The Influence of Particulate Matter on the Environmental Burden of Disease in Canada

by

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Abstract

In this thesis we investigate the environmental burden of disease in Canada. Particulate matter (PM_{2.5}) is the environmental risk factor of interest. We study its impact on mortalities from all causes, lung cancer and cardiopulmonary disease. We first start by reviewing some of the results from some of previous environmental burden of disease studies in Chapter 2. In Chapter 3 we introduce all the methodology needed for estimating the burden of disease (BoD) and environmental burden of disease (EBD). Chapter 4 is a simulation study to verify some of the methodology developed in Chapter 3. In Chapter 5 we estimate the EBD for the 1996 Canadian population in terms of years of life lost (YLL). We also estimate the population attributable fractions using PM_{2.5} concentrations data set. In Chapter 6 we investigate the correlation between years of life lost, death rates and potential years of life lost and discuss our findings.

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Chapter 1

Introduction

Quantification of a disease, or a number of diseases, and the risk factors that cause them is very crucial to health-related interventions and decision-making. The quantity obtained from quantifying a disease, or a number of diseases, is called burden of disease (BoD). The proportion of BoD that is caused by an environmental factor is known as the environmental burden of disease (EBD). Over the years, numerous studies to assess EBD have been conducted locally and globally by many different organizations. These studies have demonstrated that the impact of environment is very significant. Although estimates for both BoD and EBD for Canada were given by some studies such as the global burden of disease (GBD) investigations conducted

by the World Health Organization (WHO), these estimates were very approximate and were not obtained from detailed Canadian data. The purpose of this thesis is to estimate, for the 1996 Canadian population, the BoD for all causes of death, for lung cancer and for cardiopulmonary disease. In this research we also develop an expression for the variance of one of the health indicators used to quantify the BoD, estimate confidence intervals, and perform a simulation study for the verification of the methodology developed. We will also estimate for all causes, for lung cancer, and for cardiopulmonary disease, the percentages that are attributable to air pollution. More specifically, we will assess the impact of particulate matter (PM_{2.5}) on deaths from all causes, lung cancer and cardiopulmonary disease.

Chapter 2

Literature Review

Studies aimed at estimating the burden of disease began in 1992 when World Bank commissioned the initial global burden of disease (GBD) study for the 1990 world population (see Lopez et al. 2006). Since then, many investigations have been conducted and in this chapter we will review the results from some of those studies.

Lopez et al. (1996) conducted a GBD study for the World Bank regions for 1990-2001 (see Appendix C.2). This study reported the BoD in terms of disability adjusted life years (DALYs) that made use of a formula that incorporates time discounting Only. This formula will be discussed in Chapter 3. The authors reported the BoD estimates for the different World Bank regions

as opposed to counties separately. Canada was in the high-income countries region. The study estimated that 45% of the total deaths are attributed to leading risk factors. The population attributable fraction estimates for urban air pollution for all causes of death, lung cancer and cardiopulmonary disease were as shown in Table 2.1.

Table 2.1: Population attributable fraction estimates from Lopez et al. study

Cause	High-income countries	World
All causes	1%	1%
Lung cancer	3%	5%
Cardiopulmonary disease	2%	3%

The methods used to estimate relative risks were those developed by Pope et al. (2002). We will study the models that Pope et al. proposed in Chapter 3 and make use of them for our application study in Chapter 5.

The World Health organization (WHO) is one of the leading organizations on BoD and EBD studies. The WHO publishes BoD and EBD reports frequently (Prüss-Üstün et al. 2003; Ostro 2004; Prüss-Üstün and Corvalán 2006). These studies provide estimates for the global burden of disease for different regions as specified by WHO (see Appendix C.1 for WHO regions). The estimates are in terms of DALYs using a formula that incorporates both time discounting and age weights. For the calculation of relative risks in

the studies mentioned above, WHO uses Pope et al. approach. The WHO studies estimate that 23% of all deaths are attributable to environmental factors. They estimated that this number is higher for developing countries (25%) than in developed ones (17% only). The environmental attributable fraction estimates for lung cancer and cardiopulmonary disease for developed countries are shown in Table 2.2 (see Prüss-Üstün and Corvalán 2006).

Table 2.2: Environmental attributable fraction estimates from Prüss-Üstün and Corvalán study

Cause	Attributable environmental fraction (95%CI)
Lung cancer	
Men	30 (6,55)
Women	30 (6,55)
Cardiopulmonary disease	
Men	22 (15,29)
Women	6 (4,8)

The WHO estimates that outdoor air pollution is attributable for 5% of the deaths caused by lung cancer and 2% of the deaths caused by cardiopulmonary disease. Regarding all deaths, the WHO categorizes Canada, the United States of America and Cuba into a group referred to as AMR-A (see

Appendix C.1). For this group they estimated that 1% of the total deaths (1.4% for the world) are attributable to outdoor air pollution.

There have also been studies conducted for BoD or EBD at the local level. Boyd and Genuis (2008) performed a study to investigate the EBD in Canada. This study relied on the WHO estimates for the environmental attributable fractions and reported the BoD in terms of the number of deaths. The authors studied the impact of particulate matter on lung cancer by using an attributable fraction of 5-15%.

From the review of the literature, it became evident that there is a lack of EBD studies for Canada. We therefore focus our attention on such an investigation here, as such studies will help to improve the health of Canadians, and the economy in general.

Chapter 3

Statistical Methods for Calculating EBD

To evaluate the EBD, BoD is first calculated for a given disease, or for a number of diseases of interest. The EBD is then a percentage of the BoD attributable to a certain environmental risk factor. Quantifying the BoD always starts by life table analysis of the population of interest. From life tables, life expectancies are obtained and subsequently used to evaluate the BoD in the form of an appropriate health indicator. The population attributable fraction (PAF) is then determined. Generally speaking, the PAF represents the BoD percentage attributable to a risk factor.

In this chapter a detailed explanation of life tables, a health indicator, and the population attributable fraction will be given.

3.1 Life Tables

There are two different kinds of life tables; complete and abridged. In a complete life table, life expectancies are obtained for each age, whereas an abridged life table provides life expectancies for age intervals. For this study, because of data availability, the abridged life table will be used (see Chiang 1984).

3.1.1 The Construction of an Abridged Life Table

For a given year, an abridged life table typically consists of the following quantities for the i -th age interval, $i = 1, \dots, w$, and usually in the following order:

1. Age interval (x_i, x_{i+1}) . A commonly used convention is to have all intervals of width five years, except for the first one, <1 , second one, $1-<5$, and the last one, $85+$.

2. Interval(x_i, x_{i+1}) width. n_i .

$$n_i = x_{i+1} - x_i \quad (3.1)$$

3. Midyear population, P_i , in interval (x_i, x_{i+1}) .

4. Number of deaths, D_i , in the interval (x_i, x_{i+1}) .

5. Death Rate, M_i , in the interval (x_i, x_{i+1}) .

$$M_i = \frac{D_i}{P_i} \quad (3.2)$$

6. Fraction, a_i , of last age interval of life. It is defined as the expected fraction of the interval (x_i, x_{i+1}) lived by an individual who dies in that interval. The value of a_i is the same for all individuals falling in age interval i .

7. An estimate. $\hat{q}_i$, of the probability of death in the interval (x_i, x_{i+1}) .

$$\hat{q}_i = \frac{n_i M_i}{1 + (1 - a_i) n_i M_i} \quad (3.3)$$

8. An estimate, $\hat{p}_i$, of the probability of surviving in the interval (x_i, x_{i+1}) .

$$\hat{p}_i = 1 - \hat{q}_i \quad (3.4)$$

9. Number of people alive, l_i , at exact age x_i . An arbitrary value, l_0 , called the "radix" or "root" is required to determine l_i for each of the age intervals. This number effectively represents the size of a population that is going to

be subjected to the same mortality conditions as the real population under study. The radix is usually a convenient round number like 1000, 10000, 100000 etc. Note, however, that the choice of radix does not affect the results obtained in a life table. A proof is given at the end of this chapter.

10. Number of individuals dying, d_i , in the interval (x_i, x_{i+1}) .

$$d_i = l_i \hat{q}_i \quad (3.5)$$

Therefore,

$$l_{i+1} = l_i - d_i \quad (3.6)$$

Note that it is assumed that every individual dies in the last interval, so that

$$d_w = l_w \quad (3.7)$$

where w references the last age interval in the table.

11. Number of years lived, L_i in the interval (x_i, x_{i+1}) .

$$L_i = n_i(l_i - d_i) + a_i n_i d_i \quad (3.8)$$

Note that for the last interval,

$$L_w = \frac{l_w}{M_w} \quad (3.9)$$

12. Total number of years lived, T_i after age x_i .

$$T_i = L_i + L_{i+1} + \dots + L_w \quad (3.10)$$

13. Life expectancy, $\hat{e}_i$ at age x_i .

$$\hat{e}_i = \frac{T_i}{l_i} \quad (3.11)$$

Table 3.1 is an example of an abridged life table for the 1991 Canadian male population.

3.1.2 Variance of the Estimate of Life Expectancy, $\hat{e}_i$

Chiang (1984) proposes an expression for the variance in $\hat{e}_i$. We elaborate on the development of this expression in further detail here.

From equation (3.4) we know that

$$\hat{p}_i = 1 - \hat{q}_i$$

Therefore

$$Var(\hat{p}_i) = Var(\hat{q}_i) \quad (3.12)$$

Table 3.1: Abridged life table for 1991 Canadian male population

(x_i, x_{i+1})	n_i	P_i	D_i	M_i	a_i	$\hat{q}_i$	$\hat{p}_i$	l_i	d_i	L_i	T_i	$\hat{e}_i$
<1	1	201595	1432	0.0071033508	0.1	0.007058227	0.9929418	100000	706	99364	7433183	74.331830
1-<5	4	774170	298	0.0003849284	0.4	0.001538292	0.9984617	99294	153	396808	7333819	73.859639
5-<10	5	978220	197	0.0002013862	0.5	0.001006424	0.9989936	99141	100	495455	6937011	69.971162
10-<15	5	962930	253	0.0002627398	0.5	0.001312836	0.9986872	99041	131	494877	6441556	65.039287
15-<20	5	958404	913	0.0009526254	0.5	0.004751810	0.9952482	98910	471	493372	5946679	60.122121
20-<25	5	985220	1256	0.0012748422	0.5	0.006353960	0.9936460	98439	626	490630	5453307	55.397830
25-<30	5	1182575	1502	0.0012701097	0.5	0.006330448	0.9936696	97813	620	487515	4962677	50.736375
30-<35	5	1237690	1684	0.0013605992	0.5	0.006779934	0.9932201	97193	659	484317	4475162	46.044077
35-<40	5	1133670	1849	0.0016309861	0.5	0.008121814	0.9918782	96534	785	480707	3990845	41.341341
40-<45	5	1042185	2248	0.0021570067	0.5	0.010727187	0.9892728	95749	1028	476175	3510138	36.659788
45-<50	5	824205	2904	0.0035233953	0.5	0.017463152	0.9825368	94721	1655	469467	3033963	32.030521
50-<55	5	663285	3712	0.0055963877	0.5	0.027595846	0.9724042	93066	2569	458907	2564496	27.555670
55-<60	5	608085	5765	0.0094805825	0.5	0.046305407	0.9536946	90497	4191	442007	2105589	23.266948
60-<65	5	571940	9073	0.0158635521	0.5	0.076292101	0.9237079	86306	6585	415067	1663582	19.275392
65-<70	5	492500	12553	0.0254883249	0.5	0.119807400	0.8801926	79721	9552	374725	1248515	15.661055
70-<75	5	358955	14144	0.0394032678	0.5	0.179348998	0.8206510	70169	12585	319382	873790	12.452650
75-<80	5	252530	16081	0.0636795628	0.5	0.274670561	0.7253294	57584	15817	248377	554408	9.627813
80-<85	5	140135	14004	0.0999322082	0.5	0.399783037	0.6002170	41767	16698	167090	306031	7.327100
85+	5	86300	15571	0.1804287370	0.5	1.000000000	0.0000000	25069	25069	138941	138941	5.542343

We also know from equation 3.2

$$M_i = \frac{D_i}{P_i}$$

This, treating P_i as constant, variance of M_i is

$$Var(M_i) = \frac{1}{P_i^2} Var(D_i) \quad (3.13)$$

Since D_i is a binomial random variable with N_i trials, and probability of success q_i

$$Var(D_i) = N_i q_i (1 - q_i) \quad (3.14)$$

Here N_i is the population at the beginning of interval (x_i, x_{i+1}) . which is unknown and needs to be estimated. Since

$$q_i = \frac{D_i}{N_i} \quad (3.15)$$

Treating N_i as an unknown constant, we can estimate $N_i q_i$ by D_i and get

$$Var(D_i) = D_i (1 - q_i) \quad (3.16)$$

Substituting equation 3.16 into equation 3.13 we get

$$Var(M_i) = \frac{1}{P_i^2} D_i (1 - q_i) = \frac{M_i}{P_i} (1 - q_i) \quad (3.17)$$

Since $q_i = \frac{D_i}{N_i}$

$$Var(q_i) = \frac{1}{N_i^2} Var(D_i) = \frac{D_i}{N_i^2} (1 - q_i) = \frac{q_i^2 (1 - q_i)}{D_i} \quad (3.18)$$

Therefore

$$Var(\hat{q}_i) = \frac{\hat{q}_i^2 (1 - \hat{q}_i)}{D_i} \quad (3.19)$$

Now

$$\hat{e}_i = \frac{T_i}{l_i} = \frac{L_i + L_{i+1} + \dots + L_u}{l_i} = \frac{1}{l_i} \sum_{j=i}^w L_j \quad (3.20)$$

since

$$\begin{aligned}
 L_j &= n_j l_{j+1} + a_j n_j (l_j - l_{j+1}) \\
 &= a_j n_j l_j + (1 - a_j) n_j l_{j+1}
 \end{aligned} \tag{3.21}$$

Substituting equation 3.20 into equation 3.19 gives,

$$\begin{aligned}
 \hat{e}_i &= \frac{1}{l_i} \sum_{j=i}^w [a_j n_j l_j + (1 - a_j) n_j l_{j+1}] \\
 &= a_i n_i + (1 - a_i) n_i \frac{l_{i+1}}{l_i} + \frac{1}{l_i} \sum_{j=i+1}^w [a_j n_j l_j + (1 - a_j) n_j l_{j+1}] \\
 &= a_i n_i + \frac{1}{l_i} \sum_{j=i+1}^w (a_j n_j l_j) + \frac{1}{l_i} \sum_{j=i}^w (1 - a_j) n_j l_{j+1}
 \end{aligned}$$

Let $i = j - 1$, then $j = i + 1$ and

$$\hat{e}_i = a_i n_i + \sum_{j=i+1}^w [a_j n_j + (1 - a_{j-1}) n_{j-1}] \frac{l_j}{l_i} \tag{3.22}$$

Now

$$\frac{l_j}{l_i} = \frac{l_i \hat{p}_i \hat{p}_{i+1} \dots \hat{p}_{j-1}}{l_i} = \hat{p}_i \hat{p}_{i+1} \dots \hat{p}_{j-1} = \hat{p}_{i,j} \tag{3.23}$$

where $\hat{p}_{ij}$ is defined as the probability of survival from age x_i to age x_j .

Substituting equation 3.23 into equation 3.21 gives

$$\hat{e}_i = a_i n_i + \sum_{j=i+1}^w C_j \hat{p}_{ij} \quad (3.24)$$

where

$$C_j = (1 - a_{j-1})n_{j-1} + a_j n_j \quad (3.25)$$

The only source of variation in the life expectancy, $\hat{e}_i$, is due to variation in $\hat{p}_{ij}$. The delta method can therefore be used to derive the variance for $\hat{e}_i$. First we take the derivative of $\hat{p}_{ij}$ with respect to $\hat{p}_k$. If $k < j$ then $\hat{p}_{ik}$ and $\hat{p}_{kj}$ have $\hat{p}_i \hat{p}_{i+1} \dots \hat{p}_{k-1}$ in common and therefore, are dependent.

$$\frac{\partial}{\partial \hat{p}_k} \hat{p}_{ij} = \begin{cases} \hat{p}_{ik} \hat{p}_{k+1,j} & \text{for } i \leq k < j \\ 0 & \text{otherwise} \end{cases}$$

$$\begin{aligned}
 \frac{\partial}{\partial \hat{p}_k} \hat{e}_i &= \sum_{j=i+1}^w C_j \frac{\partial}{\partial \hat{p}_k} \hat{p}_{ij} \\
 &= \sum_{j=k+1}^w C_j \hat{p}_{ik} \hat{p}_{k+1,j} \\
 &= \hat{p}_{ik} [C_{k+1} + \sum_{j=k+2}^w C_j \hat{p}_{k+1,j}] \\
 &= \hat{p}_{ik} [(1 - a_k)n_k + a_{k+1}n_{k+1} + \sum_{j=k+2}^w C_j \hat{p}_{k+1,j}] \\
 &= \hat{p}_{ik} [(1 - a_k)n_k + \hat{e}_{k+1}]
 \end{aligned} \tag{3.26}$$

Since all age groups are distinct and do not overlap, the probabilities of surviving, p_i , are not correlated assuming that $p_i \neq 0$ for $i < w$. Therefore

$$Var(\hat{e}_i) = \sum_{k=i}^{w-1} \left(\frac{\partial}{\partial \hat{p}_k} \hat{e}_i \right)^2 Var(\hat{p}_k) \tag{3.27}$$

Substituting equation 3.25 and equation 3.18 into equation 3.26, gives the formula for the variance of $\hat{e}_i$:

$$Var(\hat{e}_i) = \sum_{k=1}^{w-1} \hat{p}_{ik}^2 [(1 - a_k)n_k + \hat{e}_{k+1}]^2 \frac{\hat{q}_k^2 (1 - \hat{q}_k)}{D_k} \tag{3.28}$$

Table 3.2 contains the variance estimates for the 1991 Canadian male

population. As expected, the variance is very small due to the fact that the variance of probability of death is very small.

Table 3.2: The variance estimates for $\hat{e}_i$ for the 1991 Canadian male population

Age interval	$\text{Var}(\hat{p}_i)$	$l_i^2[(1 - a_i)n_i + \hat{e}_{i+1}]^2 \text{Var}(\hat{p}_i)$	$\sum_{k \geq i} l_k^2[(1 - a_k)n_k + \hat{e}_{k+1}]^2 \text{Var}(\hat{p}_k)$	$\text{Var}(\hat{e}_i)$
<1	3.454395×10^{-8}	1930662.9	16126714.0	1.6126714×10^{-3}
1-<5	7.928535×10^{-9}	409420.9	14196051.1	1.4398642×10^{-3}
5-<10	5.136398×10^{-9}	230291.6	13786630.2	1.4026572×10^{-3}
10-<15	6.803466×10^{-9}	261707.3	13556338.5	1.3820138×10^{-3}
15-<20	2.461381×10^{-8}	807204.9	13294631.3	1.3589263×10^{-3}
20-<25	3.193971×10^{-8}	877167.2	12487426.4	1.2886606×10^{-3}
25-<30	2.651190×10^{-8}	597732.1	11610259.2	1.2135251×10^{-3}
30-<35	2.711155×10^{-8}	492257.1	11012527.1	1.1657811×10^{-3}
35-<40	3.538568×10^{-8}	505671.8	10520270.1	1.1289281×10^{-3}
40-<45	5.063974×10^{-8}	553561.9	10014598.2	1.0923581×10^{-3}
45-<50	1.031805×10^{-7}	836263.0	9461036.3	1.0544990×10^{-3}
50-<55	1.994924×10^{-7}	1147187.3	8624773.3	9.957850×10^{-4}
55-<60	3.547100×10^{-7}	1377443.4	7477586.0	9.130468×10^{-4}
60-<65	5.925744×10^{-7}	1455817.9	6100142.6	8.189512×10^{-4}
65-<70	1.006462×10^{-6}	1430142.4	4644324.7	7.307639×10^{-4}
70-<75	1.866312×10^{-6}	1351573.7	3214182.4	6.527997×10^{-4}
75-<80	3.402879×10^{-6}	1089684.9	1862608.6	5.617175×10^{-4}
80-<85	6.850226×10^{-6}	772923.7	772923.7	4.430677×10^{-4}
85+	0.0	0.0	0.0	0.0

3.2 Health Indicators

Health indicators are summary measures of population health. They can be as simple as number of deaths due to a specific disease, D_i , or as complex

as the number of years of life lost due to premature mortality, YLL, over the entire population. Although many health indicators have been developed, YLL will be the main focus in this study. In chapter 6, a comparison study will compare YLL with death rates, M_t , and potential years of life lost, PYLL.

3.2.1 Years of Life Lost, YLL

The years of life lost measure, YLL, is usually combined with a second measure reflecting the number of years lived with a disability, YLD, to create an indicator that combines both mortality and morbidity. This indicator is called the disability adjusted life years or DALY and is written as

$$DALY = YLL + YLD \quad (3.29)$$

The DALY measures health gaps as opposed to health expectancies. It considers the differences between a current situation and an ideal situation where everyone lives up to their life expectancy (see Prüss-Üstün et al. 2003).

The YLL is the part of the DALY that accounts for mortality. It can be broken down by age group. Specifically, the years of life lost for a particular age group, YLL_t , is essentially the number of deaths multiplied by life

expectancy for that group

$$YLL_i = D_i e_i \quad (3.30)$$

where YLL_i is the number of years of life lost for age group i , D_i is number of deaths for age group i , and e_i is the life expectancy estimate for group i

Equation 3.30 is the simplest for calculating YLL_i and does not incorporate any time or age discounting. However, some studies showed the need to include a time discount rate to account for the preference of a healthy life year now as opposed to in the future (see Lopez et. al 2006; Prüss-Üstün et al. 2003). These studies showed that the value of a year of life is decreased by a fixed percentage, r . For example, the following equation was used by Prüss-Üstün et al. (2003) to include the discount rate, r

$$YLL_i = \frac{D_i}{r} (1 - e^{-re_i}) \quad (3.31)$$

where the discount rate, r , is usually taken to be 3%

Notice that the previous equation simplifies to equation 3.30 when r approaches zero.

$$\lim_{r \rightarrow 0} \frac{D_i}{r} (1 - e^{-re_i}) = D_i e_i$$

The expression for YLL was further developed by including age weighting (see Murray and Acharya 1997). Age weighting is included so that healthy life lived at young ages and old ages are given lower weights. This choice was based on a number of studies that indicated a social preference to value a year lived by a younger adult more than a year lived by a young child or an older adult. Not all studies agree and age weights are the most controversial value choice built into the YLL_i (see Lopez et al. 2006).

Lopez et al. (2006) used the following function to model the relative age weight

$$X_{adj} = Cx e^{-\beta x} \tag{3.32}$$

where X_{adj} is the weighted age, C is the adjustment constant for age-weights ($C=0.1658$), β =age weighting constant (e.g. $\beta=0.04$), and x =age (years)

Figure 3.1 shows a general pattern of the valuation of health according to age.

With the age weights and time discounting, the general formula for calculating YLL_{ij} for individual j within age group i is (Murray and Acharya,

Figure 3.1: Reported preferences and modeling for relative value of a year of life lived.

1997)

$$YLL_{ij} = \int_{a_i}^{e_i+a_i} Cx e^{-\beta x} e^{-r(x-a_i)} dx \quad (3.33)$$

Equation 3.33 can be solved using integration by parts. First rearrange the equation into the following form,

$$YLL_{ij} = C e^{ra_i} \int_{a_i}^{e_i+a_i} x e^{-x(r+\beta)} dx$$

Letting $u = x$ and $dv = e^{-x(\beta+r)}$ then $du = dx$ and $v = \frac{-1}{(r+\beta)} e^{-x(\beta+r)}$ so that

$$\begin{aligned} YLL_{ij} &= C e^{ra_i} \left[\frac{-x}{(r+\beta)} e^{-(r+\beta)x} \right]_{a_i}^{e_i+a_i} + \frac{1}{(r+\beta)} \int_{a_i}^{e_i+a_i} e^{-(r+\beta)x} dx \\ &= C e^{ra_i} \left[\frac{-(e_i+a_i)}{(r+\beta)} e^{-(r+\beta)(e_i+a_i)} + \frac{a_i}{(r+\beta)} e^{-(r+\beta)a_i} + \frac{-1}{(r+\beta)^2} e^{-(r+\beta)x} \right]_{a_i}^{e_i+a_i} \\ &= \frac{C e^{ra_i}}{\alpha^2} \left\{ e^{-\alpha \gamma_i} [-\alpha \gamma_i - 1] - e^{-\alpha a_i} [-\alpha a_i - 1] \right\} \end{aligned} \quad (3.34)$$

where a_i is the age of death (years) in the age interval (x_i, x_{i+1}) , $\alpha = (r + \beta)$, $\gamma_i = (e_i + a_i)$, $i = 1, \dots, w$, and $j = 1, \dots, D_i$

Since the exact age of death is not known and is taken as the midpoint of the interval, YLL_{ij} will be the same for all $j = 1, \dots, D_i$ in the i -th age interval (i.e., $YLL_{i1} = YLL_{i2} = \dots = YLL_{iD_i}$). Thus, we drop the j subscript.

To calculate YLL_i for age interval (x_i, x_{i+1}) , equation 3.33 should be multiplied by the number of deaths for that interval, D_i .

$$YLL_i = D_i YLL_{ij} \quad (3.35)$$

The years of life lost for the whole population, YLL can be then calculated by summing over all age intervals.

$$YLL = \sum_{i=1}^w \sum_{j=1}^{D_i} YLL_{ij} = \sum_{i=1}^w D_i YLL_{ij} = \sum_{i=1}^w YLL_i \quad (3.36)$$

3.3 Sensitivity Analysis for YLL

In this section the YLL formula will be studied further by investigating the effect of age weighting and discounting. Also, an approximate closed form for the variance of YLL will be derived.

3.3.1 Age Weighting and Discounting

Equation 3.32 is the weighting function that was used to assign different weights for different ages. We can determine the age that yields the maximum weight by taking the first derivative and finding the critical point.

$$\frac{\partial}{\partial x} X_w = Ce^{-\beta x} - C\beta x e^{-\beta x} = 0$$

Therefore, X_w is maximized when $x = \frac{1}{\beta}$.

To make sure that the area under the curve from age 0 to 100 stays the same, the constant C should vary depending on the value of β . Table 3.3 and Figure 3.2 show the impact of different choices of β on the age-weighting function.

Table 3.3: The impact of different β values on the age-weighting function

β	C	Maximum age weight	Age of maximum age weight	Age range for which age weight is >1
0.02	0.0634	1.17	50.0	27.2-83.1
0.03	0.1051	1.29	33.3	14.9-63.0
0.04	0.1658	1.52	25.0	8.4-54.2
0.05	0.2487	1.83	20.0	5.2-50.7
0.06	0.3560	2.18	16.7	3.5-46.9

Most studies choose β to be 0.04 (See Prüss-Üstün et al. 2003). For this value, the maximum weight of 1.52 is given to a person who is 25 years old.

Figure 3.2: Age-weighting function.

The age range that is given weights higher than 1 is (8.4,54.2). It appears that a value of 0.03 could be a better choice than 0.04 for the following reasons:

1. The age that is given the highest weight is 33.3. This age is an age of a person who is most likely in the work force longer than a person who is 25. This means, economically, more valuable.
2. The age range for which age weights are higher than 1 is (14.9,63). This age range is better than the one for $\beta = 0.04$ since a person can start work at the age of 16 and retire around 62.

However, the value of 0.04 is the choice for most studies because it corresponds to the curve that best described the results obtained in previous investigations, Figure 3.1.

Figure 3.3 shows the difference in YLL for the 1991 Canadian male population using all different formulae. Here YLL is denoted $YLL(r, \beta)$ so that all four formulae are used. For example, $YLL(3,4)$ means years of life lost when using both time discounting and age-weighting.

Figure 3.3: Effect of r and β on YLL.

We notice from Figure 3.3 that $YLL(0,0)$ and $YLL(0,4)$ are close in behavior except for the fact that the presence of β changes the weights depending on age. the quantity $YLL(3,0)$ which uses only time discounting reduces the value of YLL but it does not change the weights. This causes the curve to change very slightly between age 0 and 60. $YLL(3,4)$, on the other hand, does change the weight by putting more weights between ages 0 and just before 40 and less weights after that.

Figure 3.4: Effect of r and β on the difference between male-female YLL.

Table 3.4: Effect of r and β on the difference between male-female YLL.

Age	YLL(0 0) males	YLL(0 0) females	YLL(3 0) males	YLL(3 0) females	YLL(3 4) males	YLL(3 4) females
0 5	74 331830	80 851220	29 748891	30 385645	33 189850	33 553988
3 0	73 859639	80 332116	29 697753	30 339381	35 224448	35 571803
7 5	69 971162	76 419334	29 247919	29 966482	37 025624	37 408253
12 5	65 039287	71 481177	28 596450	29 428861	37 090493	37 532948
17 5	60 122121	66 538938	27 843520	28 804838	35 779036	36 289004
22 5	55 397830	61 660616	27 007619	28 091143	33 587089	34 158637
27 5	50 736375	56 770243	26 058167	27 262775	30 852925	31 484251
32 5	46 044077	51 896926	24 958463	26 307105	27 813857	28 516291
37 5	41 341341	47 031650	23 689510	25 202947	24 644037	25 427461
42 5	36 659788	42 214128	22 235340	23 938743	21 464671	22 340195
47 5	32 030521	37 469400	20 581918	22 501645	18 357779	19 335826
52 5	27 555670	32 826532	18 749877	20 882819	15 394848	16 468069
57 5	23 266948	28 321258	16 747491	19 081007	12 618600	13 772886
62 5	19 275392	24 018456	14 637585	17 117239	10 083773	11 281015
67 5	15 661055	19 932862	12 496417	15 002729	7 836071	9 007111
72 5	12 452650	16 138485	10 391124	12 792735	5 901137	6 976061
77 5	9 627813	12 655752	8 362125	10 530488	4 278329	5 198548
82 5	7 327100	9 649079	6 577704	8 378050	3 009329	3 723070
92 5	5 542343	7 185281	5 106090	6 463628	1 790644	2 217282

Figure 3.4 is a comparison between the YLL(0,0) and YLL(3,4) for 1991 the male and female Canadian populations. We notice that besides the effects mentioned before, incorporating time discounting and age-weights reduces the difference between YLL for males and females.

Table 3.4 contains the YLL estimates for both male and female populations. The first two columns are estimates when using neither time discounting nor age-weights which are equivalent to life expectancy estimates.

3.3.2 Variance of YLL_i

From equation 3.35 we know that $YLL_i = D_i YLL_{ij}$. Where D_i and YLL_{ij} are two dependent random variables. Bohrnstedt and Glodberger (1969) derived the variance of the multiplication of two dependent random variables as follows

$$\begin{aligned} Var(YLL_i) &= Var(D_i YLL_{ij}) \\ &= E[D_i YLL_{ij} - E(D_i YLL_{ij})]^2 \end{aligned}$$

For simplicity, let $D_i = x$, $YLL_{ij} = y$, $\Delta x = x - E(x)$, and $\Delta y = y - E(y)$, then

$$\begin{aligned} xy &= [\Delta x + E(x)][\Delta y + E(y)] \\ &= (\Delta x)(\Delta y) + (\Delta x)E(y) + (\Delta y)E(x) + E(x)E(y) \end{aligned}$$

$$E(xy) = E[(\Delta x)(\Delta y)] + E(x)E(y)$$

and

$$xy - E(xy) = (\Delta x)(\Delta y) + (\Delta x)E(y) + (\Delta y)E(x) - E[(\Delta x)(\Delta y)]$$

Square both sides and take expectations to get the variance

$$\begin{aligned}
 Var(xy) &= E^2(x)Var(y) + E^2(y)Var(x) + E[(\Delta x)^2(\Delta y)^2] \\
 &\quad + 2E(x)E[(\Delta x)(\Delta y)^2] + 2E(y)E[(\Delta x)^2(\Delta y)] \\
 &\quad + 2E(x)E(y)E[(\Delta x)(\Delta y)] - E^2[(\Delta x)(\Delta y)] \quad (3.37)
 \end{aligned}$$

This is a rather complicated equation and an approximate one would be more practical. Since the variance of the number of deaths, D_i , is much larger than the variance of the life expectancy, $\hat{e}_i$, we can consider the number of deaths, D_i , as the only source of variation. Under this assumption, the variance of YLL_i becomes,

$$Var(YLL_i) = D_i(1 - q_i)YLL_{ij}^2 \quad (3.38)$$

In chapter 4 we will test equation 3.38 by performing a simulation study.

3.4 Population Attributable Fraction (PAF)

The population attributable fraction is defined as "the proportion of disease cases over a specified time that would be prevented following elimination of the exposure of interest, assuming the exposure is causal"(see Rockhill et al. 1998). There are different formulae available for calculating PAF (see

Rockhill et al. 1998). For this study, however, two formulae are relevant; single category exposure for level of exposure and multi-level of exposure formulae. The following formula is for calculating PAF when there is one level of exposure and one relative risk in the population of interest.

$$PAF = \frac{p_e(RR - 1)}{RR} \quad (3.39)$$

where p_e is the proportion of population exposed to the risk factor of interest and RR is the relative risk

In the case of multiple levels of exposure exposure and different relative risks, PAF can be calculated as follows.

$$PAF = \sum_{i=1}^n p_{e_i} \frac{RR_i - 1}{RR_i} \quad (3.40)$$

where p_{e_i} is the proportion of population exposed to the risk factor of interest in the i -th exposure category and RR_i is the relative risk from exposure in the i -th category.

Estimating PAF requires estimating the relative risk for the risk factor under study. In this study we will adopt the World health Organization (WHO) approach for calculating relative risks. The following table contains the different WHO recommended expressions used to estimate the relative risks for

the diseases that will be studied (Prüss-Üstün et al. 2004; Pope et al. 2002).

Table 3.5: WHO recommended models for estimating relative risks

Outcome	Relative risk function	Suggested Γ coefficient (95% CI)	Subgroup
All-cause mortality	$RR = e^{\Gamma(X-X_0)}$	0.004 (0.001-0.0077)	All ages
Cardiopulmonary mortality	$RR = \left\{ \frac{(X+1)}{(X_0+1)} \right\}^\Gamma$	0.15515 (0.0562, 0.2541)	Age > 30 years
Lung cancer mortality	$RR = \left\{ \frac{(X+1)}{(X_0+1)} \right\}^\Gamma$	0.23218 (0.08563, 0.37873)	Age > 30 years

where X is the current annual mean concentration of the risk factor of interest, X_0 is target or threshold concentration of the risk factor of interest, and Γ is the model coefficient.

3.5 Sensitivity Analysis for Relative Risk Models

In this section we investigate further why the WHO recommended the functions given in Table 3.5 for estimating relative risks. In addition to these functions, Table 3.6 provides others that have been considered (Cohen et al. 2003).

Table 3.6: Estimates of relative risk mortality, coefficients of concentration-response functions and study types

Health outcome	Relative risk function	Relative risk per $10\mu\text{g}/m^3$	Γ (Concentration- response slope) per $\mu\text{g}/m^3$ (standard error)
Cardiopulmonary(Log-linear)	$RR = [\frac{(X+1)}{(X_0+1)}]^\Gamma$	1.093441	0.11605(0.044790)
Cardiopulmonary(Log-linear average)	$RR = [\frac{(Y+1)}{(X_0+1)}]^\Gamma$	1.128240	0.155148(0.050460)
Cardiopulmonary(Linear)	$RR = e[\Gamma(X - X_0)]$	1.059185	0.00575(0.002160)
Cardiopulmonary(Linear average)	$RR = e[\Gamma(X - X_0)]$	1.093441	0.008933(0.002907)
Lung cancer(Log-linear)	$RR = [\frac{(X+1)}{(X_0+1)}]^4$	1.142360	0.17114(0.071968)
Lung cancer(Log-linear average)	$RR = [\frac{(X+1)}{(X_0+1)}]^\Gamma$	1.197896	0.232179(0.074770)
Lung cancer(Linear)	$RR = e[\Gamma(X - X_0)]$	1.082096	0.00789(0.003417)
Lung cancer(Linear average)	$RR = e[\Gamma(X - X_0)]$	1.135110	0.012673(0.00426)

The difference between linear average and linear, and between log-linear average and log-linear is the value of X used. For the former function in each pair, the average of the yearly averages is used as X , while for the latter function in each pair, it is the annual average that is employed. The graph in Figure 3.5 shows the four relative risk functions for cardiopulmonary calculated for different values of X .

It is easy to notice that the log-linear function is more stable for higher values of concentration. More specifically, it barely changes for a concentrations above $50\mu\text{g}/m^3$. This is desirable since concentrations above $50\mu\text{g}/m^3$ do not add to the overall impact of exposure to PM2.5. For this reason, the WHO recommends log-linear relative risks functions, and not linear ones.

Figure 3.5: Comparison between different relative risk functions

In Chapter 5, an application study will make use of all the methodology covered in this chapter and more explanations will be given on how to use the different formulae.

3.6 Proof of the Effect of the Choice of the Radix on Life Expectancy Calculations

Proof. In this proof we show that the choice of the value of the radix has no impact on life expectancy calculations.

$$\hat{e}_i = \frac{1}{l_i} [L_i + L_{i+1} + \dots + L_w]$$

$$L_i = n_i l_{i+1} + a_i n_i (l_i + l_i + 1)$$

$$d_i = l_i \hat{q}_i$$

$$l_{i+1} = l_i - d_i$$

$$\therefore l_{i+1} = l_i - l_i \hat{q}_i = l_i (1 - \hat{q}_i = l_i \hat{p}_i$$

$$L_i = n_i l_i \hat{p}_i + a_i n_i (l_i - l_i + l_i \hat{q}_i)$$

$$L_i = l_i (n_i \hat{p}_i + a_i n_i \hat{q}_i)$$

$$L_{i+1} = l_{i+1} (n_{i+1} \hat{p}_{i+1} + a_{i+1} n_{i+1} \hat{q}_{i+1})$$

$$L_{i+1} = l_i \hat{p}_i (n_{i+1} \hat{p}_{i+1} + a_{i+1} n_{i+1} \hat{q}_{i+1})$$

$$\therefore L_w = l_i \hat{p}_i \hat{p}_{i+1} \dots \hat{p}_{w-1} (n_w \hat{p}_w + a_w n_w \hat{q}_w)$$

$$\therefore \hat{e}_i = (n_i \hat{p}_i + a_i n_i \hat{q}_i) + \dots + \hat{p}_i \hat{p}_{i+1} \dots \hat{p}_{w-1} (n_w \hat{p}_w + a_w n_w \hat{q}_w)$$

□

Since the result is not a function of l_0 , then the choice of the radix does not effect the estimates of the life expectancy obtained.

Chapter 4

Simulation Study

In this chapter, we present the results of a simulation study aimed at assessing the formula derived for the variance of the estimator of years of life lost. Three different approaches were followed, which we now describe in turn.

4.1 Approach 1: Deaths from all Causes and Deaths from Lung Cancer are two Independent Binomial Random Variables

Under this first approach, we conducted a simulation where it is assumed that the number of deaths from all causes and from lung cancer are two

independent binomial random variables. Specifically, we created a simulated data set, call it j -th, by generating an outcome, x_{ij} , for the total number of deaths in age group i for $i = 1, 2, \dots, I$ and an outcome, y_{ij} , for the number of deaths in age group i due to lung cancer. These outcomes were generated according to the binomial distributions

$$x_{ij} \sim \text{binom}(D_i, D_i(1 - M_i))$$

$$y_{ij} \sim \text{binom}(D_{Ci}, D_{Ci}(1 - M_{Ci}))$$

where D_i is the number of deaths from all causes in the i -th age group, M_i is the death rate for all causes, D_{Ci} is the number of deaths from lung cancer, M_{Ci} is the death rate for lung cancer. The parameter values used for D_i , D_{Ci} , M_i and M_{Ci} are taken from Table 5.1 and Table 5.5.

For the j -th simulated data set, it is then possible to compute, for each age group, a point estimate for YLL_i , $\widehat{YLL_i}$, and an estimate of the variance of $\widehat{YLL_i}$ and an approximate 95% confidence interval using formulas 3.34, 3.35, and 3.38. We then repeated for 1000 simulated data sets, thereby producing 1000 point estimates and confidence intervals for YLL_i .

Table 4.1 contains the results summarized over the 1000 simulated data sets. Column 3 presents the YLL_i for the 1996 Canadian population, while

Column 4 shows the means of the point estimates of YLL_i obtained through the simulation. Note that the means are close to the true values

Table 4.1: Results from 1000 samples when deaths from cancer and deaths from all causes are independent

Age group	Cancer deaths	YLL	Average $\widehat{YLL}$	$\widehat{V}(YLL)$	Average $\widehat{V}(\widehat{YLL})$	$S^2(\widehat{YLL})$	Average half width	Coverage %
<1	0	0	0	0	0	0	0	-
1 <5	0	0	0	0	0	0	0	
5-<10	0	0	0	0	0	0	0	-
10-<15	0	0	0	0	0	0	0	
15 <20	1	36 09764	35 31426	1303 039	1310 859	1392 984	70 96334	62 5
20-<25	2	67 88339	67 23832	2304 075	2282 173	2330 154	93 6331	86
25-<30	4	124 97268	123 69099	3904 535	3864 467	3794 240	121 84308	90 2
30 <35	22	621 40976	619 65739	17559 848	17502 586	16263 326	259 30278	94 7
35 <40	88	2211 20686	2222 48588	55559 848	55843 141	53249 362	463 17061	95 6
40 <45	231	5083 61188	5091 17286	111863 783	112029 893	109572 946	656 02899	95 7
45-<50	476	9028 73351	9013 45667	171217 431	170927 937	163299 599	810 33127	95 5
50 <55	800	12848 26945	12843 36783	206245 117	206167 648	199182 492	889 95148	94 8
55 <60	1240	16533 09018	16574 13585	220227 972	220775 736	229310 71	920 94086	94 9
60-<65	1949	21086 76311	21120 79691	227769 083	228136 967	236596 923	936 16824	94 3
65 <70	2746	23468 24531	23472 58931	200069 569	200105 933	196179 542	876 77075	95 5
70 <75	3071	20107 60458	20123 89618	131233 132	131339 532	124121 71	710 31961	95 6
75-<80	2442	11807 36021	11797 98898	56884 441	56840 347	57314 535	467 28779	94 8
80 <85	1611	5514 18218	5511 68869	18806 637	18797 783	18621 084	268 72581	94 9
85+	1025	2078 90412	2078 8985	4203 610	4203 835	4264 597	127 08049	95 4

Column 5 gives the estimated variance of YLL_i obtained by applying equation 3.38 to the 1996 Canadian population. while Column 6 represents the means of the estimates of the variance of $\widehat{YLL}_i$ over the 1000 simulated data sets. In addition, Column 7 gives the sample variance of the estimates

of $\widehat{YLL}_i$, Column 5 very close agreement with columns 6 and 7, suggesting that equation 3.38 appears to be appropriate for estimating the variance of YLL_i . As additional verification for the appropriateness of equation 3.38, we computed approximate 95% large sample confidence intervals based on normal theory for YLL_i , and determined the percentage of intervals over the 1000 simulated data sets that covered the true value of YLL_i . These percentages, referred to as coverages, are presented in Column 9. Provided that D_{C_i} is sufficiently large so that the normal approximation to binomial be valid, the coverage percentages are very close to 95% nominal rate.

4.2 Approach 2: Death from all Causes and Deaths from Lung Cancer are two Dependent Binomial random Variables

For this approach, we repeated the simulation of Approach 1; however under the assumption that the number of deaths from all causes and from lung cancer are two dependent binomial random variables. Therefore, in this case, the j -th simulated data set ($j = 1, 2, \dots, 1000$) is obtained by generating

an outcome for the number of lung cancer deaths, y_{ij} , for the i -th age group as given in Approach 1, and an outcome for z_{ij} according to

$$z_{ij} \sim \text{binom}(D_i - D_{C_i}, [D_i - D_{C_i}][1 - (M_i - M_{C_i})])$$

So that $y_{ij} + z_{ij}$ represents outcomes for deaths from all causes.

Table 4.2: Results from 1000 samples when deaths from lung cancer and deaths from all causes are dependent

Age group	Cancer deaths	YLL	Average $\widehat{YLL}$	$\widehat{V}(YLL)$	Average $\widehat{V}(\widehat{YLL})$	$S^2(\widehat{YLL})$	Average half width	Coverage %
<1	0	0	0	0	0	0	0	-
1-<5		0 0	0	0	0	0	0	-
5-<10	0	0	0	0	0	0	0	-
10-<15	0	0	0	0	0	0	0	-
15-<20	1	36 09764	36 31418	1303 039	1310 853	1392 993	70 96319	62 5
20-<25	2	67 88339	67 23821	2304 075	2282 165	2330 135	93 63315	86
25-<30	4	124 97268	123 6915	3904 535	3864 499	3794 428	121 84358	90 2
30-<35	22	621 40976	619 65756	17559 848	17502 595	16264 193	259 30285	94 7
35-<40	88	2211 20686	2222 4858	55559 848	55843 137	53246 044	463 17059	95 6
40-<45	231	5083 61188	5091 18085	111863 783	112030 245	109580 704	656 03002	95 7
45-<50	476	9028 73351	9013 44299	171217 431	170927 419	163096 709	810 33004	95 6
50-<55	800	12848 26945	12843 28785	206245 417	206165 08	198880 301	889 94594	95
55-<60	1240	16533 09018	16573 89966	220227 972	220769 444	228910 696	920 92774	94 9
60-<65	1949	21086 76311	21120 69563	227769 083	228134 783	234909 052	936 16376	94 3
65-<70	2746	23468 24531	23472 89006	200069 569	200111 062	193795 109	876 78199	95 9
70 <75	3071	20107 60458	20124 12621	131233 132	131342 537	122140 324	710 32774	95 9
75-<80	2442	11807 36021	11798 44166	56884 441	56844 714	55527 534	467 30574	94 9
80-<85	1611	5514 18218	5511 9604	18806 637	18799 643	18058 37	268 73911	95 2
85+	1025	2078 90412	2078 91113	4203 610	4203 889	4168 416	127 08131	95 9

Table 4.2 contains the results of the simulation study. From the results, it is evident that the variance expression still works really well. As a matter of

fact, this simulation shows that the variation in the total number of deaths (deaths from all causes) does not have a significant effect on the variance of YLL_i . The coverages here are still very close to the 95% nominal rate whenever D_{C_i} is large enough.

4.3 Approach 3: Deaths from all Causes and Deaths from Lung Cancer are a Bivariate Normal Random Variable

Finally, we repeated the simulation study using an approach where number of deaths from all causes and from lung cancer are bivariate normal.

Here we generated x_{ij} and y_{ij} as defined in approach 1 according to a bivariate normal distribution as follows

$$\begin{pmatrix} x_{ij} \\ y_{ij} \end{pmatrix} \sim \mathbf{N}_2 \left(\begin{pmatrix} D_{C_i} \\ D_i \end{pmatrix}, \begin{pmatrix} D_{C_i}(1 - M_{C_i}) & -P_i M_{C_i} M_i \\ -P_i M_{C_i} M_i & D_i(1 - M_i) \end{pmatrix} \right)$$

Where P_i is mid-year population associated with the i -th age group for the 1996 Canadian population given in Table 5.1.

From the results in Table 4.3 we can see that the results of this simulation study still show that the variance expression is a good approximation.

In addition, the coverage percentages are still very close to the 95% nominal rate. This confirms that the variance formula we developed is a valid approximation for the variance of YLL ,

Table 4.3: Results from 1000 bivariate normal samples

Age group	Cancer deaths	Average YLL	Average $\widehat{YLL}$	Average $\widehat{V}(YLL)$	Average $\widehat{V}(\widehat{YLL})$	$S^2(\widehat{YLL})$	Average half width	Coverage %
<1	0	0	0	0	0	0	0	-
1-<5	0	0	0	0	0	0	0	-
5-<10	0	0	0	0	0	0	0	-
10-<15	0	0	0	0	0	0	0	-
15-<20	1	36 09764	41 64381	1303 039	1503 241	865 896	75 99245	91 5
20-<25	2	67 88339	74 2616	2304 075	2520 357	1991 975	98 4021	88
25-<30	4	124 97268	126 72169	3904 535	3959 173	3289 835	123 32704	91 9
30-<35	22	621 40976	619 20412	17559 848	17489 8	17042 473	259 20805	93 1
35-<40	88	2211 20686	2208 0414	55559 848	55480 286	54283 135	461 66337	94 5
40-<45	231	5083 61188	5076 80375	111863 783	111713 921	104949 636	655 1032	95 5
45-<50	476	9028 73351	9031 84905	171217 431	171276 352	172908 816	811 15673	94 9
50-<55	800	12848 26945	12839 105	206245 417	206098 577	186630 997	889 80239	96 4
55-<60	1240	16533 09018	16520 16992	220227 972	220055 605	210819 119	919 43766	95 4
60-<65	1949	21086 76311	21093 59069	227769 083	227841 854	227181 974	935 56254	94 7
65-<70	2746	23468 24531	23465 49166	200069 569	200045 401	203562 314	876 63813	95
70-<75	3071	20107 60458	20095 15015	131233 132	131151 308	134179 96	709 81044	95
75-<80	2442	11807 36021	11810 19831	56884 441	56897 319	53308 52	467 52191	96 3
80-<85	1611	5514 18218	5515 96365	18806 637	18812 259	18899 914	268 82926	94 6
85+	1025	2078 90412	2081 85595	4203 610	4209 391	4034 432	127 16444	95 3

Chapter 5

Application

In this chapter the methodology discussed in Chapter 3 and verified by simulation in chapter 4 will be applied to the 1996 Canadian population. All calculations are carried out using R (see Appendix A).

5.1 1996 Life Expectancy In Canada

Life expectancy was estimated using life table analysis. Two data sets were used; the 1996 population data provided by Statistics Canada and deaths by selected causes, also provided by Statistics Canada. Table 5.1 summarizes both data sets, with deaths accumulated over all causes.

Table 5.1: 1996 population and deaths estimates for Canada.

Age group	Mid-year population P_t			Deaths from all causes D_t		
	Both	Male	Female	Both	Male	Female
< 1	366690	187370	179320	2051	1155	896
1-< 5	1551135	795190	755945	461	257	204
5-< 10	1990015	1019290	970725	297	158	139
10-< 15	1993440	1023360	970080	339	206	133
15-< 20	1959120	1003355	955765	1049	730	319
20-< 25	1898050	951825	946225	1352	1034	318
25-< 30	2030680	1005285	1025395	1505	1112	393
30-< 35	2468235	1221685	1246550	2323	1641	682
35-< 40	2544035	1258020	1286015	3120	2104	1016
40-< 45	2317670	1144995	1172675	4106	2564	1542
45-< 50	2093855	1040830	1053025	5244	3210	2034
50-< 55	1616545	806685	809860	6673	4141	2532
55-< 60	1301705	643445	658260	8783	5412	3371
60-< 65	1187750	580870	606880	12915	8158	4757
65-< 70	1105945	523070	582875	19612	12237	7375
70-< 75	955990	420295	535695	26831	15935	10896
75-< 80	678250	276935	401315	30320	16416	13904
80-< 85	450585	167245	283340	33531	16344	17187
85+	337075	100280	236795	52368	18590	33778

We now analyze the previous summarized data for both genders combined and estimate life expectancy associated with each age group. The abridged results are given in Table 5.2. Note that the calculations for age groups < 1 through 80-< 85 are carried out in same manner; as an illustration we demonstrate the procedure for age group 15-< 20.

Columns 1 through 4 in Table 5.2 obtained directly from data in Table

4.1. Columns 5 through 13 are obtained as follows

$$M_5 = \frac{D_5}{P_5} = \frac{1049}{1959120} \cong 0.000535444$$

$$a_5 = 0.5$$

$$\hat{q}_5 = \frac{n_5 M_5}{1 + (1 - a_5)n_5 M_5} = \frac{5 \times 0.000535444}{1 + (1 - 0.5) \times 5 \times 0.000535444} \cong 0.0026736435$$

$$\hat{p}_5 = 1 - \hat{q}_5 = 1 - 0.0026736435 \cong 0.9964448$$

$$l_5 = l_4 - d_4 = 99249 - 85 = 99164$$

$$d_5 = l_5 \hat{q}_5 = 99164 \times 0.00267364448 \cong 266$$

$$L_5 = n_5(l_5 - d_5) + a_5 n_5 d_5 = 5 \times (99164 - 266) + 0.5 \times 5 \times 266 = 495155$$

$$T_5 = L_5 + L_6 + \dots + L_{19} = 495155 + 493610 + \dots + 239263 = 6331170$$

$$\hat{e}_5 = \frac{T_5}{l_5} = \frac{6331170}{99164} \cong 63.845448$$

Note that for the last age group, 85+; The life expectancy estimates are obtained differently. specifically, for this group $\hat{q}_{19} = 1$ ($\hat{p}_{19} = 0$) since everyone is assumed to die. the life expectancy estimate is then calculated as follows.

$$l_{19} = l_{18} - d_{18} = 54165 - 16993 = 37172 = d_{19}$$

$$L_{19} = \frac{l_{19}}{M_{19}} = \frac{37172}{0.1553600831} \cong 239263 = T_{19}$$

$$\hat{e}_{19} = \frac{T_{19}}{l_{19}} = \frac{239263}{37172} \cong 6.436646$$

We next demonstrate the calculation of the variance of the life expectancy estimate for each age group. The procedure is the same for all age groups

Table 5.2: Abridged life table for the 1996 Canadian population

(x_1, x_2+1)	n_x	P_x	D_x	M_x	a_x	$\hat{q}_x$	$\hat{p}_x$	l_x	d_x	L_x	T_x	$\hat{e}_x$
< 1	1	366690	2051	0 0055932804	0.1	0.0055652651	0.9944347	100000	557	99498	7820618	78 206180
1-< 5	4	1551135	461	0 0002972017	0.4	0.0011879596	0.9988120	99443	119	397486	7721120	77.643675
5-< 10	5	1090015	297	0.0001492451	0.5	0.0007459472	0.9992541	99324	75	496432	7323634	73 734787
10-< 15	5	1993440	339	0 0001700578	0.5	0 0008499276	0 9991501	99249	85	496032	6827202	68 788623
15-< 20	5	1959120	1049	0 0005354445	0.5	0.0026736435	0.9973264	99164	266	495155	6331170	63.845448
20-< 25	5	1898050	1352	0 0007123100	0.5	0.0035552190	0.9964448	98898	352	493610	5836015	59 010445
25-< 30	5	2030680	1505	0.0007411310	0.5	0 0036988020	0.9963012	98546	365	491817	5342405	54 212297
30-< 35	5	2468235	2323	0.0009411584	0.5	0.0046947455	0 9953053	98181	461	489752	4850588	49 404549
35-< 40	5	2544035	3120	0.0012263982	0.5	0.0061132479	0.9938868	97720	598	487105	4360836	44 625829
40-< 45	5	2317670	4106	0 0017716068	0.5	0.0088189748	0 9911810	97122	857	483467	3873731	39 885206
45-< 50	5	2093855	5244	0 0025044714	0.5	0.0124444402	0.9875556	96265	1198	478330	3390264	35.218034
50-< 55	5	1616545	6673	0.0041279395	0.5	0.0204288747	0.9795711	95067	1943	470477	2911934	30.630334
55-< 60	5	1301705	8783	0.0067473045	0.5	0.0331768861	0 9668231	93124	3090	457895	2441457	26.217269
60-< 65	5	1187750	12915	0.0108735003	0.5	0 0529287010	0.9470713	90034	4766	438255	1983562	22.031255
65-< 70	5	1105945	19612	0.0177332507	0.5	0.0849022706	0.9150977	85268	7240	408240	1545307	18.122942
70-< 75	5	955990	26831	0.0280661932	0.5	0.1311301551	0.8688698	78028	10232	364560	1137067	14.572551
75-< 80	5	678250	30320	0 0447032805	0.5	0.2010476759	0.7989523	67796	13631	304902	772507	11 394581
80-< 85	5	450585	33531	0.0744165918	0.5	0.3137183356	0.6862817	54165	16993	228342	467605	8.632973
85+	5	337075	52368	0.1553600831	0.5	1.0000000000	0.0000000	37172	37172	239263	239263	6.436646

except for the 85+ age group where the life expectancy does not vary. As an example, we now show the calculations for age group 15-< 20.

$$Var(\hat{p}_5) = \frac{\hat{q}_5^2(1 - \hat{p}_5)}{D_5} = \frac{0.0026736435^2 \times 0.9973264}{1049} = 6.796241 \times 10^{-9}$$

$$\begin{aligned} l_5^2[(1 - a_5)n_5 + \hat{e}_6]^2 Var(\hat{p}_5) &= 99164^2 \times [0.5 \times 5 + 59.010445]^2 \times 6.796241 \times 10^{-9} \\ &= 252856.78 \end{aligned}$$

If we let $l_i^2[(1 - a_i)n_i + \hat{e}_{i+1}]^2 Var(\hat{p}_i) = \eta_i$, then

$$\eta_5 + \eta_6 + \dots + \eta_{19} = 252856.78 + 293047.99 + \dots + 0 = 5728198.2$$

$$Var(\hat{e}_5) = \frac{\eta_5 + \eta_6 + \dots + \eta_{19}}{l_5^2} = \frac{5728198.2}{l_5^2} = \frac{5728198.2}{99164^2} \cong 6.082326 \times 10^{-4}$$

Table 5.3 contains the variance estimates for all age groups. As was the case before, the variance estimates are very small since the estimates for the probability of dying, $\hat{q}_i$ are small.

The analysis conducted above by pooling over both genders was repeated separately for males and females. Table 5.4 contains estimates for the life expectancy for the 1996 Canadian population for males, females and both combined. From this table, one can observe that the life expectancy for a female is about six years longer than that of a male in the 1996 Canadian population.

Table 5.3: Life expectancy variance estimates for for the 1996 Canadian population.

Age interval	$\text{Var}(\hat{p}_i)$	$l_i^2[(1 - a_i)n_i + \hat{e}_{i+1}]^2 \text{Var}(\hat{p}_i)$	$\sum_{k \geq i} l_k^2[(1 - a_k)n_k + \hat{e}_{k+1}]^2 \text{Var}(\hat{p}_k)$	$\text{Var}(\hat{e}_i)$
<1	1.501697×10^{-8}	926413.31	7268910.9	7.268911×10^{-4}
1-<5	3.057639×10^{-9}	175267.29	6342497.5	6.413748×10^{-4}
5-<10	1.872129×-9	93860.85	6167230.3	6.251464×10^{-4}
10-<15	2.129094×-9	92314.40	6073369.4	6.165629×10^{-4}
15-<20	6.796241×-9	252856.78	5981055.0	6.082326×10^{-4}
20-<25	9.315566×-9	293047.99	5728198.2	5.856566×10^{-4}
25-<30	9.056832×-9	236954.61	5435150.2	5.596720×10^{-4}
30-<35	9.443461×-9	202164.13	5198195.6	5.392594×10^{-4}
35-<40	1.190492×-8	204231.08	4996031.5	5.231886×10^{-4}
40-<45	1.877458×-8	251943.73	4791800.4	5.079997×10^{-4}
45-<50	2.916417×-8	296645.70	4539856.7	4.898976×10^{-4}
50-<55	6.126377×-8	456614.40	4243211.0	4.694994×10^{-4}
55-<60	1.211645×-7	632321.81	3786596.6	4.366423×10^{-4}
60-<65	2.054332×-7	708247.51	3154274.8	3.891226×10^{-4}
65-<70	3.363444×-7	712776.20	2446027.3	3.364257×10^{-4}
70-<75	5.568305×-7	654507.86	1733251.1	2.846823×10^{-4}
75-<80	1.065099×-6	606764.64	1078743.2	2.346983×10^{-4}
80-<85	2.014354×-6	471978.58	471978.6	1.608736×10^{-4}
85+	0	0	0	0

5.2 Burden of Disease for the 1996 Canadian Population

In this section, we use the data from the 1996 Canadian population to illustrate the estimation of burden of disease(BoD). Specifically, we consider the

Table 5.4: Life expectancy estimates by sex for the 1996 Canadian population.

Age interval	Life Expectancy Estimate		
	Male	Female	Both
<1	75 192240	81 147230	78 206180
1-<5	74 656159	80 552873	77 643675
5-<10	70 751111	76 638670	73 734787
10-<15	65 804104	71 692415	68 788623
15-<20	60 867996	66 740322	63 845448
20-<25	56 080845	61 848144	59 010445
25-<30	51 372806	56 948342	54 212297
30-<35	46 644091	52 053125	49 404549
35-<40	41 941756	47 189011	44 625829
40-<45	37 273100	42 366275	39 885206
45-<50	32 664672	37 629388	35 218034
50-<55	28 133630	32 970526	30 630334
55-<60	23 800307	28 450713	26 217269
60-<65	19 715402	24 123920	22 031255
65-<70	15 968437	19 988566	18 122942
70-<75	12 641830	16 131144	14 572551
75-<80	9 765867	12 591702	11 394581
80-<85	7 294264	9 505705	8 632973
85+	5 394273	7 010312	6 436646

estimation of BoD for all causes of death, lung cancer(ICD-9:162) and cardiopulmonary disease (ICD-9:400-440,460-519) mortality. The years of life lost (YLL) will be the health indicator used. The mortality data for lung cancer and cardiopulmonary disease was obtained from Statistics Canada and is given in Table 5.5.

Table 5.5: 1996 deaths from lung cancer and cardiopulmonary disease.

Age group	Deaths from lung cancer			Deaths from cardiopulmonary		
	Both	Male	Female	Both	Male	Female
< 1	0	0	0	68	30	38
1-< 5	0	0	0	50	29	21
5-< 10	0	0	0	14	10	4
10-< 15	0	0	0	22	10	12
15-< 20	1	1	0	45	25	20
20-< 25	2	1	1	49	36	13
25-< 30	4	2	2	110	65	45
30-< 35	22	11	11	201	119	82
35-< 40	88	36	52	380	250	130
40-< 45	231	94	137	684	477	207
45-< 50	476	229	247	1147	867	280
50-< 55	800	441	359	1787	1310	477
55-< 60	1240	742	498	2696	1915	781
60-< 65	1949	1259	690	4369	3071	1298
65-< 70	2746	1799	947	7385	4907	2478
70-< 75	3071	2022	1049	11589	7224	4365
75-< 80	2442	1592	850	14747	8135	6612
80-< 85	1611	1054	557	18163	8903	9260
85+	1025	632	393	21580	7959	13621

Table 5.6 table presents, for both genders combined, the estimates of burden of disease for all causes using year of life lost, YLL. Equations 3.34 and 3.35 were used to estimate YLL and equation 3.38 to obtain estimates for the standard deviation. In terms of YLL, the point estimate for the total burden of disease due to premature mortality for all causes of death is 1648104.6 years. The 95% confidence interval is (1607638.6,1688570.6). Similar YLL calculations for BoD across all causes of death were performed

by gender. From these, we can also observe that the burden of disease for the male population is about 1.3 of that for the female population.

Table 5.6: Years of life lost from all causes by sex and by age group.

Age group	Both	SD	Male	SD	Female	SD
< 1	68549 32	1509 3930	38399 139	1126 3874	30076 486	1002 2714
1-< 5	16339 23	760 8808	9065 539	565 4014	7258 629	508 1371
5 < 10	11068 00	642 1827	5858 606	466 0496	5201 231	441 1310
10-< 15	12667 66	687 9545	7653 309	533 1776	4993 465	432 9587
15-< 20	37866 41	1168 8265	26169 346	968 2185	11580 389	648 2691
20-< 25	45889 15	1247 5757	34804 318	1081 7748	10866 939	609 2852
25 < 30	47020 94	1211 6079	34391 516	1030 8524	12379 399	624 3384
30-< 35	65615 17	1360 7401	45779 366	1129 3371	19458 804	744 9123
35-< 40	78397 26	1402 6751	52051 564	1133 8287	25852 800	810 7540
40 < 45	90360 53	1408 9133	55320 051	1091 2814	34479 794	877 4790
45-< 50	99467 64	1371 8479	59347 284	1045 8697	39378 617	872 2985
50 < 55	107170 38	1309 2301	64306 036	996 7392	41760 347	828 6140
55-< 60	117104 57	1245 3237	69040 598	934 5263	46513 817	799 0753
60 < 65	139730 28	1222 8389	83286 767	915 6148	53773 407	776 5907
65-< 70	167609 68	1186 1862	97044 234	866 9455	66526 440	769 7474
70-< 75	175676 23	1057 3357	95006 414	738 2167	75990 252	720 5465
75-< 80	146598 40	822 8748	70981 739	537 3333	72032 864	600 2112
80-< 85	114767 58	602 9812	49007 794	364 1292	63278 694	467 8097
85+	106206 18	426 5330	32534 219	215 3664	73427 236	369 9305
Total	1648104 603	20645 901	930050 840	15741 050	694829 611	12904 360

Relative to the results in Table 5.6 for all causes of death, Table 5.7 contains analogous estimates for BoD due to premature deaths caused by lung cancer. The point estimate for both genders combined is about 130617.3 years and the 95% confidence interval is (122946.4,138288.2) years. The burden of disease for the male population is about 1.4 of that for the female

population.

Table 5.7: Years of life lost from lung cancer by sex and by age group

Age group	Both	SD	Male	SD	Female	SD
0 < 1	0	0	0	0	0	0
1-< 5	0	0	0	0	0	0
5-< 10	0	0	0	0	0	0
10 < 15	0	0	0	0	0	0
15-< 20	36 09762	36 09761	35 84842	35 84840	0	0
20-< 25	67 88335	48 00075	33 65988	33 65986	34 17276	34 17274
25 < 30	124 97261	62 48624	61 86064	43 74204	62 99949	44 54732
30 < 35	621 40929	132 48432	306 86961	92 52425	313 85168	94 62942
35-< 40	2211 20470	235 71114	890 61611	148 43389	1323 17482	183 48762
40-< 45	5083 60533	334 46001	2028 11419	209 17542	3063 37989	261 70692
45-< 50	9028 71799	413 78357	4233 80936	279 74722	4781 96575	304 23351
50-< 55	12848 23949	454 14145	6848 33661	326 02212	5920 99705	312 42900
55 < 60	16533 03695	469 28302	9465 65482	317 29470	6871 51617	307 80350
60-< 65	21086 66722	477 24942	12853 40028	361 85452	7799 80053	296 76448
65 < 70	23468 08978	447 28840	14266 77914	335 78573	8542 44596	277 36660
70-< 75	20107 40168	362 25748	12055 41069	267 45101	7315 87506	225 65913
75-< 80	11807 16632	238 50068	6883 70667	172 02791	4403 62014	150 88288
80 < 85	5514 01914	137 13324	3160 43898	97 04078	2050 74955	86 80760
85+	2078 77584	64 83125	1106 05844	43 85778	854 31061	43 05849
Total	130617 287	3913 709	74230 564	2794 466	53338 859	2623 549

Analogous estimates of burden of disease due to premature mortalities caused by cardiopulmonary disease are given in Table 5.8. It is estimated that the burden of disease is 492291.3 years and the 95% confidence interval is (475448,509134.6) years. The male burden of disease is still larger by about the same margin than that of the female. When looking at all three tables we can observe that lung cancer and cardiopulmonary disease account for

Table 5.8: Years of life lost from cardiopulmonary disease by sex and by age group

Age group	Both	SD	Male	SD	Female	SD
0 < 1	2272 7224	275 5825	997 3802	182 0813	1275 5653	206 9021
1 < 5	1772 1510	250 6160	1022 9596	189 9554	747 2118	163 0527
5 < 10	521 7240	139 4361	370 7979	117 2560	149 6757	74 8377
10 < 15	822 0902	175 2693	371 5199	117 4843	450 5382	130 0584
15-< 20	1624 3931	242 1474	896 2105	179 2399	726 0432	162 3465
20 < 25	1663 1421	237 5887	1211 7558	201 9555	444 2459	123 2108
25-< 30	3436 7467	327 6721	2010 4708	249 3602	1417 4884	211 3021
30-< 35	5677 4212	400 4381	3319 7712	304 3081	2339 6216	258 3595
35-< 40	9548 3839	489 7852	6184 8341	391 1244	3307 9371	290 1106
40-< 45	15052 7534	575 4715	10291 6008	471 1219	4628 6105	321 6823
45-< 50	21756 1755	642 2171	16029 3132	544 1572	5420 8519	323 9148
50 < 55	28699 7550	678 5404	20343 1314	561 6028	7867 1744	360 1071
55 < 60	35946 0223	691 5772	24429 5539	557 4218	10776 4139	385 3816
60-< 65	47269 1889	713 8170	31352 4958	564 2624	14672 6682	406 8242
65-< 70	63114 2910	731 9773	38914 4443	552 9121	22352 8839	448 0823
70 < 75	75879 0876	700 5686	43070 3694	502 3715	30442 1303	458 8876
75-< 80	71302 3266	580 7355	35175 2222	384 2234	34254 9840	417 7821
80-< 85	62167 0575	451 8893	26695 8142	275 2938	34093 2510	348 4558
85+	43765 8368	285 2322	13928 9859	149 8074	29609 5798	246 2994
Total	492291 269	8593 561	276616 631	6495 939	204976 875	5337 597

about 8 and 30% of the total burden of disease respectively. There are many fatal diseases and the fact that lung cancer and cardiopulmonary account for almost 40% of the burden makes them two very serious diseases that we try to reduce. In the next section we will focus on particulate matter as one of the environmental risk factors that causes lung cancer and cardiopulmonary diseases.

5.3 Particulate Matter (PM_{2.5})

Particulate matter, PM_{2.5}, is an air pollutant consisting of a mixture of solid and liquid particles that are less than 2.5 μ m in diameter. Sources of particulate matter can be natural (e.g., pollen, bacteria, viruses, fungi, mold, yeast, soil from erosion), or through human activities including diesel trucks, power plants, wood stoves, and industrial processes (see Minnesota Pollution Control Agency website). Among the effects of exposure to particulate matter are the following effects:

- Respiratory symptoms
- Adverse effects on the cardiovascular system
- Increase in hospital admissions
- Reduction in lung function
- Reduction in life expectancy due to cardiopulmonary and lung cancer mortality

To study the effect of PM_{2.5} on all causes of death, lung cancer and cardiopulmonary disease, a data set that contains PM_{2.5} concentrations for

Figure 5.1: Yearly average for PM2.5 in $\mu\text{g}/\text{m}^3$.

12 major Canadian cities (Ottawa, Toronto, Calgary, Edmonton, Halifax, Hamilton, Montreal, Quebec, St. John, Vancouver, Windsor, Winnipeg) from 1994 to 1996 was used. This data set was produced by the Canadian

National Air Pollution Surveillance (NAPS) and we acquired from Health Canada (Burnett et al. 2000). A maximum of thirteen and a minimum of three years of data are available for the 12 cities. For purposes of illustration we made use of the annual concentration for each city over the three year period from 1994 through 1996.

For each city we now estimate the relative risks for all diseases, lung cancer and cardiopulmonary disease using the expressions in Table 3.5 and taking the theoretical minimum level of exposure, x_0 , to be 7.5 (see Lopez et al. 2006). Table 5.9 contains the results obtained. To estimate the population attributable fractions, we use equation 3.40. Table 5.10 contains the population of each of the 12 cities. Please note that our population of study is now the combined populations of the 12 cities only and not the 1996 Canadian population. The proportion of individuals in each of the 12 cities in the population created is also given in Table 5.10.

We computed the population attributable fraction with equation 3.40 using the relative risks from Table 5.9. Table 5.11 contains the results.

We conclude that over both genders combined particulate matter, PM_{2.5}, attributed about 1.5%, 7.4% and 5% to the total 1996 burden of disease in the 12 cities due to all causes, lung cancer and cardiopulmonary disease

Table 5.9: PM2.5 concentrations, all causes RR, lung cancer RR and cardiopulmonary RR

City	94-96 PM 2.5 average concentration	All causes RR (95% CI)	Lung Cancer RR (95% CI)	Cardiopulmonary RR (95% CI)
Ottawa	8.826635	1.005321 (1.001328, 1.010267)	1.034247 (1.012496, 1.056464)	1.022757 (1.008184, 1.03754)
Toronto	13.64831	1.024898 (1.006167, 1.048481)	1.134697 (1.047708, 1.228909)	1.088109 (1.03106, 1.148316)
Calgary	8.657479	1.004641 (1.001158, 1.008952)	1.030085 (1.010992, 1.049539)	1.020005 (1.007201, 1.032972)
Edmonton	8.07807	1.002315 (1.000578, 1.004461)	1.015394 (1.00656, 1.025232)	1.01026 (1.003705, 1.016859)
Halifax	7.822565	1.001291 (1.000323, 1.002487)	1.008685 (1.003195, 1.014206)	1.005796 (1.002095, 1.009509)
Hamilton	17.82656	1.042171 (1.01038, 1.082761)	1.202773 (1.070465, 1.351435)	1.131309 (1.045704, 1.223923)
Montreal	11.68216	1.016869 (1.004191, 1.032727)	1.097354 (1.034857, 1.163626)	1.064048 (1.022742, 1.107022)
Quebec	9.092263	1.006389 (1.001594, 1.012336)	1.040671 (1.014812, 1.06719)	1.026998 (1.009696, 1.044595)
St. John	7.332518	1 (1, 1)	1 (1, 1)	1 (1, 1)
Vancouver	8.047693	1.002193 (1.000348, 1.004226)	1.014604 (1.005361, 1.023931)	1.009735 (1.003515, 1.015993)
Windsor	15.79123	1.033721 (1.008326, 1.065924)	1.171243 (1.060029, 1.294126)	1.111405 (1.039002, 1.188853)
Winnipeg	8.10779	1.002434 (1.000608, 1.004691)	1.016165 (1.005931, 1.026502)	1.010773 (1.003889, 1.017704)

respectively.

Table 5.10: Populations of the 12 cities and the proportions they represent of the total

City	Population			Proportion of total p_i		
	Both	Male	Female	Both	Male	Female
Ottawa	763435	372495	390940	0.052397879	0.052423032	0.05237376
Toronto	4263760	2076360	2187400	0.292640474	0.292216236	0.293043336
Calgary	821630	409235	412415	0.056392056	0.057593631	0.055250739
Edmonton	862595	426965	435635	0.059203663	0.06008886	0.058361495
Halifax	332520	160755	171765	0.0228223	0.022623833	0.02301115
Hamilton	624360	304030	320330	0.042852554	0.04278762	0.042914223
Montreal	3326510	1611035	1715475	0.228312912	0.226728787	0.229820113
Quebec	671885	323835	348050	0.046114403	0.045574874	0.046627838
St John	125705	60730	64975	0.008627683	0.008546828	0.008704622
Vancouver	1831665	900805	930860	0.12571517	0.126774667	0.12470619
Windsor	278685	135935	142750	0.019127369	0.019130793	0.019124045
Winnipeg	667210	323380	343830	0.045793537	0.045510839	0.04606249

Table 5.11: Population attributable fractions

Gender	All causes (95% CI)	Lung cancer (95% CI)	Cardiopulmonary (95% CI)
Both	0.01463782 (0.003691052, 0.02788218)	0.0738313 (0.02819839, 0.1163687)	0.05024739 (0.01863876, 0.08038464)
Male	0.01460439 (0.003682622, 0.02781853)	0.07366726 (0.02813546, 0.1161114)	0.05013548 (0.01859712, 0.08020617)
Female	0.0146696 (0.003699067, 0.0279427)	0.0739873 (0.02825823, 0.1166134)	0.05035381 (0.01867835, 0.08055437)

5.4 Discussion

We now discuss the results obtained by comparing them to results from other studies. The world health organization, WHO, estimates were 1%, 5% and 3% for all causes, lung cancer and cardiopulmonary respectively

(Ostro et al. 2004). The estimates from our study differ from those and we provide explanations as to why this is the case. The WHO studies global burden of disease (GBD) and they cover 3211 urban cities worldwide so it is reasonable to get different results from our investigation. This is true since most Canadian cities have lower pollution than most of other major cities in the world. However, lower estimates would be what is expected which is not the case here.

There are a number of differences between our research and the researches conducted by the WHO which can lead to a difference in the results. First, the concentration levels that were used for the WHO studies were for PM10 and not PM2.5. The PM2.5 estimates were obtained by multiplying PM10 by a factor. Also, the data were for 304 major cities in the world and assumptions were made to estimate concentrations for the rest of the 3211 cities. Moreover, the results for the population attributable fractions that the WHO obtained were assumed to be for the whole world and not the 3211 major cities. This means that further assumptions were made to obtain population attributable fractions for areas or cities other than the 3211 cities. Our research covers 12 major cities in Canada and we did not generalize our results for the rest of Canada. When we assumed that the rest of Canada

has a concentration that is less or equal to the theoretical minimum ($7.5 \mu\text{g}/\text{m}^3$) the estimates change to about 0.74%, 4% and 3% for all causes, lung cancer and cardiopulmonary disease respectively. These estimates are much closer to those reported by the WHO which makes us believe that a similar assumption was made by the WHO for areas where data were not available. Also, when estimating relative risks, the WHO studies used the linear model whereas we used the log-linear model, which the WHO recommends. The linear model gives lower relative risks which, as a result, gives lower estimates for the population attributable fractions.

We also compared our study to a study that was for the environmental burden of disease in Canada (Boyd et al. 2007). This study addressed the effect of particulate matter on lung cancer only. The researchers did not estimate their population attributable fractions but rather made use of previous estimates and expert opinion. The estimate they used was 5-15% and ours was about 2.8-11.6%.

Chapter 6

Health Indicators and Their Correlation

In this study we have used YLL as the indicator to quantify BoD. There are, however, a number of other indicators that could have been employed. In this chapter, we address the question of whether the choice of indicator to quantify BoD makes any difference. Specifically, we shall investigate, for ages from 0 to 75, if any correlation exists between death rate, years of life lost and potential years of life lost. We have already discussed death rates, M , and years of life lost, YLL . We now describe potential years of life lost, $PYLL$.

The concept of *PYLL* was first introduced in 1947 by Dempsey (see J-M Romeder et al. 1997). For a given individual who died from a particular disease, *PYLL* is an indicator of the years of life the would have remained had the person lived until 75. Provided that individuals are grouped by age categories, the following expression is for calculating potential years of life lost, $PYLL_k$, for a specific disease, say the k -th.

$$PYLL_k = \sum_{i=1}^{16} (75 - x_i - 0.5) D_{ik} \quad (6.1)$$

where, k denotes the k -th disease, i is the age group. x_i is the age of death in the i -th age group and D_{ik} is the total number of deaths in the i -th age group.

Death rate and years of life lost for a given disease are calculated as follows.

$$M_k = \frac{\sum_{i=1}^{16} D_{ik}}{\sum_{i=1}^{16} P_i}$$

$$YLL_k = \sum_{i=1}^{16} YLL_{ik}$$

In order to investigate the extent of correlation between M , YLL , and $PYLL$, we made use of data on deaths from 20 different diseases in the 1996

Figure 6.1: Health indicators comparison plot.

Canadian population for both genders combined.

Figure 6.1 shows scatter diagrams of YLL_k vs $PYLL_k$, YLL_k vs M_k , and $PYLL_k$ vs M_k across the 20 different diseases ($k = 1, 2, \dots, 20$). These

plots seem to suggest there is a strong positive correlation between any two of these measures. In addition, the scatter diagrams appear linear. Therefore, three separate pairwise regressions were fit where YLL_k was regressed against $PYLL_k$, YLL_K was regressed against M_k , and $PYLL_k$ was regressed against M_k . However, in each case, the scatter diagrams seem to suggest a possible violation of the assumption of a constant error term variance typically specified for a simple linear regression model. We therefore apply power transformations to remedy the non-constant variance problem.

PYLL vs YLL

We estimated the best power transformation, λ , of $PYLL$ using Box-Cox method. The estimate for λ was 0.7878788. The estimate for Pearson correlation coefficient is 0.989. with associated p-value < 0.0001.

M vs YLL

We apply the same procedure to obtain λ of 0.3030303. The correlation coefficient estimate is 0.871 and the p-value is < 0.0001.

M vs PYLL

The best λ is 0.7878788. The Pearson correlation coefficient estimate is 0.861 and p-value < 0.0001.

Since a correlation was found between pair of the three health indicators, we can conclude that it does not matter which health indicator, out of the three, to use to quantify the BoD. This is a very important finding since the three health indicators differ in complexity and data required to estimate them.

Chapter 7

Conclusion and Discussion

In this research we shed some light on the influence of PM_{2.5} on mortalities by all causes, lung cancer and cardiopulmonary disease. This research represents a first Canadian study in this area, as all studies conducted before either were conducted globally or did not use Canadian data. An important conclusion arrived at here is that the WHO estimates are not very applicable at the local level. We therefore hope that this study and its findings will motivate future Canadian studies using more recent data, additional risk factors and more diseases.

An important statistical contribution of our research is the development of a confidence interval for YLL , which was never done before as previous

studies have only considered point estimates. We first derived an expression for the variance of the estimate of YLL that we subsequently employed in the development of a confidence interval. This confidence interval formula was then verified by a simulation study that demonstrated its usefulness for estimating BoD.

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Appendix A

R Programs

A.1 Life Expectancy Function

```
leb<-function(age,p,d)
{
  result<-matrix(rep(0),19,17)
  result[,1]<-age
  result[,2]<-c(1,4,rep(5,17))
  result[,3]<-p
  result[,4]<-d
  result[,6]<-c(0.1,0.4,rep(0.5,17))
```

```
result[1,9]=100000

for(i in 1:19)
{
  result[i,5]=result[i,4]/result[i,3]

  result[i,7]=(result[i,2]*result[i,5])/
  (1+result[i,2]*(1-result[i,6])*result[i,5])

  if (i==19) { result[i,7]=1}

  result[i,8]=1-result[i,7]

  if (i==19) {result[i,8]=0}

}

for(i in 2:19)
{
  result[i,9]=floor(result[i-1,8]*result[i-1,9])

  result[i-1,10]=result[i-1,9]-result[i,9]

  if(i==19){result[i,10]=result[i,9]}

}

result[1,11]=floor(result[2,9]+0.1*result[1,10])

result[2,11]=floor(4*result[3,9]+4*0.4*result[2,10])

for(i in 4:19)
```

```

{
  result[i-1,11]=floor(5*(result[i-1,9]+result[i,9])/2)
}

result[19,11]=floor(result[19,9]/result[19,5])

result[1,12]=sum(result[,11])

for(i in 2:19)
{
  result[i,12]=result[i-1,12]-result[i-1,11]

  if (i==19){result[i,12]=result[i,11]}
}

for(i in 1:19)
{
  result[i,13]=result[i,12]/result[i,9]

  result[i,14]<-((result[i,7])^2*result[i,8])/result[i,4]
}

for(i in 1:18)
{
  result[i,15]<-(result[i,9])^2*((1-result[i,6])*result[i,2]
+result[i+1,13])^2*result[i,14]

```



```
}

result[1,16]<-sum(result[,15])

for(i in 2:18)

{

result[i,16]<-result[i-1,16]-result[i-1,15]

}

for(i in 1:18)

{

result[i,17]<-result[i,16]/result[i,9]^2

}

result

}
```

A.2 YLL Function

```
lost<-function(age1,a1)

{

r=0.03

b=0.04
```

```

ac=0.1658

y11<-c(rep(0,19))

for(i in 1:19)
{
  d1=ac*exp(r*age1[i])/(r+b)**2
  d2=exp(-(r+b)*(a1[i]+age1[i]))*(-(r+b)*(a1[i]+age1[i])-1)
  d3=exp(-(r+b)*age1[i])*(-(r+b)*age1[i]-1) y11[i]=(d1*(d2-d3))
}

y11
}

```

A.3 Generating Total Deaths as a Binomial Random Variable

```

le<-read.table("c:\\EBD\\Latest\\thesisdata96.txt",header=T)

pop<-le[,2]

probs<-le[,5]/le[,2]

b<-c(rep(0,19))

deaths<-c(rep(0,19))

```

```
total100<-matrix(0,19,100)

for(j in 1:100)

{

  for(i in 1:19)

  {

    a<-rbinom(pop[i],1,probs[i])

    b[i]<-sum(a)

  }

  deaths<-b

  total100[,j]<-deaths

}

save(total100,file="total100.Robj",ascii=TRUE)
```

A.4 Generating Bivariate Normal Data for Approach 3

```
le<-read.table("c:\\EBD\\Latest\\thesisdata96.txt",header=T)

age<-le[,1]

death<-le[,5]
```

```
pop<-le[,2]

deathc<-le[,8]

qip<-death/pop

qic<-deathc/pop

covpc<-pop*qip*qic

sim<-matrix(0,38,1000)

library(MASS)

for(i in 1:19)

{

mu<-c(deathc[i],death[i])

sigma<-matrix(c(deathc[i]*(1-qic),rep(-covpc[i],2),death[i]*(1-qip)),2,2)

a<-mvrnorm(1000,mu,sigma)

sim[i,]<-a[,1]

sim[i+19,]<-a[,2]

}

save(sim,file="normal1000.Robj",ascii=TRUE)
```

A.5 Approach 1 Program

```
le<-read.table("c:\\EBD\\Latest\\thesisdata96.txt",header=T)

age<-le[,1] death<-le[,5] pop<-le[,2] deathc<-le[,8]

load("total1000.Robj") load("cancer1000.Robj") qi<-cancer1000/pop

vardi<-cancer1000*(1-qi)

varc<-deathc*(1-deathc/pop)

lesim<-matrix(0,19,1000)

for(i in 1:1000)

{

les<-leib(pop,total1000[,i])

lesim[,i]<-les[,13]}

yll1000<-matrix(0,19,1000)

ylldi1000<-matrix(0,19,1000)

for(i in 1:1000)

{

yll1000[,i]<-lost(age,lesim[,i],deathc)

}

yllsim<-cancer1000*yll1000
```

```
avyllsim<-c(rep(0,19))

for(i in 1:19)

{

avyllsim[i]<-sum(yllsim[i,])/1000

}

yllvar<-yll1000^2*vardi

lereal<-leb(pop,death)

yllreal<-lost(age,lereal[,13],deathc)

yllreal1<-deathc*yllreal

realvar<-varc*yllreal^2

avvaryll<-c(rep(0,19))

for(i in 1:19)

{

avvaryll[i]<-mean(yllvar[i,])

}

halfwidth<-1.96*sqrt(avvaryll)

samplev<-c(rep(0,19))

for(i in 1:19)

{
```

```
samplev[i]<-var(yllsim[i,])

}

n<-matrix(0,19,1000)

for(i in 1:19)

{

for(j in 1:1000)

{

k<-ci95(yllsim[i,j],yllvar[i,j])

if((k[1]<=yllreal1[i])&&(k[2]>=yllreal1[i]))n[i,j]<-1

}

}

sum(n)

coverage<-c(rep(0,19))

for(i in 1:19)

{

coverage[i]<-sum(n[i,])/10

}
```

A.6 YLL and Variance of YLL Calculations

```

pop<-read.table("c:\\Thesisfinalfinal\\thesisdata96.txt",header=T)

cancercardio<-read.table("c:\\Thesisfinalfinal\\cancercardio.txt",header=T)

lea<-leb(pop[,1],pop[,2],pop[,5])

lem<-leb(pop[,1],pop[,3],pop[,6])

lef<-leb(pop[,1],pop[,4],pop[,7])

alls<-c(rep(0,57))

j<-1

for(i in 1:19)

{

alls[j]<-lef[i,13]

alls[j+1]<-lea[i,13]

alls[j+2]<-lem[i,13] j<-j+3

}

allab<-1-(cancercardio[,5]/cancercardio[,2])

allam<-1-(cancercardio[,6]/cancercardio[,3])

allaf<-1-(cancercardio[,7]/cancercardio[,4])

allbcan<-1-(cancercardio[,8]/cancercardio[,2])

```



```

allmcan<-1-(cancercardio[,9]/cancercardio[,3])
allfcan<-1-(cancercardio[,10]/cancercardio[,4])
allbcar<-1-(cancercardio[,11]/cancercardio[,2])
allmcar<-1-(cancercardio[,12]/cancercardio[,3])
allfcar<-1-(cancercardio[,13]/cancercardio[,4])
probs<-cbind(allab,allam,allaf,allbcan,allmcan,allfcan,
allbcar,allmcar,allfcar)
ylla<-lost(cancercardio[,1],lea[,13])
yllm<-lost(cancercardio[,1],lem[,13])
yllf<-lost(cancercardio[,1],lef[,13])
yll<-matrix(0,19,9)
sds<-matrix(0,19,9)
f<-5 j<-1
for(i in 1:3)
{
yll[,j]<-cancercardio[,f]*ylla
yll[,j+1]<-cancercardio[,f+1]*yllm
yll[,j+2]<-cancercardio[,f+2]*yllf
f<-f+3 j<-j+3

```

```

}

ylln<-cbind(ylla,yllm,yllf)

yllno<-matrix(rep(ylln,3),19,9)

sds<-sqrt(yllno^2*cancercardio[,5:13]*probs)

```

A.7 PAF Calculation

```

cityage<-read.table("c:\\Thesisfinalfinal\\pop96citybyage.txt",header=T)

pop<-read.table("c:\\Thesisfinalfinal\\thesisdata96.txt",header=T)

cityt<-read.table("c:\\Thesisfinalfinal\\citytotals.txt",header=T)

cityp<-read.table("c:\\Thesisfinalfinal\\citypercentages.txt",header=T)

x<-read.table("c:\\Thesisfinalfinal\\x.txt",header=T)

x[3,9]<-7.5

rrcancer<-matrix(0,12,3)

rrcardio<-matrix(0,12,3)

rrall<-matrix(0,12,3)

for(i in 1:12)

{

rrcancer[i,1]<-((x[3,i]+1)/8.5)^0.08563

```

```
rrcancer[i,2]<-((x[3,i]+1)/8.5)^0.23218
rrcancer[i,3]<-((x[3,i]+1)/8.5)^0.37873
rrcardio[i,1]<-((x[3,i]+1)/8.5)^0.0562
rrcardio[i,2]<-((x[3,i]+1)/8.5)^0.15515
rrcardio[i,3]<-((x[3,i]+1)/8.5)^0.2541
rrall[i,1]<-exp(0.001*(x[3,i]-7.5))
rrall[i,2]<-exp(0.004*(x[3,i]-7.5))
rrall[i,3]<-exp(0.0077*(x[3,i]-7.5))
}

percent<-cityt[3,1:36]
both<-c(seq(1,36,3))
male<-c(seq(2,36,3))
female<-c(seq(3,36,3))
percentall<-percent[both]
percentmale<-percent[male]
percentfemale<-percent[female]
pafcan<-(rrcancer-1)/rrcancer
pafcar<-(rrcardio-1)/rrcardio
pafa<-(rrall-1)/rrall pafa
```

```
perboth<-as.numeric(matrix(percentall,1,12))
permale<-as.numeric(matrix(percentmale,1,12))
perfemale<-as.numeric(matrix(percentfemale,1,12))

perboth%*%pafa
permale%*%pafa
perfemale%*%pafa

perboth%*%pafcan
permale%*%pafcan
perfemale%*%pafcan

perboth%*%pafcar
permale%*%pafcar
perfemale%*%pafcar
```

A.8 Health Indicators Comparison

```
library(MASS)

le<-read.table("c:\\EBD\\Latest\\comparisondata.txt",header=T)

age<-le[,1]
pop<-le[,2]
```

```
death<-le[,5]

disease<-le[,8:27]

p<-matrix(0,16,20)

for(j in 1:20)

{

for(i in 1:16)

{

p[i,j]<-(75-age[i]-0.5)*disease[i,j]

}

}

expectancy<-leb(age,pop,death)

l<-expectancy[,13]

yllall<-matrix(0,19,20)

yll<-lost(age,l)

for( i in 1:20)

{

yllall[,i]<-yll*disease[,i]

}

psum<-c(rep(0,20))
```

```
yllsum<-c(rep(0,20))

rates<-c(rep(0,20))

for(i in 1:20)

{

  rates[i]<-sum(disease[1:16,i])/sum(pop[1:16])

  yllsum[i]<-sum(yllall[1:16,i])

  psum[i]<-sum(p[,i])

}

alls<-c(yllsum,psum,rates)

allm<-matrix(alls,20,3)

pairs(allm,labels=c("YLL","PYLL","M"))

a<-boxcox(psum~rates)
```

Appendix B

Chapter 6 Data

Source: Statistics Canada

Table B 1: The 20 diseases used for the analysis

Disease	ICD-9 code
Lung cancer	162
Leukaemia	204-208
Liver cancer	155-156
Heart failure	428
Cardiac Dysrhythmias	427
Chronic obstructive pulmonary disease	490-496
Accidents	E800-E949
Diabetes mellitus	250
Pneumonia and influenza	480-487
Suicide	E950-E959
Chronic liver diseases and cirrhosis	571
HIV	042-044
Colon cancer	153-154
Breast cancer	174
Pancreas cancer	157
Hereditary and degenerative diseases of the central nervous system	330-337
Alzheimer's disease	331
Psychoses	290-299
Neurotic disorders, personality disorders and other nonpsychotic mental disorders	300-316
Cancer of brain and central nervous system	191-192

Table B.2: Death for both genders combined from 10 diseases in the 1996

Canadian population

162	204-208	155-156	428	427	490-496	E800-E949	250	480-487	E950-E959
0	0	2	3	13	6	28	0	21	0
0	25	2	2	5	3	130	1	15	0
0	17	1	0	2	1	136	0	3	1
0	19	0	0	2	3	102	0	1	40
1	17	0	3	8	5	500	3	5	231
2	24	3	0	4	9	568	3	8	350
4	16	6	1	9	5	463	17	16	348
22	27	8	2	17	5	557	24	15	419
88	35	12	4	19	7	523	30	29	524
231	55	32	5	31	17	493	55	45	479
476	73	53	3	47	46	405	75	63	399
800	88	69	14	49	77	367	127	91	305
1240	111	102	37	84	186	285	210	100	203
1949	154	160	79	138	410	308	366	172	153
2746	223	221	189	251	862	358	605	285	156
3071	291	295	375	362	1510	459	845	572	138
2442	327	296	532	503	1847	602	926	925	89
1611	269	240	907	655	2003	785	960	1464	60
1025	304	203	2424	1339	2346	1594	1203	3644	46

Table B.3: Death for both genders combined from 10 diseases in the 1996

Canadian population

571	042-044	153-154	174	157	330-337	331	290-299	300-316	191-192
0	1	0	0	0	13	0	0	0	6
0	5	0	0	0	11	0	0	0	18
0	1	0	0	0	10	0	0	0	19
0	1	0	0	0	6	0	1	0	20
1	6	1	0	1	5	0	0	3	8
0	10	1	0	0	4	0	1	5	12
9	87	6	9	2	3	0	1	6	23
20	265	26	45	5	8	0	0	26	35
41	311	44	132	20	24	0	4	37	63
113	241	83	253	35	22	1	8	58	73
146	164	176	314	74	47	0	4	67	107
180	105	287	388	116	58	3	8	73	98
192	60	364	439	209	52	1	20	83	158
262	24	548	473	290	157	30	44	87	167
389	18	823	565	412	251	81	88	118	196
353	5	994	661	526	482	186	208	120	209
232	0	980	628	505	817	391	440	97	142
110	2	846	538	425	1101	659	815	122	92
67	0	979	629	371	1841	1336	2381	335	45

Appendix C

World Regions

Source: The World Health Organization website

C.1 WHO Regions

Region	Member states
Africa	
Afr-D	Algeria, Angola, Benin, Burkina Faso, Cameroon, Cape Verde, Chad, Comoros, Equatorial Guinea, Gabon, Gambia, Ghana, Guinea-Bissau, Liberia, Madagascar, Mali, Mauritania, Mauritius, Niger, Nigeria, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Togo
Afr-E	Botswana, Burundi, Central African Republic, Congo, Cote d'Ivoire, Democratic Republic of the Congo, Eritrea, Ethiopia, Kenya, Lesotho, Malawi, Mozambique, Namibia, Rwanda, South Africa, Swaziland, Uganda, United Republic of Tanzania, Zambia, Zimbabwe

Americas	
Amr A	Canada Cuba United States of America
Amr B	Antigua and Barbuda Argentina Bahamas Barbados Belize Brazil Chile Colombia Costa Rica Dominican Republic El Salvador Guatemala Guyana Honduras Jamaica Mexico Panama Paraguay Saint Kitts and Nevis Saint Lucia Saint Vincent and the Grenadines Suriname Trinidad and Tobago Uruguay Venezuela(Bolivarian Republic of)
Amr D	Bolivia Ecuador Guatemala Haiti Nicaragua Peru
South East Asia	
Seasr B	Indonesia Sri Lanka Thailand
Seasr D	Bangladesh Bhutan Democratic People's Republic of Korea India Maldives Myanmar Nepal Timor Leste
Europe	
Eur A	Andorra Austria Belgium Croatia Cyprus Czech Republic Denmark Finland France Germany Greece Iceland Ireland Israel Italy Luxembourg Malta Monaco Netherlands Norway Portugal San Marino Slovenia Spain Sweden Switzerland United Kingdom
Eur B	Albania Armenia Azerbaijan Bosnia and Herzegovina Bulgaria Georgia Kyrgyzstan Poland Romania Slovakia Tajikistan The former Yugoslav Republic of Macedonia Serbia and Montenegro Turkey Turkmenistan Uzbekistan
Eur C	Belarus Estonia Hungary KazakhstanLatvia Lithuania Republic of Moldova Russian Federation Ukraine
Eastern Mediterranean	
Emr B	Bahrain Iran (Islamic Republic of) Jordan Kuwait Lebanon Libyan Arab Jamahiriya Oman Qatar Saudi Arabia Syrian Arab Republic Tunisia United Arab Emirates
Emr D	Afghanistan Djibouti Egypt Iraq Morocco Pakistan Somalia Sudan Yemen
Western Pacific	
Wpr A	Australia Brunei Darussalam Japan New Zealand Singapore
Wpr B	Cambodia China Cook Islands Fiji Kiribati Lao People's Democratic Republic Malaysia Marshall Islands Micronesia(Federation States of) Mongolia Nauru Niue Palau Papua New Guinea Philippines Republic of Korea Samoa Solomon Islands Tonga Tuvalu Vanuatu Vietnam

C.2 World Bank Regions

Source: World Bank website

Low income economies					
Afghanistan	Bangladesh	Benin	Burkina Faso	Burundi	Cambodia
Central African Republic	Chad	Comoros	Congo, Dem. Rep.	Eritrea	Ethiopia
Gambia, The	Ghana	Guinea	Guinea-Bissau	Haiti	Kenya
Korea, Dem. Rep.	Kyrgyz Republic	Lao PDR	Liberia	Madagascar	Malawi
Mali	Mauritania	Mozambique	Myanmar	Nepal	Niger
Rwanda	Senegal	Sierra Leone	Leone	Somalia	Tajikistan
Tanzania	Togo	Uganda	Uzbekistan	Vietnam	Yemen, Rep.
Zambia	Zimbabwe				

Lower middle income economies				
Albania	Angola	Armenia	Azerbaijan	Belize
Bhutan	Bolivia	Cameroon	Cape Verde	China
Congo Rep	Cote d'Ivoire	Djibouti	Ecuador	Egypt Arab Rep
El Salvador	Georgia	Guatemala	Guyana	Honduras
India	Indonesia	Iran Islamic Rep	Iraq	Jordan
Kenya	Kosovo	Lesotho	Maldives	Marshall Islands
Micronesia Fed Sts	Moldova	Mongolia	Morocco	Nicaragua
Nigeria	Pakistan	Papua	New Guinea	Paraguay
Philippines	Samoa	Sao Tome and Principe	Solomon Islands	Sri Lanka
Sudan	Swaziland	Syrian Arab Republic	Tanzania	Timor Leste
Tonga	Tunisia	Turkmenistan	Ukraine	Vanuatu
West Bank and Gaza				
Upper middle income economies				
Algeria	American Samoa	Argentina	Belarus	Bosnia and Herzegovina
Botswana	Brazil	Bulgaria	Chile	Colombia
Costa Rica	Cuba	Dominica	Dominican Republic	
Fiji	Gabon	Canada	Jamaica	Kazakhstan
Latvia	Lebanon	Libya	Lithuania	Macedonia FYR
Malaysia	Mauritius	Mayotte	Mexico	Montenegro
Namibia	Palau	Panama	Peru	Poland
Romania	Russian	Federation	Serbia	Seychelles
South Africa	St Kitts and Nevis	St Lucia	St Vincent and the Grenadines	Suriname
Turkey	Uruguay	Venezuela RB		
High income economies				
Andorra	Antigua and Barbuda	Aruba	Australia	Austria
Bahamas The	Bahrein	Barbados	Belgium	Bermuda
Brunei	Darussalam	Canada	Cayman Islands	Channel Islands
Croatia	Cyprus	Czech Republic	Denmark	Estonia
Equatorial	Guinea	Faeroe Islands	Finland	France
French Polynesia	Germany	Greece	Greenland	Guam
Hong Kong China	Hungary	Iceland	Ireland	Isle of Man
Israel	Italy	Japan	Korea Rep	Kuwait
Liechtenstein	Luxembourg	Macao China	Malta	Monaco
Netherlands	Netherlands Antilles	New Caledonia	New Zealand	Northern Mariana Islands
Norway	Oman	Portugal	Puerto Rico	Qatar
San Marino	Saudi Arabia	Singapore	Slovak Republic	Slovenia
Spain	Sweden	Switzerland	Tanzania and Tobago	United Arab Emirates
United Kingdom	United States	Virgin Islands (U.S.)		