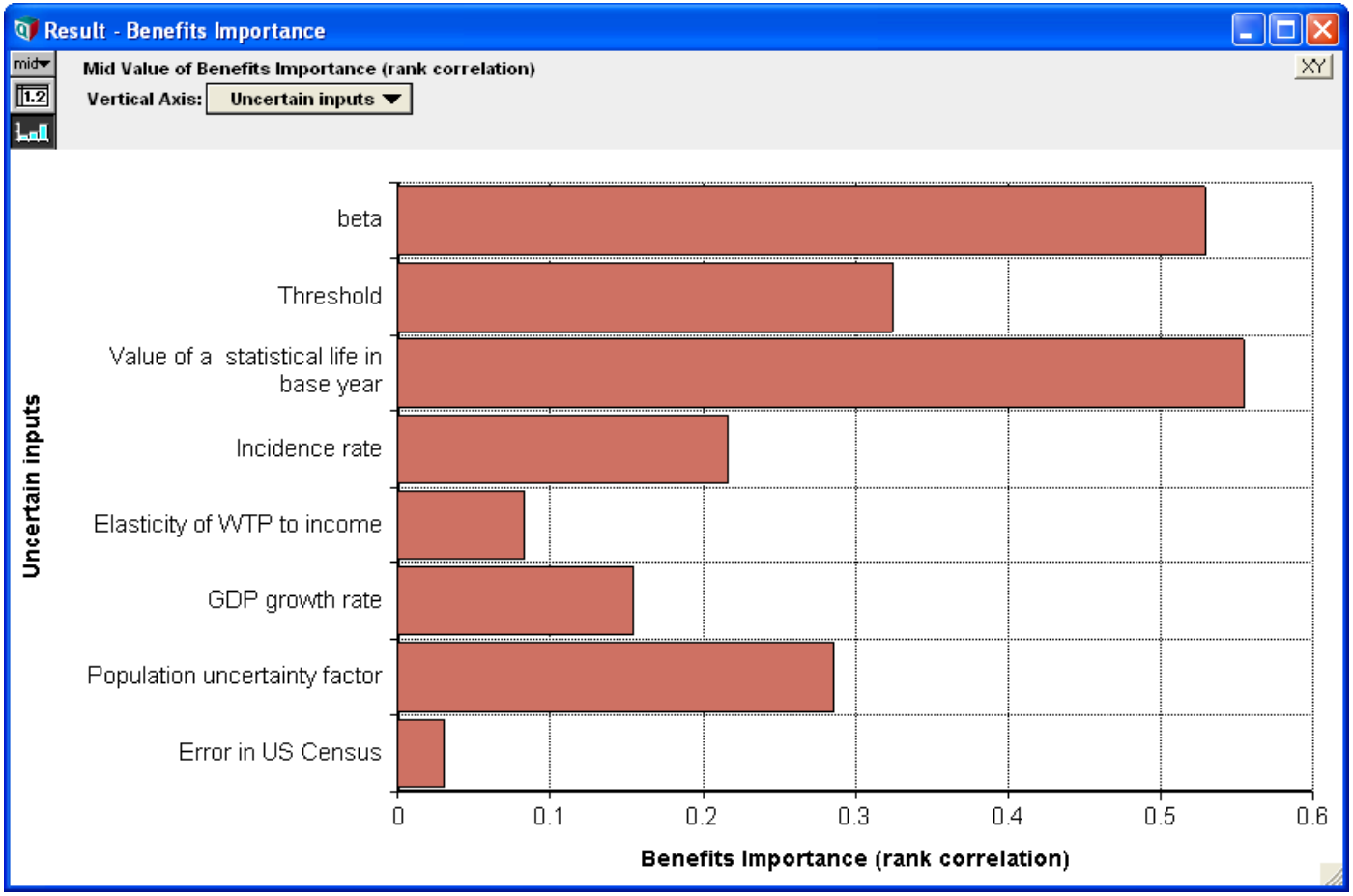
Sensitivity analysis

- **Tornado diagrams**
  - **We will conduct deterministic sensitivity analysis (Tornado diagram) over all parameter and model uncertainties, varying each from low to high values, leaving all others at their mid value.**
- **For selected pairs or groups of uncertain variables**
  - **where knowledge of the functional form leads us to suspect that interactions may be important and at least one parameter is individually important, we will also conduct multiway sensitivity, changing two (or rarely more) parameters at a time.**
- **We may also use probabilistic sensitivity analysis measures, such as rank correlations and regression measures**
  - **assuming a simple uniform or beta distributions over parameter ranges**
  - **and uniform discrete distributions over alternative functional forms**

Example tornado diagram



Example “importance analysis” to compare input uncertainties



The relative importance of each uncertain input to the benefits computed as the rank correlation of the Monte Carlo sample for the benefits with respect to each input sample

Iterative refinement of model and sensitivity analyses

- **Based on the initial analysis,**
  - **we will identify a subset of parameters as the most important contributors and**
  - **develop more careful characterization of their uncertainty, by reviewing relevant literature and/or more extended conversation with one or more experts on those quantities to refine the low, mid, and high values.**
- **We will repeat the sensitivity analyses using the refined estimates.**

Proposed comparison of simplified model with BenMAP scenarios

- Identify the most important set of **parameters** and **model forms** (perhaps 5 to 8), from initial sensitivity analysis with the simplified model
- Define 5 to 10 scenarios -- i.e. combinations of values of the parameters – to perform sensitivity runs of BenMAP.
  - The number of scenarios will depend on how many BenMAP runs are practical given human and computational resources
- Compare the results from BenMAP with the simplified model
  - Direct values, including incidence, mortality reduction, and benefits
  - Sensitivities: Relative size and ranking of sensitivities
  - Diagnose the source of any differences
- If time, we may refine the simplified model to to improve correspondence and rerun the sensitivity .

Results and recommendations from the project

- **Summarize the results, identifying the which sources of uncertainty are most critical to uncertainty in the results (and which are less so)**
- **Recommend how those uncertainties might be refined, e.g.**
  - **By conducting expert elicitations of probability distributions on uncertain quantities**
  - **Experiments on effects of alternative aggregations**
  - **Obtaining other sources of data or runs of preceding models**

Discussion

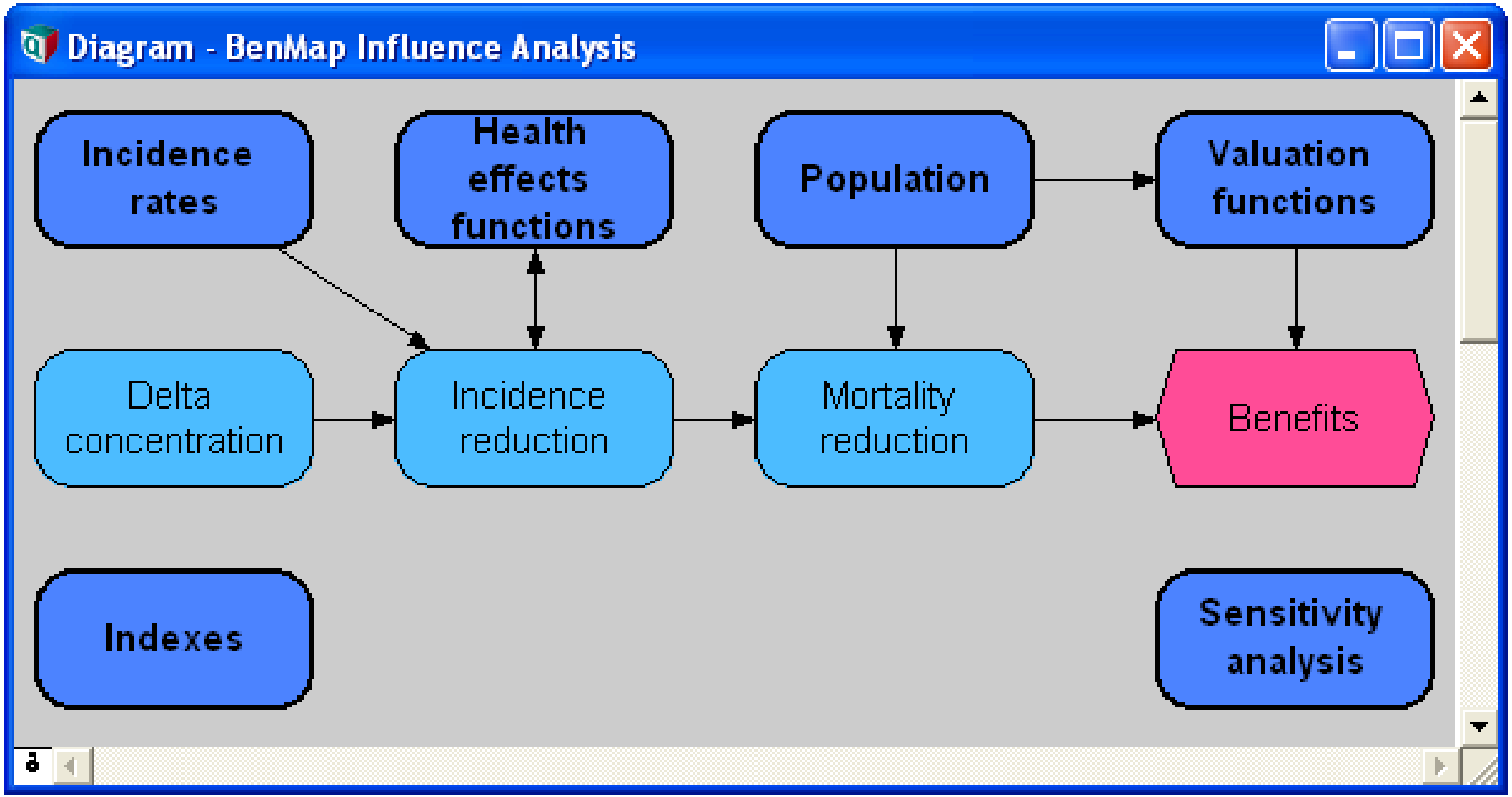
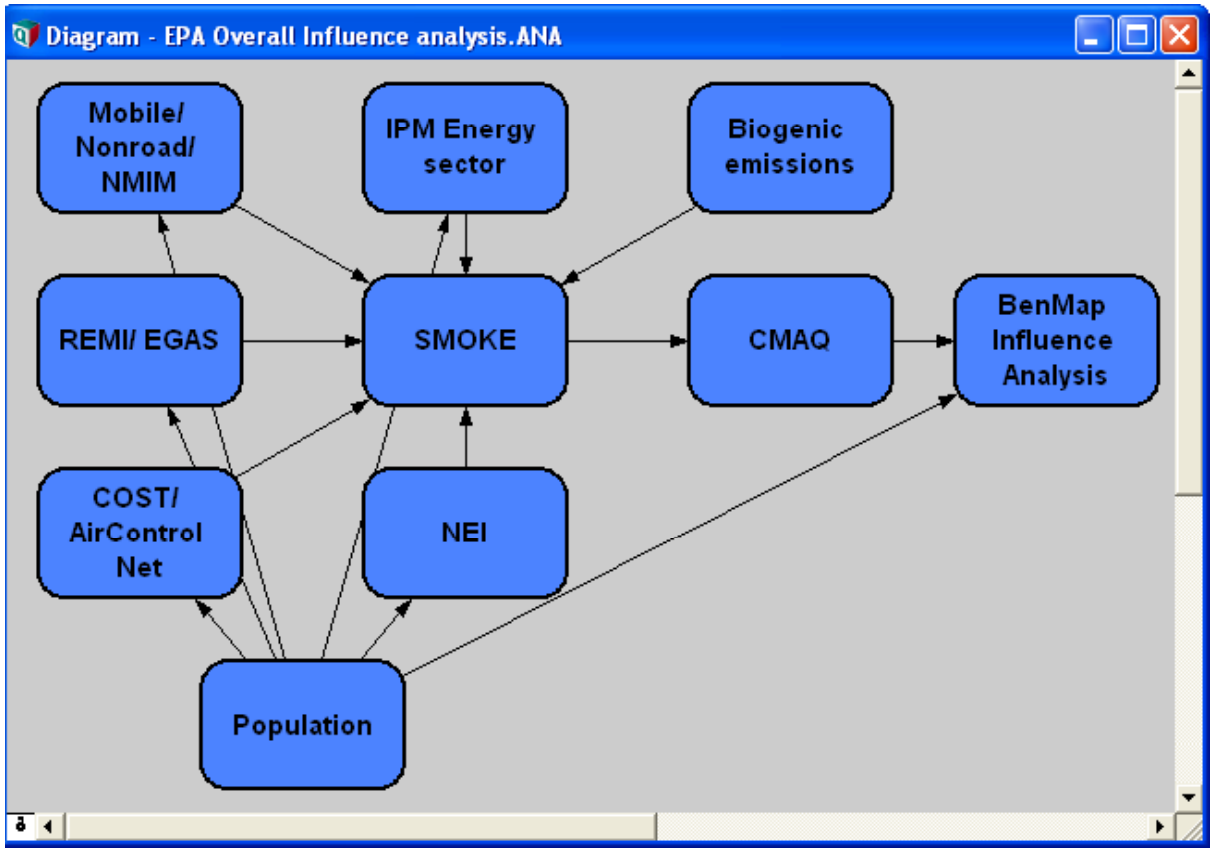


Diagram - BenMap Influence Analysis
Incidence rates
Health effects functions
Population
Valuation functions
Delta concentration
Incidence reduction
Mortality reduction
Benefits
Indexes
Sensitivity analysis

Related models that provide inputs to BenMAP



- Sensitivity analysis for CMAQ or other models are outside the scope of this project, which focuses only on BenMAP.
- Although most models use population projections as shown in the diagram, they currently do not necessarily use the same projections.

Appendix D: Influence Diagrams

Influence diagrams to support sensitivity and uncertainty analysis of BenMAP

Max Henrion

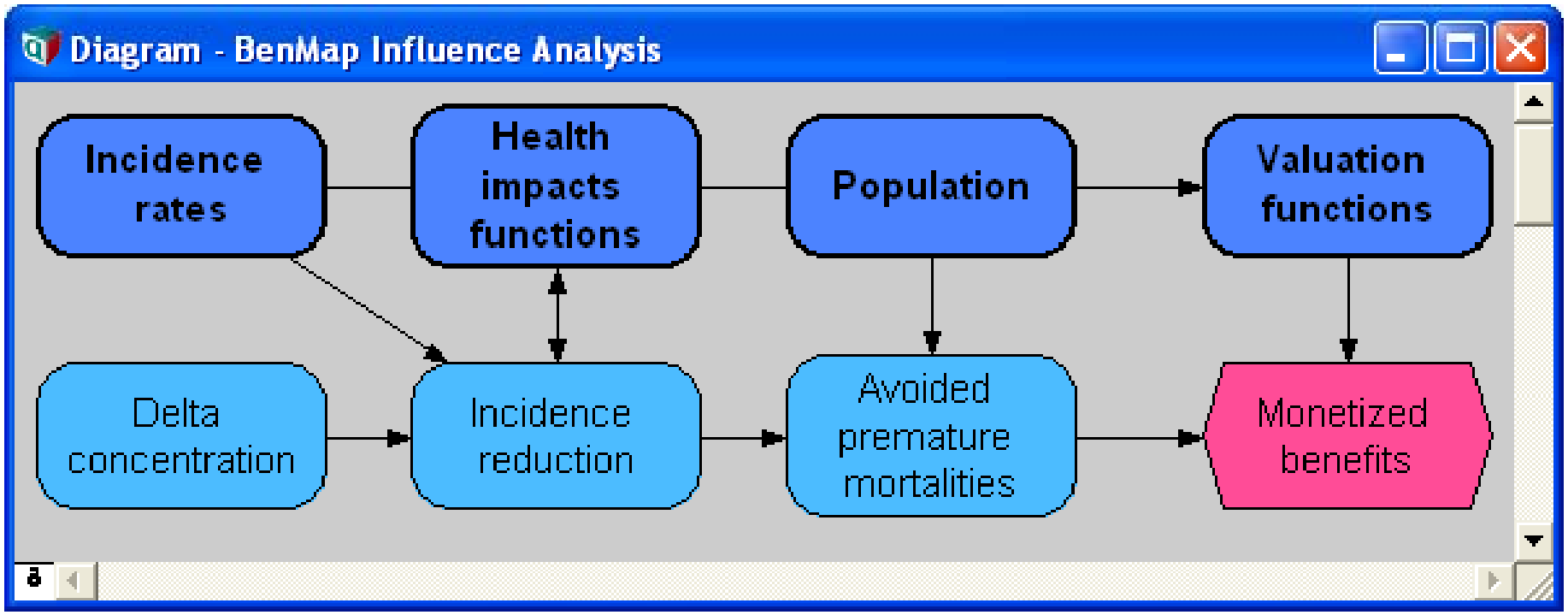
Lumina Decision Systems

Los Gatos, CA

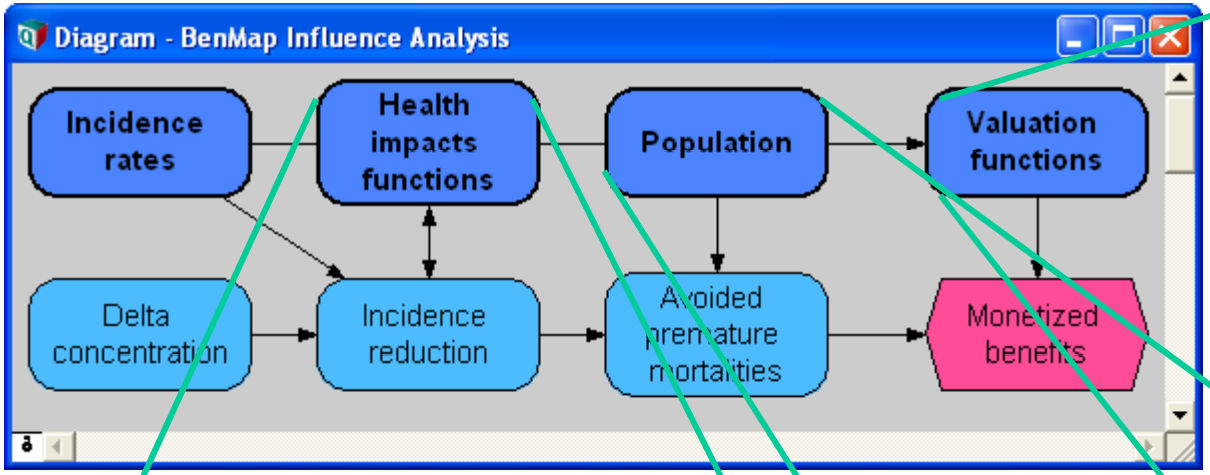
Lumina DECISION SYSTEMS

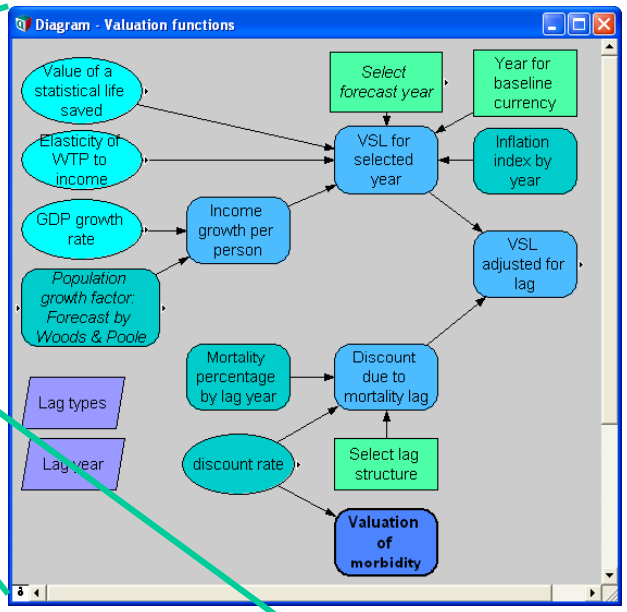
RTI INTERNATIONAL

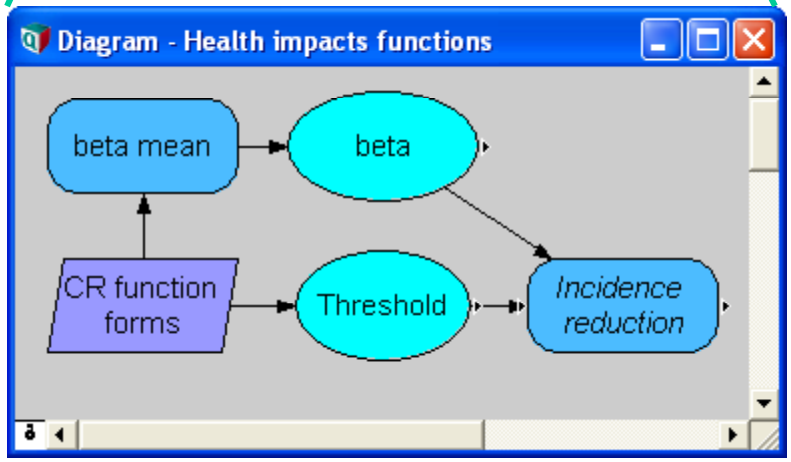
Top level influence diagram to represent BenMap structure

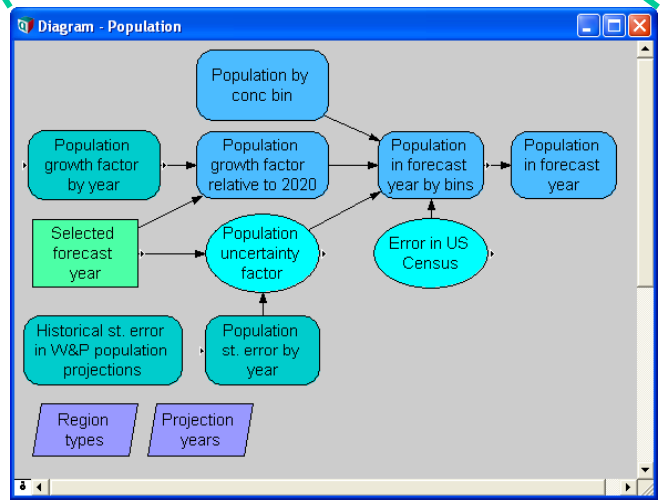


Influence diagrams for selected submodules

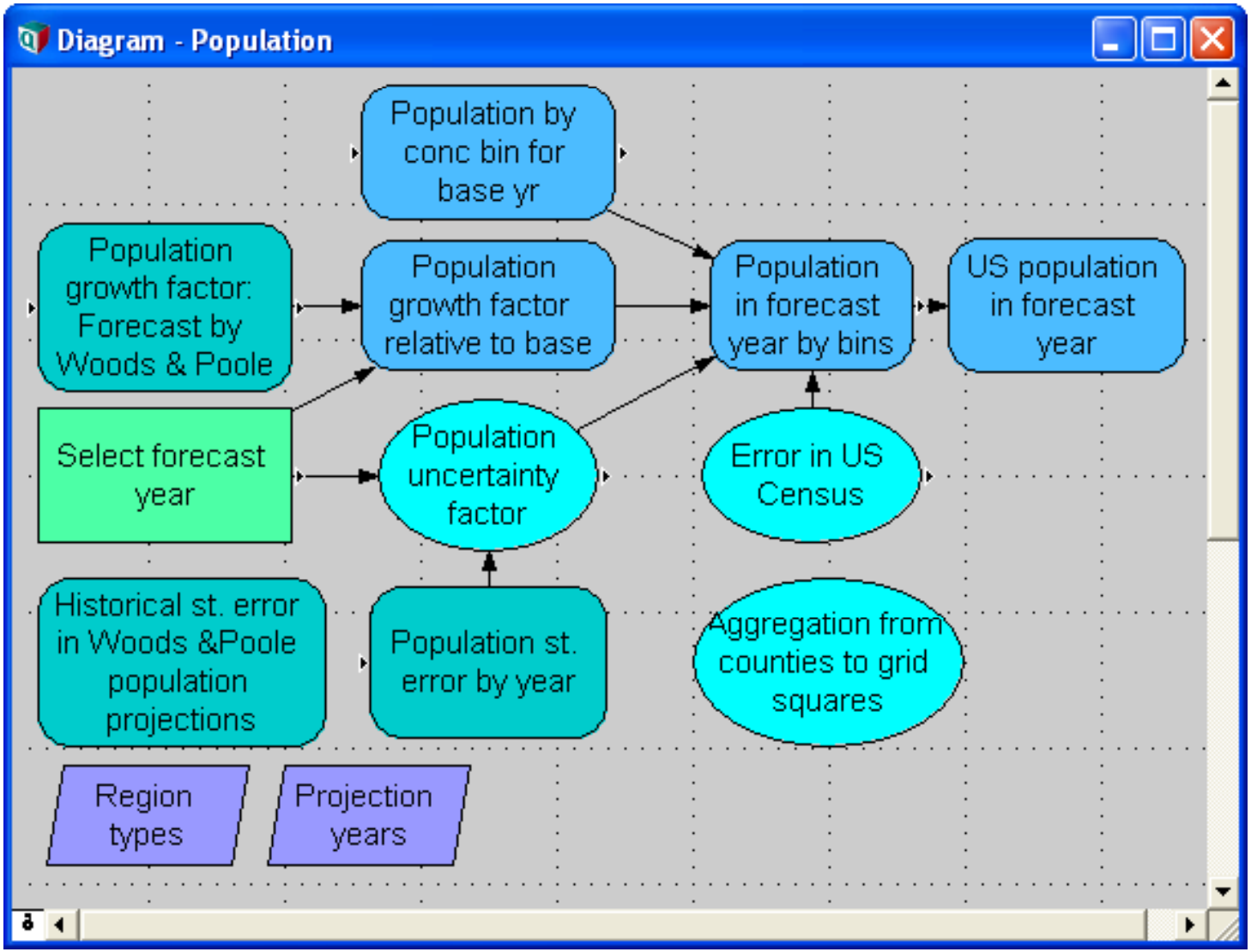








Draft influence diagram for population projections



Valuation of mortality influence diagram

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- Value of a statistical life
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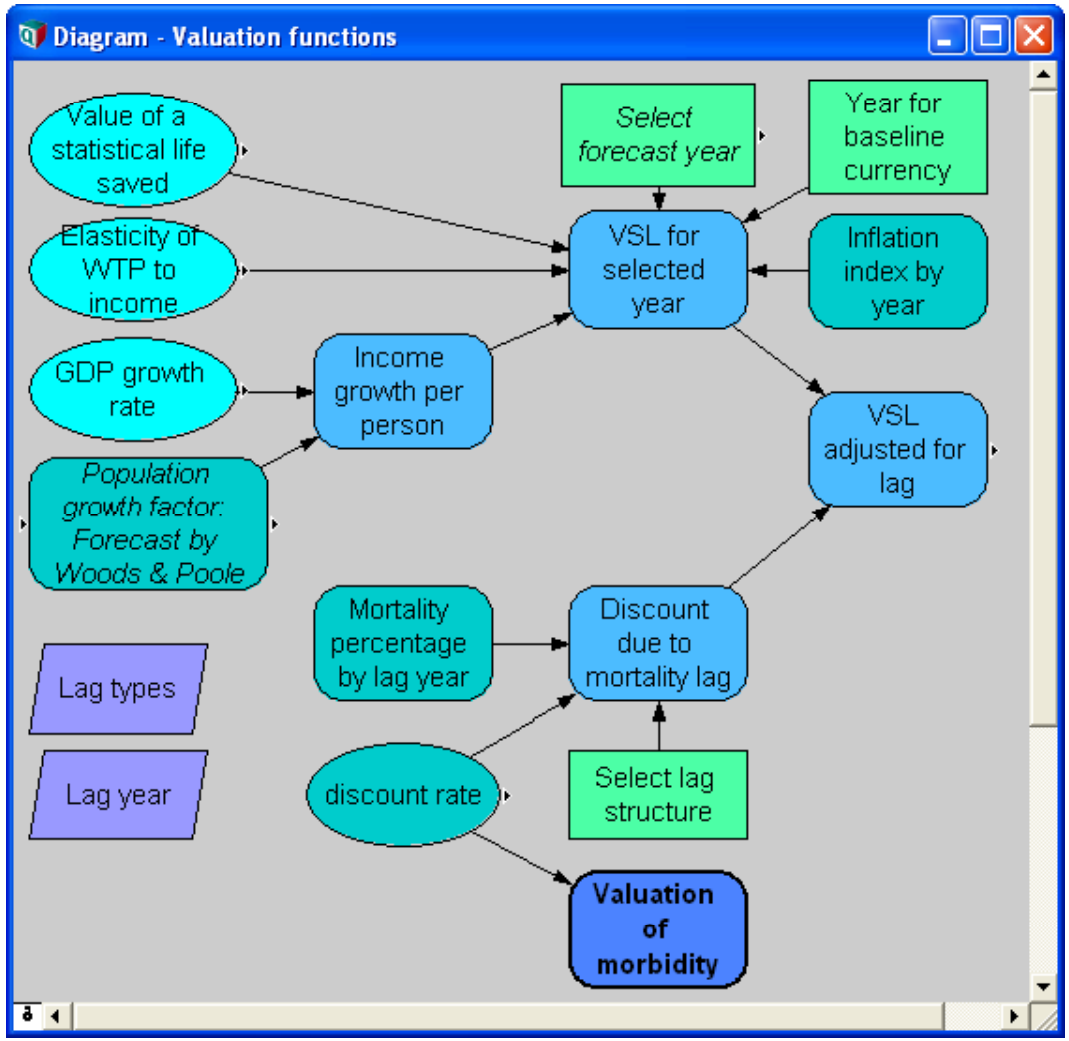
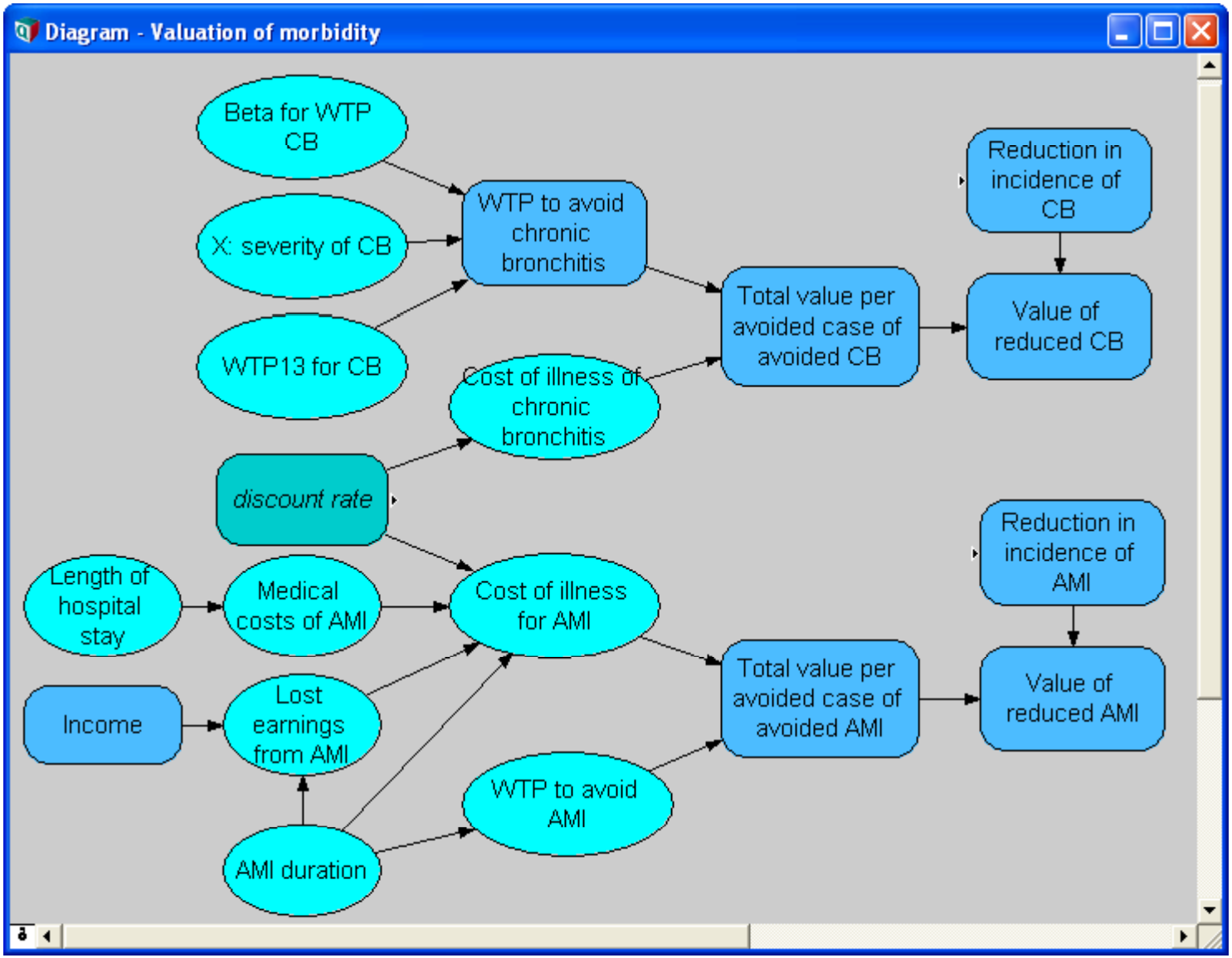
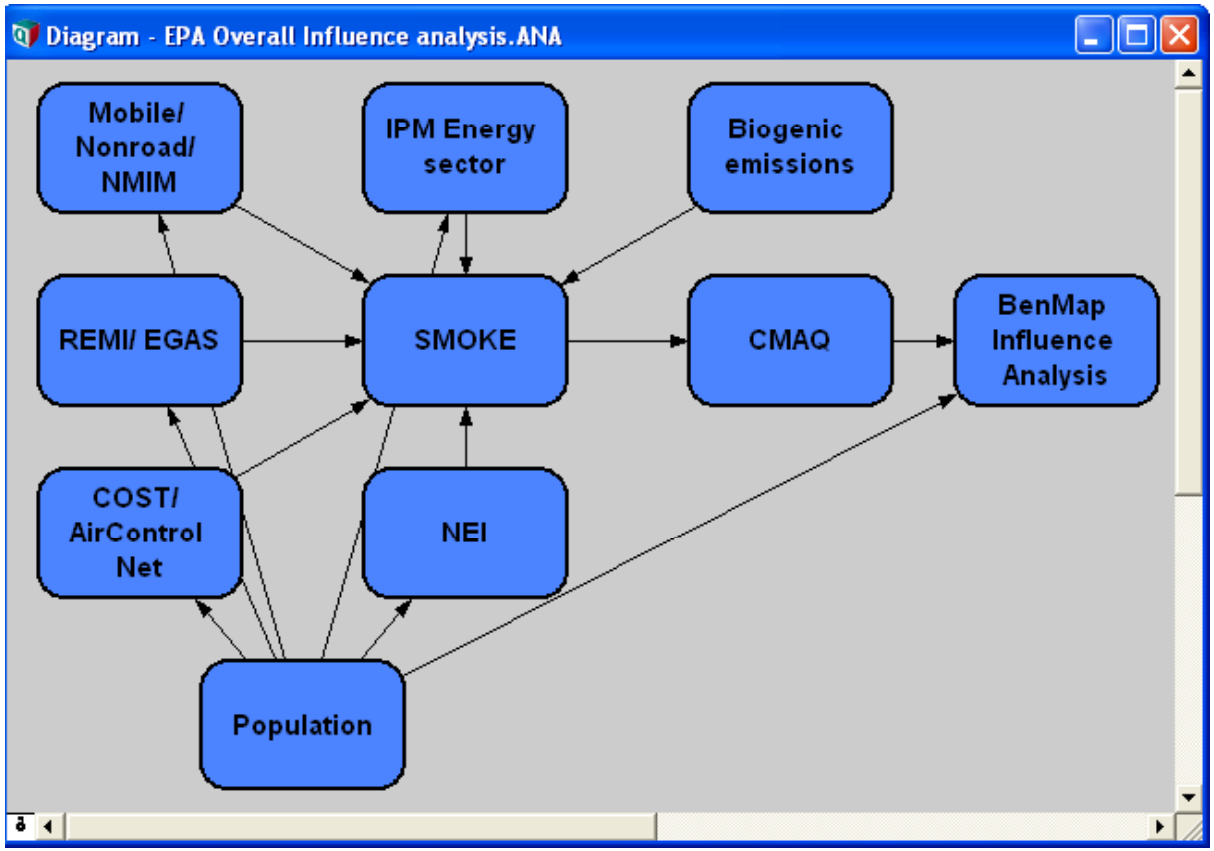


Valuation of morbidity



Related models that provide inputs to BenMAP



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