Chapter 7

ECONOMIC ASPECTS OF VULNERABILITY

According to the United Nations Department of Humanitarian Affairs (UNDHA, 1992), vulnerability is defined as the degree of loss (from 0 to 100 percent) resulting from a potentially damaging phenomenon. These losses may include lives lost, persons injured, property damage and disruption of economic activity. In the estimation of the actual or expected losses, two categories of damages (losses) are considered: direct and indirect. Direct damages include property damage, injuries and loss of life, whereas indirect damages refer to the disruption of economic activity. Many types of direct damage are difficult to express in terms that can easily be applied in public decision-making; these include loss of life, injuries, loss of cultural heritage, disruption of families and dislocation of people. That is, it is difficult for a decision maker to compare and choose between a public-works project that will create 500 jobs and a flood-mitigation measure that will reduce the frequency of people being evacuated from their houses because of flooding. Therefore, economic aspects of loss and vulnerability are discussed in this chapter. Loss of life and to a lesser extent injuries are considered in economic terms for the purpose of public decision-making to indicate the level of financial and other resources that should be dedicated to natural-disaster-risk mitigation.

It is possible that a potentially damaging natural phenomenon may occur at a time when society and the economy have not recovered from a previous natural disaster. For example, a flood may occur at a location that had recently suffered from an earthquake. In this case, the vulnerability of the area may be increased because the buildings, infrastructure and lifeline systems are already weakened. However, some aspects of damage may be reduced because structures have already been destroyed and people may already be evacuated (if the flood occurs within weeks of the earthquake). Because such joint occurrences are rare, but not unknown (e.g., torrential rain occurred during the eruption of Mount Pinatubo in the Philippines), and an economic evaluation would require an estimate of the level of recovery at the time of the second potentially damaging natural phenomenon, sequential natural disasters are not considered in this chapter.

7.1 VULNERABILITY

To properly understand the role of vulnerability in the assessment of risk, vulnerability must be considered in the context of computing the consequences of a potentially damaging phenomenon. This determination of consequences is the ultimate product of a risk assessment. The consequences of a potentially damaging phenomenon may be computed as (Plate, 1996):

$$K = \sum_{i=1}^{n_o} v_i k_i \tag{7.1}$$

where K is the total consequences summed over all people or objects affected, n_o is the number of elements (people or objects) at risk, v_i is the vulnerability of the ith element to a given potentially damaging phenomenon, and k_i is the extreme consequence to the ith element from a given potentially damaging phenomenon. The total consequences may be expressed in terms of money, lives lost or persons injured. The damage to houses on a floodplain during a flood with magnitude x is an example of monetary consequences. In this case, n_o is the number of houses affected, k_i is the damage cost if the ith house is totally destroyed, i.e. the replacement cost for both the structure and contents, and v_i is the degree of partial destruction of a building expressed as a percentage of the repair cost to the total cost of replacing the building and contents. In the case of lives lost, K is the number of people killed when an event of magnitude x occurs with no people affected. A value of $k_i = 1$ indicates that the person affected is killed. The vulnerability v_i in this case expresses the probability that a person affected is killed. Thus, in this case, K represents, on the average, the number of people killed. In the case of persons injured, the computation of K is more complicated because several different levels of injury (k_i) need to be considered ranging from out-patient treatment to permanent disability. Issues related to persons injured are discussed further in section 7.2.2.

The vulnerability is distributed with respect to the magnitude of the potentially damaging phenomenon, x. For example, the relation between Vulnerability and event magnitude could be expressed as a linear function such as that shown in Figure 7.1. For the example shown in Figure 7.1, if the event magnitude is less than x_{min}, no failure or consequences would result; and if the event magnitude is greater than x_{max}, failure results with certainty yielding the full consequence of failure, The vulnerability of structures constructed with different types of structural materials to different earthquake magnitudes represented by peak ground accelerations is shown in Figure 7.2.

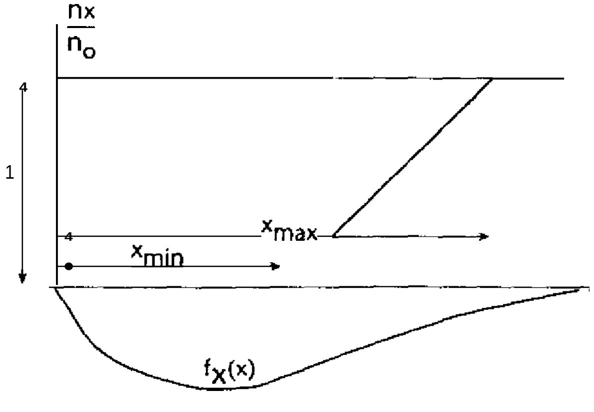

Figure 7.1 — Schematic representation of a consequence function with linear vulnerability above a threshold value $x = x_{max}$ (after Plate, 1996)

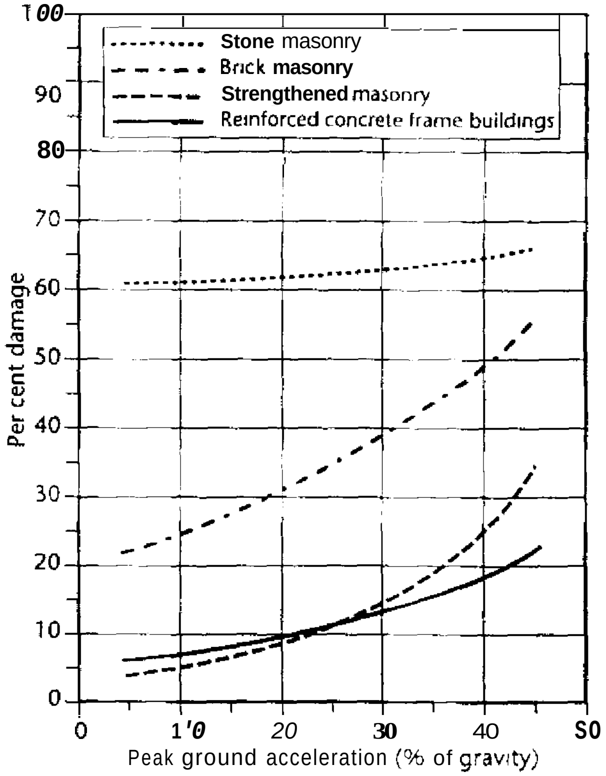

Figure 7.2 — *Vulnerability of structures constructed with different materials to earthquake magnitude (after UNDRO, 1991)*

The vulnerability may be estimated in several ways including those listed below.

(*a*) The vulnerability may be obtained from experience in many different locations, involving many different populations, with a total number of n_0 people at risk, of which n_x would suffer the consequences of failure if an event of magnitude x occurs (Plate, 1996). That is, $v_t(x) = n_x/n_0$.

(*b*) The vulnerability of objects at risk also can be obtained from experience in many different locations.

(*c*) The vulnerability of structures may be determined by computer simulation of structural damage resulting from an event of magnitude x. This approach is a central component of minimum life-cycle-cost design of earthquake resistant structures discussed in detail in section 8.3

The vulnerability of a structure or land use is a quality of the structure or land use, irrespective of where it is built or located (UNDRO, 1991).

Usually, it is assumed that n_0 is a known constant and K is a deterministic function of the event magnitude x, i.e it is assumed that for every event of magnitude x one and only one value of K results. However, K is actually a random variable because both k and v are subject to substantial uncertainty. For example in standard practice the risk resulting from flooding is computed as follows (see also Chapter 3): (1) the flood magnitude corresponding to a specified return period is determined from frequency analysis; (2) the discharge is converted to a corresponding stage (flood elevation) through hydraulic analysis; (3) the flood damages corresponding to this stage is determined from economic analysis; finally, (4) the damages corresponding to floods of different frequencies are integrated with the probabilities to determine an expected risk. Steps 1 and 2 determine which areas are vulnerable (v_i), step 3 determines the consequences (k_t), and step 4 is the summation of equation 7.1. However, the flood frequency-magnitude relation is subject to uncertainties because of sample limitations, the stage-discharge relation is subject to uncertainties in the hydraulic analysis, and the stage-damage relation is subject to uncertainties in the economic evaluation. Some of the methods discussed in Chapter 8 attempt to consider the uncertainties in k_i and v_t explicitly. In particular, the US Army Corps of Engineers (USACE) risk-based analysis for flood-damage-reduction projects (section 8.4.1) considers uncertainties in the hydrologic, hydraulic and economic computations previously described. The minimum life-cycle cost design of earthquake resistant structures (section 8.3) considers the uncertainties in structural strength.

7.2 DIRECT DAMAGES

7.2.1 Structures and contents

Potential damage to structures and their contents are typically estimated through a combination of field surveys of structures in the area that would be affected by potentially damaging phenomena and information obtained from post-disaster surveys of damage. The USACE (1996) has developed a detailed procedure for estimating the potential damages to structures and their contents resulting from flooding. A similar procedure could be applied to determine potential damages from other types of natural disasters: such as hurricanes, volcanoes, earthquakes, etc. Therefore, in this section, the procedure for estimating potential flood damage provides an example on how to approach damage estimation for other types of natural disasters.

The traditional USACE procedure for estimating a stage-damage function for residential structures involves the following steps.

(1) Identify and categorize each structure in the study area based upon its use and construction.

(2) Establish the first-floor elevation of each structure using topographic maps, aerial photographs, surveys, and (or) hand levels.

(3) Estimate the value of each structure using real-estate appraisals, recent sales prices, property tax assessments, replacement cost estimates or surveys.

(4) Estimate the value of the contents of each structure using an estimate of the ratio of contents value to structure value for each unique structure category.

(5) Estimate damage to each structure due to flooding to various water depths at the site of the structure using a depth-per cent damage function for the category of the structure along with the value from step 3.

(6) Estimate damage to the contents of each structure due to flooding to various water depths using a depth-per cent damage function for contents for the structure category along with the value calculated in step 4

(7) Transform the depth-damage function for each structure to a stage-damage function at an index location for the flood plain using computed water-surface **profiles** for reference floods.

(8) Aggregate the estimated damages for all structures by category for common water depths.

The aggregated stage-damage function then is integrated with the stage-probability function, which is determined using hydrologic and hydraulic models, to determine the total flood damages or risk for various flood-mitigation scenarios.

The **USACE** applies a "rational planner" model and the willingness-to-pay principle to compute the depreciated replacement value for a structure as per step **3.** The three most common approaches to estimate the replacement value **are** use of the Marshall and Swift Valuation Service (MSVS), real-estate-assessment data and recent sales prices. The MSVS develops a replacement construction-cost estimate based on information on the foundation, flooring, walls, roofing, heating system, plumbing, square footage, effective age and built-in appliances. This estimate requires detailed surveys of representative structures. The estimate is adjusted for depreciation. See the World Wide Web site **(http:/lwww.marshallswift.com)** for more information on the MSVS. The use of real-estate-assessment data involves adjusting real-estate tax-assessment values for deviations between assessed value and market value and subtracting the land component of market value. It is assumed that the remainder is the depreciated replacement value **of the** structure. The use of recent sales prices requires sufficient resent property sales in the area for each structure and construction type for which a structure value **is** to be estimated. **As** with the real-estate-assessment data, the land value must be subtracted from the sales price to estimate the value **of** the structure.

Typically, the value of contents is specified as a fraction of the value of the structure. This approach is similar to ***the*** approach normally applied by residential casualty insurers in setting rates and content coverage for homeowners insurance. The value of contents may be determined from detailed surveys of representative structures. The value of contents also may be estimated from experience with past floods. The USACE (1996) has summarized the claims records of the Flood Insurance Administration for various categories of residential structures. The ratio ***of*** the value of contents to the value of the residential structure is:

— **0.434** for one-story structures without a basement,
— 0.435 for one-story structures with a basement,
— 0.402 for two-story structures without a basement,
— 0.441 for two-story structures with a basement,
— 0.421 for split-level structures without a basement,
— 0.435 for split-level structures with a basement, and
— 0.636 for mobile homes.

The value of contents found in any structure is highly variable because it represents the wealth, income, tastes and lifestyle ***of the*** occupants. Nevertheless, the above ratios provide insight on the relative value ***of*** the contents and the structure. Similar values of the ratio of the value of contents to the value of the structure were applied in the minimum life-cycle-cost design of earthquake-resistant commercial structures described in section 8.3.1. **Ratios** of 0.5 and 0.4 were applied for Mexico City and Tokyo, respectively. The ratio of the value of contents to the value of the structure may be adjusted as necessary to reflect economic conditions and cultural values of **a** given locality. The values given here are examples of typical magnitudes of the ratio.

Similar information on value, damage as **a** function of depth and flood depth at a site is necessary to develop stage-damage functions for non-residential structures and other property. For non-residential property, the stage-damage function ***is*** frequently determined from the results of post-flood surveys or through personal interviews with plant engineers, plant managers or other experts. Then, instead of developing dimensionless depth-per cent damage functions, damages incurred at various water-surface elevations **are** directly approximated. Use of post-disaster damage surveys (De Leon and Ang, **1994;** Lee, 1996) also have been used to estimate structural damage resulting from earthquakes in the minimum life-cycle-cost design of earthquake-resistant structures described **in** section 8.3.1.

7.2.2 Value of life and cost of injuries

Estimation of the value of human life and, thus, the value of lives saved by risk-mitigation measures used €or decision-making is difficult and controversial. The reason why it is necessary to estimate the value of human life for decision-making **is** described by Kaplan (1991) as follows:

> "If the **risk** in question is a **risk** to human life, **there is a school** of thought, often quite vocal, that says 'You cannot **put** a dollar value on human **life** — human **life** is priceless.' **True** enough, **but** the hitch **is** that when **we** talk about paying the price of safeguards [*reductions* in *vulnerability*], we are not talking **about** dollars. We **are** talking about **what** dollars represent, i.e., time, talent, and resources. Time, talent, and **resources are** limited. What we **spend** on reducing one **risk is** not **available** to spend on **another**."

Schwing (1991) illustrates how these resource limitations may be considered as follows:

> "Since we know the **US GNP** [*Gross National* Product] and the number of deaths each year, we can **calculate** the **willingness** to **pay** by long division. It turns out **that** if you ignore **the fact** that we also value education. our homes, our mobility, the arts, and other indices of the quality of life, each Life could claim a Little over $2 million."

The simple analysis done by Schwing is not truly representative of a means to estimate the value of human lives saved by risk-mitigation measures, but rather it highlights the fact that the societal resources available ***to*** save lives are limited, Thus, in order for society to decide how it will allocate the available resources among the various means to protect life, safety and regional economy, and among other public goods. an estimate of the value of human lives **saved** must be used.

Numerous methods have been proposed to estimate the value of human life including those based on the following:

(1) Life-insurance coverage;
(2) court awards for wrongful death;
(3) regulatory decisions;
(4) calculations of direct out-of-pocket losses associated with premature death (i.e. the present value of expected future earnings); and
(5) examination of how much people are willing to pay to reduce their risk of death.

Methods based on data derived from 4 and 5 are most commonly applied in the literature on public decision–making.

Method 4 is commonly known as the human-capital approach. Rice and Cooper (1967) note that the human-capital approach had its beginnings in the 17th and 18th centuries as economists tried to determine the value of slave labour. The human-capital approach generally has been discredited for moral reasons because the value of human life is more than just the sum of one's future earnings. Sugden and Williams (1978, p. 173) describe the moral problems with the human-capital approach quite bluntly in that this approach "would imply that it would be positively beneficial to society that retired people be exterminated".

The current consensus in the field of economics is that the appropriate way to measure the value of reducing the risk of death is to determine what people are willing to pay (Lanoie *et al.*, 1995). The reasons for this preference are that the willingness-to-pay (WTP) approach (method 5) is likely to produce estimates that are theoretically superior and potentially more acceptable to the public than the other approaches (Soby *et al.*, 1993). In the WTP approach, no attempt is made to determine the value of an actual individual as is done with the human-capital approach — method 4 — and in methods 1 and 2. Rather, the value of a statistical life is estimated. That is, a safety improvement resulting in changes dp_i ($i = 1,...,n$) in the probability of death during a forthcoming period for each of n individuals, such that $\Sigma\, dp_i = -1$, is said to involve the avoidance of one "statistical" death or the saving of one "statistical" life (Jones-Lee *et al.*, 1985). Thus, the willingness to pay for the saving of one "statistical" life may be computed as

$$\text{Value of statistical life} = -\sum_{i=1}^{n} m_i dp_i \qquad (7.2)$$

where m_i denotes the marginal rate of substitution of wealth for risk of death for the ith individual. In practical terms, the value of a statistical life represents what the whole group, in this case society, is willing to pay for reducing the risk for each member by a small amount (Lanoie *et al.*, 1995). The main requirement for practical application of the WTP approach is empirical estimation of the marginal rates of substitution of wealth for risk of death or for risk of injury (Jones-Lee *et al.*, 1985). These estimates may be made based on the contingent-valuation (CV) method or the revealed-preferences (RP) method.

In the CV method, questionnaires are used to elicit the actual willingness to pay for specified risk reductions from respondents. The primary advantage of the CV method relative to the RP method, where market data are utilized, is that the CV method is not constrained by the availability of market data and, thus, may provide insight into classes of outcomes that cannot be addressed with available market data. That is, the researchers can tailor the questionnaire and selection of respondents to elicit precisely the needed information. The primary problems with the CV method are: (1) do those surveyed truly understand the questions? and (2) do the respondents give honest thoughtful answers? Viscusi (1993) reviewed the results of six CV studies of the value of life and concluded that in practice, truthful revelation of preferences (2) has proven to be less of a problem than has elicitation of meaningful responses because of a failure to understand the survey task (1).

The primary difficulty is that most people have difficulty discerning the meaning of very low probability events. In theory, if someone was willing to pay $1 for a device that would reduce some risk from 2/10 000 to 1/10 000, they should be willing to pay $0.10 for another device that would reduce some other risk from 2/100 000 to 1/100 000. However, people tend to take a view that if cutting one risk in half is worth a dollar, then cutting another risk in half is worth another dollar. Viscusi (1993) further notes that "the evidence in the psychology and economics literature indicates that there is a tendency to overestimate the magnitude of very low probability events, particularly those called to one's attention" by the media.

There are two general sources of data for the RP method-consumer-market data and labour-market data. In each case, the goal is to determine from actual risk-wealth tradeoffs the amount of money people are willing to pay to reduce risk (e.g., purchase of safety devices) or willing to accept in order to do tasks that involve greater risk (i.e. risk premiums in pay). The primary advantage of the RP method is that actual tradeoffs are used to determine the marginal rate of substitution of wealth for risk of death, whereas the CV method must utilize hypothetical data. The disadvantages include: (1) the tradeoff values are pertinent only in the "local range" of the workers studied and generalization to the entire population of the society is difficult; and (2) it is difficult to properly identify the marginal rate of substitution from the available data. Consumer-market data are rarely used to determine the value of life, and so procedures based on these data are not discussed in detail here. Because the RP method using labour-market data is the predominant method in economics, its application, assumptions and problems are discussed in detail in the following paragraphs.

The basic approach is to identify the relation between wages and risk through a linear regression that considers the various factors that affect the wage rate and the workers willingness to accept this rate. This "wage equation" may be defined as (Viscusi, 1993)

$$w_i = \alpha + \sum_{m=1}^{M} \psi_m x_{im} + \gamma_0 p_i + \gamma_1 q_i + \gamma_2 q_i WC_i + \mu_i \qquad (7.3)$$

where w_i is the wage rate for worker i (or its logarithm), α is a constant, the x_{im} are different personal characteristic and job characteristic variables for worker i ($m = 1$ to M), p_i is the fatality risk for the job of worker i, q_i is the nonfatal risk for the job of worker i, WC_i reflects the workers' compensation benefits that are payable for a job injury incurred by worker i, m_i is a random error term reflecting unmeasured factors that affect the wage rate and $\Psi_m, \gamma_0, \gamma_1$, and γ_2 are coefficients to be determined by regression. It is important to consider that the RP method is not concerned with the total wage rate w_i, which is a function of the strength of the national and/or regional economy, but rather it is concerned with the risk premiums p_i and g_i the workers require to accept risk.

One of the most difficult aspects of this approach is to determine the fatality risk and the nonfatal risk for the job of a given worker. Typically, the job fatality risk is determined from government statistics for different job classifications. However, many inconsistencies and inaccuracies are included in these data as discussed by Leigh **(1995)** in a comparison among "value of life" estimates obtained using data from the US Bureau of Labor Statistics and the National Institute of Occupational Safety and Health. Also, if both the fatality risk and the nonfatal risk are included in the regression, the strong correlation between these variables may obscure the relations to wages, whereas if the nonfatal risk is excluded, the fatality risk premium may be overvalued. Some of these problems may be mitigated by regression approaches that are less affected by colinearity — e.g., ridge regression and regression of principle components. However, these approaches may be difficult to apply and may not solve all regression-related problems.

The larger difficulty with the determination of the fatality risk is that it should be based on the worker's perception of risk of death rather than the actual risk of death from government statistics. Also, the workers must be able to freely move to new jobs if they determine that the wealth-risk tradeoff is unacceptable. If the workers do not accurately understand the risks they **face** or have limited work alternatives, the risk premium determined may be inaccurate in assessing society's willingness to accept risk.

Application of the RP method using labour-market data also may be difficult for estimating the acceptable wealth-risk tradeoff for the entire society. As noted by Jones-Lee *et al.* (1985) no doubt the wages of steeplejacks and deep-sea divers include clearly identifiable **risk** premiums, but it Seems unlikely that the attitudes of these individuals toward risk will be typical of society. Further, as noted by Lanoie *et al.* (1995), risk-averse workers are probably concentrated in jobs where the existence of explicit risk premium is unlikely or difficult to detect. Thus, Lanoie *et al.* (1995) suggested that the results of the CV method may be more representative of the preferences of the entire society, provided a representative sample of the population is questioned.

Another difficulty with the use of labour-market data is that the workers willingness to accept **risk** in return **for** wealth is measured. However, public decision-making should be based on society's willingness to pay to reduce risks. Viscusi (1993) notes that individuals may require a large financial inducement to accept an increase in risk from their accustomed risk level that generally exceeds their willingness to pay for equivalent incremental reductions in risk. Thus, willingness to pay estimates of the value of life obtained with application of the RP method based on labour-market data tend to be higher than society's actual willingness to pay.

The job characteristics considered in the regression analysis of equation 7.3 have included (Viscusi, 1993; Lanoie *et al.*, 1995):

- Does the job require physical exertion?
- Does the job involve exposure to extreme cold, humidity, heat, noise and/or dust?
- Does the job require long hours?
- Does the job require experienced workers?
- Does the worker **have** supervisory or decision-making responsibilities?
- Does the job require that the worker not make mistakes?
- The speed **of work**
- Job security
- Worker training

The personal characteristics of the workers considered in the regression analysis have included [Viscusi, 1993; Lanoie *et al.*, 1995) union membership, age, age squared (as a measure of the decrease of the rate of wage increases with age), experience, level of education, gender, martial status and spouse's employment, number of dependents, experience and/or discounted years of remaining life. Also, a number of industry dummies (transportation, manufacturing, government, etc.) may be included in the analysis to account for industry-specific effects (Lanoie *et al.*, **1995;** Leigh, 1995).

Application of the RP method using labour-market data requires a large amount of job and personal characteristic data for a representative sample of workers in **the** region **of** interest. Viscusi (1993) states that application of the RP method with labour-market data using industry-wide, aggregate data sets often results in difficulties in distinguishing wage premiums for job risks. He notes that the reliance on aggregate industry data pools workers with heterogeneous preferences, and firms with differing wage-offer curves, so that the estimated tradeoffs at any particular **risk** level cannot be linked to any worker's preferences or any firm's wage-offer curve. The need for extensive data sets for jobs and workers limits the practical application **of** this approach. The literature search done by Viscusi (1993) revealed that the RP method using labour-market data had only been applied in five countries: the US (value of life US $3–7 million in 1990), the UK (US $2.8 million), Canada (US $3.6 million), Australia (US **$3.3** million) and Japan (US $7.6 million).

If the extensive labour-market data needed to apply the RP method are available, this method is recommended for **risk** assessment for natural-disaster mitigation. Otherwise, application of the CV method to an appropriate sample of the affected population is recommended,

The value of injury reduction also can be computed through the WTP approach. However, Soby *et al.* (1993) reported difficulties in applying approaches used to estimate the monetary value of life to determine the value of injury reduction. These difficulties result because of the wide variety of injury states: no overnight hospital stay, overnight hospital stay, one-week hospital stay, long-hospital stay with major rehabilitation, etc. Viscusi (1993) summarized the results of 14 studies of the value of injury reduction computed by the WTP approach with the RP method using US labour-market **data.** Most of the estimates considered data for all injuries regardless of severity range **and** resulted in values of injury reduction from $25 000–50 000 (in 1990 US$). The value of injuries requiring at least one lost workday was approximately $50 000, or at the high end of the range **of** estimates for the implicit value of injuries. Only data for the US are available with respect to the value of injury reduction. The ratio between the value of injury reduction and the value of lives saved is approximately 0.01 (determined from US data as $50 000/ $5 000 000). This ratio could be applied as a first approximation in other countries for which labour **costs** are not as high as in the US Therefore, if the value of lives saved in a given region were $1 million. then the value of injury reduction would be $10 000.

7.3 INDIRECT **DAMAGES**

7.3.1 General considerations

Indirect damages are determined from the multiplier or ripple effect in the economy caused by damage to infrastructure resulting from a natural disaster. In particular, damage done to lifelines, such as **the** energy-distribution network, transportation facilities, water-supply systems and waste-management systems, can result in indirect financial losses greater than the direct financial damages to these systems and a long-term drain on the regional or national economy. Munich Reinsurance (1997) noted in their Annual Review of Natural Catastrophes 1996 that numerous natural disasters of recent years have **shown how** vulnerable the infrastructure of **major** cities is to minor breakdowns' and how severe shortages of supply can develop in **a short** time. Industry optimizes storage, production, supply of components and dispatch of goods using sophisticated control programmes. Thus, industry is dependent on a perfectly working infrastructure. In the event of a natural disaster, lack of standby supply systems can lead to enormous losses **of** revenue and profits that **can** mean the ruin **of** manufacturers, suppliers, processors and/or wholesalers. On the basis of the experiences of the 1995 Kobe, Japan earthquake, loss estimates for a similar **or more** severe earthquake in the area of Greater Tokyo **are** on the order of **US** $1–3 trillion (Munich Reinsurance, 1997). Thus, the possible extent of losses caused by extreme natural disasters in one of the world's major metropolises **or** industrial centres could be so great as to result in the collapse of the economic system of the country and could even bring about the collapse of the world's financial markets.

Wiggins (1994) described five problems affecting the determination of indirect economic losses (damages) **as** follows:

(a) Any aggregated loss data from previous natural disasters do not discern between **how** much of the loss to a particular economic sector resulted from disruption to lifelines, and how much resulted from direct damage.

(b) Available loss data, such **as** gathered by a questionnaire may be inaccurate, because many companies prefer not to disclose detailed financial loss data.

(c) The ripple effects of a changing local economy are difficult to measure and positively attribute to particular disruptions, such **as** telephone, electricity, direct damage, etc.

(d) It is difficult to determine if selected short-term losses are actually postponed rather than cancelled. That is, permanent losses result from economic activity — purchases, trips, use of services, etc. — that was cancelled because **of a** natural disaster, whereas other **similar** economic activity may be merely postponed **to be** "made up" at a later time.

(e) It is difficult to define the region of impact, **and** have economic data and models available for that region only. The determination **of** regions experiencing indirect financial losses is not limited to the areas suffering physical damage, but also include the normal **delivery points** of the affected industries. The larger the region chosen, the more difficult it becomes to **positively** justify that changes in economic activity solely result from the natural disaster, rather than other influences.

These problems indicate that it is unlikely that **data** on damages from previous natural disasters can be used to estimate indirect damages from possible future **natural** disasters. Thus, some type of macroeconomic model must ***be*** utilized to estimate indirect damages.

Lee (1996) reports that analyses of the indirect **damages** resulting from earthquakes have been done with appropriate models of the regional economy that include: (1) input-output (I-O) models; (2) social accounting matrix models; **(3)** computable general equilibrium models; and (4) other macroeconomic models. The complexity of the relation between direct damages and indirect **damages** that **these** models must approximate **is** illustrated in Figure 7.3. This figure **shows** the facets of the macroeconomic model developed by Kuribayashi ***et al.*** (1984) to estimate indirect losses from earthquakes in Japan. This chapter **focuses** on the application of I-O models to estimate indirect damages resulting from natural disasters because I-O models are available for many countries **(as** described in 7.3.2) and they are generally accepted as good tools for economic planning.

7.3.2 The input-output (I-O) **model**

I-O models are frequently selected for various economic analyses and are widely applied throughout the world (Lee, 1996). The United Nations has promoted their **use** as a practical planning tool for developing countries and has sponsored a standardized system of economic accounts **for** developing the models (Miller and Blair, 1985). More than **50** countries have developed I-O models and applied them to national economic planning and **analysis (Lee,** 1996). Wiggins (1994) notes that I-O models **may** be particularly well suited to estimation of indirect damages because it is thought that a properly applied I-O model can largely overcome the first four problems **with** the estimation of indirect economic losses listed previously. Definition of the appropriate "region of impact" for indirect losses or damages remains a difficult problem for all macroeconomic models.

Input-output models constitute a substantially simplified method for analysing interdependency between sectors

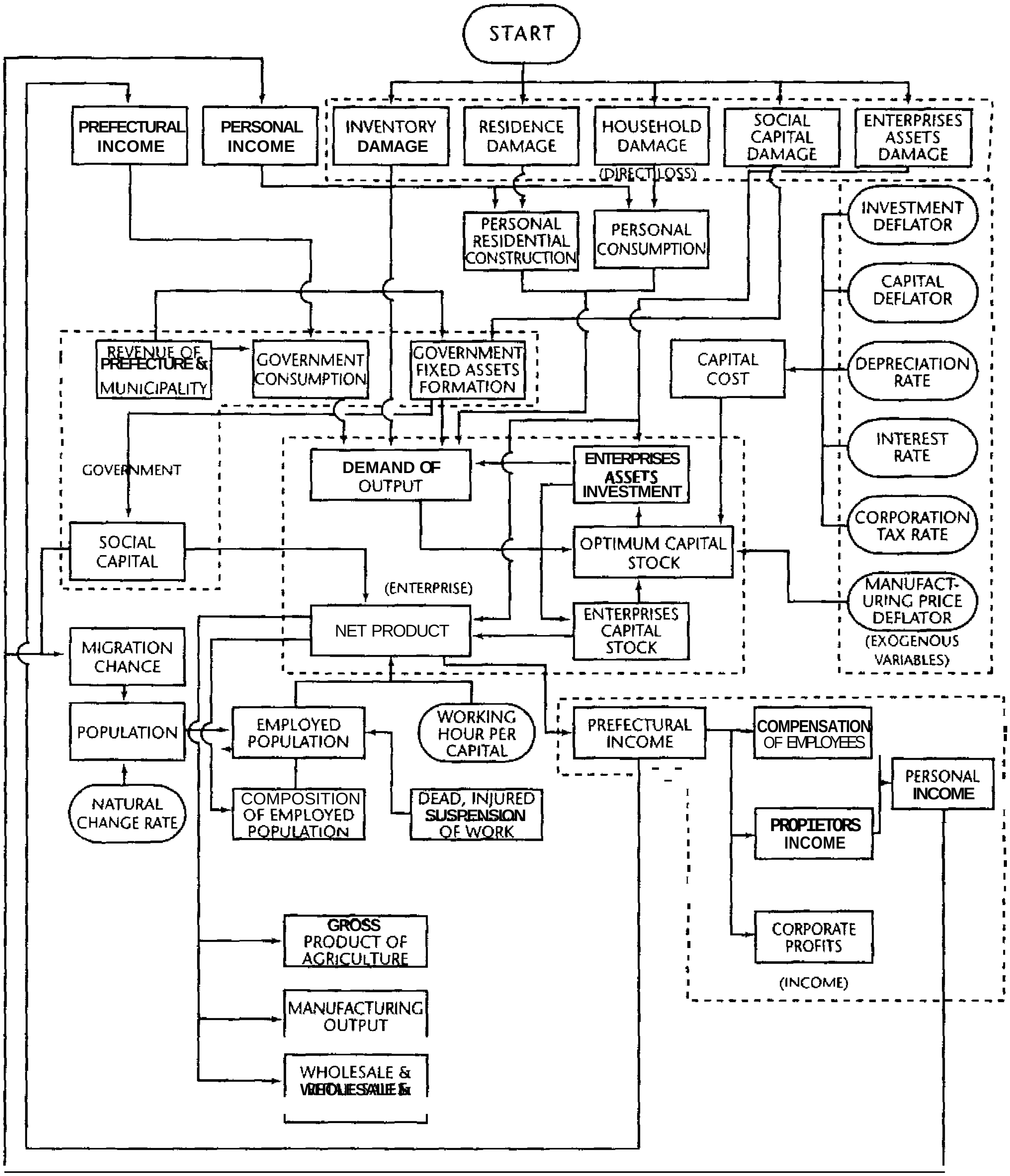

Figure 7.3 — Economic interactions that affect the indirect economic losses (damages) resulting from a natural disaster (after Kuribayashi et al, 1984)

in the economy. As such, it is necessary to understand the magnitude of the simplifications applied in I-O models, which include the following (Randall, 1981, p. 316):

(*a*) *the* industrial sector, rather than the firm, is taken to be the unit of production,

(*b*) the production function for each sector is assumed to be of the constant-coefficient type;

(c) the question of the optimal level of production is not addressed,

(*d*) the system contains no utility functions; and

(*e*) consumer demands are treated as exogenous.

Further, Young and Gray (1985) note that I-O models are production models characterized by. the lack of any specified objective function; no constraining resources; lack of choice on the production or consumption side; constant factor and product prices; and a production function returning constant returns to scale. Randall (1981, p. **316)** states that these are rather radical assumptions, but these assumptions have the advantage of permitting a simple interactive model that may be empirically estimated with relative ease Thus, I-O models have become accepted, despite their rigid and somewhat unrealistic assumptions. as the basic tool in the analysis of regional economic systems. In the application of I-O models to estimation of indirect damages, a comparison is made between economic production with and without the occurrence of a natural disaster. Thus, because the goal is to estimate relative economic output and not exact economic output, the effects of some of the assumptions on the reliability of the estimated indirect damages are reduced. Further, as described in the following discussion, the constants in the I-O model are modified to reflect lost productivity in various sectors resulting from a natural disaster. Therefore, I-0 models are more reliable for estimating indirect damages than for estimating economic output because some of the problems listed above do not substantially affect estimation of indirect damages.

As discussed previously, the approach to evaluating the indirect damages resulting from a natural disaster **is** *to* compare the post-disaster scenario with an estimate of what the economy would have looked like without the disaster. Lee (1996) presents an outstanding summary of how an I-O model could be applied to estimate the indirect damages resulting from an earthquake. **This** summary forms the basis for the following paragraphs.

An I-O model is **a** static general equilibrium model that describes the transactions between the various production sectors of an economy and the various final demand sectors An I-O model *is* derived from observed economic **data** for a specific geographical region (nation, state, county, etc). The economic activity in the region is divided into a number of industries or production *sectors.* The production sectors may be classified as agriculture, forestry, fishery, mining, manufacturing, construction, utilities, commercial business. finance and insurance, real estate, transportation, communication, services, official business, households and other sectors. In practice, the number of sectors may vary from only a few to hundreds depending on the context of the problem under consideration. For example, Wiggins (1994) utilized 39 sectors in estimating the indirect economic losses resulting from earthquake damage to three major oil pipelines in the USA.

The activity of a group of industries that produce goods (outputs) and consume goods from other industries (inputs) in the process of each industry producing output is approximated with the I-O model. The necessary data are the flows of products from each "producer" sector to each "purchaser" sector. These intersectoral flows are measured in monetary terms for a particular time period, usually a year. Using this information on intersectoral *flows,* a linear equation can be developed to estimate the total output from **any** sector of the n-sector model as

$$\sum_{j=1}^{n} Y_{ij} + C_i = Y_i \qquad (7.4)$$

where Y_{ij} is the value of output of sector i purchased by sector j, C_i is the final consumption for the output of sector i, Y_i is the value of the total output of sector i, **and** n is the number of sectors in the economy. Thus, the I-O model may be expressed in matrix form as:

$$Y = AY + C \qquad (7.5)$$

where Y is the vector of output values, C is the vector of final consumption and **A** is the input coefficient matrix whose elements A_{ij} are equal to Y_{ij}/Y_i. The **rows** of **the A** matrix describe the distribution of the output of a producer throughout the economy, and ***the*** columns of the **A** matrix describe the composition of inputs required by a particular industry to produce its **output.** The consumption matrix, C, shows the sales by each sector to final markets, such as purchases for personal consumption.

Most of the I-O model coefficients that have been developed at the national level or provincial/state level are based on extensive surveys of business, households and foreign trade. These detailed lists of model coefficients are very expensive and time consuming to produce and can easily become out of date. The I-O model coefficients for regions within **a** country or province/state generally are prepared by reducing the national coefficients so that they match whatever economic data are available for the particular area. Interpolation of the production and consumption coefficients on the basis of population also seems to provide reasonable results at an aggregated economic sector level (Wiggins, 1994).

From equation 7.5, the output of the economy if the natural disaster does not occur may **be** obtained as

$$Y_N = (I - A)^{-1}C \qquad (7.6)$$

where I is an $n \times n$ identity matrix, the subscript N indicates no disaster, and the exponent –1 indicates *the* inverse function of the matrix **The** indirect loss or damage resulting from structural and infrastructure damage caused by a natural disaster can be divided into a first-round loss and a second-round loss The first-round loss comes from the reduction in output related specifically to loss of function resulting from damage to a given sector of the economy The second-round loss results as the loss of capacity in one sector of the economy reduces the productivity of other sectors of the economy that obtain inputs from the first sector.

The primary factor that drives both the first-round and second-round losses is the amount of time a given sector of the economy will be out of service because **of** damage from a natural disaster. The concept of a restoration function has been used to describe the relation between structural damage to **the** loss of function of a facility and, ultimately, of a sector of the economy. The loss of function depends on the level of damage to the economic sector. For a particular state of damages, the restoration function may be expressed as a time-to-restore curve as shown in Figure 7.4, where the horizontal axis is the elapsed ***time*** after the event and the vertical axis is the restored functionality, $F_R(t)$. The loss of function for the given damage state, t_{loss}, measured in time, may be **calculated** as the area above the time-to-restore curve and can be estimated as:

$$t_{loss} = \int_0^{t3} \left(1 - F_R(t)\right) dt \tag{7.7}$$

where $F_R(t)$ is the functionality of the economic sector, and $t3$ is the amount of time required to restore the facility to full functionality. Different types of facilities and economic sectors under the same level of damage may experience different losses of functionality depending on the nature of the economic sector. Reasonable estimates of the loss of function for a given economic sector as a result of a natural disaster may be obtained on the basis of the estimated direct damage and the restoration time observed in previous disasters.

The production loss for a given sector, i, may be estimated as:

$$Y_{i,loss} = (t_{loss}/t_{IO})\ Y_{i,N} \tag{7.8}$$

where $Y_{i,loss}$ is the production loss from economic sector i resulting from a natural disaster, t_{IO} is the time interval over which the I-O model coefficients are estimated, and $Y_{i,N}$ is the total output from sector i without any disaster. For given damage levels to the various economic sectors, the total first-round loss then is obtained as

$$C_{B1} = \sum_{i=1}^{n} \varepsilon_i\ Y_{i,loss} \tag{7.9}$$

where C_{B1} is the total first-round loss, and ε_i is the economic surplus per unit of total output of sector i in the I-O model.

Using the estimated change in output from the various economic sectors, the new post-disaster demand is obtained as

$$C^* = (I - A)\ Y^* \tag{7.10}$$

where $Y^* = Y_N - Y_{loss}$. As described previously, in the application of I-O models for conventional inter-industry studies, it is assumed that the intermediate input requirements reflected in the **A** matrix are invariant. However, this cannot be assumed after a natural disaster because of the reduction in capacity resulting from the damage to structures and the interruption of service. Thus, the changing structure of the economy must be accounted for through changes in the **A** matrix in order to adequately estimate the indirect losses or damages. In the post-disaster economy, matrix **A** may be approximated by assuming that the direct input requirements of sector i per unit output j are reduced in proportion to the reduction in output i (Boisvert, 1992). That is, local purchases of sector j products by sector i to meet the reduced levels of final consumption are reduced in proportion to the damage in sector i (Lee, 1996). The post-disaster level of production is estimated as

$$\begin{aligned} Y_D &= (I - A^*)^{-1}\ C^* \\ &= (I - A^*)^{-1}\ (I - A)Y^* \end{aligned} \tag{7.11}$$

where Y_D is the post-disaster level of production, and **A*** is the I-O model coefficient matrix for the post-disaster economy whose elements $A_{ij}^* = (Y_i^*/Y_{i,N})A_{ij}$. For given damage levels to the various economic sectors, the total second-round loss is then obtained as

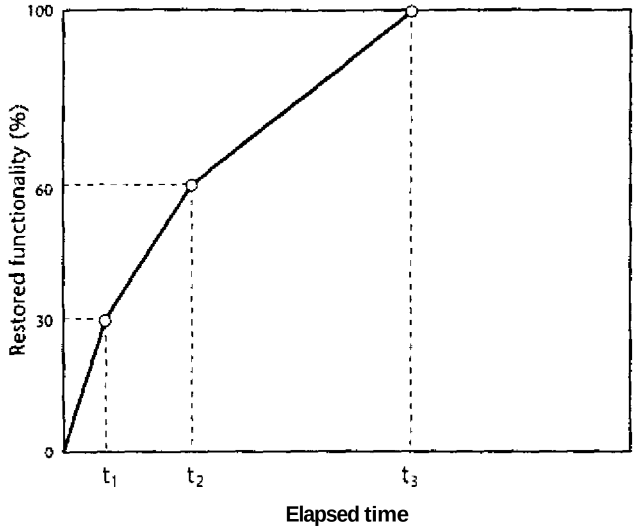

Figure 7.4 — Time-to-restore *functionality* of an *economic* rector *(after Lee, 1996)*

$$C_{B2} = \sum_{i=1}^{n} \varepsilon_i \left(Y_i^* - Y_{i,D}\right) \tag{7.12}$$

where C_{B2} is the total second-round loss. The total indirect loss for given damage levels resulting from a natural disaster is the sum of the first-round loss and second-round loss.

The methodology described previously in this section does not account for the redistribution effects of spending on restoration. Such spending results in increased economic activity as governments inject higher-than-normal amounts of money in the region to aid in disaster recovery. Restoration spending takes the form of a direct increase in the construction sector with subsequent ripple effects throughout the affected regional economy. From the point of view of planning fur natural-disaster mitigation at the national level, it is reasonable to omit the effects of restoration spending on the regional economy. The entire nation will experience the total economic losses expressed by equations 5.9 and 5.12 because of the opportunity costs of the resources used for reconstruction. It is not possible to accurately estimate how much lost production can be made up after recovery is in progress (Lee, 1996). Thus, planners may make assumptions regarding the make up of lost productivity to moderate the likely overestimate of indirect damages obtained as the sum of C_{B1} and C_{B2}. For example, Wiggins (1994) assumed that 80 per cent of the time-dependent losses resulting from damage to oil pipelines because of an earthquake would be recovered over time. However, such assumptions are highly dependent on the economic sectors invoked and the magnitude of the damage. A conservative overestimate is probably most useful for planning for natural-disaster mitigation.

7.4 GLOSSARY OF TERMS

Consequences: Property damage, injuries and loss of life that may occur as a result of a potentially damaging phenomenon. Computed as the product of vulnerability and extreme consequence (replacement cost, death, etc.) summed over all elements at risk.

Contingent valuation: A method to determine the value of lives saved wherein questionnaires are used to elicit the actual willingness to pay for specified risk reductions from respondents who represent the affected population.

Depreciation: The loss of value of items because of wear and tear and age.

Direct damages: Property damage, injuries and loss of life that occur as a direct result of a natural disaster.

***Economic** surplus:* The value of the products made by an economic sector in excess of the cost of production.

Elements at risk: The population, buildings and civil engineering works, economic activities, public services, utilities and infrastructure, etc. exposed to hazard.

*Fatality **risk:*** The probability that someone will die while participating in an activity or doing a job.

First-round loss: The indirect damage resulting from the reduction in output related specifically to loss of function resulting from damage to a given sector of the economy,

Human capital approach: A method to determine the economic value of human life wherein the direct out-of-pocket losses associated with premature death (i.e. the present value of expected future earnings) are calculated.

Indirect damages: Economic losses resulting from the multiplier or ripple effect in the economy caused by damage to infrastructure resulting from a natural disaster. Damage done to lifelines such as the energy-distribution network, transportation facilities, water-supply systems and waste-management systems, can result in indirect economic losses greater than the direct economic damage to these systems and a long-term drain on the regional or national economy.

Input-output model: A static general equilibrium model that describes the transactions between the various production sectors of an economy and the various final demand sectors. This model is derived from observed economic data for a specific geographical region (Nation, State, county, etc.).

Macroeconomics: Economics studied in terms of large aggregates of data whose mutual relationships are interpreted with respect to the behaviour of the system as a whole.

Marginal rate *of substitution:* The point at which the increase in utility or benefit gained from one objective (e.g., financial gain) from an activity is exactly equal to the decrease in utility or benefit gained from another objective (e.g., safety). Thus, if financial gain were to further increase, safety would unacceptably increase relative to the individual's overall utility preferences.

Nonfatal **risk:** The probability that someone will be injured while participating in an activity or doing a job.

Opportunity cost: The benefits lost to society or an individual because resources were expended on another activity.

Restoration function: The restoration of economic sector productivity as a function of time after a natural disaster. For a particular state of damages, the restoration function may be expressed as a time-to-restore curve, where the horizontal axis is the elapsed time after the event and the vertical axis is the restored functionality.

*Restoration **spending:*** The Government spends higher than normal amounts of money in a region affected by a natural disaster to aid in disaster recovery. This spending results in increased economic activity in the region, but an overall loss for the national economy.

Revealed preferences: A method to determine the value of lives saved wherein the amount of money people are willing to pay to reduce risk (e.g., purchase of safety devices) or willing to accept in order to do tasks that involve greater risk (i.e., risk premiums in pay) are used to establish the societally acceptable wealth-risk tradeoff.

***Risk** premium:* The extra amount of money a worker must be paid to accept a job with higher fatality risk and nonfatal risk. This depends on a worker's perception of the risk posed by the job and his or her ability to select less risky jobs.

Second-round loss: The indirect damage resulting as the loss of capacity in one sector of the economy reduces the productivity of other sectors of the economy that obtain inputs from the first sector.

Sectors: Subsections of the economy that produce certain types of goods; these include agriculture, forestry, fishery, mining, manufacturing, construction, utilities, commercial business, finance and insurance, real estate, transportation, communication, services, official business and households.

Value of a *statistical life:* A safety improvement resulting in changes dp_i ($i = 1,\ldots,n$) in the probability of death during a forthcoming period for each of n individuals, such that $\Sigma dp_i = -1$, is said to involve the avoidance of one "statistical" death or the saving of one "statistical" life. The value of a statistical life represents what the whole group, in this case society, is willing to pay for reducing the risk for each member by a small amount.

Value of injury reduction: The monetary value society places on reducing injuries through infrastructure improvements, public-health programmes, land-use management and other activities.

Value of lives saved: The monetary value society places on protecting and preserving human life through infrastructure improvements, public-health programmes, land-use management and other activities.

Vulnerability: The degree of loss (from 0 to 100 per cent) resulting from a potentially damaging phenomenon. These losses may include lives lost, persons injured, property damage and disruption of economic activity. The vulnerability is distributed with respect to the magnitude of the potentially damaging phenomenon.

Willingness to accept: The amount of money that a person must be paid to accept increased fatality and (or) nonfatal risks; generally greater than the willingness to pay.

Willingness to pay: The amount of money that a person will pay to reduce fatality and (or) nonfatal risks; generally less than the willingness to accept.

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