



UNITED STATES ENVIRONMENTAL PROTECTION AGENCY  
WASHINGTON D.C. 20460

OFFICE OF THE ADMINISTRATOR  
SCIENCE ADVISORY BOARD

October 12, 2007

EPA-SAB-08-001

Honorable Stephen L. Johnson  
Administrator  
U.S. Environmental Protection Agency  
1200 Pennsylvania Avenue, N.W.  
Washington, D.C. 20460

Subject: SAB Advisory on EPA's Issues in Valuing Mortality Risk Reduction

Dear Administrator Johnson,

The EPA National Center for Environmental Economics (NCEE) requested the Science Advisory Board's advice on how the Agency should use meta-analysis to combine estimates of the value of reducing mortality risks (i.e., estimates of the Value of a Statistical Life (VSL)). The NCEE also asked the SAB for advice on how the Agency should incorporate information on remaining life expectancy when valuing reductions in risk of death. To respond to this advisory request, the SAB's Environmental Economics Advisory Committee (EEAC) was augmented with SAB chartered members as well as members of the Advisory Council on Clean Air Compliance Analysis. The SAB Panel reviewed two NCEE papers on these subjects: *Report of the EPA Workgroup on VSL Meta Analysis*, and *Willingness to Pay for Environmental Health Risk Reductions When There are Varying Degrees of Life Expectancy: A White Paper*.

In answer to the meta-analysis charge questions, the SAB does not believe that meta-regression—a particular form of meta-analysis—is an appropriate way to combine VSL estimates for use in policy analyses. The SAB does, however, agree that meta-regression is a useful statistical technique for identifying various aspects of study design or population characteristics that are associated with differences in VSL estimates. Once important sample characteristics, model and estimation factors affecting the VSL have been identified, the Agency must determine a set of criteria for what constitutes a set of acceptable empirical studies of the VSL. The SAB urges the Agency to establish such criteria. The Agency must also determine which studies are appropriate for estimating the VSL in a specific policy context, depending on the nature of the risk addressed by a policy and the population affected. Once these criteria have been determined, and an acceptable sample of VSL estimates from the literature has been formed, appropriate statistical techniques can be used to combine these estimates. Two that have been used to weight individual study estimates include the random effects and the empirical Bayes estimator.

In addition, the SAB believes that both stated preference and revealed preference studies should be considered in valuing mortality risks and that weight should be given to each of them in proportion to how well they each address the policy question at hand. Both approaches have strengths and weaknesses in a particular context, and, as a result, we do not believe that the Agency should rely exclusively on one or the other in all contexts. Furthermore, the SAB believes that the Agency should make needed adjustments when using VSL estimates from the literature and consider reasonable priors regarding the magnitude of the VSL when including or excluding the results from previous studies.

Regarding the role of life expectancy in valuing mortality risks, the Committee notes that economic theory, in general, places no restrictions on the relationship between the VSL and remaining life expectancy: the VSL may increase, decrease or remain constant as life expectancy decreases. The relationship between the VSL and life expectancy is therefore an empirical matter. In practice, because life expectancy is difficult to observe, the Agency will have to relate the VSL to factors related to life expectancy—namely age and health status. Although the literature on the relationship between age and the VSL is growing, the Committee does not believe that it is sufficiently robust to allow the Agency to use a VSL that varies with age. The Committee also believes that the use of a constant Value of a Statistical Life Year (VSLY), which assumes that the VSL is strictly proportional to remaining life expectancy, is unwarranted. If there is insufficient information to indicate that the VSL declines with age, there is not sufficient information to indicate that the VSL is strictly proportional to remaining life expectancy. Thus, the SAB recommends that at present the Agency use an age-independent VSL to value mortality risk reductions. However, we also urge the Agency to report the age distribution of statistical lives saved and the average remaining life expectancies of persons in each age group.

The SAB urges the Agency to fund more research on empirical estimates of the VSL. Reductions in risk of death constitute the majority of benefits from air pollution and drinking water regulations. Accurately estimating the value of these benefits is crucial to promoting efficient environmental policy, both now and in the future.

Finally, we remind the Agency, that there is a much larger normative element in the selection of VSL for regulatory evaluation and analysis than arises for many of the other issues with which the Science Advisory Board deals. For example, while there is no denying the reality of income effects, it is a policy judgment, not a scientific question, whether the same VSL should be employed in all regulatory decisions across a society or different values should be chosen depending upon the preferences and income of the population affected by a specific regulation.

Thank you for the opportunity to provide advice on this important and timely topic. The SAB looks forward to receiving your response to this advisory.

Sincerely,

/signed/

Dr. M. Granger Morgan, Chair,  
EPA Science Advisory Board

/signed/

Dr. Maureen Cropper, Chair  
Environmental Economics Advisory  
Committee

## NOTICE

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**Science Advisory Board**  
**Advisory on**  
**EPA's Issues in Valuing Mortality Risk Reduction**

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<sup>1</sup> / Members during Fiscal Year 2006.

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## Introduction

Reductions in mortality risk constitute the largest quantifiable category of benefits for many EPA rules and regulations. As such, mortality risk valuation estimates are an important input to the Agency's benefit cost analysis. The EPA uses a value of statistical life (VSL) to express the benefits of mortality risk reductions in monetary terms for use in cost-benefit analyses of its rules and regulations. EPA has used the same central default value (adjusted for inflation) in its primary analyses since 1999 when the Agency updated its *Guidelines for Preparing Economic Analyses* (2000). Prior to the release of the Guidelines, EPA sought advice from the Science Advisory Board on the appropriateness of this estimate and its derivation. In 2000, EPA also consulted with the SAB on the appropriateness of making adjustments to VSL estimates to capture risk and population characteristics associated with fatal cancer risks (*An SAB Report on EPA's White Paper Valuing the Benefits of Fatal Cancer Risk Reductions*, (EPA-SAB-EEAC-00-013, July 27, 2000.)). Again in 2004, the SAB's Environmental Economics Advisory Committee (EEAC) held a consultation to respond to the National Center for Environmental Economics' (NCEE) charge questions on meta-analysis and valuing mortality risk reductions. In 2006, the EEAC, augmented with economists from the chartered SAB and the Advisory Council on Clean Air Compliance Analysis, met to discuss specific charge questions related to two NCEE papers: *Report of the EPA Workgroup on VSL Meta Analysis*, and *Willingness to Pay for Environmental Health Risk Reductions When There are Varying Degrees of Life Expectancy: A White Paper*. Both of these papers may be found at <http://yosemite.epa.gov/EE/epa/erm.nsf/vwRepNumLookup/>.

NCEE's charge questions and the SAB Panel's responses are provided below.

## Meta-analysis of Mortality Risk Valuation Estimates: Charge Questions and Responses

- 1. In light of the workgroup's findings, what approach or approaches are the most scientifically appropriate to derive summary estimates of mortality risk valuation for use in environmental policy analysis? Should meta-regression techniques be applied to selected estimates or are other methods (e.g., fitting distributions) more appropriate? Please specify which methods, aside from or in addition to meta-regression techniques the Agency should explore.*

We believe that, once EPA has assembled a set of studies that are applicable to the population affected by a regulation and that meet appropriate criteria for a well-executed study, it is appropriate to combine these using meta-analysis. For example, the VSL estimates could be combined using a random effects estimator, in which individual VSL estimates are weighted in inverse proportion to their variance. We do not, however, believe that meta-regression—a particular form of meta-analysis—is an appropriate way to combine VSL estimates for use in policy analysis, or to perform benefits transfer, for reasons described below. Meta-regression is, however, a useful technique for understanding what factors may explain variation in VSL estimates across studies.

A meta-regression, in which the characteristics of study participants (e.g., percent female, percent over 65) and study design (e.g., does an hedonic wage study control for a worker's industry) are used as covariates is useful in understanding what factors affect empirical estimates of the VSL. It can be thought of as an empirical literature review which may highlight factors affecting the VSL that would not otherwise be detected. By highlighting correlates of the VSL, meta-regression may suggest features of study design for which criteria should be established. For example, it might be determined that an acceptable hedonic wage study must control for the worker's industry at the 2-digit level because this has a significant effect on the VSL estimate obtained in an hedonic wage study.

It is, however, another matter to treat a meta-regression as a reduced-form model that can be used for obtaining the VSL for a given sub-population or the VSL conditional on an appropriate study design. To illustrate, a meta-regression may control for the functional form of the dependent variable in an hedonic wage regression by setting a dummy variable equal to 1 if the dependent variable is the log of wage rather than the wage. If researchers believe that the appropriate form of the equation is to use the log of the wage, this should be one criterion for an acceptable study and only studies satisfying the criterion should be combined in the meta-analysis. Setting the dummy equal to 1 in the meta-regression is not equivalent to altering the functional form of the underlying studies.

Similar problems exist when population characteristics in the meta-regression are used for benefits transfer. Suppose that one of the covariates on the right-hand side (RHS) of a meta-regression is the proportion of the study sample over 65. It is one thing for estimates of the VSL across studies to show that this coefficient is negative and statistically significant, suggesting that the VSL is lower for persons over 65, and another to set this variable equal to 1 to compute the

VSL for persons over the age of 65. The latter treats the meta-regression as a reduced-form model that can be used for benefits transfer. If the meta-regression suggests that age is important, EPA should use the results of studies that control for age, and other factors that are correlated with age, using individual data. These factors (e.g., wealth and income) are controlled for imperfectly in a meta-regression in which the population characteristics are summarized by an aggregate number for each study. The results of various studies may be combined in a structural model, but this is not what is happening in a meta-regression.

How should studies be combined in lieu of using meta-regression? A weighting scheme needs to be selected for calculating a central estimate from the selected study results. One possibility is to combine the estimates in inverse proportion to their variance, i.e., to use a random effects estimator. Another approach would be to use an empirical Bayes estimator (Kochi, Hubbell and Kramer 2006) which weights individual study estimates using measures of between as well as within study variability. Other approaches may also be appropriate depending on the nature of the data and the policy application context. The analyst should explain the rationale for the selected approach.

When studies are combined to inform a particular regulation, it is imperative that (a) the studies pertain to the population affected by the regulation; and (b) that the studies satisfy appropriate criteria regarding their design. We urge EPA to establish such criteria. For example, EPA may wish to specify criteria to minimize the possibility that fatal job risk in an hedonic wage study is correlated with the error term (i.e., that fatal risk is endogenous), which would cause estimates of the VSL to be biased.<sup>2</sup> In combining studies we do not recommend the use of quality weights, other than the 0-1 weights that are implicit in deciding which studies are of sufficiently high quality to be included in the meta-analysis. Although, in principle, there is no reason why weights should not vary between 0 and 1, in practice determining these weights is likely to be difficult. In the interests of transparency, we urge that a set of criteria for acceptable studies be established and then applied to the literature.

Formulating a list of criteria for an acceptable study and applying them to the literature will necessarily involve expert judgment. Expert elicitation is also useful in determining whether it is appropriate to transfer a VSL estimate in the literature to a specific policy context. The SAB Panel does not, however, recommend expert elicitation for combining estimates from the literature that are amenable to quantitative assessment with meta-analysis techniques. EPA should not directly elicit appropriate VSL values from experts, asking them, for example, to specify a range of acceptable VSL values and/or a mean value based on their knowledge of the literature, if there are published estimates of sufficient number and quality to support a meta-analysis. When adequate empirical estimates are available, expert elicitation would require that the expert mentally combine the results of dozens of studies, thus losing transparency in the process.

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<sup>2</sup>/ Fatal risk may be correlated with the error term in an hedonic wage study for several reasons: unobserved worker characteristics may be correlated with fatal job risk if more able workers choose safer jobs; or objective risk may be mismeasured (Black et al. 2003).

2. *Using the approach identified above, what measures/estimates should be combined? VSL estimates? The coefficient on fatal risk? Other? How should the Agency select the measures to be combined? Should a single, preferred estimate be selected from each study or should all estimates be included?*

We believe that a meta-analysis (e.g., a random effects estimator) should be used to pool VSL estimates from acceptable studies that pertain to the population affected by a regulation. The SAB Panel recommends that normally only one estimate should be selected from a study that reports several models all estimated from the same dataset. Which estimate should be selected when a study reports several estimates of the VSL depends on the set of criteria that the Agency establishes to determine what is an acceptable study. For example, if different models use different sets of covariates, the Agency should select the model with the preferred set of covariates.

3. *Should original studies be required to use a common empirical specification (functional form and choice of covariates) in order to be included in a meta-analysis? What data are required of the original studies to be included?*

For compensating wage studies, the SAB Panel recommends that original studies report the results of a common specification of the compensating wage regression, in addition to the author(s)' own specifications. The compensating wage study report or article should also report the estimate of the VSL calculated by the authors and its standard error—the latter being essential for creating the weights to be deployed in the meta-analysis—and ample details on how exactly both were calculated. Listed below is additional information that should be provided about compensating wage and stated preference studies that are included in a meta-analysis. We emphasize that all studies included in a meta-analysis should satisfy criteria specified by the Agency as to what constitutes an acceptable study. These criteria are not limited to the information listed below.

We recommend that the compensating wage studies ultimately to be included in a meta-analysis:

- provide information on the source of data on risk to include both information on the death statistics as well as how that data is converted to a risk rate, worker pay (including whether the workers are paid an hourly rate) and worker characteristics;
- include codes for creating the sample used for the compensating wage regressions and for transforming variables;
- report detailed statistics on risk, such as mean, mode, minimum/maximum rates and standard deviation and average pay for the sample;
- explain whether the author(s) did or did not include non-fatal risks in the compensating wage regression, in addition to the fatal risks variable;
- explain whether the sample contains only union workers, or if union membership was controlled for in the regression;
- explain whether high-risk workers (e.g., police officers, firefighters, etc.) are included or excluded from the sample;

- explain clearly whether the researcher(s) included a quadratic term in risk, and interactions between risk and other variables, in the regression; and
- explain clearly all covariates included in the regressions. For example, if a set of dummy variables are included for the industry and occupation of the worker, details should be provided on each category included in the model.

For stated preference studies, we recommend that the answers to the following questions be included:

- Was the study a (i) contingent valuation survey, (ii) conjoint choice experiments, or (iii) another type of hypothetical valuation exercise?
- What was the mode of administration of the survey?
- What was the sampling frame? Was a specific population targeted, or was the sample supposed to mirror the general population?
- What was the age of the respondents, split by gender, income, education, health status (if available)?
- What was the type of risk reduction respondents were to value in the SP study? (Was it a reduction in the risk of dying for all causes? Cardiovascular/respiratory causes? Road-traffic accidents?)
- Was the risk reduction immediate and incurred over the next year, or was it delayed into the future?
- Were respondents asked to consider a private risk reduction or one delivered by a public program? What was the payment vehicle (e.g., out-of-pocket costs of medical treatment, taxes, increases in the prices of products or the cost of living)?
- Was the payment one-time or an annual payment to be repeated each year for a number of years? How many years?
- Did each respondent have to value more than one risk reduction in the survey?
- Was the size of the (annual) risk reduction varied across respondents in the study? If so, (i) report the min, max and average risk reductions used in the study, and (ii) did WTP pass the scope test?

4. *Given the various approaches used in the literature, what is the most scientifically appropriate measure to derive when combining estimates from multiple studies? A single central point estimate, a single distribution, or a range of estimates in economic analyses? How can such a measure best reflect the uncertainty and variability in mortality risk valuation estimates?*

Meta-analysis should be used to provide a description of the probability distribution of the estimates. The resulting probability distribution can be used for uncertainty analysis, and the expected value and other relevant point estimates (e.g., median, 5th and 95th percentiles) can be drawn from it.

5. *How should stated preference studies and revealed preference studies be considered together in a scientifically appropriate method to derive summary estimates of mortality risk valuation?*

The SAB Panel believes that both stated preference (SP) and revealed preference (RP) studies should be considered in valuing mortality risks and that weight should be given to each of them in proportion to how well they each address the policy question at hand. For example, the analyst may have greater confidence in the mean estimates from the wage-risk studies, but they are limited to a working age population and an on-the-job risk context. For some EPA policy questions, SP studies may be a better match to the policy question, such as for an elderly population and an illness-related risk context, although the analyst may have less confidence in the specific mean results from the SP studies. This implies some weighting based on analyst judgment is necessary. We elaborate below on the fact that the two types of studies may, in practice, measure different concepts. We also discuss the strengths and weaknesses of each approach.

Revealed preference (RP) studies, such as compensating wage studies, measure the rate of substitution between risk and wealth. Stated preference (SP) studies measure ex ante willingness to pay for a discrete risk change and can involve changes in other aspects of a respondent's health conditions, such as a period of morbidity or a latency period for a fatal disease. This additional information presented as part of the stated preference questions may influence the measures of ex ante willingness to pay. The mechanism offered for reducing the risk may be a plan or a policy that may also influence the responses and thus the estimated willingness to pay. All of these factors affect comparability among VSL estimates from SP and wage hedonic studies.

Both RP and SP studies rely on several important maintained assumptions. Some economists prefer the SP framework because it is possible to describe the circumstances giving rise to the risk and the health outcomes involved that more closely correspond to the actual expected benefits of environmental regulations. However, other economists are skeptical of whether respondents treat the choice situations presented as "real" in the sense that the choices made correspond to what actually would happen if the same individual confronted an actual choice. In addition, some SP studies have demonstrated respondents' difficulty in providing consistent answers to valuation questions, especially those involving small probabilities of serious outcomes. RP studies on the other hand rest on the maintained hypothesis that individuals correctly perceive risks as the researcher measures them—for example, that parents correctly perceive the reduction in risk of death from a child wearing a helmet when riding a bicycle. The assumption that people have good quantitative estimates of small risks has little empirical support. It is also the case that compensating wage studies must infer the VSL by controlling for many other factors that affect wages, such as worker ability and risk of nonfatal injury, which may be measured inaccurately but also may be correlated with risk of fatal injury on the job. Because different economists weight SP and RP advantages and disadvantages differently, there is no professional consensus about these methodological alternatives. Thus we do not recommend that the Agency rely exclusively on either SP or RP studies, but rather give some consideration to results from both types of studies.

6. *How should the Agency use studies based on specific sub-samples (e.g., elderly) in developing summary estimates of mortality valuation estimates for environmental policy analysis?*

As the SAB Panel noted in answering Life Expectancy Charge Questions 1 and 2, EPA should aim to distinguish the VSL according to age and, possibly, health status, the empirical correlates of life expectancy. This implies that separate meta-analyses would be performed for studies of different populations, for example, persons 30-65 and persons 65 and over if sufficient numbers of such studies are available. However, it is an empirical question as to what population subgroups may have significantly different valuations for mortality risk reductions. Identifying such subgroups should be based on empirical evidence, not assumption. Meta-analyses may be helpful in identifying population characteristics that are important when determining whether a study's results are applicable for a particular policy analysis.

7. *Most studies that combine estimates adjust the data from the original studies to some extent. For example, some studies adjust for after-tax wages, whereas others do not. Is there a set of such modifications that the SAB-EEAC believes to be critical when deriving summary estimates from the literature? Are there some data modifications that are generally incompatible with a sound approach to synthesizing existing estimates? What are the implications for interpreting results?*

In synthesizing estimates from multiple studies, it is important to adjust as well as possible for differences among the studies, especially for differences in the monetary units used in the studies. Such adjustments can be made to studies before including their estimates in a meta-analysis.

One adjustment that can and should be made is to adjust for monetary inflation between studies by converting all nominal monetary values into real values. Because there is uncertainty about the best estimate of inflation over a period (reflected, for example, in different measures such as the various consumer price indices and the GDP deflator), the best adjustment is not clear. However, if one relies only on relatively recent studies (that are likely to be most relevant to the evaluation of current policy), differences between the alternative indices are likely to be modest and contribute little to uncertainty about the appropriate valuation compared with other factors. Similarly, if valuation estimates using other currencies are included, it is necessary to adjust for the purchasing power of the currencies (again, uncertainty about the best conversion rate is not likely to be a major concern). In the case of wages, differences in fringe benefit provisions across countries may be pronounced and must also be considered.

Other adjustments that are in principle desirable are more difficult to make, and so the SAB Panel recognizes our current empirical abilities may not permit these adjustments. One is to adjust for differences in real income and wealth between study populations. Since the value of reducing mortality risk increases with income and wealth, differences in these factors are expected to yield differences in estimated valuation. However, the appropriate magnitude of adjustment is not clear, because of uncertainty about the value(s) of the income elasticity and

very little empirical evidence concerning the relationship between wealth and mortality valuation.

A second potential adjustment is to convert all estimates into marginal changes in consumer income (net of taxes and benefits). In hedonic-wage studies, workers' choices are in principle driven by comparing the total incremental compensation with the total incremental risk between jobs, where total compensation includes wages, health insurance, retirement income, compensation conditional on injury, and other benefits, all evaluated post tax. In stated-preference studies, respondents are likely to view payments as coming from post-tax income (in principle, respondents may be asked about payments that would be made using either pre- or post-tax income; this detail is usually not specified but may be inferred from question wording). Adjustment for these factors is difficult because of variation in marginal tax rates and benefit schedules across populations, and so the SAB Panel does not view it as critical, but suggests that research attention be directed toward determining whether such adjustments can be made.

8. *What reporting and other protocols should the researchers conducting the combination study follow? How should the analysis handle zero or negative mortality risk valuation estimates from studies that otherwise meet its selection criteria for inclusion?*

The purpose of the combination study should be clearly defined. For what population is the study attempting to combine estimates? There should also be an explicit description of the rules for the inclusion and exclusion of items in the combination study, and of the search rule by which the candidate studies were identified in the first place.

There should be systematic coding of important features of the items included in the combination study, for example the metric in which wages are expressed, the metric for risk itself, the other variables included in models involving VSL, and the populations for which VSL was evaluated.

In general, the preferred approach for selecting studies is based on study design criteria, not study results, but there may be limited circumstances when it is appropriate to exclude studies based on results. One of these is a finding of statistically significant negative values for mortality risk reduction (implying the population would prefer a shorter lifespan to a longer one—an implausible result for anything but extreme circumstances). Obtaining statistically insignificant results, implying zero value for an incremental risk reduction, is on the other hand, a theoretically plausible result and is not sufficient reason for exclusion of a study. Implausibly high valuations may raise concerns about study design problems that may not have been identified, but it is very difficult to determine a criterion for exclusion based on “high” results. A preferable approach would be to include an analysis of the effects of outliers on the estimates of mean values and some eventual judgment about how much weight may be appropriate to give the outliers.

9. *What future research or additional data would offer the most improvement in the Agency's ability to derive summary estimates of mortality risk valuation for*

*environmental policy analyses over the short run? What longer-term research is most needed for improved summary mortality risk valuation estimates?*

- Fund more studies that will examine how the VSL varies with age and health status, the empirical correlates of life expectancy.
- Fund more studies that will shed light on the relationship between wealth and mortality valuation (income elasticity of VSL).
- Reanalyze the Pope et al. data to determine whether the impact of air pollution on mortality varies with age, rather than using a constant proportional hazard model).
- Attempt to improve hedonic wage estimates of the value of mortality risk reductions. Existing estimates, as pointed out by Dan Black and co-authors, suffer from omitted variable bias problems and problems of measurement error (in measuring risk of death), which cause estimates of the VSL to be biased.
- Fund studies to assess the advantages and disadvantages of combining RP and SP estimates of the VSL, for example, using structural approach.
- Fund studies to clarify the relationship between: (a) private willingness to pay to reduce own mortality risk (e.g., a private good), (b) private willingness to pay for programs that reduce mortality risk in the community (e.g., a public good) that may incorporate altruistic preferences, and (c) social preferences over programs that reduce mortality risk to people with different characteristics or risks from different sources. Some studies of each of these concepts have been published, but the literature is insufficient to identify possible systematic differences among results and to judge their relevance for EPA decisions.

## Life Expectancy and Mortality Risk Valuation: Charge Questions<sup>3</sup> and Responses

1. *What is the most appropriate methodology to use when valuing changes in mortality risk for persons with different remaining life expectancies? Is it appropriate to use a standard VSL to value reductions in mortality risk when information on remaining life expectancy is not available?*
2. *It is anticipated that EPA will need to issue rules affecting persons who differ in their remaining life expectancies in a relatively short time-frame. What does existing research imply about approaches to valuing mortality risk when people have life expectancies of varying lengths? How applicable and relevant is the existing literature and how does the existing theoretical and empirical literature inform these issues?*

According to standard welfare economics the value of a reduction in mortality risk (e.g., in the probability of dying over a stated period) is what a person is willing to pay for it. This amount may be affected by a person's remaining life expectancy, but theory (e.g., the lifecycle consumption model with uncertain lifetime) has little to say about the relationship between willingness to pay (WTP) and remaining life expectancy. Under specific assumptions, the lifecycle model predicts WTP for mortality risk reduction to be first increasing with age and then decreasing with age (an inverted U shape over the adult lifespan). Only in very special cases can it be said that WTP should be an increasing function of remaining life expectancy.<sup>4</sup> However, there are offsetting influences and it is not possible to predict based on theoretical analysis alone whether WTP is increasing, decreasing, or unchanged over a person's lifetime.

The relationship between WTP for mortality risk changes and remaining life expectancy is, therefore, an empirical matter. Unfortunately, this relationship is difficult to measure since remaining life expectancy is not observable while an individual is still alive. Individuals could be asked in a stated preference study what they would pay to reduce their probability of dying, *assuming different life expectancies*. However, this is a difficult question. In revealed and stated preference studies all that can be observed *ex ante* are correlates of life expectancy: viz., age and health status. So, one could try to measure how WTP varies with age and health status.

This suggests that EPA may, in principle, want to allow WTP to vary with age and health status. It is, however, the SAB Panel's judgment that the empirical literature is not advanced enough at present to provide clear guidance as to how age and health status affect WTP for changes in mortality risk.

Krupnick (2007) and Aldy and Viscusi (2007) provide recent summaries of the empirical literature on age and the VSL. Aldy and Viscusi (2007) focus on revealed preference studies while Krupnick (2007) summarizes the stated preference literature. Aldy and Viscusi (2007)

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<sup>3/</sup> In some cases, the charge questions were slightly revised to better reflect the Agency's intent, as discussed with the National Center for Environmental Economics.

<sup>4/</sup> The Appendix to this report discusses the implications of the life-cycle model with uncertain lifetime for the value of mortality risk reductions, explaining that, in general, theory places no restriction on the relationship between WTP and age or remaining life expectancy.

review compensating wage studies by Smith et al. (2004), Kniesner et al. (2006) and Aldy and Viscusi (2006).<sup>5</sup> Smith et al. (2004) find that the VSL is higher for workers aged 61-65 than for younger workers. Kniesner et al. find a VSL declines slightly after age 50 and then reaches a plateau, whereas Aldy and Viscusi (2006) find a significantly lower VSL for workers 55-62 than for younger workers. Krupnick (2007) reviews 35 studies, 20 of which find some evidence of the VSL declining with age and 15 of which do not. He concludes that, “Thus, considering the weight of the evidence, the implication is that for countries that apply a single VSL to adults of all ages, there is insufficient information and consensus to make a reasoned decision to switch to using either different VSLs for different ages (in a private good context) or a VS LY, which imposes a linear (discounted) relationship between life-years remaining and the VSL.” The SAB Panel agrees with this statement.

We suggest that EPA should, at present, use an age-independent VSL to value mortality risk reductions according to the conventional paradigm. However, we also urge the Agency to report the age distribution of statistical lives saved and the average remaining life expectancies of persons in each age group.

- 3. Are there other areas of the literature that should be examined and how would they inform this issue in the short term (i.e., less than 6 months)?*

The SAB Panel agrees that the White Paper by Dockins, Maguire, and Simon covered the appropriate literature.

- 4. What type of long-term research can inform these issues?*

The SAB Panel agrees that willingness to pay for risk reduction is likely to be affected by remaining life expectancy, which is related to both age and baseline health status. The existing evidence on these relationships is weak and occasionally contradictory. The SAB Panel recommends that additional research be funded to improve these estimates.

- 5. What paradigms should be considered in valuing changes in mortality risk for person with different life expectancies? How will these paradigms inform us in the short term?*

One paradigm that is commonly used to allow remaining life expectancy to affect the value of a reduction in mortality risk is the *Value of a Statistical Life Year (VSLY)*. As applied in practice, the VSLY assumes that the value of mortality risk reductions is proportional to remaining life expectancy (or discounted remaining life expectancy) and uses this assumption to calculate a value per life year saved. More specifically, the VSLY is derived by dividing the VSL by the discounted expected number of life years remaining for the average individual studied. This approach assumes that the VSL is the sum of the present value of each life year (the VSLY) weighted by the probability that an individual survives to that year, which is

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<sup>5</sup> Although many compensating wage studies interact worker age with fatality risk, they do not measure risk of death by age. Aldy and Viscusi (2007) note that these early studies may therefore yield biased estimates of how the VSL changes with age.

equivalent to assuming that the value of each remaining life year is constant.<sup>6</sup> The resulting VS LY is then applied to the expected number of discounted life years saved by the regulation (i.e., to the predicted increase in discounted life expectancy).

This procedure is difficult to justify on either theoretical or empirical grounds, if the appropriate valuation concept is what a person would pay to reduce his own risk of dying. There is no empirical evidence to suggest that the VS LY is constant, or that the VSL declines in proportion to remaining life expectancy, which the constant VS LY implies. (See answer to charge question 1.) To apply the VS LY correctly would require first estimating how the VS LY varies with age. If this can be done, it would be simpler to use an age-adjusted VSL than using an age-adjusted VSL to calculate and age-adjusted VS LY.

6. *More generally, based on the economics literature, under what conditions is it most important to provide information on life expectancy and baseline risks as part of an economic analysis of environmental policy? If the information cannot be incorporated directly into monetized benefits estimates, how might it best be provided as a supplemental analysis?*

In general, the measure of benefits based on WTP should reflect the WTP of the population that is affected by the change. The central VSL EPA has used in their most recent RIAs (PM and ozone NAAQS) is a midpoint between \$1 million and \$10 million. The former is the lower interquartile estimate from Mrozek and Taylor (2002)'s meta-analysis and the latter is the upper interquartile estimate from Viscusi and Aldy (2003)'s meta-analysis. The Agency notes that the midpoint (\$5.5 million in 1999 dollars and 1990 income levels) is very similar to the mean estimate from the Kochi et al. (2006) meta-analysis, which also included stated preference studies. The wage studies obviously reflect a population of working individuals, which implies at least some minimal health status (i.e., healthy enough to work) and a specific age distribution (i.e., working age adults) with an associated average life expectancy (estimated to be 35 years). If the population most affected by an EPA regulation or policy change differs from the population represented in these studies, then the WTP estimates generated by these studies may be a biased estimate of the true WTP of the affected population. *Whenever* this is the case, it will be important to provide information on the life expectancy and baseline risk<sup>7</sup> of the affected population as part of an economic analysis of the policy.

Unfortunately, the current economics literature does not provide convincing evidence regarding the direction of the bias that would exist if the baseline risk and life expectancy of the affected population differ from those of the population included in the WTP studies, i.e., there is mixed evidence on whether increases in baseline risk or reductions in life expectancy increase or

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<sup>6</sup> Formally, the approach assumes that the VSL at age  $j$  is,  $VSL_j = \sum_{t=j}^T q_{j,t} (1 + \delta)^{j-t} VS LY$ , where  $q_{j,t}$  is the probability that an individual at age  $j$  survives to age  $t$  and  $\delta$  is the discount rate. VS LY can be factored out of this expression, and  $\sum_{t=j}^T q_{j,t} (1 + \delta)^{j-t}$  is discounted remaining life expectancy.

<sup>7</sup> Strictly speaking, the term baseline risk refers to the survival curves of the members of the population affected by the regulation.

decrease WTP estimates (see discussion of other charge questions). Nonetheless, it is important to include these characteristics of the affected population for two reasons: (1) to highlight the potential for bias, even if it is not possible to predict its direction, and (2) to highlight the fact that the policy is likely to affect certain sub-populations disproportionately. While this latter information may not be formally incorporated into the benefit-cost analysis (e.g., by providing WTP estimates that are specific to affected sub-populations), it would provide the basis for an equity assessment, which in many cases is required by statute, executive order, or agency policy. Information about disproportionate impacts can be important input into policy decisions.

The information about baseline risk and life expectancy is most useful if provided in the form of a distribution (rather than simply an average) across the affected population. This is particularly true when the distribution is bi-modal. A bi-modal distribution would exist, for example, in cases where the very young and the very old are susceptible to pollution effects.

## Appendix to Life Expectancy Charge Questions

This Appendix consists of two parts. The first describes the concept of a survival curve and its relationship to life expectancy. The second presents the life-cycle consumption saving model with uncertain lifetime, which forms the theoretical basis for examining the relationship between the Value of a Statistical Life, age and remaining life expectancy.

### *Survival Curves and Life Expectancy*

The effects of an environmental intervention on mortality risk can be summarized using survival curves. Survival curves can be constructed for an individual or a population. An individual survival curve plots the probability that an individual is still alive as a function of her age (or calendar date). A population survival curve plots the fraction of people who are still alive as a function of date. A survival curve can be constructed beginning at any age or date and slopes downward (or is constant) everywhere. A steeper downward slope corresponds to greater mortality risk. The area under an individual's survival curve equals his remaining life expectancy.

Any pattern of change in mortality risk over time can be characterized as a shift in the survival curve. For example, a one year reduction in mortality risk (e.g., from reducing exposure to an acutely lethal pollutant such as carbon monoxide) flattens the survival curve for that year and hence increases its height for later time periods. A risk reduction having only delayed effects (e.g., reducing exposure to a pollutant that causes cancer to develop after a latency period) has no effect on the curve for the time between the change in exposure and the end of the latency period but flattens the curve and increases its height for subsequent periods. Any change in the survival curve produces a unique expected number of life years saved or lost (the change in the area under the curve).

What is typically valued in empirical studies is a change in the probability of dying over the coming year. As explained above, a reduction in the probability of dying over the coming year raises the individual's survival curve for all future years and thereby increases his life expectancy. The next section discusses how a rational, expected-utility maximizing individual would value this change in the context of the life-cycle consumption saving model.

### *Implications of the Life-Cycle Model for Age and the VSL*

This section uses the life-cycle model with uncertain lifetime to derive WTP for a change in the conditional probability of dying at any age (Cropper and Sussman, 1990; Cropper and Freeman, 1991) and to examine how this might vary with age and remaining life expectancy. The model assumes that at age  $j$  the individual chooses his future consumption stream to maximize expected lifetime utility,

$$V_j = \sum_{t=j}^T q_{j,t} (1 + \delta)^{j-t} U_t(C_t) \quad (1)$$

where  $V_j$  is the present value of expected utility of lifetime consumption,  $U_t(C_t)$  is utility of consumption at age  $t$ ,  $q_{j,t}$  is the probability that the individual survives to age  $t$ , given that he is alive at age  $j$ , and  $\delta$  is the subjective rate of time preference. We assume that (1) is maximized subject to a budget constraint that allows the individual to invest in annuities and to borrow via life-insured loans (Yaari, 1965). This is equivalent to assuming that the present value of expected consumption equals the present value of expected earnings plus initial wealth,

$$\sum_{t=j}^T q_{j,t} (1+r)^{j-t} C_t = \sum_{t=j}^T q_{j,t} (1+r)^{j-t} y_t + W_j, \quad (2)$$

where  $r$  is the riskless rate of interest,  $y_t$  is income at time  $t$  and  $W_j$  is initial wealth.

Now consider a program that alters  $D_k$ , the conditional probability of dying at age  $k$ , given that the individual survives to that age. Since  $q_{j,t} = (1-D_j)(1-D_{j+1}) \dots (1-D_{t-1})$ , any program that alters  $D_k$  will necessarily alter the probability of surviving to all future ages. For small changes in  $D_k$ , willingness to pay may be written as the product of the rate at which the individual is willing to trade wealth  $W_j$  for a change in  $D_k$ , which we term  $VSL_{j,k}$ , times the size of the change in  $D_k$ ,

$$WTP_{j,k} = - \frac{dV_j / dD_k}{dV_j / dW_j} dD_k \equiv VSL_{j,k} dD_k. \quad (3)$$

Applying the Envelope Theorem to the Lagrangian function formed by (1) and (2), the rate at which the individual substitutes current wealth for  $D_k$  may be written (Cropper and Sussman, 1990) as:

$$VSL_{j,k} = \frac{1}{1-D_k} \sum_{t=k+1}^T q_{j,t} [(1+\delta)^{j-t} U_t(C_t) \lambda_j^{-1} + (1+r)^{j-t} (y_t - C_t)]. \quad (4)$$

Equation (4) says that the value of a change in the probability of dying at age  $k$  equals the loss in expected utility from age  $k+1$  onward, converted to dollars by dividing by the marginal utility of income ( $\lambda_j$ ). Added to this is the effect of a change in  $D_k$  on the budget constraint. Cropper and Sussman (1990) show that, by substituting first-order conditions for utility maximization into (4) and rearranging terms, the VSL at age  $j$  for a risk reduction at age  $j$  equals

$$VSL_{j,j} = \frac{1}{1-D_j} \sum_{t=j+1}^T q_{j,t} (1+r)^{j-t} [U_t(C_t)/U_t'(C_t) + y_t - C_t]. \quad (5)$$

If the individual does not have access to fair annuities, but can save at the riskless rate  $r$  (i.e., he can never be a net borrower), then the expression in (5) holds without the last two terms inside the brackets.

It is  $VSL_{jj}$  that is estimated in compensating wage studies. Most stated preference studies measure (3) (with  $j=k$ ). The question is how (5) changes with  $j$ . If  $U_t(C) = U(C)$  for all  $t$ , and  $r = \delta$ , then  $C_t$  is constant for all  $t$ . In the case in which the individual can save at rate  $r$  (but never be a net borrower), the term in brackets is constant and  $VSL_{jj}$  becomes

$$VSL_{jj} = \frac{1}{1-D_j} \sum_{t=j+1}^T q_{j,t} (1+r)^{j-t} [U(C)/U'(C)]. \quad (6)$$

In this special case, if  $(1-D_j)^{-1}$  is close to 1,  $VSL_{jj}$  is likely to decline with age,  $j$ . Since

$$\sum_{t=j+1}^T q_{j,t} (1+r)^{j-t}$$

represents discounted remaining life expectancy,  $VSL_{jj}$  is approximately proportional to discounted remaining life expectancy, which would justify the use of a constant VSLY. Equation (6) is, however, a very special case.

In general, as equation (5) demonstrates, one cannot make any statement regarding how  $VSL_{jj}$  varies with age  $j$ . This depends entirely on the pattern of consumption and utility of consumption over the lifecycle.

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