A Theoretically-Consistent Empirical Model of Non-Expected Utility: An Application to Nuclear-Waste Transport

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Abstract

Risk aversion is well established in the health and safety literature, and ambiguity is addressed in theoretical and experimental economics literature, but few theoretically-consistent empirical models addressing the relationship between ambiguity, risk, and preferences exist. Even fewer address ambiguity about health or mortality risks. To fill this gap, we propose a theoretical non-expected-utility model (NEUM) that is relatively easy to estimate. The NEUM we develop hinges upon two sources of variability, one over risk and the other over uncertainty about the risk. The model, like the second-order probability models of Segal (1987) and Quiggin (1982), grounds ambiguity in the compound lottery context. However, our model differs from previous approaches by assuming that the moments of the subjective-risk distribution drive preferences through the utility function rather than via the usual probability weights. Moreover, the model allows for heterogeneity in information sets and/or personal characteristics thereby offering individual-specific estimates of utility and the value of welfare changes.

Using data from a survey of Nevada residents concerning risks from high-level nuclear-waste transport, we explore heterogeneity in the moments of their subjective-risk distributions. Next, we estimate the ex-ante value of those risks as a function of the moments of the subjective-risk distribution. Our findings suggest that negative externalities associated with nuclear-waste transport based on perceived risks may be quite substantial. We also find that uncertainty about the program clouds individuals' understanding of the risks, and that ambiguity significantly influences choices and values.

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Researchers seeking to estimate the social costs arising from health and safety risks are faced with two dimensions of uncertainty. The first dimension, referred to as event uncertainty or "risk," arises because the event of an accident or health outcome is inherently a random variable. The second type of uncertainty arises from imprecise, unreliable, or incomplete information, and/or other factors that prohibit the precise quantification of risk. Referred to as ambiguity, this uncertainty leads to the nondeterministic nature of subjective risks.[1] While studies of the effects of risk and ambiguity on preferences abound in the theoretical and experimental literature, there are few empirical studies of the effect of ambiguity on decision making outside the laboratory.

This paper makes two contributions to the literature. First, we propose a theoretical non-expected-utility model (NEUM) that allows for ambiguity about health and safety risk on the part of households. The model hinges upon two sources of variability, one over subjective risk and the other over ambiguity surrounding the risk. The latter is treated as a second-order random variable, similar to that in the second-order probability models of Segal (1987) and Quiggin (1982). Like those models, our approach can be interpreted as grounding ambiguity within the compound lottery context: with ambiguity the compound lottery reduction axiom of expected utility theory does not hold. However, our model differs from previous models by assuming that the moments of the subjective-risk distribution drive preferences through the utility function rather than through probability weights. As such, it reflects another approach to adding a richer dimension to the well-known Marschak-Machina triangle.[2] Our resulting model has properties that make it especially suited for jointly estimating the effects of risk and ambiguity on preferences. This is a significant departure from the standard expected utility model (EUM) where the event probability is typically deterministic and exogenous.

This paper makes a second contribution to the risk literature by developing a model that generates theoretically-based welfare measures that allow for heterogeneity in individual risk perception and utility. Using a survey that elicits individuals' perceived risks and stated preferences for high-level nuclear-waste transport, we first examine heterogeneity and show that information sets and demographic variables such as health and gender affect the location and shape of the subjective-risk distribution. Next, we operationalize the theoretical non-expected-utility model and apply it to estimating the ex-ante social cost, in terms of a generalized option price (GOP). Subjective risk and ambiguity estimates enter the econometric model as independent variables thereby allowing the value of mortality-risk changes to vary with perceived risk and ambiguity for each survey respondent.[3] Joint estimates of the effect of risk and ambiguity in decision-making are rare, and those that do exist are not linked to a micro-theoretic model. Our study attempts to bridge the gap between psychologists' recommendations regarding the incorporation of ambiguity and an econometric model of behavior that allows for it.

The model results indicate that the external social cost of nuclear-waste transport in Nevada is likely to be substantial unless risk perceptions change markedly from those implied by our sample. Notwithstanding, we show that risk and ambiguity are important components of the current social cost of nuclear-waste transport. Most importantly, people display ambiguity aversion thereby markedly increasing the social cost associated with risk. This leaves open the possibility for public education programs aimed at reducing ambiguity and ameliorating some of the associated social costs.

1. Literature Review

In this section we review relevant literature on risk and ambiguity, then briefly discuss past studies targeting the social costs of nuclear-waste storage and transportation.

1.1 Uncertainty

Graham's option price (OP) is an ex-ante payment that equates expected utility with and without some risk-related program (Graham 1981). The conventional EUM, the cornerstone of Graham's OP, has been undermined in recent years because observed behaviors, particularly in laboratory or experimental settings, are not consistent with the EUM's predictions. Criticism has been levied most strongly at the independence axiom that constrains the EUM to be linear in probabilities, in turn implying parallel, linear indifference curves for gambles. At least two important violations of the independence axiom have been observed consistently in the experimental laboratory setting 1) ambiguity about what risks may eventually materialize can affect choices and 2) people place a higher marginal value on changes in low-risk events than on otherwise equivalent changes in high-risk events.

To rectify the apparent limitation of the conventional EUM alternative models, generalized expected-utility models (GEUMs), some perhaps more appropriately deemed non-expected-utility models (NEUMs), have been developed [see for example, the prospect theory of Kahneman and Tversky 1979, Schmeidler's Choquet expected-utility model (1989), the theory of anticipated behavior or rank-dependent expected utility by Quiggin 1982]. There are important differences between each of these models, but they share the general characteristic that they relax the independence axiom allowing for a variety of behaviors in response to risk, such as ambiguity aversion. Machina (1982) shows that most of the behavioral predictions of the EUM are unchanged when an assumption of differentiability is substituted for independence. This has paved the way for the development of new NEUMs.

Harless and Camerer (1994) test competing theories of behavior under risk including the prospect theory, EUM, mixed fan, and expected value models.[4] They do not find a clear "winner", rather, all theories fail systematically under some circumstances. EU theory tends to approximate decisions for lotteries on the interior of the Marschak-Machina triangle; whereas, fanning out theories tend to work well for boundary lotteries.

Ambiguity has been modeled using a variety of approaches.[5] One popular approach is to express uncertainty about risks as a second-order random variable. Many of these second-order probability models (SOPs) assume that a compound lottery (the lottery over the event and that over the probability of the event) can at least theoretically be reduced to a single stage so that predictions will be consistent with those from known-probability models. Other models, such as the ones proposed by Quiggin (1982) and Segal (1987), relax the reduction assumption and allow for ambiguity by assigning weights to event probabilities. Kahn and Sarin (1988) address ambiguity using an SOP model that adds a decision weight to the value function. In some instances Choquet integration is required so that non-additivity of probabilities can be accommodated (Schmeidler 1989).

Whatever the theoretical approach, nearly all existing empirical work addressing ambiguity aversion examines preferences for financial and investment decisions in an experimental or laboratory setting (Ellsberg 1961, Curly and Yates 1985, Kahn and Sarin 1988, Chow and Sarin 2001, Mukerji and Tallon 2001, Ho et al. 2002**).** We emphasize two points: first, existing empirical results come from laboratory experiments, and second, nearly all empirical results on ambiguity pertain to financial gambles, or choices involving simple probability experiments such as balls drawn from urns.

Economists have only recently begun to develop empirical welfare models containing ambiguity effects for uncertain health or environmental outcomes in a real-world setting (Viscusi and Chesson 1999). A handful of surveys have been designed to allow ambiguity to be explored outside the laboratory setting. Cameron (2005, 2003) extends the empirical risk literature and allows for ambiguity about mean, future global temperatures using a single variable mean-variance approach.[6] She applies the model to a convenience sample of college students and shows that ambiguity affects the willingness to pay (WTP) for climate-change mitigation programs. Riddel et al. (2003) use a survey-based study of nuclear waste disposal to examine housing-location decisions when mortality and morbidity risks are uncertain.

1.2 Nuclear-Waste Storage and Transport Studies

In 1987, the U.S. Congress named Yucca Mountain Nevada, 90 miles northwest of Las Vegas, as the only candidate site for a central high-level nuclear waste repository. If completed, the Yucca Mountain (YM) project is expected to cost over $55 billion, making it among the most expensive U.S. government projects ever constructed (Slovic 1991, Slovic 1993, Desvousges et al. 1993, Flynn and Slovic 1995, Flynn et al. 1997). Over 77,000 tons of high-level radioactive waste will be shipped by rail or highway from commercial and U.S. Department of Energy (DOE) sites across the U.S., in approximately 53,000 shipments, taking place over the course of 24 years.

At the projects' inception, the DOE funded several studies examining the public's reaction to a central repository for the nation's high-level nuclear waste. In one such study, Kunreuther and Easterling (1990) used survey-based methods to examine attitudes and values associated with nuclear-waste transport. They found that just over 70 percent of a national sample agreed with the statement "highway and rail accidents will occur in transporting nuclear waste." When offered a payment of $5,000 to offset the risks of nuclear-waste transport, 32 percent of the respondents reported they would accept the compensation. It is important to note that the study did not find significant risk-perception differences between the national and Nevada samples. A flurry of papers following these studies focused on the importance of the psychology and perceptions of risk in forming preferences for nuclear-waste transport (Flynn and Slovic 1995, Flynn et al 1997, Slovic 1993).

More recently, Gawande and Jenkins-Smith (2001) examined the impact on residential property values of transporting high-level nuclear waste through three counties in South Carolina. Respondents in a telephone survey were asked to grade the likelihood that an accident during transport could occur on a scale of 1 to 10. Respondents felt that an accident was quite likely with the mean perceived threat falling at the midpoint of the scale. They also found significant real-estate price effects arising from the perceived transportation risk providing evidence of positive and significant ex-ante welfare impacts associated with nuclear-waste transport.

Using data from a different part of the same survey mentioned above on housing location decisions (Riddel et al. 2003), Riddel and Shaw (2003) derived losses in bequest value from storing nuclear waste at Yucca Mountain. They found that ambiguity and perceived risk significantly affect preferences for both housing-location and bequest values.

In the following section, we develop our version of a NEUM, framing it in terms of modeling nuclear-waste transport. With modest modifications, our model could be used to examine other programs resulting in changes in health and safety risks. Our approach provides a novel means of estimating the influence of ambiguity on stated and intended behavior, but with the knowledge of risk perceptions as we have, there is no reason why it could not be similarly used to examine observed behavior. We provide a clear link between the empirical and theoretical risk models. Thus, the tests for risk and ambiguity aversion we present are generated by a theoretical decision model rather than by specifications of ambiguity that may depend solely on respondent's stated attitudes.

2. Modeling Health-Risk Ambiguity

There are convincing arguments that ambiguity about risk exists (Camerer and Weber 1992, Manski 2004, Starmer 2000). This may be particularly true for those risks, such as nuclear-waste transport or global warming, that are outside the sphere of current experience for most or all of those affected. Many individuals may not have formed deterministic beliefs because they view the currently available information regarding the risk change as incomplete, unreliable, and/or difficult to assess. Further, many researchers have demonstrated that individuals have difficulty assessing small and unfamiliar risks. As seen below, while the assessed mortality risk of nuclear-waste transport is deemed quite small by the DOE, the public perceives the risk to be many orders of magnitude larger. Taking these arguments together, it is likely that many people who might be exposed to nuclear waste have a considerable degree of ambiguity about what risks will eventually materialize. In the next section we develop what might best be described as a non-expected-utility model, setting up the microeconomic theory to accommodate the ambiguity in such a way that an empirical model flows directly from it.

2.1 The Theoretical Model

Assume that there are two states--the current, or baseline state without ongoing high-level nuclear-waste transport and an alternative state, with such transport. We ignore background radiation levels and assume that the baseline risk of accident with mortality equals zero, since no threat of high-level nuclear-waste exposure currently exists. If transport occurs, then some households face mortality risk from exposure following transport accidents.

Assume that mortality risk from a transport accident (π) is a random variable with mean μ_π and variance σ_π^2 for some general distribution bounded on the zero-one interval. The mean risk, μ_π, represents an individual's "best guess" as to what risk they may face should transport commence. Because it is based on the individual's assessment of risk, it is a "subjective risk."

Ambiguity is introduced by defining the variance of risk as a random variable such that $\sigma_\pi^2 \sim \psi(\mu_{\sigma_\pi^2}, \sigma_{\sigma_\pi^2}^2)$ for some general distribution, ψ, bounded below at zero. The mean, $\mu_{\sigma_\pi^2}$, is the ambiguity measure. Conflicting information, as well as unresolved questions about the routes, shipping, and handling methods induce ambiguity about the probability that an accident will occur. Larger values of $\mu_{\sigma_\pi^2}$ represent higher levels of ambiguity.[7]

Thus, two random variables are evident: risk and ambiguity. An increase in the mean risk represents a general shift in risk perception whereas increasing the average variance of perceived risk means an increase in ambiguity. If ambiguity is entirely absent then the risk distribution is degenerate and $\sigma_\pi^2 = 0$. In that case, the model is a variant of the subjective expected-utility model where health, rather than income, is random. And, because ambiguity is expressed as uncertainty in one of the moments of the risk distribution, it can be viewed as a type of second-order probability model.

Define Y as income and X as a vector of individual-specific attributes affecting utility. V^0 is utility when there is no threat from nuclear-waste transport, perceived or otherwise. V^1 describes utility when nuclear-waste transport has commenced and there is a potential risk of an accident with mortality. Assume that payment A compensates each household for bearing the risk of transport so that utility is equalized across the two states. Let $f(\pi)$ be the risk function relating random risk to utility. Finally, let an additive term (ε^i) measure the observation error for state i. Define the following levels of indirect random utility:[8]

$$\begin{aligned} V^0 &= \alpha^0{}' X + \beta \ln Y + \varepsilon^0 \\ V^1 &= \alpha^1{}' X + \beta \ln(Y + A) + f(\pi) + \varepsilon^1. \end{aligned} \qquad (1)$$

Because V^i is log-linear in income, it has the attractive property of diminishing marginal utility of income that is consistent with financial risk aversion. The utility function allows individuals to have a nonconstant marginal utility of income. Income effects may be appropriate when the good, here safety, accounts for a significant portion of a household's perceived wealth. However, a linear-in-income utility function could also be used if income effects are thought to be unimportant.

Although many authors have equated health- and financial-risk aversion, this is problematic because diminishing marginal utility of income implies little about an individual's taste for changes in health and safety risks (see Eeckhoudt and Hammitt 2004). Thus, we add a risk function $f(\pi)$ to V^1 to account for changes in utility stemming from mortality-risk aversion. Analogous to financial-risk aversion, $f(\pi)$ should accommodate either linear or nonlinear relationships between mortality risk and utility. Health or mortality risk aversion is evident if utility and increasing health risk are inversely related. We use the functional form proposed by Cameron (2005) that assumes that risk and the squared deviation from risk affect utility so that: [9]

$$f(\pi) = \gamma_1 \pi + \gamma_2 (\pi - E[\pi])^2. \qquad (2)$$

The next step is to find the expected value of the utility difference based on the risk function. We note that the unconditional expected value of the risk function can be found by applying the formula $E[f(\pi)] = E_{\sigma_\pi^2}[E_\pi[f(\pi) \mid \sigma_\pi^2]]$. The expected value of the risk function conditional on the variance, σ_π^2, is:

$$E_\pi[f(\pi) \mid \sigma_\pi^2] = \gamma_1 \mu_\pi + \gamma_2 \sigma_\pi^2, \qquad (3a)$$

thus the unconditional expected value is:

$$E[f(\pi)] = E_{\sigma_\pi^2}[E_\pi[f(\pi) \mid \sigma_\pi^2]] = \gamma_1 \mu_\pi + \gamma_2 \mu_{\sigma_\pi^2}. \tag{3b}$$

Using 3b, the unconditional expected utility difference can be found by applying the formula: $E_\pi[V^1 - V^0] = E_{\sigma_\pi^2}[E_\pi[V^1 - V^0 \mid \sigma_\pi^2]]$. Taking the expectation of the utility difference conditional on σ_π^2 over π yields:

$$\begin{aligned} E_\pi[V^1 - V^0 \mid \sigma_\pi^2] &= \alpha' X + \beta[(\ln(Y + A)/Y)] + \gamma_1 E_\pi[\pi \mid \sigma_\pi^2] + \gamma_2 E_\pi[(\pi - E[\pi])^2 \mid \sigma_\pi^2] + \varepsilon \\ &= \alpha' X + \beta[(\ln(Y + A)/Y)] + \gamma_1 \mu_\pi + \gamma_2 \sigma_\pi^2 + \varepsilon \end{aligned} \tag{4}$$

where $\alpha = \alpha^1 - \alpha^0$ and $\varepsilon = \varepsilon^1 - \varepsilon^0$. The unconditional expectation is then:

$$\begin{aligned} E_\pi[V^1 - V^0] &= \alpha' X + \beta[(\ln(Y + A)/Y)] + \gamma_1 E[\mu_\pi] + \gamma_2 E[\sigma_\pi^2] + \varepsilon \\ &= \alpha' X + \beta[(\ln(Y + A)/Y)] + \gamma_1 \mu_\pi + \gamma_2 \mu_{\sigma_\pi^2} + \varepsilon \end{aligned} \tag{5}$$

Setting (5) equal to 0 and solving for A gives a generalized option price (GOP) defined as the ex-ante payment that equates utility over the risky and nonrisky states. Assuming a standard-normal observation error (ε) the formulas for the GOP and the median GOP, or $Med_\varepsilon[GOP]$[10] are:

$$\begin{aligned} GOP &= Y[\exp\{-(\alpha' X + \gamma_1 \mu_\pi + \gamma_2 \mu_{\sigma_\pi^2} + \varepsilon)/\beta\} - 1] \\ Med_\varepsilon[GOP] &= Y[\exp\{-(\alpha' X + \gamma_1 \mu_\pi + \gamma_2 \mu_{\sigma_\pi^2})/\beta\} - 1] \end{aligned} \tag{6}$$

As constructed, the GOP is an exponential function of income, individual-specific characteristics, the expected mortality risk, and random variation in that risk. Note that variables, such as risk, that presumably decrease utility cause WTA to rise. Although the philosophy of our approach mirrors other SOP models (see Kahn and Sarin, 1988, for example), our mechanics are novel. Our second-order random variable deviates from an approach based on nonlinear probability weights by assuming that the moments of the risk distribution drive preferences through the utility function. Changes in the mean risk affect utility and GOP. And, for a given mean risk, changes in ambiguity shift expected utility and the corresponding GOP.

Our empirical model, like that of Kahn and Sarin's (1988), allows us to distinguish between ambiguity preference and ambiguity aversion by testing the sign of γ_2. A value of $\gamma_2 > 0$ implies a preference for ambiguity; i.e. increasing ambiguity causes expected utility to rise and the GOP to fall. A value of $\gamma_2 < 0$ implies ambiguity aversion meaning that given a choice, people prefer to bet on known rather than unknown probabilities. As a result, we can derive a statistical test for the relationship between ambiguity, utility, and the GOP based on a log-likelihood test of the model parameters. This is in contrast to a split-sample design laboratory experiment where the statistical significance of ambiguity is tested by presenting an ambiguous risk to one of two groups of subjects and looking differences in choice patterns between the groups.

Another attractive feature of this model is that it allows for a nonlinear relationship between risk and GOP. Risk affects the GOP through the exponential function in (4). This allows for the s-shaped relationship, recognized by Kahneman and Tversky (1979), between GOP and risk. Experimental evidence suggests that individuals overvalue changes in low-level risks and undervalue similar changes in high-level risks relative to the linear-in probabilities expected-utility model.[11] The GOP proposed in (6) accommodates nonlinear risk preferences and allows us to develop a statistical test for that nonlinearity based on the signs of γ_1 and γ_2.

Finally, note that the model allows GOP to explicitly account for heterogeneity in perceived risk. Rather than having a Bayesian updating model, where individuals form priors and the model assesses the degree to which information influences dependence on a posterior distribution, our model makes the welfare measure a simple and direct function of perceived risk. Thus, the model may be used to calculate how the GOP varies across households or for a given household as their risk perception changes with changes in the household information set.

In summary, we present a model based on a non-expected utility approach with a mean-variance component that leads to welfare measures for a change in risk. The resulting welfare measure, the GOP function in (4), has four attractive properties: 1) it accounts for health-risk aversion together with financial-risk aversion, 2) it allows for testable ambiguity effects, 3) it allows for the nonlinear risk preferences that are often observed in the experimental risk literature, and 4) it allows for heterogeneity in risk perception and preferences.

3. Yucca Mountain Application: The Survey and the Data

Data collection follows the phone-mail-phone survey implementation plan and corresponding protocols. This plan is recommended when information given to respondents is somewhat complex. Residents of Southern Nevada were surveyed because all of the waste slated for relocation to Yucca Mountain must pass through that region.[12] Residential telephone numbers were randomly selected from a comprehensive list of telephone numbers provided by the local telephone company, Centel.

To begin, a trained interviewer telephoned each household on the list.[13] Those contacted were asked to participate in a survey, to be given at a later date. If they agreed, they were mailed a color information brochure in anticipation of the telephone survey. The brochure contained a description of the Yucca Mountain Project and the potential risks and damages that it may pose, several illustrations of key parts of the project facility, a map of the proposed transportation route, and on the final page, a risk ladder depicting the annualized lifetime probability of death from a variety of familiar causes (see Corso et al. 2001, Carson and Mitchell 2000, or Loomis and duVair 1993). In addition to familiar causes of death, the risk ladder gave DOE estimates of the annualized lifetime risks of nuclear-waste transport and storage that vary with the distance from the site and proximity to transportation routes. The household member had ample time to review the booklet before the telephone interview.

In the telephone interview, respondents were first queried about risk perceptions related to nuclear-waste transport. Using the risk ladder, respondents reported either a point estimate or a range of the mortality risk from transporting the nuclear waste along the proposed route. The respondents could offer their own estimates, even if this was off the risk ladder's depicted scale. Although a few respondents (fewer than 5 percent) reported that their subjective mortality risks were outside the ladder's range, the overwhelming majority of individuals placed the risk somewhere along the ladder, though as will be seen, not necessarily at a point corresponding to the DOE estimates.

Following the risk assessment, respondents were presented with a hypothetical risk-compensation program. Respondents were told that nuclear waste would be transported along the route depicted in the map and that some amount of compensation, *A*, would be offered to those living near the route. Respondents were asked if they would accept the compensation and stay at their present location or if they would relocate to protect themselves from the risks associated with nuclear-waste transport. Respondents were told that their moving costs would be paid if they chose to move. Moving presumes that the household continues to face no risk from nuclear-waste transport, with certainty, though no compensation is received. If the compensation offsets the individual's lost utility from the increase over the baseline risk, the respondent prefers to stay and accepts the compensation in lieu of the costs associated with nuclear-waste exposure risk.

The compensation amount was presented as a federal-tax rebate. This method of payment is reasonable, as the federal nuclear-waste program required that the host state be compensated. Under the 1987 amendments to the Nuclear Waste Policy Act, Nevada was to be compensated at $10 million per year during the site-characterization phase, and $20 million per year once waste began to be delivered to the site. States can then use these federal dollars to compensate or relocate households asked to bear additional risks (Flynn and Slovic 1995).

We asked respondents about relocation decisions to avoid protest responses encountered in focus groups. In direct valuation questions, focus-group participants tended to reject compensation amounts that were sometimes 25% or more of their annual income. When confronted about whether they would actually return a federal-tax rebate, some responded that they would relocate thereby indirectly refusing compensation whereas others said that they would not relocate or return a tax rebate. Thus, we interpreted the latter group's decision to refuse compensation as a protest response. In a follow-up focus group, we found that respondents where more comfortable answering the "stay" versus "relocate" question rather than being offered a choice of accepting or rejecting compensation directly.

The overall response rate, calculated as the number who completed the entire survey (both phone interviews) divided by the total number of people contacted, was

27.4%.[14] This response rate is relatively high for the highly transient Nevada community, reflecting interest in the topic. Nevada is notorious for telemarketing and junk mail and low survey response rates are the norm. Many of those who were initially called hung up before being told the purpose of the telephone call. Thus, the low response rate likely overstates those that actually rejected the survey topic because it includes those that simply rejected any telephone contact from an unfamiliar party.

Low response rates may cause bias if they are not representative of the target population. To gauge the representative nature of the sample of respondents, we carefully compared the demographic profile to that of the larger Clark County population using the 2000 Census figures and found that the demographic statistics were comparable overall. Those responding to our survey were slightly more affluent than the county population as a whole. Median household income in Clark County is $44,616 compared to our sample-mean income of $51,100. Household sizes in the sample were similar to that in Clark County; 2.74 persons per household in the sample versus the Census estimate of 2.65 persons per household. And, as in many surveys, the sample was modestly skewed toward older individuals: 21 percent of Clark County households contain at least one retiree, and the sample contained 24 percent with retirees. Other demographics features of the sample were quite similar to those reported by the U.S. Census Bureau for Clark County.

Further reassurance concerning our sample comes from the striking similarity between our risk estimates and those from an in-person interview survey conducted later for the DOE, in March 2003 (see Riddel, Boyett, and Schwer 2003). In the 2003 in-person survey, the same basic risk ladder was used as we used for this study with the addition of a blow-up of the low-risk end of the ladder (that depicting causes of death less than 1 in 1,000 annual lifetime deaths) following Carson and Mitchell (2000). The mean perceived death rate was 425 in 100,000 in the 2003 survey compared to a death rate of 454 in 100,000 estimated from our 2001 survey. The fact that in-person interviews with the visual expansion of low-end risks in the risk ladder produced roughly the same mean risk estimate as our earlier phone-mail-phone survey offers further support for the validity of the survey instrument and basic risk ladder.

4. Empirical Development

The ultimate goal of this paper is to provide a model that will calculate a risk-related welfare measure (our GOP) for nuclear-waste transport for a broad range of subjective-risk distributions. This section presents the model in two parts. First, we explore heterogeneity in the moments of the subjective risk distribution. Following that, we present the choice model used to estimate the GOP.

4.1 Modeling Risk and Ambiguity

Our welfare measure in (6) requires individual-specific estimates for the mean and expected variance of the subjective-risk distribution. The survey respondents either offered their current perceived risk as one point on the ladder, or offered a range for the risk rather than one point. The risk distribution for those offering a point estimate is degenerate, as the variance is zero. We charted the empirical risk distribution for those that gave point estimates and it is skewed to the right. The expected value is the midpoint of a symmetric distribution but falls to the right or left of the midpoint for probability distributions with a right or left skew. As such, a model that allows for asymmetry could provide superior estimates over that of the midpoint of the range. Further, a model that relates the mean risk for respondent i, $\hat{\mu}_{\pi_i}$, to individual-specific covariates, Z_i offers a clear picture of the source of the heterogeneity in subjective-risk distributions. This section explores heterogeneity by providing individual-specific estimates of the likelihood of an accident during transport involving human exposure.[15]

Risk as a probability or chance is inherently bounded on (0,1) so the beta distribution, also bounded on (0,1), is a natural and reasonably tractable choice to describe the variation in π (Heckman and Willis 1977). Thus, assume perceived risk for individual i, π_i, follows the beta distribution so that $\pi_i \sim Beta(a_i, b_i)$ with $E[\pi_i] = \mu_{\pi_i} = \frac{a}{a+b_i}$ where $a > 0$ and $b_i > 0$ are the parameters of the beta distribution for person i. Note that the variation across respondents arises solely from b_i, thus a is fixed and identical for all of the respondents.

We estimate values for a and b_i using an iterative approach. We estimate preliminary parameter values by graphing the empirical density function and comparing it to actual beta distributions. We then select values for $\hat{a}$ and $\hat{b}$ that offer the best match between the empirical and actual distributions. The resulting estimates are equivalent starting values in the standard maximum likelihood context. We then condition on the starting value of $\hat{a}$ to obtain a new estimate of $\hat{b}_i$ as a linear function of the covariate set ($\hat{b}_i = \hat{\theta}' \mathrm{Z}_i$) using maximum likelihood to estimate the coefficient vector $\hat{\theta}$ (see Appendix A for a description of the likelihood function).

Given the estimates of $\hat{a}$ and $\hat{b}_i$, we compare the implied distribution to the empirical distribution and choose the value of $\hat{a}$ that best improves the fit. Conditioning on that value, we obtain a second preliminary estimate of $\hat{\theta}$. This procedure is repeated until convergence is achieved.

The converged value estimate for $\hat{a} = 0.00091$. As mentioned above, we allow the expected risk to vary with a set of respondent-specific independent variables, thus $\hat{\mu}_{\pi_i} = \frac{\hat{a}}{\hat{a}+\hat{b}_i} = \frac{\hat{a}}{\hat{a}+\hat{\theta}' Z_i}$. The marginal change in the mean risk for a change in Z_i is $\frac{\partial \mu_{\pi_i}}{\partial Z_i} = \frac{-\hat{a}}{\hat{\theta}(\hat{a}+\hat{\theta}' Z_i)^2}$. Since the covariate set is unique to the respondent, $\hat{\mu}_{\pi_i}$ is respondent specific. Note that because $\hat{b}_i$ appears in the denominator, positive values of $\hat{\theta}$ suggest that risk perception is negatively related to the corresponding variable.

Past research in risk communication suggests that the amount of information an individual is exposed to affects his or her risk perception. Along these lines, we asked respondents if they had heard about the proposed repository from local media, national media, DOE reports, other federal government sources, state and local government, or environmental-group publications. To gauge the amount of information held by each respondent, we calculated an index of the total information, INFOLEVEL, by scoring a one for each information source and summing to get the total index value. A zero value indicates that the respondent had not heard of the proposed facility whereas, subsequently higher values correspond to more information exposure. Another information variable, TOUR, takes on a value of one if the respondent had toured the facility and a zero otherwise, representing a high degree of familiarity with the facility.[16]

INFOLEVEL, TOUR, a dummy variable representing household health insurance coverage (INSURANCE), FEMALE, AGE, and the distance (DISTANCE), in miles, of the respondent's residence from the waste-transport route are used to estimate the parameters of the risk distribution.

Table 1 presents the coefficient estimates, standard errors, and marginal death rates for two candidate beta-based risk models. The first model includes gender, age, the health insurance variable, distance from the transportation route, and the two information variables, TOUR and INFOLEVEL.[17] The INSURANCE variable and the TOUR variable are not statistically different from zero. We drop INSURANCE from this model, giving model II. TOUR becomes very weakly significant at the 0.15 level. This suggests that the standard error of the TOUR coefficient is overstated in model I and offers some evidence that facility tours may act to diminish the level of perceived risk. A likelihood-ratio test between Models I and II fails to reject the null hypothesis of independence between risk perception and insurance coverage.

The variables FEMALE, DISTANCE, AGE, and INFOLEVEL have statistically significant effects on the perceived death rate. The marginal death rate for females in model II is 22.6 deaths per 100,000 people, indicating that women perceive a higher death rate than men, on average. The marginal impact of age is 0.65/100,000 in model II implying that perceived risk increases with the age of the respondent. The distance of the household from the transport route significantly affects risk perception: each additional mile removed from the transportation route translates to a reduction in the perceived death rate of 0.41/100,000. INFOLEVEL and TOUR are shown to both be associated with statistically lower perceived risks.

The average perceived death rate is 214/100,000 and 216/100,000, for models I and II, respectively. These estimated averages are thousands of times higher than the engineering-based risk calculations reported by the DOE and depicted on the risk ladder. This enormous discrepancy is consistent with much previous research that finds large differences between expert and subjective risk assessments (Slovic 1993).

Conditioning on the stated risk, we next queried respondents about their willingness to accept compensation for that risk. The following section presents the econometric model, the results, and an estimate of med[GOP].

4. 2 Choice Model and Results

We now turn to operationalizing the NEUM developed above. If the individual accepts payment *A* she or he bears the perceived transport risk implying that utility under the risky state exceeds that of the no-risk state. According to the theoretical model, the probability that individual i accepts compensation of A and bears the risk of transporting nuclear waste is a function of income, the level of perceived risk, the ambiguity about the risk, and individual-specific characteristics that account for different preferences between the risky and non-risky state.

The choice model can be estimated using the interval-data probit model (see Appendix C and Hanemann et al. 1991 for a thorough discussion).

People act based on their beliefs, and the subjective risk estimate is the key relevant variable for the NUEM model (see Viscusi 1989, for a discussion of subjective risks). For those reporting a definite value for transportation mortality risk we use the reported risk in the empirical NEUM. The variance of risk is equal to zero implying a degenerate risk distribution that reflects the non-ambiguous nature of their response. For those respondents that expressed ambiguity by reporting a range, we use the mean-risk estimate implied by the beta distribution ($\hat{\mu}_{\pi_i} = \frac{\hat{a}}{\hat{a} + \hat{b}_i}$) and the reported range as an estimate of the ambiguity measure, $\hat{\mu}_{\sigma_\pi^2}$.[18]

Other individual-specific traits included in the estimation are: a self-reported measure of the respondent's health status, graded from 1 to 5 with 1 representing poor health and 5 representing excellent health (HEALTH), the number of children in the household (CHILDREN), a dummy variable equal to one if the household owns the home where they reside (OWNHOME), and a dummy variable representing retirement status (RETIRED). Homeownership is included in the model to control for intangible moving costs such as time and money spent selling the current home and purchasing a new home and/or employment relocation costs.

Table 2 reports the results of a double-bounded logit model. The double-bounded survey question format was used to add precision to the estimates (Hanemann al. 1991).[19] For both models, the estimate of the marginal utility of income, $\hat{\beta}$, is positive and significant.[20] Health and retirement status of respondents play significant roles in determining the variation in responses to the WTA question. Healthier respondents are more likely to refuse the compensation offered, indicating that healthy individuals place a higher value (GOP) on potential mortality risks than those whose health is compromised. This is consistent with a diminishing marginal value of health. Similarly, the positive and significant coefficient of RETIRED indicates that retired individuals express a greater readiness to accept compensation and have a correspondingly lower GOP for the risk from nuclear transport. Studies have shown that older people are less likely to relocate

(Ermisch and Jenkins 1999), which seems intuitive. Also note that the Bush administration suggested that the federal cost-benefit studies allow the value of a statistical life (VSL) to vary with age so that older people have a lower VSL. The findings here offer some support of that hypothesis, particularly for the oldest age group.[21]

The OWNHOME and CHILDREN variables are not significant in Model I. Having children present does not affect welfare estimates in our sample. The homeownership variable was included to control for intangible moving costs that are likely higher for homeowners than renters. The finding that the variable is not an important component of preferences offers some assurance that our GOP measure will not be biased by intangible moving costs. OWNHOME and CHILDREN are therefore dropped and the reduced model, Model II, is estimated. A likelihood ratio test supports the reduced model.

The coefficient of μ_{π_i} is negative and significant in both models. As the perceived danger from transporting nuclear waste increases, the probability that the respondent will accept the offered compensation falls and OP increases. The coefficient is robust with respect to model changes. This underscores our claim that preferences are based largely on perceived risk; intentions and subsequent behavior are products of the belief system held by the decision maker.

The effects of ambiguity are also evident in the models in Table 2. The coefficient of $\hat{\mu}_{\sigma_\pi^2}$ is negative and significant, suggesting that as ambiguity about transport risks climbs, people are more likely to accept the offered compensation implying a higher value for GOP. The importance of ambiguity in modeling preferences is consistent with

Ellsberg's well-known paradox: many people prefer certain payments to uncertain gambles even when the expected value of the uncertain gamble is higher than, or equivalent to the certainty payment. Our results extend this observation to the realm of health risks and highlight the paradoxical value of information when risk is at issue. Uncertainty about transportation vehicle and cask designs, transport routes, and general DOE reliability intensifies ambiguity leading to higher welfare measures.

The models in Table 2 provide a test of the NUEM and the standard EUM. A log-likelihood test of the joint hypothesis that $H_0: \gamma_1 = \gamma_2 = 0$ *vs* H_A $\gamma_1 < 0$ and $\gamma_2 < 0$ assesses the appropriateness of the chosen functional form. We reject the null hypothesis and infer that models reflecting risk aversion together with a tendency to place a premium on ambiguous risks are preferred to the simpler linear expected-utility model.

4.3 Ex-Ante Welfare

The sample average med[GOP]s are given at the bottom of Table 2. Model II, the preferred model in terms of a log-likelihood test, gives a med[GOP] of $5,400 per household. This is our estimate of the annual ex-ante welfare loss from high-level nuclear-waste transport. If transportation occurs over a 24-year period as projected, then the discounted present value per per-person (using a discount rate of 6 percent and a sample household size of 2.74 persons per household) is $24,734. Expressed another way, the implied VSL is $5.45 million.[22] This number is in line with estimates of the VSL from other studies. Olson (1981) estimated a VSL for an on-the-job accident of $7.46 million in 2002 dollars. Viscusi (1994) uses a VSL estimate of $8.99 (in 2002 dollars) to compare the costs and benefits of federal risk-reduction programs. Alberini and Krupnick (2001), averaging over a variety of studies, report a mean VSL near $4 million. VSLs used by the U.S. Environmental Protection Agency vary between $4 million and $6 million; an update and larger world view is provided by Viscusi and Aldy (2003).

Inferences from this study to a larger population than Nevada residents require great care. There are indeed several strong similarities between the national and Nevada samples investigated by Desvousges et al. (1993), Slovic (1991), and Slovic (1993). Our results, therefore, could potentially be used for estimating losses nationally for any group of households with homes near designated transportation routes (see Kunreuther and Easterling 1990). An important caveat is that risk perception may vary significantly from region to region. In fact, a large body of research supports the finding that people update their risk beliefs given new information (Viscusi, 1989). And, because the YMP has been widely discussed in the media and by Nevada government officials for many years, it is likely that Nevadans possess more information about the YMP than residents of other states. Our risk models control for changes in information, but we are hesitant to translate the values estimated in Nevada to a national model without further research on risk perception of non-Nevadans. That said, the model allows for heterogeneity in welfare estimates so that the model can be used to give welfare estimates for those outside Nevada if good measures of perceived risk are provided for those households.

5. Conclusions

This paper presents a new formulation of a NEUM that addresses many of the problems facing the EUM and is especially well-suited to empirical estimation of welfare estimates of mortality or health risk and ambiguity changes. The model incorporates preferences for mortality risk when respondents exhibit ambiguity about those risks, while accommodating many of the preference relations established and desired by expected-utility theorists. We know of very few empirical models that incorporate mortality risks, and none that incorporate ambiguity. We present a statistical test for risk and ambiguity preferences and find that a functional form that allows for these components is warranted. The results buttress past findings such as Kahneman and Tversky's (1979) that stress psychological factors, information, and ambiguity as a source of variation in both risk perception and valuation.

We apply our model to estimating the welfare costs, in terms of a generalized option price, of the risk from nuclear-waste transport. Our results reveal that the level of perceived risk, the amount of ambiguity surrounding transportation-safety strategies, and individual-specific characteristics such as health and retirement status all play key roles in influencing risk preferences. Social costs, as reflected in the GOP, increase as the risk to health and safety from transport increases. The option price is increasing in respondent uncertainty, suggesting that people feel that ambiguity about transport diminishes their utility thereby increasing their WTA nuclear-waste transport.

If and when high-level transport occurs in Nevada, people along the route may become accustomed to the transport and their perceived risk may fall, barring any accidents. Conversely, accidents may draw attention to transport, causing perceived risk to rise even if the consequences to human health and safety are minimal. Our empirical results will still be applicable even if general perceptions of transport risk change because the empirical model allows the social costs to change as perceived risk and ambiguity change.

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Table 1. Beta Maximum-Likelihood Models of Latent Subjective Risk: Dependent Variable is $\hat{b}_i = \hat{\theta}' Z_i$ where $\hat{\mu}_{\pi,i} = \frac{\hat{a}}{\hat{a} + \hat{b}_i}$ and $\hat{a} = 0.0091$.

	Model I		Model II	
Variable	Coeff ($\hat{\theta}$)	$\frac{\partial \mu_\pi}{\partial Z}$	Coeff ($\hat{\theta}$)	$\frac{\partial \mu_\pi}{\partial Z}$
CONSTANT	0.4519***	-2.28E-03	0.475***	-2.43E-03
	(0.0452)	-----	(0.0347)	
FEMALE	-0.0434***	2.19E-04	-0.0441***	2.26E-04
	(0.0151)	-----	(0.016)	-----
AGE	-0.0013**	6.55E-06	-0.0013***	6.65E-06
	(0.0004)	-----	(0.0004)	-----
INSURANCE	0.0286	-1.44E-04	-----	-----
	(0.0348)	-----	-----	-----
DISTANCE	0.0008**	-4.03E-06	0.0008***	-4.09E-06
	(0.0005)	-----	(0.0005)	-----
TOUR	0.0442	-2.23E-04	0.0389*	-1.99E-04
	(0.053)	-----	(0.0265)	-----
INFOLEVEL	0.009***	-4.53E-05	0.0091***	-4.66E-05
	(0.0045)	-----	(0.0037)	-----
Deaths/100,000#	214		216	
Log-Likelihood	-112.70		-112.70	

*,**, and *** represent significance at the 0.15, 0.1, and 0.05 levels, respectively.
This is the average death rate for certain and “ambiguous” respondents that is predicted by the model.

Table 2. Interval-Data Probit Models for the Indirect-Utility Difference (Choice) Function: Dependent Variable =1 if Respondents Report They Will Accept Compensation.

Variable	Model I coeff.	Model I prob.	Model III coeff.	Model III prob.
C	1.3448	0.0029	1.3538	0.0029
ln((Y+A)/Y)	3.0346	0.0103	3.0586	0.0054
$\hat{\mu}_{\pi}$ (risk)#	-0.8025	0.0000	-0.7892	0.0000
$\hat{\mu}_{\sigma_{\pi}^2}$ (ambiguity)	-0.3069	0.0888	-0.2970	0.1050
RETIRED	0.4160	0.0195	0.4605	0.0081
HEALTH	-0.1380	0.1311	-0.1461	0.1074
CHILDREN	-0.0935	0.1897	------	------
OWNHOME	0.1589	0.2843	------	------
E[GOP]*	$5,413		$5,406	
Log-likelihood	-241.14		-242.67	

Mean risk estimates ($\hat{\mu}_{\pi}$) are the stated risk for "certain" respondents. For "uncertain" respondents, risk estimates are calculated using the beta distribution (Table 1) and the reported range is used as an estimate of mean ambiguity ($\hat{\mu}_{\sigma_{\pi}^2}$).

*calculated as the sample average of the predicted median GOPs.

Appendix A.

We assume that risk is distributed as a beta probability function (James Heckman and Robert J. Willis 1977). In other words, $\pi \sim beta(a,b)$, where beta represents the beta probability distribution:

$$f(\pi) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} \pi^{a-1}(1-\pi)^{b-1} I_{(0,1)}\,[23]. \qquad \text{(A.1)}$$

The probability of an accident with exposure, π, lies in the interval [0,1] with

$E[\pi] = \frac{a}{a+b}$. The mean of π is allowed to be individual specific by the parameterization

$b_i = \theta' Z_i$. Thus, b_i is a linear function of a parameter set θ and a set of individual-specific characteristics Z_i that potentially influence risk perception.

The probabilities of the possible responses are described as:

$$\begin{aligned}
&P\{q\} = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} \pi^{a-1}(1-\pi)^{b-1}, \\
&P\{l < \pi < u\} = P\{l,u\} = \int_l^u \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} \pi^{a-1}(1-\pi)^{b-1} d\pi, \\
&P\{\pi > l\} = P\{l,1\} = \int_l^1 \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} \pi^{a-1}(1-\pi)^{b-1} d\pi,\ and \qquad \text{(A.2)} \\
&P\{\pi < u\} = P\{0,u\} = \int_0^u \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} \pi^{a-1}(1-\pi)^{b-1} d\pi
\end{aligned}$$

where l, u, and q are the lower and upper bounds and point estimate, respectively, offered by the respondent. Individual i's contribution to the log-likelihood function is:

$$\ln L = I_{\{q\}} \ln P\{q\} + I_{\{l,u\}} \ln P\{l,u\} + I_{\{0,u\}} \ln P\{0,u\} + I_{\{l,1\}} \ln P\{l,1\} \qquad \text{(A.3)}$$

where $I_{\{\cdot\}}$ are indicator functions for the corresponding probabilities.

Appendix B

Survey Text of the Valuation Question

Q12. Suppose the route shown on the map in red is chosen for transporting high level radioactive waste to a containment facility. In return, the citizens of Nevada will receive _____________ per year in the form of a federal tax rebate. If the rebate exceeds the taxes owed, then a check will be issued for the remainder. If you decide to move, you will not receive the rebate. But the federal government will pay your moving costs. Will you stay in your present location, or move because of the risk to your health from transporting the spent nuclear fuel? STAY____ MOVE_______

IF STAY, GO TO A. IF MOVE, GO TO B.

Q12a (STAY) What if the rebate was ___________? STAY________ MOVE __________

Q12b (MOVE) What if the rebate was ___________? STAY________ MOVE _________

Appendix C

Interval Data Model. We use the empirical model developed by Hanemann et al. 1991 to estimate welfare measures from double-bounded contingent valuation data. Assuming a normal WTA distribution, the response probabilities are given by:

$$\begin{aligned} &P\{stay/stay\} = P^{yy} = F(R_d), \\ &P\{stay/leave\} = P^{yn} = F(R) - F(R_d), \\ &P\{leave/stay\} = P^{yy} = F(R_u) - F(R), \textit{ and} \\ &P\{leave/leave\} = P^{nn} = 1 - F(R_u) \end{aligned} \qquad \text{(B.1)}$$

where $F(R_j) = \Phi(\alpha' X + \beta[(\ln(Y + A_j)/Y)] + \gamma_{11}\pi + \gamma_{21}\sigma^2_{\hat{w}} + \gamma_{22}\sigma^2_{\Gamma})$, A is the initial compensation offered, and A_u and A_d are the step-up and step-down bids in the follow-up question, respectively. The contribution to the log-likelihood function for respondent i is:

$$\text{Ln } L_i = I_i^{yy} \ln \Phi(R_d) + I_i^{yn} \ln(\Phi(R) - \Phi(R_d)) + I_i^{ny} \ln(\Phi(R_u) - \Phi(R)) + I_i^{nn} \ln(1 - \Phi(R_u)). \qquad \text{(B.2)}$$

where I^{jk} with j = yes or no and k = yes or no are indicator functions for the response to the initial and follow-up question, respectively.

Endnotes

[1] Ellsberg (1961) defined ambiguity as "a quality depending upon the amount, type, reliability and 'unanimity' of information, and giving rise to one's degree of 'confidence' in an estimate of relative likelihoods."

[2] The Marschak-Machina triangle is a graphical representation of risk indifference for fixed levels of expected utility. The EU model predicts parallel and straight indifference curves. See Machina 1987.

[3] The model we propose explicitly accounts for heterogeneity in perceived risk. Thus, the model may also be used to calculate how the med[GOP] may change over time for a given household as their perceived risk of nuclear-waste transport changes.

[4] Mixed fan models allow for "fanning out" of risk indifference curves in the Marschak-Machina triangle when lotteries are less favorable and "fanning in" for more favorable lotteries.

[5] An excellent review of theoretical and empirical work on ambiguity up to the early 1990's is provided by Camerer and Weber (1992).

[6] Note that Cameron's 2005 paper is a revision of an on-going paper that she kindly gave us in draft form several years ago.

[7] To date, the DOE EIS is the only publicly-released document that details the YMR, however, some environmental groups have distributed their own information in the form or posters and advertisements in magazines. The DOE document proposes 15 alternative Nevada transport routes but maintains that other routes not included in the EIS may be considered as alternatives. Container and truck designs are also presented as preliminary.

The information available from the DOE lacks precision and that, coupled with sources of other, conflicting information, is likely a source of ambiguity on the part of respondents.

[8] All notation below assumes that the model is for an individual or household, but we have omitted individual-specific subscripts to avoid clutter.

[9] Admittedly, the quadratic functional relationship between utility and π is implied by a mean-variance model is somewhat arbitrary. However, functional magnetic resonance imaging studies of the brain suggest that the mean-variance approach is consistent with brain functions (See Preuschoff, Bossaerts and Quartz 2005).

[10] We use the median of the OP term because it offers more stable values than the average. See Kanninen and Hanemann 1999.

[11] Kahneman and Tversky's (1979) discomfort with the incongruity between EUM and s-shaped risk preferences helped motivate prospect theory, one of the early NEUMs.

[12] Note that Environmental Protection Agency 's safety threshold relates exposure risk to an actual accident occurring rather than to an unconditional risk.

[13] The phone-mail-phone method frequently used in CVM studies is applied here to obtain responses to a survey of a sample of Nevada residents. UNLV students were trained as telephone interviewers.

[14] This percentage includes all of those contacted as a base, including those that hung up without being informed of the purpose of the telephone call. Many surveys report only refusals after the topic has been presented, thus the reader should take care when comparing this to other response rates; ours is the more conservative number.

[15] Viscusi (1989) proposes using the individual's prior and updated assessments of risk in a Bayesian approach to risk assessment. However, only the current estimate is relevant to the expected-utility function. Thus, acknowledging that people will update not only the mean, but also the variance of their subjective risk and consequently their option price as future information becomes available, we use their current risk perception in the model. One of the strengths of this model is that it allows us to calculate E[OP]s for any risk level.

[16] Part of the scientific investigational phase of the repository has entailed constructing tunnels and access routes intended for eventual waste storage. The DOE has been offering tours of the site for several years.

[17] Several models were run that included the other information sources including state and local government, federal government, media, and other people. Only the TOUR and information index, INFOLEVEL, variables showed any promise in explaining risk perception.

[18] Other models, not presented here, used the midpoint of the range for the estimated mean risk for uncertain respondents. The coefficient of the variable was very close in magnitude to those presented here, but their standard errors were significantly larger. Thus, we prefer the estimates arising from the beta distribution rather than those from the midpoint.

[19] We assume that the reader is familiar with the double-bounded procedure: Hanemann et al. (1991) is the standard reference on this approach.

[20] β is the coefficient of the income term $\ln\left(\frac{Y+A}{Y}\right)$.

[21] The value of a statistical life (VSL) is the mean WTP divided by the change from the baseline risk. An age variable was also included in the indirect utility-difference model but was not significant. Thus, the functional form implied by the model II in table II suggests a threshold rather than a continuous relationship between WTA and age.

[22] The VSL estimate is based on the sample mean risk (the stated risk for certain respondents and the model-based risk estimate for "ambiguous" respondents) of 454 deaths per 100,000 and the present value of the 24 years of transport of $24,734 per person. The mean sample household size of 2.74 people per household is used to adjust the value of the statistical household to the VSL of $5.45 million.

[23] $\Gamma(t)$ represents the gamma function on t where $\Gamma(t) = \int_0^\infty x^{t-1} e^{-x} dx$ for $t > 0$.