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A risk benefit calculation method based on consumer behavior and household risk production function

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Abstract

Stated preference methods (SPMs) require researchers to use questionnaires to elicit from respondents their monetary values for benefits from a hypothetical risk reduction by the implementation of a particular project. The complexity of questionnaires makes it more difficult for respondents to choose the benefit values and complicates executing the risk reduction benefit surveys in the short term for policy-makers. The purpose of this study is to propose a risk reduction benefit evaluation model that incorporates individual behavior and subjective risks. The household production function approach is employed to express the individual's expected utility function. The results indicate that the SPM benefit values might be underestimated by the marginal change in the subjective risk. The method presented in this study is flexible and can be applied to measuring various patterns of risk reduction benefits using the economic market behavior data.

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1. Introduction

Valuation methods on risk reduction benefits (RRBs) have helped policy makers to show the risk reduction policy effects in monetary terms to their citizens. However, since the availability of risk related economic market data is limited, researchers tend to use stated preference methods (SPMs).

SPMs measure a RRB value by directly asking respondents to value the benefits from a hypothetical safety measure, for example, a road maintenance project aimed at reducing the mortality risk from traffic accidents from, say, 5/10,000 persons to, say, 4/10,000 persons. While the flexibility of designing a hypothetical project and its effects enable researchers to value various research objects, it sometimes is a cause of a bias to true RRB values. For example, respondents sometimes may not be able to distinguish the benefits from a small amount of risk reduction (e.g., a traffic fatality reduction of 1/10,000 persons in the above-mentioned example). Moreover, fixed risk values presented in a survey (e.g., 5/10,000 persons and 4/10,000 persons in the above example) require researchers to perform additional surveys if they plan to measure the RRB values under different amounts of risk reductions (e.g., a mortality risk from a traffic accident will vary with the distance from an emergency hospital).

The purpose of this study is to examine a RRB valuation model that incorporates the individual subjective risk changes to economic market behaviors in order to avoid these issues. A household production function approach is employed to model the behaviors.

In previous studies, Graham (1981) and Jones-Lee (1976) developed theoretical frameworks for RRBs. Concepts of option price (OP) and value of statistical life are mainly used in valuing RRBs by SPMs. Corso et al. (2001), Krupnick et al. (2002), and Smith and Desvousges (1987) find that some respondents do not exactly understand a risk reduction amount in SPM questionnaires due to some biases. Treich (2010) argues that ambiguity aversion, which is one of the biases, increases respondents' benefit values above the true ones. The SPM studies imply that a direct answer for RRB under a small amount of risk reduction might bias respondent's answer.

One solution is to examine a revealed preference method (RPM) that formulates subjective risk changes by an individual behavior. Kniesner et al. (2014) use a hedonic wage method for RRB, which can be used only in hazardous risk levels influencing economic markets. Shogren and Crocker (1991) theoretically analyze an individual self-protection behavior that affects the probability of a risk. This study aims to develop a risk benefit calculation model when an individual subjective risk is dependent on his or her behavior. Larson and Flacco (1992) examine the RRB calculations by the expenditure function approach using compensating and equivalent variations given fixed risks with and without implementing a project. Thus, Larson and Flacco's (1992) model cannot be used to measure the RRB values corresponding to various risk reduction levels. Such flexible benefit valuations would be possible by modeling an individual subjective risk function. This study employs the household production function (HPF) approach by Ebert (2007) that could incorporate individual (self-protection) behavior and their subjective risk in Shogren and Crocker (1991) in the HPF framework. Table 1 shows the summary of features of previous studies.

Table 1. List of previous studies and their features

Previous studies	Empirical or not	With or without: Subjective risk	: HPF
Shogren and Crocker (1991)	No	With	With
Larson and Flacco (1992)	Probably No [a]	Without	Without
Ebert (2007)	Probably Yes [a]	Without	With
Kniesner et al. (2014)	Yes	Without	Without

a: the difference of “probably yes” with “probably no” is with/without numerical simulations

This study is organized as follows. Section 2 develops a model of an individual behavior using the household risk production function. The definitions and analyses of RRBs are considered in sections 3 and 4, respectively. Section 5 presents the concluding remarks.

2. Model

In this section, a model of an individual behavior based on Ebert (2007) is developed. An individual is assumed to have the following household risk production function: $\pi = \pi(x,q)$. Here, $\pi \in (0,1)$ is an individual’s subjective probability of suffering a damage from an accident, $1-\pi$ is the probability of avoiding a damage from an accident, x is a demand for a risk-related good (or service), q is the level of good’s safety measure, and $\pi(\cdot)$ is a household risk production function with inputs x and q to produce π. For example, x can be food consumption or recreational activity. The individual faces a risk of injury and/or negative health effects from the consumption of said good or activity. It is assumed that $\partial\pi(x,q)/\partial x > 0$, that is, an incremental increase in demand would raise the value of π. Since, generally, governments provide prevention services, such as food safety standards and life-saving services in wilderness in order to reduce risks, $\partial\pi(x,q)/\partial q < 0$ is assumed. Here, $\partial\pi(x,q)/\partial x$ and $\partial\pi(x,q)/\partial q$ denote the first order partial derivatives with respect to x and q, respectively. For simplicity, hereafter the partial derivatives with respect to input variables x and q will be denoted by π_x and π_q respectively.

The individual’s expected utility function is defined as $E[u] \equiv (1-\pi(x,q))\cdot u(z,x\,|\,N)$ $+\pi(x,q)\cdot u(z,x\,|\,D)$. Here, $E[u]$ is an expected utility level and z is a composite good. Let H be a health state variable, where $H = D$ if an individual’s health status is worse and $H = N$ if it is normal. Thus, u^H is a utility level determined by a utility function

$u^H = u(z,x \mid H)$. Without loss of generality, $u(z,x \mid N) > u(z,x \mid D)$ is assumed for $\forall z > 0$ and $\forall x > 0$. Then, an individual faces the following maximization problem:

$$\underset{z,x}{Max.}\ (1-\pi(x,q)) \cdot u(z,x \mid N) + \pi(x,q) \cdot u(z,x \mid D) \ \ s.t.\ \ z + p \cdot x = y \tag{1}$$

Here, y is the individual's household income, while 1 and p represent the prices of z and x, respectively. Let λ be a Lagrange multiplier on the income budget constraint. The first order conditions from the Lagrangian equation (2) reduce to equations (3) to (5).

$$L \equiv (1-\pi(x,q)) \cdot u(z,x \mid N) + \pi(x,q) \cdot u(z,x \mid D) - \lambda \cdot (z + p \cdot x - y) \tag{2}$$

$$L_z = (1-\pi) \cdot u_z(z,x \mid N) + \pi \cdot u_z(z,x \mid D) - \lambda = 0 \tag{3}$$

$$\begin{aligned} L_x = & -\pi_x(x,q) \cdot u(z,x \mid N) + (1-\pi(x,q)) u_x(z,x \mid N) \\ & + \pi_x(x,q) \cdot u(z,x \mid D) + \pi(x,q) \cdot u_x(z,x \mid D) - \lambda \cdot p = 0 \end{aligned} \tag{4}$$

$$L_\lambda = z + p \cdot x - y = 0 \tag{5}$$

From equation(4), if $\lambda > 0$, then:

$$\Theta \equiv -\pi_x(x,q) \cdot u(z,x \mid N) + (1-\pi(x,q)) \cdot u_x(z,x \mid N) + \pi_x(x,q) \cdot u(z,x \mid D) + \pi(x,q) \cdot u_x(z,x \mid D) > 0 \tag{6}$$

By solving equations (3) to (5), the Marshallian demand functions for z and x are derived as $z^* = z(1,p,q,y)$ and $x^* = x(1,p,q,y)$, respectively. Similarly, solving the equations for λ yields $\lambda^* = \lambda(1,p,q,y)$. For notational simplicity, the health status indicator variable (H) is omitted from the solutions. The superscripted asterisk (*) means the demand for each variable is at its optimal consumption level. Substituting these demand functions into the expected utility function produces the individual's expected *indirect* utility function, $E[v]$, as follows.

$$E[v] \equiv (1-\pi(x^*,q)) \cdot u(z^*,x^* \mid N) + \pi(x^*,q) \cdot u(z^*,x^* \mid D) - \lambda^* \cdot (z^* + px^* - y) \tag{7}$$

$$= (1-\pi(x^*,q)) \cdot v(1,p,q,y \mid N) + \pi(x^*,q) \cdot v(1,p,q,y \mid D) \tag{7'}$$

Here, $v(1,p,q,y \mid H)$ is an indirect utility function derived from $u(z^*,x^* \mid H)$. Further, the expenditure function, $y \equiv e(1,p,q,E[v])$, is derived by solving the equation (7)' for y. Applying the Envelop theorem to equation (7) and using the equation (4) produce the following equations:

$$dE[v]/dp = -\lambda^* \cdot x^*, \tag{8}$$

$$dE[v]/dy = \lambda^*, \tag{9}$$

$$dE[v]/dq = -\pi_q(x^*,q) \cdot u(z^*,x^* \mid N) + \pi_q(x^*,q) \cdot u(z^*,x^* \mid D), \tag{10}$$

$$dE[v]/d\pi = -u(z^*,x^* \mid N) + u(z^*,x^* \mid D). \tag{11}$$

3. Risk reduction benefits

3.1 Definition of marginal risk reduction benefit

First, the marginal benefit of risk reduction (MBRR) is given by $-dy/d\pi$ as in equation (12) below, which is derived by using the equations (4), (9), and (11). Klose (2002) claims that when an individual suffers from a severe health-damaging event (e.g., death), the individual's utility level will be close to zero for $\forall z \geq 0$ and $\forall x \geq 0$. Assuming $u(z, x \mid D) \approx 0$, it simplifies to equation (12)'.

$$MBRR \equiv -dy / d\pi \equiv -(dE[v] / d\pi) / (dE[v] / dy) = \frac{u(z^*, x^* \mid N) - u(z^*, x^* \mid D)}{\Theta} p \quad (12)$$

$$\approx \frac{u(z^*, x^* \mid N)}{-\pi_x(x^*, q) \cdot u(z^*, x^* \mid N) + (1 - \pi(x^*, q)) \cdot u_x(z^*, x^* \mid N)} p \quad (12)'$$

Second, MBRR from a service quality change (hereafter MBRRQ) is given by $-(dy / d\pi) \cdot (d\pi / dq) = -dy / dq$ and is derived as in equation (13). The equation (13)' is obtained similarly as above.

$$MBRRQ \equiv -dy / dq \equiv -(dE[v] / dq) / (dE[v] / dy) = \frac{\pi_q(x^*, q) \cdot u(z^*, x^* \mid N) - \pi_q(x^*, q) \cdot u(z^*, x^* \mid D)}{\Theta} p \quad (13)$$

$$\approx \frac{\pi_q(x^*, q) \cdot u(z^*, x^* \mid N)}{-\pi_x(x^*, q) \cdot u(z^*, x^* \mid N) + (1 - \pi(x^*, q)) \cdot u_x(z^*, x^* \mid N)} p \quad (13)'$$

Then, from equations (12)' and (13)', $MBRRQ = \pi_q(x^*, q) \cdot MBRR$. This equation implies that 1) a MBRR value is a part of the benefit from improved safety measure (q), and 2) subjective risk plays a role in adjusting the MBRR value to get the MBRRQ value.

3.2 Difference from the stated preference approach

The RRB value was determined as in equation (12) in the previous SPM studies since the MBRR formula only considered a change in the risk level. The relationship between the models developed in this study and the previous SPM studies is shown in equation (14), which is the difference between equations (12) and (13).

$$MBRR - MBRRQ = \frac{\{1 - \pi_q(x^*, q)\} \cdot \{u(z^*, x^* \mid N) - \cdot u(z^*, x^* \mid D)\}}{\Theta} p \quad (14)$$

From equation (14), $MBRR > MBRRQ$ if $1 - \pi_q(x^*, q) > 0$, $MBRR < MBRRQ$ if $1 - \pi_q(x^*, q) < 0$, and $MBRR = MBRRQ$ if $1 - \pi_q(x^*, q) = 0$. Let $\Delta\pi \equiv \pi(x^*, q') - \pi(x^*, q)$ and $q' = q + \varepsilon$. From $0 < \pi(x^*, q') < 1$, it follows that $0 \leq \Delta\pi < 1$ and $0 < 1 - \Delta\pi \leq 1$. For $\varepsilon \to 0$, $\Delta\pi \approx \pi_q(x^*, q)$. Then, $MBRR > MBRRQ$ when the condition $0 < 1 - \pi_q(x^*, q) \leq 1$ holds. This result implies that traditional RRB values are underestimated by the marginal change in the subjective risk level.

4. Benefit calculations

4.1 Indirect utility function approach

This section discusses the estimation of RRB values from data on economic behavior. The first approach uses the OP technique developed by Graham (1981).

Let the superscript s denote the state of the project, with $s = w$ if the project was implemented and $s = wo$ if it was not. Assuming p and y remain constant, regardless of the project's status, the expected utility function can be rewritten as in equation (15).

$$E[v^s] \equiv (1-\pi(x,q^s)) \cdot v(1,p,q^s,y \mid N) + \pi(x,q^s) \cdot v(1,p,q^s,y \mid D) \tag{15}$$

The measure of OP under compensating variation (CV) is defined as in equation (16).

$$\begin{aligned} E[v^{wo}] \equiv\ & (1-\pi(x(1,p,q^w,y),q^w)) \cdot v(1,p,q^w,y-OP_{CV} \mid N) \\ & + \pi(x(1,p,q^w,y),q^w) \cdot v(1,p,q^w,y-OP_{CV} \mid D) \end{aligned} \tag{16}$$

Letting $\tilde{y} = y - OP$ and applying the first-order Taylor expansion to equation (16) around y yields $v(1,p,q,\tilde{y} \mid H) \approx v(1,p,q,y \mid H) - v_{\tilde{y}}(1,p,q,y \mid H) \cdot OP$. Assuming $v_{\tilde{y}}(1,p,q^s,y \mid H) \approx v_y(1,p,q^s,y \mid H)$, the equation (17) can be obtained, which simplifies to equation (17)' for $v(1,p,q,y \mid D) \approx 0$.

$$OP_{CV} = \frac{E[v^w] - E[v^{wo}]}{(1-\pi(x(1,p,q^w,y),q^w)) \cdot v_y(1,p,q^w,y \mid N) + \pi(x(1,p,q^w,y),q^w) \cdot v_y(1,p,q^w,y \mid D)} \tag{17}$$

$$\approx \frac{\{(1-\pi(x^*,q^w))v(1,p,q^w,y) - (1-\pi(x^*,q^{wo}))v(1,p,q^{wo},y)\}}{(1-\pi(x(1,p,q^w,y),q^w)) \cdot v_y(1,p,q^w,y \mid N)} \tag{17'}$$

Similarly, the measure of OP based on equivalent variation is derived as follows.

$$\begin{aligned} E[v^w] \equiv\ & (1-\pi(x(1,p,q^{wo},y),q^{wo})) \cdot v(1,p,q^{wo},y-OP_{EV} \mid N) \\ & + \pi(x(1,p,q^{wo},y),q^{wo}) \cdot v(1,p,q^{wo},y-OP_{EV} \mid D) \end{aligned} \tag{18}$$

$$OP_{EV} = \frac{E[v^w] - E[v^{wo}]}{(1-\pi(x(1,p,q^{wo},y),q^{wo})) \cdot v_y(1,p,q^{wo},y \mid N) + \pi(x(1,p,q^{wo},y),q^{wo}) \cdot v_y(1,p,q^{wo},y \mid D)} \tag{19}$$

$$\approx \frac{\{(1-\pi(x^*,q^w))v(1,p,q^w,y) - (1-\pi(x^*,q^{wo}))v(1,p,q^{wo},y)\}}{(1-\pi(x(1,p,q^{wo},y),q^{wo})) \cdot v_y(1,p,q^{wo},y \mid N)} \tag{19'}$$

4.2 Expenditure function approach

This section describes the expenditure function approach due to Larson and Flacco (1992). Hayashiyama and Nohara (2009) evaluate the benefits from an environmental quality change by the household production function approach. This study follows Hayashiyama and Nohara's (2009) method. The benefit of risk reduction from a quality change under equivalent variation ($BRRQ_{EV}$) is derived as in equation (20) using the expenditure function ($e(1,p,q,E[v^s])$). Equation (21) is obtained by substituting $E[v]_y / E[v]_y$ into equation (20). An approximation of equation (21) yields the equation (22). Finally, equation (23) is derived by substituting $e^{wo}_{E[v]}E[v]_y \equiv 1$, $e^{w}_{E[v]}E[v]_y \approx e^{wo}_{E[v]}E[v]_y + e^{wo}_{E[v]}E[v]_{yq}(q^w - q^{wo})$, $E[v]_{qy} = E[v]_{yy} MBRR^{wo} + E[v]_y MBRR^{wo}_y$, and $e^{wo}_{E[v]}E[v]_{yq} = MBRR^{wo}_y$ into equation (22).

The benefit of risk reduction from a quality change under compensating variation ($BRRQ_{CV}$) is obtained similarly and is given in equation (24).

$$BRRQ_{EV} \equiv e(1,p,q,E[v^w]) - e(1,p,q,E[v^{wo}]) = \int_{E[v^{wo}]}^{E[v^w]} e_{E[v]} dE[v] \tag{20}$$

$$= \int_{q^{wo}}^{q^w} e_{E[v]} E[v]_y MBRRQ dq \tag{21}$$

$$\approx \frac{1}{2}(e^{wo}_{E[v]}E[v]_y MBRRQ^{wo} + e^{w}_{E[v]}E[v]_y MBRRQ^{w})(q^w - q^{wo}) \tag{22}$$

$$\approx \frac{1}{2}\left(MBRR^{wo} + (1 + MBRRQ_y^{wo}(q^w - q^{wo})MBRRQ^w)\right)(q^w - q^{wo}) \quad (23)$$

$$BRRQ_{CV} \approx \frac{1}{2}\left(MBRRQ^w + (1 + MBRRQ_y^w(q^w - q^{wo})MBRRQ^{wo})\right)(q^w - q^{wo}) \quad (24)$$

4.3 Discussion of applications

This section describes estimation of equations given in (17), (19), (23), and (24). These equations require researchers to specify a Marshallian demand function, an indirect utility function, and a household risk production function.

First, the integrating back approach by Hausman (1981), Larson and Flacco (1992), and Von Haefen (2007) can be used to specify an indirect utility function through a Marshallian demand estimation. For example, $v^H = (1/\beta_p)x(\cdot) - (1/\beta_y)\exp(-\beta_y y)$ is obtained by applying Roy's identity to semi-log demand function: $-(dv/dp)(dv/dy) = x = x(\cdot)$ $= \exp(\beta_p p + \beta_q q + \beta_y y + \boldsymbol{\beta}_{\mathbf{k}}\mathbf{k} + \beta_H H)$. Here, each β is a parameter of variables and $\mathbf{k}$ is a vector of individual characteristics. The demand function could be estimated by using data on x, p, q, y, and H for the past year. Data on q, such as food expiration dates, transportation time to the emergency hospital, and numbers of rescue teams in recreation sites, etc., can be collected from the public service entities.

Next, a household risk production function is estimated using the data on x, q, and π. While the data on x and q are the same as the data used in demand function estimation, data on π need to be collected using risk perception studies, as in Andersson and Lundborg (2007), and Chung *et al.* (2009). For example, π can be defined as the number of health damaging experiences in individual's lifetime resulting from the consumption of a particular good / the total number of the goods purchased in individual's lifetime. The particular functional form of the production function will be determined by empirical analysis. For example, the constant elasticity of substitution (CES) production function can be estimated using the data mentioned above (the restriction $0 < \pi < 1$ might be violated in some cases). If the dependent variable is binary with $\pi = 1$ for persons with health–damaging experience from the consumption of good in the past year and $\pi = 0$ for others, then estimation by the logistic functional form will be more appropriate.

As discussed above, the method presented in this study is easy to apply. Importantly, it 1) reduces the bias in RRB values and 2) saves time and resources needed for policy evaluations of risk management projects.

In addition, the study discussed two approaches (i.e., indirect utility and expenditure function approaches) suitable for benefit calculations. The indirect utility function approach may be preferred because 1) it could be used for direct comparisons with the results from the most SPM studies, and 2) the calculations are simpler than the ones using the expenditure function approach.

Finally, the hypothetical OP values are calculated by equations (17) and (19) though simulations. Semi-log demand function and CES type risk production function are assumed. The hypothetical variable and parameter values are $p = 5{,}000$ yen, $y = 50{,}000$ yen, $k = 0.37$, and (average) $H = 45$; $\beta_0 = 5$, $\beta_p = -0.0012$, $\beta_q = -0.01$, $\beta_y = 0.0001$, $\beta_k = -2$, and $\beta_H = -0.06$ for the demand function; $\alpha_0 = 1.4$, $\alpha_x = 1.5$, and $\alpha_q = 1.5$ for the risk production function. Here, α_0 and β_0 are constant variables. Let hypothetical health state values of H be $H = N = 20$ and $H = D = 80$. A hypothetical project scenario is to reduce transportation time from a recreation site to an emergency hospital; $q^{wo} = 60$ minutes and $q^{w} = 30$ minutes. Then, OP_{CV} and OP_{EV} are calculated as USD 23.30 (Japanese Yen 2,634; hereafter JPY) and USD 31.55 (JPY 3,567), respectively. Here, the USD value is calculated by using the average exchange rate of USD 1 = JPY 113.05, as of May 2016, taken from the Bank of Japan (2017). The sensitivity analyzes on parameters in the risk production function shows that OP_{CV} and OP_{EV} are calculated as USD 23.53 (JPY 2,660) and USD 31.78 (JPY 3,593) when $\alpha_x = 1.5 \times 2$; OP_{CV} and OP_{EV} are calculated as USD 290.18 (JPY 32,805) and USD 98.20 (JPY 11,102) when $\alpha_q = 1.5 \times 2$.

5. Concluding remarks

Stated preference methods (SPMs) are often used for measuring risk reduction benefits. There are several issues related to their applications. First, there is a greater probability of bias in the estimated benefits. Second, it is time-consuming and costly to measure the benefits under different risk and risk reduction scenarios. The purpose of this study is to present a model that avoids these issues by incorporating the changes in individual's subjective risk into the economic market behavior. The model is developed using a household risk production function approach. Two important results follow from the study. First, the marginal change in the subjective risk for a safety measure might underestimate benefit values by SPMs due to lack of information on the subjective risk. Second, the proposed method is relatively easy to apply in benefit estimations, which helps save time and resources needed for policy evaluations of risk management projects.

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