Outdoor Plus Indoor Air Pollution From Fossil Fuels, Biofuels, Bioenergy, and Biomass Burning is the Second Leading Cause of Death Worldwide, and a 100 Percent WWS World Will Eliminate Most of These Deaths

In

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7.6.2. Avoided Health Costs from Air Pollution

Transitioning homes, towns, cities, states, provinces, and countries to WWS immediately reduces air pollution health problems. Fewer health problems save money by reducing hospitalization rates, emergency room visits, lost work days, lost school days, insurance rates, taxes, workman's compensation rates, and loss of companionship while improving quality of life.

Air pollution causes premature mortality in several ways. It contributes to death from heart disease, stroke, **chronic obstruction pulmonary disease** (**COPD**), lower respiratory tract infection, lung cancer, and asthma. Common types of COPD are chronic bronchitis and emphysema. Common types of lower respiratory tract infections are the flu, bronchitis, and pneumonia.

In 2016, 56.9 million people died from all causes worldwide (WHO, 2017a). Table 7.13 shows that air pollution caused between 24 and 45 percent of the deaths for each of five out of the six leading causes of death. About 4.5 million people died prematurely from outdoor air pollution and 7.1 million, from indoor plus outdoor pollution in 2016 (Table 7.13). Thus, about 12.5 percent of all deaths worldwide in 2016 were due to indoor plus outdoor air pollution, making it the **second leading cause of death after heart disease**. Twenty percent of premature air pollution deaths were children age five and younger.

Table 7.13. Leading causes of death worldwide in 2016. Also shown are the percentage and number of deaths in each category due to indoor plus outdoor air pollution and, separately, outdoor air pollution alone.

Cause of death	Total all-cause [a]	Indoor plus outdoor air pollution		Outdoor air pollution only	
	Number of deaths/y (millions)	Percent of all-cause deaths[b]	Number of deaths/y (millions)	Percent of all-cause deaths[c]	Number of deaths/y (millions)
1. Ischemic heart disease (coronary artery disease)	9.43	25	2.36	17	1.60
2. Stroke	5.78	24	1.39	16	0.81
3. COPD (chronic bronchitis, emphysema)[d]	3.04	43	1.31	25	0.76
4. Lower respiratory infection (flu, bronchitis, pneumonia)	2.96	45	1.32	26	0.77
5. Alzheimer's disease/dementia	2.00	0	0	0	0
6. Trachea, bronchus, lung cancers	1.71	29	0.50	16	0.27
7. Diabetes	1.60	0	0	0	0
8. Road accidents	1.40	0	0	0	0
9. Diarrheal disease (cholera, dysentery)	1.38	0	0	0	0
10. Tuberculosis	1.29	0	0	0	0
Asthma	0.42	43	0.18	25	0.10
Total number of deaths worldwide	**56.9**	**12.5**	**7.1**	**7.9**	**4.5**

[a]WHO (2017a).

[b]WHO (2017b), except that the percentage of lower respiratory infection deaths that are due to indoor plus outdoor air pollution is estimated as the percentage of respiratory deaths that are from outdoor air pollution from WHO (2017b) multiplied by the ratio of the percentage of deaths from outdoor-plus-indoor to outdoor air pollution for COPD. The asthma percentage is assumed to be the same as the COPD percentage.

[c]WHO (2017b), except that the percentage of stroke deaths that are due to outdoor air pollution is estimated as the percentage of stroke deaths that are from indoor plus outdoor air pollution from WHO (2017b) multiplied by the ratio of the percentage of outdoor to indoor-plus-outdoor air pollution for ischemic heart disease. The asthma percentage is assumed to be the same as the COPD percentage.

[d]Chronic obstructive pulmonary disease (COPD) deaths are due to smoking and air pollution. They exclude asthma deaths, which are added separately.

Table 7.14 shows the 2016 mean number of deaths from indoor plus outdoor air pollution by country for 183 out of 195 countries of the world. China and India absorb the brunt of mortalities, a combined total of 2.6 million per year (37 percent of all deaths). In addition, Nigeria, Pakistan, Indonesia, Bangladesh, the Philippines, and Russia all suffer more than 100,000 air pollution deaths per year. The highest per capita air pollution death rates are in North Korea (Korea, DPR), Georgia, Chad, Nigeria, Bosnia and Herzegovena, Somalia, Sierra Leone, the Ivory Coast (Cote d'Ivoire), India, Bulgaria, the Central African Republic, China, Niger, and Montenegro, respectively.

Table 7.14. 2016 Mean number of indoor plus outdoor air pollution (AP) deaths, deaths per 100,000 population (WHO, 2017c), and population by country, for 183 countries of the world. Ranked from highest to lowest number of deaths.

	Country	2016 AP deaths	2016 AP deaths per 100,000	2016 Population		Country	2016 AP deaths	2016 AP deaths per 100,000	2016 Population
1	China	1,912,570	140	1,366,119,400	93	Tajikistan	5,830	70	8,328,400
2	India	1,785,870	141	1,266,575,400	94	Azerbaijan	5,430	55	9,866,000
3	Nigeria	299,500	159	188,363,000	95	Canada	5,300	15	35,357,400
4	Pakistan	228,270	113	202,012,600	96	Netherlands	5,270	31	17,014,400
5	Indonesia	209,070	81	258,113,600	97	Kyrgyzstan	4,430	74	5,993,200
6	Bangladesh	176,940	103	171,788,200	98	Belgium	4,080	39	10,456,200
7	Philippines	130,520	117	111,558,600	99	Dominican Rep.	4,030	38	10,605,000
8	Russian Fed.	116,320	86	135,256,400	100	Australia	3,910	17	22,988,600
9	Ethiopia	87,400	82	106,591,200	101	Croatia	3,830	86	4,457,400
10	Congo, DR of	82,160	101	81,350,000	102	Moldova	3,760	107	3,510,400
11	United States	78,060	24	325,264,000	103	Congo	3,570	73	4,892,800
12	Brazil	66,460	31	214,398,400	104	Liberia	3,570	83	4,302,200
13	Myanmar	65,980	116	56,881,200	105	Ecuador	3,540	22	16,075,400
14	Egypt	65,730	73	90,041,600	106	Honduras	3,470	39	8,890,600
15	Vietnam	61,900	65	95,223,400	107	Mongolia	3,260	97	3,361,400
16	Ukraine	59,900	137	43,719,400	108	Mauritania	3,240	88	3,678,600
17	Thailand	58,150	85	68,406,800	109	Slovak Republic	3,240	59	5,495,600
18	Korea, DPR	58,020	231	25,115,000	110	Austria	3,210	39	8,223,200
19	Japan	54,450	43	126,637,400	111	Albania	3,190	105	3,038,200
20	Sudan	53,640	105	51,082,400	112	Paraguay	3,160	46	6,864,800
21	Nepal	42,670	133	32,082,600	113	Libya	3,120	43	7,257,400
22	Mexico	39,560	33	119,882,000	114	Portugal	3,030	28	10,828,400
23	Turkey	38,350	46	83,369,800	115	Lithuania	2,860	82	3,483,000
24	Germany	36,320	45	80,715,200	116	Turkmenistan	2,700	51	5,290,600
25	Tanzania	35,170	75	46,896,200	117	Macedonia	2,620	125	2,099,400
26	Cote d'Ivoire	34,180	144	23,736,800	118	El Salvador	2,590	42	6,156,200
27	Afghanistan	31,710	95	33,380,000	119	Nicaragua	2,570	43	5,967,000
28	Uganda	30,700	74	41,491,000	120	Armenia	2,420	81	2,990,600
29	Italy	30,360	49	61,964,600	121	Singapore	2,250	39	5,781,200
30	South Africa	29,480	61	48,334,800	122	Lesotho	2,210	113	1,952,200
31	Poland	29,060	76	38,231,400	123	Lebanon	2,170	52	4,169,400
32	Iran	28,970	35	82,767,800	124	Latvia	2,090	98	2,137,000
33	Niger	27,690	140	19,777,000	125	Gambia	1,950	97	2,009,200
34	Ghana	27,300	101	27,024,800	126	Switzerland	1,930	25	7,708,600
35	Romania	26,560	123	21,593,400	127	Guinea-Bissau	1,900	108	1,759,400

36	Cameroon	25,730	118	21,803,800	128	Israel	1,850	23	8,043,800
37	Yemen	24,550	90	27,279,000	129	Jordan	1,760	26	6,754,000
38	Chad	21,460	181	11,856,000	130	Denmark	1,680	30	5,594,000
39	United Kingdom	20,620	32	64,422,600	131	Namibia	1,670	75	2,222,200
40	Madagascar	20,320	80	25,395,600	132	Sweden	1,650	18	9,171,400
41	Sri Lanka	19,780	89	22,220,200	133	Costa Rica	1,320	27	4,870,800
42	Kenya	18,680	40	46,711,600	134	Botswana	1,170	53	2,208,800
43	Burkina Faso	18,170	93	19,541,200	135	Slovenia	1,130	57	1,976,600
44	Peru	17,830	58	30,739,000	136	Uruguay	1,070	32	3,351,200
45	Mali	17,280	107	16,152,400	137	Kuwait	1,050	37	2,830,000
46	Korea, Rep. of	17,210	35	49,164,400	138	Finland	1,000	19	5,271,200
47	France	16,640	25	66,544,400	139	Swaziland	1,000	69	1,451,400
48	Mozambique	16,620	64	25,963,000	140	Timor-Leste	1,000	77	1,295,400
49	Somalia	16,480	152	10,844,200	141	Ireland	990	20	4,949,000
50	Argentina	16,210	37	43,821,400	142	Panama	960	26	3,704,400
51	Colombia	16,050	34	47,206,600	143	Jamaica	950	32	2,970,200
52	Uzbekistan	15,920	54	29,473,000	144	United Arab Emir.	950	16	5,923,000
53	Guinea	15,380	127	12,108,000	145	Norway	910	19	4,770,400
54	Algeria	14,810	40	37,030,800	146	Montenegro	900	140	645,400
55	Cambodia	13,880	87	15,952,600	147	Gabon	890	51	1,739,400
56	South Sudan	13,680	109	12,546,200	148	Djibouti	840	99	846,800
57	Angola	13,530	67	20,196,800	149	Equatorial Guinea	760	100	760,000
58	Morocco	13,460	40	33,649,600	150	Comoros	750	94	794,000
59	Spain	13,100	27	48,520,000	151	Estonia	740	60	1,239,800
60	Haiti	12,990	127	10,226,600	152	Oman	740	22	3,356,600
61	Benin	12,790	119	10,750,400	153	Fiji	690	76	914,400
62	Burundi	11,950	100	11,945,000	154	Bhutan	660	88	750,000
63	Iraq	11,910	35	34,025,800	155	Mauritius	650	48	1,347,800
64	Saudi Arabia	10,980	39	28,165,400	156	New Zealand	630	14	4,473,400
65	Malaysia	10,830	35	30,941,600	157	Guyana	560	76	742,000
66	Senegal	10,600	74	14,328,000	158	Trinidad & Tobago	550	45	1,219,400
67	Kazakhstan	10,460	57	18,344,000	159	Solomon Islands	430	67	634,600
68	Belarus	10,340	110	9,401,000	160	Cyprus	400	33	1,204,600
69	Syria	10,230	44	23,252,000	161	Cape Verde	380	69	553,400
70	Zambia	10,160	63	16,128,200	162	Suriname	300	51	586,000
71	Cuba	9,910	90	11,011,200	163	Qatar	290	13	2,244,800
72	Malawi	9,830	54	18,212,800	164	Bahrain	210	15	1,378,600
73	Zimbabwe	9,750	67	14,550,400	165	Malta	180	44	415,000
74	Bulgaria	9,600	141	6,807,400	166	Vanuatu	180	76	239,000
75	Togo	8,930	115	7,763,200	167	Barbados	170	57	291,800
76	Sierra Leone	8,920	148	6,029,000	168	Sao Tome+Principe	160	82	197,400
77	Serbia	8,720	122	7,144,000	169	Belize	120	35	353,600
78	Venezuela	8,610	29	29,675,200	170	Luxembourg	120	23	532,800
79	Georgia	8,290	184	4,508,000	171	Samoa	120	62	199,200
80	Greece	8,290	77	10,769,200	172	Micronesia	100	93	104,400
81	Hungary	8,190	83	9,872,800	173	Kiribati	90	88	107,200
82	Cent. Afr. Rep.	7,770	141	5,511,800	174	Bahamas	70	22	327,600
83	Laos	7,720	110	7,019,000	175	Saint Lucia	60	38	164,400
84	Rwanda	7,670	59	12,995,000	176	Tonga	60	57	106,800
85	Guatemala	7,590	50	15,188,000	177	Grenada	50	44	111,400
86	Bosnia & Herz.	7,330	159	4,612,800	178	Iceland	50	17	321,000
87	Czech Republic	6,470	64	10,106,600	179	Maldives	50	14	392,800
88	Eritrea	6,340	95	6,674,400	180	St. Vinc. & Grenad.	50	48	102,600
89	Tunisia	6,340	57	11,128,400	181	Seychelles	50	56	92,800
90	Chile	6,150	35	17,559,600	182	Brunei Darussalam	40	9	436,800
91	Papua New Guinea	6,110	90	6,789,400	183	Antigua & Barbuda	30	28	93,200
92	Bolivia	6,030	55	10,968,800					
						Total	**7.01 mil.**	**95.6**	**7.33 billion**

The Global Burden of Disease study (GBD, 2015) similarly estimated that about 5.5 (5.1 to 5.9) million deaths worldwide in 2013 were caused by indoor plus outdoor air pollution. Of these, 2.8 to 3.1 million were from outdoor $PM_{2.5}$, 0.16 to 0.27 million were from outdoor ozone, and 2.5 to 3.3 million were from indoor air pollution from solid fuel burning.

More recently, Burnett et al. (2018) calculated 8.9 (7.5 to 10.3) million deaths per year worldwide in 2015 due to indoor plus outdoor air pollution. They hypothesized that the additional deaths from air pollution may have been because previous studies considered only a limited number of categories of death that air pollution contributes to.

The air pollution deaths in Tables 7.13 and 7.14 are due almost all to combustion products of fossil fuels, biofuels, bioenergy, open biomass burning, and human-caused wildfires. The indoor mortalities are additionally due to the indoor burning of bioenergy (e.g., wood, dung, waste), coal, and gas for home heating and cooking, primarily in developing countries. A 100 percent WWS world will eliminate about 90 percent of the outdoor plus indoor air pollution deaths. Controlling open biomass burning and human-caused wildfires will address most of the rest (Section 2.9.1).

Because premature mortalities arising from a BAU energy infrastructure result in a social health cost to society, it is important to quantify the avoided cost of reducing such mortalities, related morbidities, and non-health costs due to air pollution. This is done next.

The total annual damage cost ($/y USD) of air pollution due to conventional fuels (fossil fuel and biofuel combustion and evaporative emissions) in a country is estimated as

$$AP_{C,Y} = D_{C,Y} VOSL_{C,Y} F_1 F_2 \qquad (7.5)$$

(Jacobson et al., 2017), where $D_{C,Y}$ is the air pollution premature mortality rate (deaths/y) in country C in target year Y, $VOSL_{C,Y}$ is the value of statistical life ($/death) in the country and for the target year, F_1 is the ratio of mortality plus **morbidity** (illness) costs to mortality costs alone, and F_2 is the ratio of health cost (mortality plus morbidity costs) plus non-health costs to health costs alone. **Non-health costs** include costs due to animal health impacts, lost visibility, reduced agricultural output, and corrosion to building materials and works of art. Table 7.15 gives low, medium, and high estimates of F_1 and F_2. These are held constant for all countries and years.

The premature mortality rate in a country in target year Y is projected from a base year (BYD) during which death rates from air pollution are available, with

$$D_{C,Y} = D_{C,BYD}\left(e^{\Delta A_C[Y-BYD]}\right)\left(\frac{P_{C,Y}}{P_{C,BYD}}\right)^{\kappa} \qquad (7.6)$$

where ΔA_C (Table 7.15) is the fractional rate of change per year in the air pollution death rate in country C due to emission controls, P is population, and κ is the change in exposed population per unit change in population (Table 7.15). Figure 7.1 shows the application of Equation 7.6 to 24 world regions encompassing 143 countries. These countries were home to 96 percent of 2016 indoor plus outdoor air pollution mortalities worldwide.

Figure 7.1. Year 2016 and projected year 2050 indoor plus outdoor air pollution mortalities per year in 24 world regions encompassing 143 countries (see Table 8.5 for a list of countries in each region). Year 2016 data are obtained by multiplying country-specific indoor plus outdoor air pollution deaths per 100,000 population from WHO (2017c) by 2016 country population. 2050 estimates are obtained from Equation 7.6. BAU energy is responsible for about 90 percent of the mortalities. Most of the rest are from open biomass burning, wildfires, and dust.

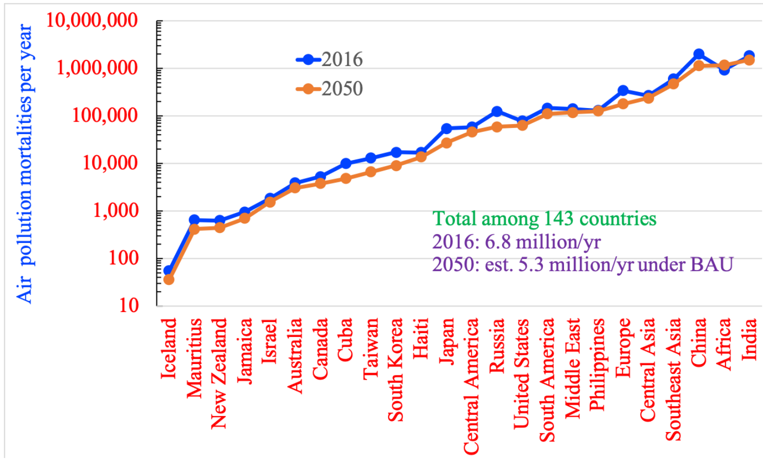

Figure 1 indicates that BAU mortalities may be, on average, about 22 percent less in 2050 than in 2016. Reductions occur in almost all world regions despite higher populations in all regions in 2050. The reason is that improvements in BAU emission-reduction technologies between 2016 and 2050 outpace population growth in almost all regions. The only exception is in Africa, where population growth is so high, it outpaces technology improvements, resulting in higher air pollution mortality in 2050 than in 2016.

The **value of statistical life** is a widely used metric determined by economists to assign the cost of reducing mortality risk. It is the value of reducing 1 statistical mortality in a population. For example, if the average person in a city of 100,000 is willing to pay \$75 to reduce her or his mortality risk by 1/100,000th, the statistical value of reducing one mortality is \$7.5 million. The value of statistical life is also determined from how much more employers pay their workers who have a higher risk of dying on the job.

The VOSL varies with time and country. An estimate of the variation of VOSL (USD \$million per death in 2013 USD) in country C during year Y is

$$VOSL_{C,Y} = VOSL_{US,Y}\left(T + \left[1-T\right]\left[\frac{G_{C,Y}}{G_{US,Y}}\right]^{\gamma_{GDP,US,BYV}\left(\frac{G_{C,Y}}{G_{US,BYV}}\right)^{\gamma_{GDP}}}\right) \tag{7.7}$$

where

$VOSL_{US,Y}$ is the VOSL in the U.S. in year Y (given in Table 7.15 for Y=2050);
T is the fraction of the country's VOSL that is held constant at the U.S. VOSL for that year;
$G_{C,Y}$ is the **gross domestic product** (**GDP**) per capita in the country in year Y;
$G_{US,Y}$ is the U.S. GDP per capita in year Y (estimated in Table 7.15 for Y=2050);
$G_{US,BYV}$ is the U.S. GDP per capita in base year BYV for calculating VOSL (Table 7.15 for BYV=2006);
$\gamma_{GDP,US,BYV}$ is the elasticity of the GDP per capita in base year BYV (Table 7.15 for BYV=2006); and
γ_{GDP} is the elasticity of the GDP per capita for all years (Table 7.15).

The GDP per capita in Equation 7.7 is the GDP at **purchasing power parity** (**PPP**). The GDP at PPP means that the GDP is determined by equalizing the value of a basket of goods in one country versus another, taking into account the currency exchange rate. For example, suppose countries A and B have a normal GDP per capita of \$20 and \$40, respectively, but a cup of coffee costs \$5 in country A and \$20 in country B. In that case, a consumer in country B can purchase only one-fourth the goods that a consumer in country A can for the same amount of money. If we make country A the reference country, then its GDP at PPP is still \$20 per person, but the GDP at PPP of the second country is \$40 per capita × (\$5 per cup in country A / \$20 per cup in country B) = \$10 per person. So, although the normal GDP per capita is higher in Country B, the GDP at PPP is higher in Country A.

Equation 7.7 and the corresponding values of T in Table 7.15 indicate that a small portion of the VOSL is assumed to be constant across all countries. This constant portion is the fraction of the VOSL that is independent of relative wealth, productivity or consumption. The equation also indicates that the VOSL is a function of change in income. In addition, the elasticity of the GDP per capita is itself a function of the GDP per capita ratio between the country and the U.S.

Table 7.15. Parameters in the calculation of the value of statistical life over time and by country.

Parameter	LCHB	Middle	HCLB
U.S. VOSL in base year 2006 ($VOSL_{US,BYV}$) (\$mil/death USD 2006)	9.00	7.00	5.00
U.S. VOSL in target year 2050 ($VOSL_{US,Y}$) (\$mil/death USD 2013)	15.37	10.40	6.47
2006 global average VOSL (\$mil/death USD 2006)	4.00	3.48	3.43
2050 global average VOSL (\$mil/death USD 2013)	8.15	7.09	6.99
U.S. GDP per capita in 2006 ($G_{US,BYV}$) (USD \$/person 2006)	52,275	52,275	52,275
U.S. GDP per capita target year 2050 ($G_{US,Y}$) (USD \$/person 2013)	96,093	96,093	96,093
Multiplier for morbidity impacts (F_1)	1.25	1.15	1.05
Multiplier for non-health impacts (F_2)	1.10	1.10	1.05
Fractional reduction in mortalities per year (ΔA_c)	-0.014	-0.015	-0.016
Exponent giving change in mortality with population change (κ)	1.14	1.11	1.08
Fraction of country's VOSL fixed at U.S. TY value (T)	0.10	0.00	0.00
GDP/capita elasticity ($\gamma_{GDP,US,BYV}$) of VOSL, U.S. base year 2006	0.75	0.50	0.25
GDP/capita elasticity (γ_{GDP}) of VOSL, all years	-0.15	-0.15	-0.15

LCHB = low cost, high benefit. HCLB = high cost, low benefit. VOSL = value of statistical life. GDP = gross domestic product at purchasing power parity (PPP). From Jacobson et al. (2017), except that the low and high fraction reduction in mortalities per year are updated here.

Example 7.4. Estimating the value of statistical life.
Estimate the medium number of premature air pollution deaths in Country C in 2050 if the number of deaths in base year 2018 is 10,000/y, the population in the base year is 30 million, and the population in 2050 is 50 million. Also, estimate the VOSL and cost of air pollution in 2050 in the country assuming the GDP per capita in 2050 in the country is USD \$40,000/person.

Solution
From Equation 7.6, the number of premature deaths in the country is estimated to increase to about 10,909/y. Thus, the impact of the increase in population is offset partly by the impact of better emission controls. From Equation 7.7, the value of statistical life in the country in 2050 is \$6.59 million in 2013 USD. Finally, from Equation 7.5, the air pollution mortality, morbidity, and non-health effects cost is \$90.9 billion/y.

Equation 7.6 requires a premature mortality rate from air pollution in a base year in each country. Such an estimate can be obtained from data, such as those data shown in Table 7.13, but for individual countries. Such data include the number of actual deaths occurring in each country due to a specific cause, as denoted on death certificates, and an approximation of how many deaths by each cause were due to air pollution.

Table 7.11 estimates the avoided premature mortalities from air pollution by country in 2050 upon a conversion to 100 percent WWS. The mortalities are determined from Equation 7.6 using base-year death rates from 2016. Base-year indoor plus outdoor air pollution death rates are determined for each country by multiplying the country-specific total number of air pollution mortalities per 100,000 population from WHO (2017b) by the population of the country.

Table 7.11 also shows the resulting avoided health cost (from Equation 7.5) per unit of BAU energy eliminated due to switching to WWS. Transitioning to 100 percent WWS will avoid millions of premature deaths each year and save the equivalent of 16.9 ¢/kWh (USD 2013), which is more than the direct cost of energy. The cost savings per unit energy translates to an aggregate avoided air pollution mortality, morbidity, and non-health cost in 2050 of about \$30 trillion/y.

A second way to determine premature air pollution mortalities by region or country is with a health effects equation. The equation combines concentrations of $PM_{2.5}$ and O_3 with estimates of the population exposed to those concentrations and with relative risk estimates of premature mortality as a function of $PM_{2.5}$ and O_3 concentrations.

The **health effects equation** gives the death rate (e.g., deaths per year), cancer rate, hospitalization rate, etc., due to exposure to a pollutant as

$$y = y_0 P\left(1 - \exp\left[-\beta \times \max\left(x - x_{th}, 0\right)\right]\right) \tag{7.8}$$

where x is the average concentration or mixing ratio of the pollutant, x_{th} is the threshold concentration or mixing ratio below which no health effect occurs, β is the **relative risk**, or fractional increase in the risk of the health effect occurring per unit concentration x, y_0 is the baseline health effect rate per unit population (e.g., all-cause deaths per year per 100,000 population), and P is the population (e.g., Jacobson, 2010b).

The concentrations are obtained from measurements or computer model simulation. The advantage of using measurements is that they are fairly accurate. However, such data are usually scattered sparsely throughout a country, and concentrations measured in one location may not be representative of concentrations nearby. The advantage of using a model is that it has complete horizontal and vertical coverage of a country. The disadvantage is that the model estimates are less accurate than the measurements.

Table 7.16 gives relative risks and threshold values for $PM_{2.5}$, O_3, and carcinogens.

Table 7.16. Relative risks (β) of premature mortality due to $PM_{2.5}$ and O_3, and of cancers over 70 years for various carcinogens.

	Low	Medium	High
Long-term $PM_{2.5}$ exposure[a]			
All-cause mortality	0.0035	0.0055	0.0076
Cardiopulmonary mortality	0.0100	0.0129	0.0159
Ischemic heart disease mortality	0.0175	0.0217	0.0259
Lung Cancer mortality	0.0055	0.0129	0.0203
Short-term O_3 exposure[b]			
All-cause mortality (1-h max O_3)	0.0002	0.0004	0.0006
All-cause mortality (8-h max O_3)	0.00027	0.00053	0.0008
All-cause mortality (24-h O_3)	0.0005	0.001	0.0015
Cancers over 70 years[c]	U.S. EPA CURES		OEHHA CURES
Formaldehyde	1.3×10^{-5}		6.0×10^{-6}
Acetaldehyde	2.2×10^{-6}		2.7×10^{-6}
Butadiene	3.0×10^{-5}		1.7×10^{-4}
Benzene	5.0×10^{-6}		2.9×10^{-5}

[a]The relative risks due to the long-term effects of $PM_{2.5}$ are the fractional increases in the cause of death specified per $\mu g/m^3$ increase in annual average outdoor $PM_{2.5}$ concentration (Krewski et al., 2009, based on data for 1999 to 2000; CARB, 2010). The relative risks apply only above a threshold concentration of $x_{th} = 5.8\ \mu g/m^3$, the lowest annual averaged $PM_{2.5}$ concentration measured in Krewski et al. (2009). The relative risks apply only for people older than 30 years. The low threshold due to health problems from $PM_{2.5}$ is $0\ \mu g/m^3$, but the relative risk down to zero is uncertain. Jacobson (2010b) estimate the relative risk down to zero as one-fourth that above x_{th}. The low and high values in the table represent 95 percent confidence intervals. Ischemic heart disease is a subset of cardiopulmonary causes of death. Those two and lung cancer are a subset of the all-cause death rate.

[b]The relative risks (for all ages) due to the short-term effects of O_3 are the fractional increase in all-cause daily mortality that is due to short-term exposure to a 1 ppbv increase in the highest 1-hour average ozone level during a day, the highest 8-hour average ozone level during a day, or the 24-hour average ozone during a day (Ostro et al., 2006). The low threshold for ozone health effects is $x_{th} = 35$ ppmv.

CURES are cancer unit risk estimates. They are 70-year cancer risks per $\mu g/m^3$ sustained concentration change of a carcinogen. Thus, divide the CURES by 70 years for use in Equation 7.8 to obtain the number of new cancers (not necessarily cancer deaths) per year due to exposure to the carcinogen. No low thresholds apply. The two sources of CURES are the U.S.

Environmental Protection Agency (U.D. EPA) and the California Office of Environmental Health Hazard Assessment (OEHHA) (Jacobson, 2010b).

Equation 7.8 can be applied over very small regions, such as a neighborhood, or a whole country. When it is applied to each of many small regions adjacent to each other, results are summed over all regions to obtain a total number of premature mortalities per year, for example.

Example 7.5. Estimating the number of premature mortalities due to ozone.
Estimate the number of premature mortalities in the United States per year due to short-term ozone exposure if the entire population of 300 million were exposed to 40 ppbv ozone over a year. Assume the all-cause death rate is approximately y_0 = 833 deaths per year per 100,000 population.

Solution
Substituting y_0=0.00833 deaths per person, P=300,000,000 people, β=0.0004 per ppbv, x=40 ppbv, and x_{th}=35 ppbv into Equation 7.8 gives y≈5,000 additional premature deaths per year due to ozone in the U.S.

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