Canada Wide Standard for Particulate Matter and Ozone: Cost-Benefit Analysis using a Life-Quality Index

M.D. Pandey[1] and J.S. Nathwani[2]

Institute for Risk Research
University of Waterloo, Waterloo,
Ontario, Canada

Accepted for publication in *Int. J. Risk Analysis*

[1] Associate Professor of Civil Engineering
[2] Professor (Adj), Department of Management Sciences
Dr. Nathwani is the Manager, Strategic Planning, Hydro One Inc, 483 Bay Street, Toronto, ON

Abstract

The adverse impacts of particulate air pollution and ground level ozone on public health and the environment have motivated the development of Canada Wide Standards (CWS) on air-quality. In cost-benefit analysis of air-quality options, valuation of reduction in mortality is a critical step as it accounts for almost 80% of the total benefits and any bias in its evaluation can significantly skew the outcome of the analysis. The overestimation of benefits is a source of concern since it has the potential of diverting valuable resources from other needs to support broader health care objectives, education and social services that contribute to enhanced quality of life.

We have developed a framework of reasoning for the assessment of risk reduction initiatives that would support the public interest and enhance safety and quality of life. The paper presents the Life Quality Index (LQI) as a tool to quantify the level of expenditure beyond which it is no longer justifiable to spend resources in the name of safety. It is shown that the LQI is a compound social indicator comprising societal wealth and longevity, and it is also equivalent to a utility function consistent with the basic principles of welfare economics and decision analysis. The LQI approach overcomes several shortcomings of the method used by CWS Development Committee and provides guidance on the compliance costs that can be justified to meet the Standards.

Notations

AQVM = Air Quality Valuation Model
BCR = Benefit to Cost Ratio
CBA = Cost Benefit Analysis
CCME = Canadian Council of Ministers of the Environment
CWS = Canada Wide Standards
CWSDC = Canada Wide Standards Development Committee
LE = Life Expectancy
LQI = Life-Quality Index
PM = Particulate Matter
RSC = Royal Society of Canada
RGDP = Real Gross Domestic Product per Person
rtp = Rate of Time Preference
VSL = Value of Statistical Life

1 Introduction

1.1 Background

Adverse health effects and increased mortality associated with particulate air pollution originating from combustion sources is a major concern for population health and quality-of-life. Fine-particulate pollution typically contains a mixture of soot, acid condensates, sulfate and nitrate particles primarily produced by combustion of fossil fuels in transportation, manufacturing and power generation. The toxic nature of these substances and their ability to penetrate deep into the lungs pose a risk to health. Several pollution exposure studies have found statistically significant relationships between increased PM/ozone levels and premature mortality/morbidity. For example, Pope et al. (1995) studied the effect of air pollution on a large cohort, half a million adults living in 151 U.S. metropolitan areas, and concluded that mortality risk in the most polluted area is 17% higher than that in the least polluted area [1].

In Canada, the Canada Wide Standards (CWS) for particulate matter (PM) and ozone were ratified by the Canadian Council of Ministers of the Environment (CCME) in June 2000. The standards for $PM_{2.5}$ 30 $\mu g/m^3$, and for ozone 65 *ppb*, will come into effect by 2010 [2-4]. The Government of Canada's Regulatory Policy requires federal authorities to demonstrate that the benefits of regulatory requirements outweigh the costs to Canadians, their governments and businesses [5]. The consideration of socio-economic impacts in the process of setting a standard is also endorsed as a fundamental requirement by the Council of Ministers [5]. To address these concerns, a detailed cost-benefit analysis (CBA) of various scenarios of improved air-quality in Canada has been performed [2].

The cost-benefit analysis is confronted by large uncertainties associated with the effects of pollution on human health, monetary valuation of the improvements in health and the environment, variation of benefits in time and space, and costs of emission reduction to industry and society. To minimize the complexity arising from such uncertainties, the Standards Development Committee (CWSDC) made several simplifying assumptions and relied on rough estimates of input parameters. The Royal Society of Canada (RSC) appointed an expert panel to provide an independent, expert review and critique of the cost benefit analysis performed by the Committee.

The Royal Society Panel [5] concluded that cost benefit analysis performed by the Committee is preliminary, and in some instances, a cursory analysis that provides a limited degree of guidance to decision-makers. Although reduction in premature deaths is the most anticipated benefit of improved air quality, its monetary valuation, as highlighted by the RSC Panel, is a major deficiency in the approach adopted by the Standards Committee and a potential source of bias in the results of the analysis. The method used by the Committee appears to produce very large estimates of benefits that are difficult to reconcile given the size of other health related programs. For example, the aggregate benefit of reducing particulate matter to background level is estimated at 7,976to a rmostifit ofssirs to amp$32.8 inlln prsirs to ufrom ggretionotheres,titedcurcng T* -0.0

disproportionate to the benefits, then it reduces the efficiency of resource utilization. The balancing of impacts on the quality of life and health against economic costs of risk reduction, although controversial, is necessary.

1.2 Risk Management in Public Interest

Here we develop a framework of reasoning for the quantitative assessment of risk reduction initiatives and illustrate its application to cost-benefit analysis of pollution control options. The paper presents the Life Quality Index (LQI), a compound social indicator comprising societal wealth and longevity, as a tool to guide the selection of optimal strategies for managing risk. The LQI is also equivalent to a utility function that is consistent with several principles of decision analysis.

The proposed framework is intended to satisfy some basic reasoning and principles of risk management in public interest, namely, accountability, maximum net benefit, compensation and life measure, which have been discussed in detail elsewhere [6, 7]. These principles attest to the need for

(i) A unified rationale for application to all risks, if we are to have a working basis for practical professional action in society's interest when risks to life, health or property are important.

(ii) A simple and meaningful test of the effectiveness of allocation of scarce resources: how much life saving does risk reduction buy, and could the same resource, if directed elsewhere, results in better gain for society as a whole?

(iii) Compensation to ensure implementation of a policy is socially beneficial where there is a need to compensate the losers.

(iv) Enhancing a relevant measure of life by maximizing the net benefit in terms of quality of life in good health for all members at all ages.

1.3 Organization

The next Section summarizes the approach and results of cost-benefit analysis undertaken by the Standards Development Committee. Section 3 documents the development of the Life-Quality Index and discusses several issues related to its application to risk management. Section 4 illustrates application of LQI model to cost-benefit analysis of pollution control options. Main conclusions of the study are presented in Section 5.

2 Approach Used by the Canada Wide Standards Development Committee

2.1 Background

The cost-benefit analysis performed by the Committee considered various air-quality options for $PM_{10}/PM_{2.5}$ levels ranging from 70/35 to 50/25 mg/m^3 and for ozone concentration between 60 to 70 *ppb*. Reduction targets to achieve these air-quality options were determined using the 1994-1996 ambient air quality data (PM and ozone levels) for large urban centres in Canada. The Air Quality Valuation Model (AQVM) was used to estimate health and environmental benefits associated with reductions in ambient levels of PM and ozone [3]. The estimate of the costs of reducing PM and ozone pollution in Canada has based on the U.S. EPA data on cost and efficiency of various emission control options. The U.S. data were combined with Canadian emission inventory data collected by Environment Canada [4]. The cost estimates did not incorporate implementation, administration and other indirect costs, and ignored forecasts of future growth in emissions. Our analysis is based on data taken from CWS and RSC Panel reports that use 1996 as base year for all cost and benefit estimates [2-5].

2.2 Valuation of Mortality Reduction

The AQVM applies a *damage function* approach to benefit estimation that requires a concentration-response (CR) function and value of statistical life (VSL) as inputs. The CR function describes the increased risk of death due to a unit increase in pollution concentration.

Pollution exposure studies have been used to develop CR functions that are summarized in Table 1. The AQVM model assumed no the threshold in the pollution "dose-response" relation due to uncertainty about the safe level of PM concentration that has no adverse health effects.

The estimation of VSL has been a challenging and controversial topic in decision analysis. Table 2 shows empirical estimates of VSL ranging from \$2 million to \$10 million that are obtained from wage risk approach and contingent valuation surveys reported in the literature [5]. The AQVM adopted \$4.1 million as an age-adjusted central estimate of VSL to reflect the fact that about 85% pollution related deaths occur in population over age 64.

For economic valuation of mortality, the number of avoided death (N_d) is calculated for a given reduction in pollution level as

$$N_{\mathrm{d}} = \text{(risk of death per person per unit pollution)} \times \text{(units of pollution reduction)} \times \text{exposed population} \quad (1)$$

Tables 3 summarizes the number of avoided deaths in Canada corresponding to reduction to various levels of PM and ozone concentrations. The monetary valuation of avoided mortality is subsequently calculated as $N_{\mathrm{d}} \times \mathrm{VSL}$.

For example, the number of avoided deaths in Canada is estimated as 1039 per year for the proposed Standard of 30 $\mu g/\mathrm{m}^3$ $PM_{2.5}$ (see Table 3). The corresponding benefit is estimated as $1039 \times 4.1 = \$4{,}259.9$ million/year. Net present value of this benefit over a 30 years period with 5% discount rate can be obtained as \$65.5 billion. Similarly the benefit of achieving a CWS of 65 *ppb* ozone can be estimated as \$832 million/year corresponding to 203 lives saved per year. Benefits for other air-quality options are summarized in Table 4.

The monetary value of avoided morbidity (e.g., chronic bronchitis, asthma symptom days, and respiratory and cardiac hospital admissions) was carried out in a similar manner in AQVM.

Since the impact of avoided mortality dominates the benefit calculation, morbidity effects are not considered further in our study.

2.3 Results of Cost-Benefit Analysis

Estimates of annual costs of pollution reduction, associated benefits and benefit to cost ratio (BCR) are presented in Table 4 for various optional levels of PM and ozone. For the proposed standard of 60/30/65 (PM_{10}/$PM_{2.5}$ /Ozone), the total number of avoided deaths is estimated as 1,842 per year, which is sum of the number of lives saved by achieving 60 PM_{10}, 30 $PM_{2.5}$ and 65 ozone concentration Canada wide. The monetary value of associated benefit is calculated as \$7,552 million/year, whereas the total cost estimate is \$2,491 million/year. Thus, the benefit to cost ratio (BCR) turns out to be 7,552/2,491 =3, suggesting that societal gains are much larger than the cost of reducing pollution. Results summarized in Table 4 show that reduction in PM is highly beneficial as evident from large values of BCR (7 – 24). However, it is not true for ozone reduction options for which benefits are always less than costs (BCR ≈ 0.2-0.9). It is evident that large benefits associated with PM options compensate for inefficiency of ozone standards, so that the overall standard for PM and ozone passes the CBA test (BCR≈3).

2.4 Discussion

Some of the conceptual limitations of Committee's approach to valuation of mortality are summarized below.

1. Basis for selecting of VSL value may not be relevant to pollution control programs.

The selection of VSL (≈\$4.1 million) in CWS method is based on surveys of various life saving programs and regulations in which the implied value of "cost per life" can vary from few thousand dollars to billions of dollars [8]. The RSC Panel [5] however argues that such estimates reflect subjective decisions (preferences) of program administrators rather than being indicative of tradeoffs or peoples' willingness-to-pay (WTP) for risk reduction. More importantly, the nature of risks in many life saving interventions is different than that associated with environmental interventions. Therefore, VSL of $4.1 million appears to be large and a main contributor to benefit overestimation [5].

2. The use of term “lives saved” is a misleading measure of policy.

As Schwing (1979) pointed out that relevant policy issue is not life or death but reduction (or removal) in a specific cause of mortality that is in competition with several other existing causes of mortality [9]. Therefore longevity or life expectancy is a more useful and scientifically correct measure than “lives saved” in the assessment of safety programs. For example, if elimination of a 5 in 10,000 risk of death were equated to saving 5 lives, then it ignores the probabilistic nature of risk, i.e., there is no certainty about saving 5 lives. The use of life expectancy (LE) is receiving wider acceptance in literature quantifying the impact of air pollution [10, 11].

3. Age related adjustments to mortality valuation are inaccurately applied.

The Standards Committee proposed an age-weighted average of VSL (Table 2) to account for the fact that reduction in air pollution lowers death rates primarily among older persons over age 64. This method ignores realistic probabilities of survival such as those given in a national life table, and also ignores the impact of competing mortality risks that vary with age. For example, a recent contingent-valuation survey by Krupnick et al. (2000) reported that people’s willingness-to-pay (WTP) for a future gain in LE depends on their age and health status [12]. The Committee’s approach fails to address such issues either.

4. Discounting of benefits of mortality reduction is incorrectly performed.

In Committee’s approach, the net present values of annual benefit of mortality reduction accruing over 30 year period were calculated using interest rates from 2% - 7.5%. This approach ignores the discounting for time related preferences for consumption, which is conceptually different from that used in financial accounting [13]. The fact that a person's preference for consumption and willingness-to-pay for life saving programs vary with age makes the effect of discounting variable with age. Therefore discounting should be applied to all age groups and then the outcome should be integrated over the population age distribution. This point is explained in detail in Section 3.2.

3 Life-Quality Index

3.1 General

We present a model to determine an acceptable level of expenditure that can be justifiably incurred on behalf of the public interest in exchange for a small reduction in the risk of death that results in improved life-quality for all. This value can be considered as the Societal Willingness to Pay (SWTP). Its estimation is based on a Life-Quality Index (LQI) which is derived using the principles of welfare economics under uncertainty and expected utility theory. The LQI for a society is derived as

$$L = G^q E \tag{2}$$

where G is the real gross domestic product (RGDP) per person/year, E is the life expectancy (LE) in the country, and q is the elasticity of utility of consumption. It will be shown that q is the ratio of average work to leisure time available to members of society.

The LQI consists of two major indicators: the real gross domestic product per person as a measure of resources and the quality of life [14], and life expectancy which has been validated over time and again as a universal indicator of social development, environmental quality and public health [15]. Both indicators have been in use for half a century to express the wealth and health of a nation in numbers, and they are reliably measured. The chart in Figure 1 shows the three components of the index as they relate to the key human concerns: creation of wealth, duration of life and the time available to enjoy life in good health. The derivation of LQI is briefly described below.

3.2 Derivation

The general idea is that a person's enjoyment of life, or utility in an economic sense arises from a continuous stream of resources available for consumption over the entire life. Therefore income required to support consumption and the time to enjoy are two determinants of the life quality.

Denote the consumption rate at some age τ as $c(\tau)$ (\$/year), and assume that a valid function, $u[c(\tau)]$, exists that can quantify the utility derived from consumption. The present value of life-time utility for a person is equivalent to integration of $u[c(\tau)]$ from the present age a till a terminal age T with a suitable discount rate [16]

$$U(a, t) = \int_a^t u[c(\tau)]e^{-r(\tau-a)}d\tau \qquad (3)$$

where r is the discount rate, also referred to as the rate of time preference (rtp) for consumption. The discounting reflects a common fact that individuals tend to undervalue a prospect of future consumption in comparison to that of present consumption [17]. Implications of discounting are discussed further in subsection 3.2.3.

If the probability of surviving exactly up to age t is denoted by $p(t)$, then the product $U(a, t)\times p(t)$ is the expected value of utility. Since the age at death can vary randomly between a and T (≈100 years) with probabilities described by an actuarial survival function (e.g., life tables), the expected value of life time utility can be obtained as

$$L(a) = \int_a^T p(t)U(a,t)dt \qquad (4)$$

Substituting for $U(a, t)$ from eqn.(3) into (4) and subsequent simplification leads to

$$L(a) = \int_a^T S(a,t)u[c(t)]e^{-r(t-a)}dt \tag{5}$$

where $S(a\ ,t) = \int_a^t p(t)dt$ defines the probability of survival in the period a to t. Assuming a power utility function and a constant consumption rate, i.e., $c(t) = c$, and $u(c) = c^q$, eqn.(5) can be written in a compact form as

$$L(a) = c^q \int_a^T S(a,t)e^{-r(t-a)}dt = c^q e(a) \tag{6}$$

Note that the discounting factor applied to utility of consumption is now merged in eqn.(6) with the survival probability integral. This integral is equivalent to the discounted value of remaining life years at age a, denoted by $e(a)$. We propose the life-time utility, $L(a)$, as a surrogate measure of quality-of-life of a person of age a. This type of reasoning primarily originates from the fundamental work of Usher (1973) on the impact of improvement of life expectancy on economic growth [18].

The life-quality at the societal level is an aggregate of the values for all individuals in the society. We assume that the consumption rate is equivalent to the real gross domestic product per person per year (G), a valid measure of average consumption in society, and then integrate $L(a)$ over the population age-distribution, $f(a)$, leads to

$$L = \int_0^T L(a)\, f(a)da = c^q \int_0^T e(a)\, f(a)da = G^q E \tag{7}$$

where E denotes the discounted life expectancy averaged over the age-distribution of the national population.

In essence, the aggregated function, L, is indicative of quality of life (wealth and health) enjoyed by the population, and is referred to as Life-Quality Index (LQI) in our analysis. By setting E equal to LE at birth ($= E_o$) and ignoring the discounting, L ($=G^q E_o$), was used to rank the level of national development [7] similar to Human Development Index proposed by the United Nations Development Program [14]. The following Sections address issues related to properties of utility function and significance of exponent q and discount rate r.

3.2.1 Utility Function for Consumption

We have selected a simple and generic power utility function, $u(c) = c^q$, that is commonly used in the economic literature [16-18]: The exponent q is referred to as the elasticity of utility with respect to consumption, which is taken as a constant regardless of the level of consumption. It means that the utility (enjoyment) of consumption is the same for rich and poor persons. Note that the "elasticity" of a function $u(c)$ is technically defined as $[(\partial u(c)/\partial c)/(u(c)/c)]$. The value of q should be bounded between 0 and 1 to satisfy the following desirable principles and values of decision making:

(1) $\dfrac{\partial u(c)}{\partial c} = qc^{q-1} > 0$ since $q > 0$

It means that the person prefers more consumption rather than less at any period in life.

(2) $\dfrac{\partial^2 u(c)}{\partial c^2} = q(q-1)c^{q-2} < 0$ when $q < 1$

This constraint implies that the marginal utility of consumption declines at higher levels of consumption. The utility function has the property of constant proportion risk aversion (=1-q) as defined by Pratt [19]. It means that the person is financially risk averse, and the degree of aversion depends on the proportion of asset likely to be lost in a gamble, regardless of the actual amount of asset under possession.

Given that the function $L(a)$, eqn.(6), is a product of two utility functions, the exponent q serves as a measure of tradeoff between the utility of longevity and utility of consumption [20]. When the value of q is small (close to zero), an increase in consumption has minor effect, implying that the life-quality is largely derived from the state of being alive. A value of q close to 1 implies that utility is nothing more than cumulative consumption over life time (i.e., human capital). The person would not be willing to pay to extend life when $q = 1$, because the advantage of increased life span is completely offset by decrease in the consumption rate. An intuitive implication of $q < 1$ is that quantity (longevity) and quality (money) of life are imperfect substitutes for each other (i.e., the person has a limited preference for substitution of consumption across years of life). In the context of welfare economics, the function G^q with $q < 1$ implies aversion to unequal distribution of wealth, because the expected utility decreases with increasing inequality in distribution of wealth [21].

3.2.2 Utility Function for Longevity

The utility function for longevity is a linear function of discounted life years, which implies a "risk neutral" preference [22]. It means that the person is indifferent to lotteries (uncertainty) about gaining (or loosing) discounted life years. Although it may appear ambiguous, it is a rational altitude given that discounting implicitly accounts for person's uncertainty about survival [23]. To understand this better, recall that if life expectancy of a person (age a) is t years then discounted LE is given as

$$e(a) = \frac{1}{r}(1 - e^{-rt}) \tag{8}$$

As shown by Pratt (1964), this function exhibits constant risk aversion with the discount rate, r, being the coefficient of aversion [19]. It means that persons, irrespective of their age being young or old, place identical preference to gaining or aversion to loosing a fixed number of life years. Because of the "risk neutral" property, the function $L(a)$ is analogous to quality-adjusted life year (QALY) used in health economics, where quality implies health related adjustments to life years [22]. In LQI model however, the adjustment to life year is based on utility of consumption.

3.2.3 Work versus Leisure Tradeoff

Now return to a central question: what is a reasonable value of the elasticity term q? We propose to use the work vs. leisure tradeoff for the estimation of q. We assume that people on average work just enough so that the marginal value of the wealth produced, or income earned, is equal to the marginal value of the time they lose when at work. This reasoning is based on a notion that disposition of time is the ultimate source of utility, since the quality of life after all depends on the way we spend our time [24].

Let w denote the fraction of time spent in producing income that supports the consumption. The leisure time available to a person is then a fraction of life expectancy. In other words, $c\,\boldsymbol{\mu}\,w\,e(a)$ and leisure time $e_L \propto (1\text{-}w)e(a)$, such that the life-quality function can be expressed in a proportional form

$$L(a) \propto (w \times e)^q\,[(1\text{-}w)e] \qquad (9)$$

Now we apply a first order condition for maximizing life-quality, $dL/dw = 0$, which along with eqn.(9) leads to

$$q = \frac{w}{(1 - w)} \qquad (10)$$

Nathwani et al. [7] proposed the value of w can be approximately taken as 1/8 on the basis of time budget studies available for OECD countries. From eqn.(10), $q = 1/7 \approx 0.15$ can be easily calculated, which compares well with other empirical estimates reported in the literature. For example, Shepard and Zeckhauser [25] used a value of 0.2, and Lutter et al. (1999) estimated income elasticity range of 0.12 to 0.22 by analyzing expenditures on both healthy and risky products and services [26]. Low values of q implied here and in other studies can be justified on the ground that in countries with well-developed economies and high standards of living, an increase in longevity is expected to outweigh consumption consideration. In contrast, utility of additional living in poor countries might be offset by large reductions in consumption due to lack of adequate income, pension and social support.

Since w is practically constant, especially for industrialized and developed countries, we drop the factor (1-w) from eqn.(9) and obtain the following expressions

$$L(a) = c^{w/(1-w)} e(a) \quad \text{or} \quad \text{LQI} = c^{w/(1-w)} E \tag{11}$$

3.2.4 Comments on Discounting

The purpose of discounting is to establish some relative weights on deferred outcomes as opposed to immediate impacts in the assessment of risk mitigation programs and regulations that involve inter-temporal tradeoffs. In eqn.(3), discounting the utility of future consumption is intended to reflect the fact that owing to uncertainty about future people have higher preferences for present consumption. The discount rate is referred to as the rate of time preference for consumption and it should be conceptually distinguished from the interest rate. The discounting of future consumption is equivalent to discounting of life expectancy when the rate of consumption is constant, as seen from eqn.(6). An effect of ignoring discounting, according to Viscusi (1996), is that societal decisions will place more emphasis on well being of future generations rather than improving welfare of those now alive [13]. Although discounting of life years has been debated extensively, there is growing consensus that it is necessary to achieve consistency in cost benefit analysis.

To illustrate the variation of effect discounting with age, Figure 2 displays life expectancy in Canada at various ages with and without discounting. The effect of discounting is pronounced in early ages. Originally the LE at birth is 77 years, whereas its discounted value reduces to 40 and 24 years for the rate of 2% and 4%, respectively. It is however interesting that the effect of discounting in advanced ages diminishes rapidly. In some sense, discounting evens out disparity between young and old lives, and thus addresses a common criticism of LE measure that it over values a young lives in decision analysis.

An important point is that discounting has practically no effect beyond age 70 owing to the fact that "future" is much closer than at young ages. Interestingly, the effect of increased force of mortality plays the role of discounting. To explain this effect, denote by $m(t)$ the mortality rate (hazard rate), i.e., probability of dying at age t, and write the survival probability in terms of $m(t)$ as $S(a,t) = \exp(-\int m(\tau)dt)$. From eqn.(6), discounted LE becomes

$$e(a) = \int_a^T S(a,t)e^{-r(t-a)}dt = \int_a^T \exp\left[-\int_a^t [r + m(t)]dt\right] \tag{12}$$

It is clear now the mortality rate works exactly like a discount rate and both are additive. In early ages, discount rate dominates since mortality rate $m(\tau)$ is small. In advanced ages, the situation is reversed. Higher force of mortality makes a person to act more "impatiently" and place less value on future prospects/utility of life. Viscusi [13] reported typical values of discount rate in the range of 1% to 4%.

3.3 Judging Risk with the Life Quality Index

Any project, program or regulation that materially affects the public by modifying risk through expenditure will have an impact on the Life-Quality Index. The net benefit criterion requires that a small change in the LQI due to a project or regulation should be positive or,

$$\frac{dL}{L} = q\frac{dG}{G} + \frac{dE}{E} \geq 0 \tag{13}$$

Here dG may represent the monetary cost of implementing a regulation (dG negative) or the monetary benefits that arise from a project (dG positive). The term dE is the change in life expectancy due to a change in the level of risk to the population associated with a project or, regulation.

The concept of societal willingness to pay (SWTP) originates from the definition of compensating variation by Hicks (1939). It is the sum received by or from the individuals which, following a welfare change, leaves them at their original level of welfare [27]. It can obtained from eqn.(13) by setting $dL/L = 0$ and rearranging the terms as

$$(-dG) = \frac{G}{q}\frac{dE}{E} \quad (\$/\text{person/year}) \tag{14}$$

Suppose benefits of a safety regulation are received by a population of size N, the aggregated value of SWTP, i.e., the amount that will not alter the population life-quality (C) is equivalent to

$$C = (-\,dG) \times N = \frac{NG}{q}\frac{dE}{E} \quad (\$/\text{year}) \tag{15}$$

The proposed measure of SWTP is consistent with general principle of welfare economics that the benefits of a public program are most appropriately measured by the aggregate willingness to pay on the part of those benefiting from the program. The rationale for using SWTP in public policy rests on the acceptance of the "potential Pareto improvement criterion" which asks if the gainers gain enough to compensate fully the losers.

Concepts of life-time utility, discounting, WTP, and age related variation of preferences for consumption and survival have been discussed in scattered forms in the literature. Our main contribution is to integrate consistently and comprehensively all these concepts into the life-quality index model that also satisfies basic principles of welfare economics and expected utility theory for decision making.

4 Applications of the LQI Model

4.1 Calculation of Societal Willingness-to-Pay

To illustrate the LQI method, we estimate the societal willingness-to-pay (SWTP) for implementing a safety standard that can permanently decrease the probability of death by 1 in one million in the population of one million people under the following three distinct scenarios:

(1) uniformly risk reduction across persons of all ages (0 – 100 years),
(2) risk reduction for persons above age 64 only, and
(3) risk reduction for persons under age 65.

The second case is addressing the fact that pollution related deaths are more dominant among older people (age over 64), whereas the third case is a complement of the second one. The Canadian life table is used to model population survival pattern and calculate changes in LE. The age distribution, $f(a)$, of stationary population of life table shown in Figure 3 is used to determine the population average of change in LE (i.e., dE/E). The RGDP in Canada in 1996 was approximately \$28,575 (= G) per person per year.

As an example, for a given risk reduction (1×10^{-6}) and a discount rate of 4%, an increase in LE was calculated as $dE/E = 7.48\times10^{-6}$. Using eqn.(14), dG was calculated as \$1.5 per person per year, and SWTP was calculated as \$1.5 million per year from eqn.(15). This value is analogous to VSL which is obtained as individual WTP divided by incremental reduction in risk, i.e., \$1.5/ 10^{-6} = \$1.5 million. Without discounting, the SWTP is estimated at \$4.4 million.

In case (2), SWTP without discounting for reducing the risk exposure for all individuals over age 64 turns out to be \$0.96 million per year. This is substantially lower when compared to that of \$3.46 million per year estimated for age under 64 in third case. SWTP values for all the three cases and discount rates ranging from 0%, to 8% are given in Table 5. If we consider the assumption used by the Canada Wide Standards Committee that 85% of the mortality risk from exposure to air pollution is to be applied to age over 64, the age-weighted average of SWTP is calculated as $0.85\times0.96+0.15\times3.46$ = \$1.33 million/year/death.

4.1.1 Remarks

It is important to note that the smaller SWTP for risk reduction in age group over 64 dose not mean that older people are valued less in policy analysis. Also, it is not a result of discounting of life years, which has minimal impact in advanced ages as shown in Figure 2. The lower valuation arises from the fact that competing (or background) risk of mortality in advanced ages is so large that a minute reduction in death risk has a little impact on prospect of life extension.

Eeckhoudt and Hammit (2001) have also reported that the willingness-to-pay (WTP) to reduce a specific risk declines in the presence of large and independent competing risks [28]. If the person is pessimistic about surviving the competing risk, there is little benefit to be gained from preventing a small increment to another risk, often referred to as "*why bother?*" effect. In summary, persons under high background risk tend to discount heavily the future prospect of longevity as shown by eqn.(12). The opposite effect is in play for age groups under 65 leading to a higher estimate of WTP. If we ignore the effect of competing risks, WTP will not be sensitive to age. The fact that a reduction in mortality risk at any particular age has the effect of improving life expectancy for all ages is precisely accounted in our analysis.. The damage function approach used by the Standards Committee is incapable of including this interaction effect.

The quality-adjusted life year (QALY) is a commonly used measure in cost-benefit analysis of programs and medical interventions that have impacts on health. The gains or loss of QALY is generally estimated from a life-table based analysis similar to that adopted in this paper. However, the monetary valuation of QALY (\$/life year) becomes problematic due to arbitrary nature of valuation and uncertain adjustments made to the calculated life-year values.

The proposed LQI model however is a generalization of QALY that integrates the monetary impact with change in life expectancy in a decision analysis framework. In this way, the LQI model attempts to overcome a weakness of QALY approach, and therefore motivates its use in cost-benefit analysis as outlined in the paper.

4.1.2 Empirical Validation

It is interesting to compare results of LQI model with other VSL estimates reported in the literature. The implied cost per life saved (no discounting) in LQI model is $4.4 million (Table 5) which is in the range of $4 - $5 million inferred from labor market studies [5]. LQI estimate of age adjusted VSL of $3.46 million without discounting is close to $4.1 million value used by CWSDC [3].

Using results of a WTP survey in Hamilton (Canada), Krupnick et al. (1999) estimated VSL as $1.2 – $3.8 million [12]. This range of VSL is seen in Table 5 for discount rates between 5% and 1%, respectively. For persons of age over 70, Krupnick et al. estimated VSL of $0.8 million. This value is strongly favored by the RSC Panel as this age group is expected beneficiary of pollution control programs. Our model also provides a comparable estimate of $0.7 million/life (1999$) without any discounting. The point here to make is that the implied VSL estimates from the proposed model are in line with those obtained by wage differential and contingent valuation surveys, thus providing an empirical validation of the LQI approach.

4.2 CBA of Pollution Control Options

The LQI model is applied to calculate monetary equivalent of benefit of improvement in life quality resulting from reduction in air pollution. Firstly, assume that mortality risk reduction due to improved air quality is uniform across all ages. The risk factors for Canada are calculated using data given in Table 3. Benefits for various air quality options, associated costs and resulting benefit-cost ratios (BCRs) are presented in Table 6 for three LE discount rates, 0%, 2% and 4%. As expected, the estimated benefits decline with increase in LE discount rate. The benefits associated with options to reduce particulate matter always outweigh the pollution control costs, as evident from BCRs ranging from 2 to 26. On the other hand, for all ozone options, these ratios are less than one, and so they do not satisfy the LQI criterion.

It should be emphasized that the purpose of calculating benefit-cost ratios is to provide a comparative measure of efficiency. The absolute values may have limited significance owing to large uncertainties associated with the estimates of costs as well as the health impacts of pollution, but the comparative measure provides some useful guidance.

For the proposed CWS of 60/30 PM, value of BCR is 11.7, and the BCR for 65 *ppb* ozone is 0.5 (no discounting case in Table 6). Despite large differences in BCRs for PM and ozone options, the combined BCR is 3.3 implying that overall CWS passes the LQI test. Considering that a reasonable value of discount rate is expected to be within 1% to 4% [13], we suggest 2% rate as a representative value for which overall BCR for the Standard turns out as 1.9.

Consider the case of age-adjusted mortality risk that follows the argument that 85% of total pollution related deaths are experienced over age 64 and remaining 15% are in under age 65. The changes in LE (dE/E) and associated benefits were calculated separately for these two age groups, and aggregated values are reported in Table 7. The BCR for 60/30 PM option declines to 3.5 from 11.7, and for ozone the decline in benefits is even sharper, declining to 0.1 from 0.5. The overall benefit for the combined Standard is just balances the total cost as indicated by unit BCR, in spite of ignoring the discounting of life years. Even for 2% discount rate benefits of all

PM options exceed the cost, BCR of the combined Standard declines to 0.6, and thus fails the LQI test.

A general observation is that options for ozone concentration are inefficient in comparison to PM options. Ignoring the age-related adjustment to mortality causes significant overestimation in the valuation of mortality benefits. The consideration of the effect of time preference rate (discounting of life years) is important, as benefit estimates are sensitive to rates as small as 1 - 2%.

5 Conclusions

In response to increasing evidence that particulate air pollution and ground level ozone have adverse impact on public health and environment, the Canada Wide Standards Committee has proposed air-quality standards for $PM_{2.5}$ at 30 $\mu g/m^3$, and for ozone at 65 *ppb*. The total pollution control costs were estimated to be in the order of \$2.5 billion per year, and its justification largely rests on the monetary valuation of reduction in mortality and morbidity.

The monetary valuation of expected reduction in mortality over a period of time is a critical and controversial element of cost benefit analysis. The Standards Committee used an average value of statistical life of \$4.1 million that results in \$8.1 billion per year as benefit of avoided mortality. A general conclusion of the Expert Review Panel appointed by the Royal Society of Canada is that benefits of reduced mortality are over-valued owing to the simplistic nature of analysis adopted by Standards Committee. The Royal Society Panel emphasized the need for a more sophisticated model that addresses the issue of statistical gain in life years and adjusts for demographic factors and health states, and provides confidence in the results of cost-benefit analysis.

The Life Quality Index model proposed in this paper is an improvement for judging the efficacy of regulatory standards for health, safety and the environment. The LQI leads to a necessary criterion that can determine the level of expenditure beyond which it is no longer justifiable to spend resources in the name of safety.

A comprehensive framework using life-quality as a basis for cost-benefit analysis is the primary contribution of the paper. The approach is comprehensive as it incorporates several difficult issues/concepts in public policy analysis, namely, discounting of life years, competing mortality risks, inter-temporal tradeoffs, and age-dependent risk and willingness to pay. The significant aspect is that integration of these issues is done in a consistent and transparent manner to support a credible analysis. In this respect, the proposed approach overcomes all the major shortcomings of the approach used by the Canada Wide Standards Development Committee in its method for valuation of mortality.

In the context of cost benefit analysis of improved air-quality options, the Life Quality Index-based analysis highlights several sources of bias in the estimation of benefits of mortality reductions. The proposed PM option (60/30) is shown to be efficient under a variety of assumptions about imposition of risk and discounting of life years, as evident by the benefit-cost ratios exceeding one. However, the options for controlling ozone are inefficient as shown by a benefit to cost ratio substantially below one.

6 References

[1] Pope, C.A., Thun, M.J., Namboodiri, M.M., Dockery, D.W., Evans, J.S.,, Speizer, F.E., and Heath, C.W. (1995). Particulate air pollution as a predictor of mortality in a prospective study of U.S. adults. American Journal of Respiratory and Critical Care Medicine, 151, 669-675.

[2] Canada-Wide Standards Development Committee for Particulate Matter (PM) and Ozone (1999). Discussion paper on PM and ozone. Canada Wide Standards Scenarios for Consultation. www.ccme.ca/pdfs/pm_ozone/pm_discussion.pdf

[3] Canada-Wide Standards Development Committee for Particulate Matter (PM) and Ozone (1999). Compendium of Benefits Information. 99-08-17.

[4] Canada-Wide Standards Development Committee for Particulate Matter (PM) and Ozone (1999). Compendium of Cost Information. 99-08-17.

[5] The Royal Society of Canada (2001). "Report of an Expert Panel to Review The Socio-Economic Models and Related Components Supporting the Development of Canada Wide Standards for Particulate Matter and Ozone".

[6] Nathwani, J.S. and Narveson, J. (1995). Three principles for managing risk in the public interest. Risk Analysis, 15(6), 615-626.

[7] Nathwani, J.S., Lind, N.C., Pandey, M.D. (1997). *Affordable Safety by Choice: The Life Quality Method*. Institute for Risk Research, University of Waterloo, Waterloo, Canada, pp 230.

[8] Tengs, T.O., Adams, M.E., Pliskin, J.S., Safran, D.G., Siegel, J.E., Weinstein, M.C. and Graham, J.D. (1995). Five hundred life-saving interventions and their cost-effectiveness. Risk Analysis, 15(3), 369-390.

[9] Schwing, R.C. (1979). Longevity benefits and costs of reducing various risks. Technological Forecasting and Social Change, 13, 333-345.

[10] Leksell, I. and Rabi, A. (2001). Air pollution and mortality: quantification and valuation of years of life lost. Risk Analysis, 21(5), 843-857.

[11] Nevalainen, J and Pekkanen, J. (1998). The effect of particulate air pollution on life expectancy. The Science of the Total Environment, 137-141.

[12] Krupnick, A.J., Alberini, A., Cropper, M., Simon, N., O'Brien, B., Goeree, R. and Heintzelman, M. (2000). Age, health and willingness to pay for mortality risk reduction. Discussion Paper, Resources For Future, DP00-37, Washington DC.

[13] Viscusi, W.K. (1996). Discounting health effects for medical decision. In *Valuing Health Care: Costs, benefits, and Effectiveness of Pharmaceuticals and other Medical Technologies*. F.A. Sloan (ed), pp. 125-147. Cambridge University Press, U.K.

[14] United Nations Development Program (1990). The Human Development Report. Oxford University Press, England.

[15] Gulis, G. (2000). Life expectancy as an indicator of environmental health. European Journal of Epidemiology, 16, 161-165.

[16] Yaari, M.E. (1965). Uncertain lifetime, life insurance, and the theory of the consumer. The Review of Economic Studies, 32(2), 137-150.

[17] Skinner, J. (1985). Variable life span and the interntemporal elasticity of consumption. The Review of Economics and Statistics, 67(4), 616-23.

[18] Usher, D. (1973). An imputation to the measure of economic growth for changes in life expectancy. Published in *National Accounting and Economic Theory: The Collected Papers of Dan Usher – Volume* 1, pp.105-144. Edward Elgar Publishing Ltd., U.K. 1994.
[19] Pratt, J. W. (1964). Risk aversion in the small and in the large. Econometrica, 32(1-2), 122-136.
[20] Arthur, W.B. (1980). The economics of risks to life. The American Economic Review. 71(1), 54-64.
[21] Dolan, P. (1998). The measurement of individual utility and social welfare. Journal of Health Economics, 17, 39-52.
[22] Pliskin, J. S., Shepard, D. S. and Weinstein, M. C. (1979). Utility functions for life years and health status. Operations Research, 206-224.
[23] Bleichrodt, H., Wakker, P. and Johannesson, M. (1997). Characterizing QALYs by risk neutrality. Journal of Risk and Uncertainty, 15, 107-114.
[24] Zeckhauser, R. (1973). Time as the ultimate source of utility. The Quarterly Journal of Economics, 87(4), 668-675.
[25] Shepard, D.S. and Zechhauser, R.J. (1984). Survival vs. consumption. Management Science, 30 (4), 423-439.
[26] Lutter, R., Morrall, J.F. and Viscusi, W.K. (1999). The cost-per-life-saved cutoff for safety-enhancing regulations. Economic Inquiry, 37 (4), 599-608.
[27] Hicks, J.R. (1939). The foundation of welfare economics. The Economic Journal, 49(196), 696-712.
[28] Eeckhoudt, L.R. and Hammitt, J.K. (2001). Background risks and the value of a statistical life. Journal of Risk and Uncertainty, 23(3), 261-279.

Table 1: *Central estimates of annual mortality reduction in* 1 *million exposed population* (C-R Function)

Pollutant	Number of avoided deaths (person/year)	Reduction in pollution
$PM_{2.5}$	21	1 $\mu g/m^3$ per year
PM_{10}	12	1 $\mu g/m^3$ per year
Ozone	2	1 *ppb* per year

Table 2: Estimates of value of statistical life used in AVQM

Population Age Group	**VSL Estimates (1996 C$ million)**		
	Low	**Central**	**High**
Age $\geq$ 65 years old	$2.3	$3.9	$7.8
Age < 65 years old	$3.1	$5.2	$10.4
Age-weighted average VSL = 0.85(age $\geq$ 65)+0.15(age<65)	$2.4	$4.1	$8.2

Table 3: Central Estimates of the number of avoided Mortality in Canada

Target Pollutant Level	Avoided Mortality		
	Annual Estimate (Year 2015)	30-year Period (2005-2035)	Exposed Population in 1996 (million)
$PM_{2.5}$ ($\mu g/m^3$)			14.9
(Background Level) 2.5	3,563	112,579	
20	2,043	64,564	
30	1,039	32,824	
40	326	10,288	
PM_{10} ($\mu g/m^3$)			17.8
(Background Level) 5	4,416	139,769	
25	3,387	102,257	
40	1,899	60,211	
60	600	19,097	
80	77	2,464	
Ozone (*ppb*)			18.1
60	239	7,546	
70	167	5,278	
80	98	3,094	

Table 4: Valuation of mortality and benefit-cost ratios obtained from CWSDC approach

Target Pollutant Level	Avoided Mortality	Benefit of avoided mortality[1]	Estimated Cost	Benefit to Cost Ratio
	(death/year)	(million \$/year)	(million \$/year)	
$PM_{10}/PM_{2.5}$ ($\mu g/m^3$)				
70/35	1,021	4,186	170	24.6
60/30	1,639	6,720	620	10.8
50/25	2,790	11,439	1,600	7.1
Ozone (*ppb*)				
70	167	685	790	0.9
65	203	832	1,871	0.4
60	239	980	6,502	0.2
CWS				
$PM_{10}/PM_{2.5}$ /Ozone				
60/30/65	1,842	7,552	2,491	3.0

Notes:
[1] Using central estimate of VSL = $ 4.1 million/person
[1]Base year 1996, and discount rate 5%

Table 5: LQI estimates of societal willingness to pay for averting 1×10^{-6} annual risk of death in one million population

Rate of Time Preference	Societal Willingness to Pay (million \$/year)		
(Discount Rate for Life Years)	Risk Applied to All Ages	Risk Applied to ages over 64	Risk Applied to ages under 65
0	4.4	0.96	3.46
1%	3.4	0.82	2.58
2%	2.6	0.70	1.89
3%	2.0	0.60	1.37
4%	1.5	0.51	0.98
5%	1.1	0.44	0.70
6%	0.9	0.39	0.51
7%	0.7	0.34	0.36
8%	0.6	0.30	0.27

Table 6: Cost-benefit analysis using LQI approach: Reduction in mortality is uniformly distributed to all ages

Target Pollutant Level	Avoided Mortality	Benefit of avoided mortality (million \$/year)			Estimated Cost (million \$/year)	Benefit to Cost Ratio		
	(death/year)	*rtp* = 0%	*rtp* = 2%	*rtp* = 4%		*rtp* = 0%	*rtp* = 2%	*rtp* = 4%
$PM_{10}/PM_{2.5}$ ($\mu g/m^3$)								
70/35	1,021	4,523	2,647	1,527	170	26.6	15.6	9.0
60/30	1,639	7,261	4,250	2,451	620	11.7	6.9	4.0
50/25	2,790	12,361	7,234	4,171	1,600	7.7	4.5	2.6
Ozone (*ppb*)								
70	167	740	433	250	790	0.9	0.5	0.3
65	203	899	526	304	1,871	0.5	0.3	0.2
60	239	1,059	620	357	6,502	0.2	0.1	0.1
CWS								
$PM_{10}/PM_{2.5}$ /Ozone								
60/30/65	1,842	8,161	4,776	2,754	2,491	3.3	1.9	1.1

Table 7: Cost-benefit analysis using LQI approach: Age specific reduction in mortality (85% reduction in pollution related death is limited to age over 64 and 15% reduction under age 65)

Target Pollutant Level	Avoided Mortality	Benefit of avoided mortality (million \$/year)		Estimated Cost (million \$/year)	Benefit to Cost Ratio	
	(death/year)	*rtp* = 0%	*rtp* = 2%		*rtp* = 0%	*rtp* = 2%
$PM_{10}/PM_{2.5}$ ($\mu g/m^3$)						
70/35	1,021	1,366	897	170	8.0	5.3
60/30	1,639	2,193	1,440	620	3.5	2.3
50/25	2,790	3,733	2,452	1,600	2.3	1.5
Ozone (*ppb*)						
70	167	223	147	790	0.3	0.2
65	203	272	178	1,871	0.1	0.1
60	239	320	210	6,502	0.0	0.0
CWS						
$PM_{10}/PM_{2.5}$ /Ozone						
60/30/65	1,842	2,465	1,619	2,491	1.0	0.6

Figures

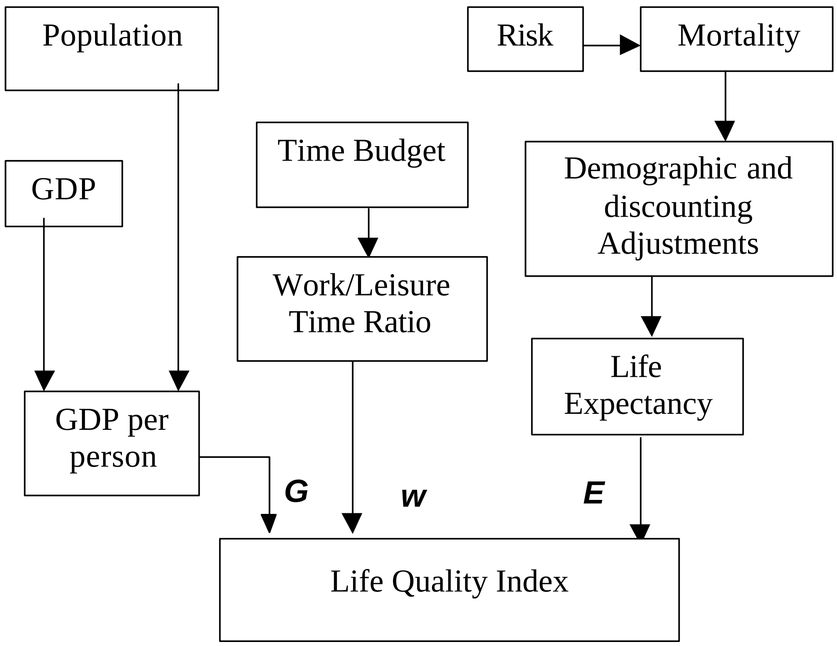

Figure 1: Conceptual Model of the Life-Quality Index

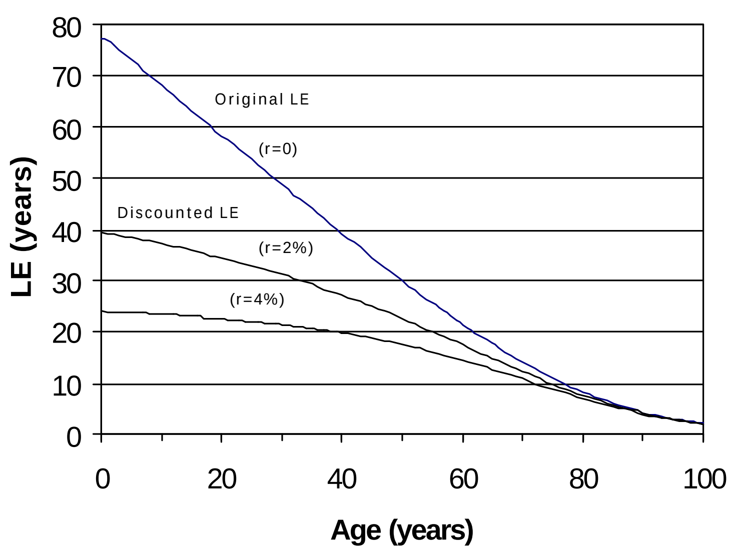

Figure 2: Variation of Life Expectancy in Canada with Age and Discounting

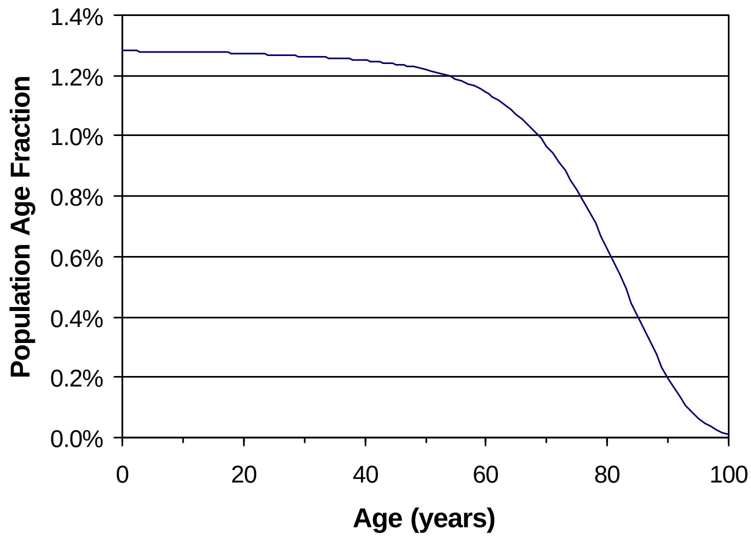

Figure 3: Age distribution in stationary (life table) population of Canada