C-R Functions Linking Air Pollution and Adverse Health Effects

After selecting studies appropriate for the present analysis, the published information was used to derive a C-R function for estimating nationwide benefits for each health effect considered. In general, these functions combine air quality changes, the affected population and information regarding the expected per person change in incidence per unit change in pollutant level. The following tables present the functions used in this analysis, information needed to apply these functions, and references for information.

Carbon Monoxide

Four C-R relationships are available for estimating hospital admissions related to ambient CO levels. These are summarized in Table D-15.

Table D-15
Summary of C-R Functions for Carbon Monoxide

Health Endpoint	C-R Function	Source of C-R Function
hospital admissions – asthma	$\Delta asthma\,admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta CO} - 1)\right] \cdot pop$, where: y_0 = daily hospital admission rate for asthma per person = 4.75 E-6 β = CO coefficient = 0.0332 ΔCO = change in daily average CO concentration (ppm) pop = population of all ages σ_β = standard error of β = 0.00861	Study: Burnett et al. (1999) Location: Toronto, Canada Other pollutants in model: $PM_{2.5-10}$, O_3
hospital admissions – obstructive lung disease	$\Delta obs.\,lung\,disease\,admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta CO} - 1)\right] \cdot pop$, where: y_0 = daily hospital admission rate for obstructive lung disease per person = 5.76 E-6 β = CO coefficient = 0.0250 ΔCO = change in daily average CO concentration (ppm) pop = population of all ages σ_β = standard error of β = 0.0165	Study: Burnett et al. (1999) Location: Toronto, Canada Other pollutants in model: $PM_{2.5-10}$, O_3
hospital admissions – COPD	$\Delta COPD\,admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta CO} - 1)\right] \cdot pop$, where: y_0 = daily hospital admission rate for COPD per person = 3.75 E-5 β = CO coefficient = 0.0573 Δ CO = change in daily average CO concentration (ppm) pop = population age 65 and older σ_β = standard error of β = 0.0329	Study: Moolgavkar (1997) Location: Minneapolis-St. Paul Other pollutants in model: O_3, PM_{10}
hospital admissions – asthma	$\Delta asthma\,admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta CO} - 1)\right] \cdot pop$, where: y_0 = daily hospital admission rate for asthma per person = 4.52 E-6 β = CO coefficient = 0.0528 Δ CO = change in daily average CO concentration (ppm) pop = population of ages < 65 σ_β = standard error of β = 0.0185	Study: Sheppard (1999) Location: Seattle, WA Other pollutants in model: $PM_{2.5}$
hospital admissions – dysrhythmias	$\Delta dysrhythmias\,admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta CO} - 1)\right] \cdot pop$, where: y_0 = daily hospital admission rate for dysrhythmias per person = 6.46 E-6 β = CO coefficient = 0.0573 ΔCO = change in daily average CO concentration (ppm) pop = population of all ages σ_β = standard error of β = 0.0229	Study: Burnett et al. (1999) Location: Toronto, Canada Other pollutants in model: $PM_{2.5}$, O_3

Health Endpoint	C-R Function	Source of C-R Function
hospital admissions – congestive heart failure	$$\Delta congestive\ heart\ failure\ admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta CO} - 1)\right] \cdot pop,$$ where: y_0 = daily hospital admission rate for congestive heart failure per person = 9.33 E-6 β = CO coefficient = 0.0340 ΔCO = change in daily average CO concentration (ppm) pop = population of all ages σ_β = standard error of β = 0.0163	Study: Burnett et al. (1999) Location: Toronto, Canada Other pollutants in model: NO_2
hospital admissions – ischemic heart disease	$$\Delta ischemic\ heart\ disease\ admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta CO} - 1)\right] \cdot pop,$$ where: y_0 = daily hospital admission rate for ischemic heart disease per person 65 and older = 9.96 E-5 β = CO coefficient= 0.000467 ΔCO = change in daily one-hour maximum CO concentration (ppm) pop = population age 65 and older σ_β = standard error of β = 0.000435	Study: Schwartz and Morris (1995) Location: Detroit, MI Other pollutants in model: PM_{10}
hospital admissions – congestive heart failure	$$\Delta congestive\ heart\ failure\ admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta CO} - 1)\right] \cdot pop,$$ where: y_0 = daily hospital admission rate for congestive heart failure per person 65 and older = 5.82 E-5 β = CO coefficient = 0.0170 ΔCO = change in daily one-hour maximum CO concentration (ppm) pop = population age 65 and older σ_β = standard error of β = 0.00468	Study: Schwartz and Morris (1995) Location: Detroit, MI Other pollutants in model: PM_{10}
hospital admissions – cardiovascular	$$\Delta cardiovascular\ admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta CO} - 1)\right] \cdot pop,$$ where: y_0 = daily hospital admission rate for cardiovascular disease per person 65 and older = 2.23 E-4 β = CO coefficient = 0.0127 ΔCO = change in daily one-hour maximum CO concentration pop = population age 65 and older σ_β = standard error of β = 0.00255	Study: Schwartz (1999) Location: eight U.S. counties Other pollutants in model: PM_{10}
hospital admissions – cardiovascular	$$\Delta cardiovascular\ admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta CO} - 1)\right] \cdot pop,$$ where: y_0 = daily hospital admission rate for cardiovascular disease per person 65 and older = 2.23 E-4 β = CO coefficient = 0.0139 ΔCO = change in daily one-hour maximum CO concentration pop = population age 65 and older σ_β = standard error of β = 0.00715	Study: Schwartz (1997) Location: Tucson, AZ Other pollutants in model: PM_{10}

Nitrogen Dioxide

Nitrogen dioxide (NO_2) is the primary focus of health studies on the nitrogen oxides and serves as the basis for this analysis. Table D-16 summarizes the C-R functions that are used to quantify the relationship between NO_2 and adverse health effects.

Table D-16
Summary of C-R Functions for Nitrogen Dioxide

Health Endpoint	C-R Function	Source of C-R Function
hospital admissions – all respiratory	$\Delta All\ respiratory = -\left[y_0 \cdot (e^{-\beta \cdot \Delta NO_2} - 1)\right] \cdot pop$, where: y_0 = daily hospital admission rate for all respiratory per person = 2.58 E-5 β = NO_2 coefficient = 0.00378 ΔNO_2 = change in daily 12-hour average NO_2 concentration (ppb) pop = population of all ages σ_β = standard error of β = 0.00221	Study: Burnett et al. (1997b) Location: Toronto, Canada Other pollutants in model: $PM_{2.5-10}$, O_3, SO_2
hospital admissions – respiratory infection	$\Delta Respiratory\ Infection\ Admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta NO_2} - 1)\right] \cdot pop$, where: y_0 = daily hospital admission rate for respiratory infection per person = 1.56 E-5 β = NO_2 coefficient = 0.00172 ΔNO_2 = change in daily average NO_2 concentration (ppb) pop = population of all ages σ_β = standard error of β = 0.000521	Study: Burnett et al. (1999) Location: Toronto, Canada Other pollutants in model: $PM_{2.5}$, O_3
hospital admissions – pneumonia	$\Delta pneumonia\ admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta NO_2} - 1)\right] \cdot pop$, where: y_0 = daily hospital admission rate for pneumonia per person = 5.30 E-5 β = NO_2 coefficient = 0.00169 ΔNO_2 = change in daily average NO_2 concentration (ppb) pop = population age 65 and older σ_β = standard error of β = 0.00125	Study: Moolgavkar et al. (1997) Location: Minneapolis, MN Other pollutants in model: O_3, SO_2, PM_{10}
hospital admissions – congestive heart failure	$\Delta Congestive\ Heart\ Failure\ Admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta NO_2} - 1)\right] \cdot pop$, where: y_0 = daily hospital admission rate for congestive heart failure per person = 9.33 E-6 β = NO_2 coefficient = 0.00264 ΔNO_2 = change in daily average NO_2 concentration (ppb) pop = population of all ages σ_β = standard error of β = 0.000769	Study: Burnett et al. (1999) Location: Toronto, Canada Other pollutants in model: CO

Health Endpoint	C-R Function	Source of C-R Function
hospital admissions – ischemic heart disease	$\Delta Ischemic\ Heart\ Disease\ Admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta NO_2} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for ischemic heart disease per person = 2.23 E-5 β = NO_2 coefficient = 0.00318 ΔNO_2 = change in daily average NO_2 concentration (ppb) pop = population of all ages σ_β = standard error of β = 0.000521	Study: Burnett et al. (1999) Location: Toronto, Canada Other pollutants in model: SO_2
respiratory symptoms	$\Delta resp.symptoms = \left[\frac{1}{1+e^{-\alpha - NO_{2,pre-CAAA} \cdot \beta - gender \cdot \gamma}} - \frac{1}{1+e^{-\alpha - NO_{2,post-CAAA} \cdot \beta - gender \cdot \gamma}}\right] \cdot pop,$ where: α = constant = -0.536 β = NO_2 coefficient = 0.0275 γ = gender coefficient (used for males only) = -0.0295 ΔNO_2 = change in annual NO_2 concentration (ppb) pop = children ages 6-7 σ_β = standard error of β = 0.0132	Study: Hasselblad et al. (1992) Location: Middlesborough, England Other pollutants in model: none Comments: The NO_2 coefficient was reported by Hasselblad et al. The constant and the gender coefficient were obtained via personal communication with V. Hasselblad 2/28/95 by Abt Associates. The equation is based on study results by Melia et al. (1980).

Ozone

The health effects literature includes studies of the relationships between ozone and a variety of health effects. Table D-17 summarizes the ozone C-R functions used in this analysis.

Table D-17
Summary of C-R Functions for Ozone

Health Endpoint	C-R Function	Source of C-R Function
mortality	$\Delta Mortality = -\left[y_0 \cdot (e^{-\beta \cdot \Delta O_3} - 1)\right] \cdot pop,$ where: y_0 = non-accidental deaths per person of any age β = ozone coefficient = 0.000634 ΔO_3 = change in daily one-hour maximum ozone concentration (ppb) pop = population all ages σ_β = standard error of β = 0.000251	Study: Ito and Thurston (1996) Location: Chicago, IL Other pollutants in model: PM_{10}
mortality	$\Delta Mortality = -\left[y_0 \cdot (e^{-\beta \cdot \Delta O_3} - 1)\right] \cdot pop,$ where: y_0 = non-accidental deaths per person of any age β = ozone coefficient = 0 ΔO_3 = change in daily 1-hour maximum ozone concentration (ppb) pop = population all ages σ_β = standard error of β = 0.000214	Study: Kinney et al. (1995) Location: Los Angeles, CA Other pollutants in model: PM_{10}
mortality	$\Delta Mortality = -\left[y_0 \cdot (e^{-\beta \cdot \Delta O_3} - 1)\right] \cdot pop,$ where: y_0 = non-accidental deaths per person of any age β = ozone coefficient = 0.000611 ΔO_3 = change in daily average ozone concentration (ppb) pop = population all ages σ_β = standard error of β = 0.000216	Study: Moolgavkar et al. (1995) Location: Philadelphia, PA Other pollutants in model: SO_2, TSP
mortality	$\Delta Mortality = -\left[y_0 \cdot (e^{-\beta \cdot \Delta O_3} - 1)\right] \cdot pop,$ where: y_0 = non-accidental deaths per person of any age β = ozone coefficient = 0.000936 ΔO_3 = change in daily average ozone concentration (ppb) pop = population all ages σ_β = standard error of β = 0.000312	Study: Samet et al. (1997) Location: Philadelphia, PA Other pollutants in model: CO, NO_2, SO_2, TSP
adult onset asthma	$\Delta Chronic\ Asthma = -\left[\frac{y_0}{(1-y_0) \cdot e^{\Delta O_3 \cdot \beta} + y_0} - y_0\right] \cdot pop,$ where: y_0 = annual asthma incidence rate per person = 0.00219 β = estimated O_3 coefficient = 0.0277 ΔO_3 = change in annual average 8-hour O_3 concentration pop = population of non-asthmatic males ages 27 and older σ_β = standard error of β = 0.0135	Study: McDonnell et al. (1999) Location: California Other pollutants in model: none
hospital admissions – all respiratory	$\Delta All\ respiratory = -\left[y_0 \cdot (e^{-\beta \cdot \Delta O_3} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for all respiratory per person = 2.58 E-5 β = O_3 coefficient = 0.00498 ΔO_3 = change in daily 12-hour average O_3 concentration (ppb) pop = population of all ages σ_β = standard error of β = 0.00106	Study: Burnett et al. (1997b) Location: Toronto, Canada Other pollutants in model: $PM_{2.5-10}$, NO_2, SO_2

Health Endpoint	C-R Function	Source of C-R Function
hospital admissions – asthma	$\Delta Asthma\ Admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta O_3} - 1)\right] \cdot pop$, where: y_0 = daily hospital admission rate for asthma per person = 4.75 E-6 β = ozone coefficient = 0.00250 ΔO_3 = change in daily average ozone concentration (ppb) pop = population of all ages σ_β = standard error of β = 0.000718	Study: Burnett et al. (1999) Location: Toronto, Canada Other pollutants in model: CO, $PM_{2.5\text{-}10}$
hospital admissions – obstructive lung disease	$\Delta Obstructive\ Lung\ Disease\ Admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta O_3} - 1)\right] \cdot pop$, where: y_0 = daily hospital admission rate for obstructive lung disease per person = 5.76 E-6 β = ozone coefficient = 0.00303 ΔO_3 = change in daily average ozone concentration (ppb) pop = population of all ages σ_β = standard error of β = 0.00110	Study: Burnett et al. (1999) Location: Toronto, Canada Other pollutants in model: CO, $PM_{2.5\text{-}10}$
hospital admissions – respiratory infection	$\Delta Respiratory\ Infection\ Admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta O_3} - 1)\right] \cdot pop$, where: y_0 = daily hospital admission rate for respiratory infection per person = 1.56 E-5 β = ozone coefficient = 0.00198 ΔO_3 = change in daily average ozone concentration (ppb) pop = population of all ages σ_β = standard error of β = 0.000520	Study: Burnett et al. (1999) Location: Toronto, Canada Other pollutants in model: $PM_{2.5}$, NO_2
hospital admissions – all respiratory	$\Delta all\ respiratory\ admissions = \beta \cdot \Delta O_3 \cdot pop$, where: β = ozone coefficient = 1.68 E-8 ΔO_3 = change in daily one-hour maximum ozone concentration (ppb) pop = population all ages σ_β = standard error of β = 9.71 E-9 .	Study: Thurston et al. (1994) Location: Toronto, Canada Other pollutants in model: $PM_{2.5}$
hospital admissions – pneumonia	$\Delta pneumonia\ admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta O_3} - 1)\right] \cdot pop$, where: y_0 = daily hospital admission rate for pneumonia per person = 5.30 E-5 β = O_3 coefficient = 0.00370 ΔO_3 = change in daily average O_3 concentration (ppb) pop = population age 65 and older σ_β = standard error of β = 0.00103	Study: Moolgavkar et al. (1997) Location: Minneapolis, MN Other pollutants in model: SO_2, NO_2, PM_{10}
hospital admissions – COPD	$\Delta COPD\ admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta O_3} - 1)\right] \cdot pop$, where: y_0 = daily hospital admission rate for COPD per person = 3.75 E-5 β = O_3 coefficient = 0.00274 ΔO_3 = change in daily average O_3 concentration (ppb) pop = population age 65 and older σ_β = standard error of β = 0.00170	Study: Moolgavkar et al. (1997) Location: Minneapolis, MN Other pollutants in model: CO, PM_{10}

Health Endpoint	C-R Function	Source of C-R Function
hospital admissions – pneumonia	$\Delta pneumonia\,admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta O_3} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for pneumonia per person = 5.30 E-5 β = O_3 coefficient = 0.00280 ΔO_3 = change in daily average O_3 concentration (ppb) pop = population age 65 and older σ_β = standard error of β = 0.00172	Study: Schwartz (1994c) Location: Minneapolis, MN Other pollutants in model: PM_{10}
hospital admissions – pneumonia	$\Delta pneumonia\,admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta O_3} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for pneumonia per person = 5.18 E-5 β = O_3 coefficient = 0.00521 ΔO_3 = change in daily average O_3 concentration (ppb) pop = population age 65 and older σ_β = standard error of β = 0.0013	Study: Schwartz (1994b) Location: Detroit, MI Other pollutants in model: PM_{10}
hospital admissions – COPD	$\Delta COPD\,admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta O_3} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for COPD per person = 3.05 E-5 β = O_3 coefficient = 0.00549 ΔO_3 = change in daily average O_3 concentration pop = population age 65 and older σ_β = standard error of β = 0.00205	Study: Schwartz (1994b) Location: Detroit, MI Other pollutants in model: PM_{10}
hospital admissions – all respiratory	$\Delta all\,respiratory\,admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta O_3} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admissions for all respiratory per person 65 and older = 1.187 E-4 β = ozone coefficient = 0.00265 ΔO_3 = change in daily average ozone concentration (ppb) pop = population age 65 and older σ_β = standard error of β = 0.00140	Study: Schwartz (1995) Location: New Haven, CT Other pollutants in model: PM_{10}
hospital admissions – all respiratory	$\Delta all\,respiratory\,related\,admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta O_3} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admissions for all respiratory conditions per person 65 and older = 1.187 E-4 β = ozone coefficient = 0.00715 ΔO_3 = change in daily average ozone concentration (ppb) pop = population age 65 and older σ_β = standard error of β = 0.00257	Study: Schwartz (1995) Location: Tacoma, WA Other pollutants in model: PM_{10}
hospital admissions – cardiac	$\Delta cardiac = -\left[y_0 \cdot (e^{-\beta \cdot \Delta O_3} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for cardiac per person = 3.81 E-5 β = O_3 coefficient = 0.00531 ΔO_3 = change in daily 12-hour average O_3 concentration (ppb) pop = population of all ages σ_β = standard error of β = 0.00142	Study: Burnett et al. (1997b) Location: Toronto, Canada Other pollutants in model: $PM_{2.5\text{-}10}$

Health Endpoint	C-R Function	Source of C-R Function
hospital admissions – dysrhythmias	$$\Delta Dysrhythmias\ Admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta O_3} - 1)\right] \cdot pop,$$ where: y_0 = daily hospital admission rate for dysrhythmias per person = 6.46 E-6 β = ozone coefficient = 0.00168 ΔO_3 = change in daily average ozone concentration (ppb) pop = population of all ages σ_β = standard error of β = 0.00103	Study: Burnett et al. (1999) Location: Toronto, Canada Other pollutants in model: $PM_{2.5}$, CO
emergency room visits - asthma	$$\Delta asthma\ related\ ER\ visits = \frac{\beta}{BasePop} \cdot \Delta O_3 \cdot pop,$$ where: β = ozone coefficient = 0.0203 BasePop = baseline population in northern New Jersey = 4,436,976 ΔO_3 = change in daily five-hour average ozone concentration (ppb) pop = population all ages σ_β = standard error of β = 0.00717	Study: Cody et al. (1992) Location: Northern NJ Other pollutants in model: none Comment: 63 % of estimate used to avoid double-counting hospital admissions for asthma.
emergency room visits - asthma	$$\Delta asthma\ related\ ER\ visits = \frac{\beta}{BasePop} \cdot \Delta O_3 \cdot pop,$$ where: β = ozone coefficient = 0.0443 BasePop = baseline population in northern New Jersey = 4,436,976 ΔO_3 = change in daily five-hour average ozone concentration (ppb) pop = population all ages σ_β = standard error of β = 0.00723	Study: Weisel et al. (1995) Location: Northern, NJ Other pollutants in model: none Comment: 63 % of estimate used to avoid double-counting hospital admissions for asthma.
emergency room visits - asthma	$$\Delta asthma\ related\ ER\ visits = \frac{\beta}{BasePop} \cdot \Delta O_3 \cdot pop,$$ where: β = ozone coefficient = 0.0035 BasePop = baseline population in Saint John, New Brunswick = 125,000 ΔO_3 = change in the daily one-hour maximum ozone concentration (ppb) pop = population all ages σ_β = standard error of β = 0.0018	Study: Stieb et al. (1996) Location: New Brunswick, Canada Other pollutants in model: none Comment: 63 % of estimate used to avoid double-counting hospital admissions for asthma.
presence of any of 19 acute respiratory symptoms	$$\Delta ARD2 \cong \beta^*_{PM_{10}} \cdot \Delta O_3 \cdot pop,$$ where: β^* = first derivative of the stationary probability = 0.000137 ΔO_3 = change in daily one-hour maximum ozone concentration (ppb) pop = population aged 18-65 years old σ_β = standard error of β^* = 0.0000697	Study: Krupnick et al. (1990) Location: Glendora-Covina-Azusa, CA Other pollutants in model: SO_2, COH
self-reported asthma attacks	$$\Delta asthma\ attacks = -\left[\frac{y_0}{(1-y_0) \cdot e^{\Delta O_3 \cdot \beta} + y_0} - y_0\right] \cdot pop,$$ where: y_0 = daily incidence of asthma attacks = 0.027 β = ozone coefficient = 0.00184 ΔO_3 = change in daily one-hour maximum ozone concentration (ppb) pop = population of asthmatics of all ages = 5.61% of the population of all ages σ_β = standard error of β = 0.000714	Study: Whittemore and Korn (1980) Location: Los Angeles, CA Other pollutants in model: TSP

Health Endpoint	C-R Function	Source of C-R Function
respiratory and nonrespiratory conditions resulting in a minor restricted activity day (MRAD)	$\Delta MRAD = -\left[y_0 \cdot (e^{-\beta \cdot \Delta O_3} - 1)\right] \cdot pop,$ where: y_0 = daily MRAD incidence per person = 0.02137 β = inverse-variance weighted $PM_{2.5}$ coefficient = 0.00220 ΔO_3 = change in two-week average of the daily one-hour maximum ozone concentrations (ppb) pop = adult population aged 18 to 65 σ_β = standard error of β = 0.000658	Study: Ostro and Rothschild (1989b) Location: U.S. Other pollutants in model: $PM_{2.5}$ Comments: An inverse-variance weighting used to estimate the coefficient, based on Ostro and Rothschild.

Particulate Matter

The C-R functions used to quantify expected changes in health effects associated with reduced exposure to particulate matter are summarized in Table D-18. The measures of particulate matter used in this analysis are $PM_{2.5}$ and PM_{10}, with a preference for $PM_{2.5}$. Other measures of PM, however, have been used, including total suspended particulates (TSP) and coefficient of haze.

Table D-18
Summary of C-R Functions for Particulate Matter

Health Endpoint	C-R Function	Source of C-R Function
mortality	$$\Delta Nonaccidental\,Mortality = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{2.5}} - 1)\right] \cdot pop,$$ where: y_0 = county-level annual non-accidental deaths of persons ages 30+ per person β = $PM_{2.5}$ coefficient = 0.006408 $\Delta PM_{2.5}$ = change in annual median $PM_{2.5}$ concentration pop = population ages 30 and older σ_β = standard error of β = 0.001509	Study: Pope et al. (1995) Location: 50 U.S. cities Other pollutants in model: none
mortality	$$\Delta Nonaccidental\,Mortality = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{2.5}} - 1)\right] \cdot pop,$$ where: y_0 = county-level annual non-accidental deaths of persons ages 25+ per person β = $PM_{2.5}$ coefficient = 0.0124 $\Delta PM_{2.5}$ = change in annual mean $PM_{2.5}$ concentration pop = population ages 25 and older σ_β = standard error of β = 0.00423	Study: Dockery et al. (1993) Location: six U.S. cities Other pollutants in model: none
neonatal mortality	$$\Delta Infant\,Mortality = -\left[\frac{y_0}{(1-y_0)\cdot e^{\Delta PM_{10}\cdot\beta} + y_0} - y_0\right] \cdot pop,$$ where: y_0 = county annual postneonatal infant deaths per infant 0-1 years old β = PM_{10} coefficient = 0.00392 ΔPM_{10} = change in annual average PM_{10} concentration pop = population infants ages 0-1 σ_β = standard error of β = 0.00122	Study: Woodruff et al. (1997) Location: 86 U.S. metropolitan areas Other pollutants in model: none
chronic bronchitis	$$\Delta Chronic\ Bronchitis = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{10}} - 1)\right] \cdot pop,$$ where: y_0 = annual bronchitis incidence rate per person = 0.00378 β = estimated PM_{10} logistic regression coefficient = 0.00932 ΔPM_{10} = change in annual average PM_{10} concentration pop = population ages 27 and older "without chronic bronchitis" σ_β = standard error of β = 0.00475	Study: Abbey et al. (1993) Location: California Other pollutants in model: none Comments: Abbey et al. used TSP to measure PM. The TSP coefficient is applied to changes in PM_{10}.

Health Endpoint	C-R Function	Source of C-R Function
chronic bronchitis	$\Delta Chronic\ Bronchitis = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{2.5}} - 1)\right] \cdot pop,$ where: y_0 = annual bronchitis incidence rate per person = 0.00378 β = estimated $PM_{2.5}$ logistic regression coefficient = 0.09132 $\Delta PM_{2.5}$ = change in annual average $PM_{2.5}$ concentration pop = population ages 27 and older "without chronic bronchitis" σ_β = standard error of β = 0.00680	Study: Abbey et al. (1995) Location: California Other pollutants in model: none
chronic bronchitis	$\Delta Chronic\, Bronchitis = -\left[\frac{y_0}{(1-y_0)\cdot e^{\Delta PM_{10}\cdot\beta} + y_0} - y_0\right]\cdot\left[\frac{z_0}{y_0}\right]\cdot pop,$ where: y_0 = national chronic bronchitis prevalence rate for individuals 18 and older= 0.0535 z_0 = annual bronchitis incidence rate per person = 0.00378 β = estimated PM_{10} logistic regression coefficient = 0.0123 ΔPM_{10} = change in annual average PM_{10} concentration pop = population ages 30 and older "without chronic bronchitis" σ_β = standard error of β = 0.00434	Study: Schwartz (1993) Location: 53 U.S. urban areas Other pollutants in model: none
hospital admissions – all respiratory	$\Delta All\ respiratory = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{2.5-10}} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for all respiratory per person = 2.58 E-5 β = $PM_{2.5\text{-}10}$ coefficient = 0.00147 $\Delta PM_{2.5\text{-}10}$ = change in daily average $PM_{2.5\text{-}10}$ concentration pop = population of all ages σ_β = standard error of β = 0.00179	Study: Burnett et al. (1997b) Location: Toronto, Canada Other pollutants in model: O_3, NO_2, SO_2
hospital admissions – asthma	$\Delta Asthma\ Admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{2.5-10}} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for asthma per person = 4.75 E-6 β = $PM_{2.5\text{-}10}$ coefficient = 0.00321 $\Delta PM_{2.5\text{-}10}$ = change in daily average $PM_{2.5\text{-}10}$ concentration pop = population of all ages σ_β = standard error of β = 0.00106	Study: Burnett et al. (1999) Location: Toronto, Canada Other pollutants in model: CO, O_3

Health Endpoint	C-R Function	Source of C-R Function
hospital admissions – obstructive lung disease	$\Delta OLD\ Admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{2.5-10}} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for obstructive lung disease per person = 5.76 E-6 β = $PM_{2.5-10}$ coefficient = 0.00310 Δ $PM_{2.5-10}$ = change in daily average $PM_{2.5-10}$ concentration pop = population of all ages σ_β = standard error of β = 0.00163	Study: Burnett et al. (1999) Location: Toronto, Canada Other pollutants in model: CO, O_3
hospital admissions – respiratory infection	$\Delta Respiratory\ Infection\ Admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{2.5}} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for respiratory infection per person = 1.56 E-5 β = $PM_{2.5}$ coefficient = 0.00328 $\Delta PM_{2.5}$ = change in daily average $PM_{2.5}$ concentration pop = population of all ages σ_β = standard error of β = 0.000735	Study: Burnett et al. (1999) Location: Toronto, Canada Other pollutants in model: NO_2, O_3
hospital admissions – all respiratory	$\Delta all\ respiratory\ admissions = \beta \cdot \Delta PM_{2.5} \cdot pop,$ where: β = ozone coefficient = 1.81 E-8 $\Delta PM_{2.5}$ = change in daily average $PM_{2.5}$ pop = population all ages σ_β = standard error of β = 1.79 E-8 .	Study: Thurston et al. (1994) Location: Toronto, Canada Other pollutants in model: O_3
hospital admissions – pneumonia	$\Delta pneumonia\ admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{10}} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for pneumonia per person = 5.30 E-5 β = PM_{10} coefficient = 0.000498 Δ PM_{10} = change in daily average PM_{10} concentration pop = population age 65 and older σ_β = standard error of β = 0.000505	Study: Moolgavkar et al. (1997) Location: Minneapolis, MN Other pollutants in model: O_3, SO_2, NO_2
hospital admissions – COPD	$\Delta COPD\ admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{10}} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for COPD per person = 3.75 E-5 β = PM_{10} coefficient = 0.000877 Δ PM_{10} = change in daily average PM_{10} concentration pop = population age 65 and older σ_β = standard error of β = 0.000777	Study: Moolgavkar et al. (1997) Location: Minneapolis, MN Other pollutants in model: CO, O_3

Health Endpoint	C-R Function	Source of C-R Function
hospital admissions – pneumonia	$\Delta pneumonia\,admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{10}} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for pneumonia per person = 5.18 E-5 β = PM_{10} coefficient = 0.00157 Δ PM_{10} = change in daily average PM_{10} concentration pop = population age 65 and older σ_β = standard error of β = 0.000677	Study: Schwartz (1994c) Location: Minneapolis, MN Other pollutants in model: O_3
hospital admissions – COPD	$\Delta COPD\,admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{10}} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for COPD per person = 3.75 E-5 β = PM_{10} coefficient = 0.00451 Δ PM_{10} = change in daily average PM_{10} concentration pop = population age 65 and older σ_β = standard error of β = 0.00138	Study: Schwartz (1994c) Location: Minneapolis, MN Other pollutants in model: none
hospital admissions – pneumonia	$\Delta pneumonia\,admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{10}} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for pneumonia per person = 5.30 E-5 β = PM_{10} coefficient = 0.00174 Δ PM_{10} = change in daily average PM_{10} concentration pop = population age 65 and older σ_β = standard error of β = 0.000536	Study: Schwartz (1994a) Location: Birmingham, AL Other pollutants in model: none
hospital admissions – COPD	$\Delta COPD\,admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{10}} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for COPD per person = 3.75 E-5 β = PM_{10} coefficient = 0.00239 Δ PM_{10} = change in daily average PM_{10} concentration pop = population age 65 and older σ_β = standard error of β = 0.000838	Study: Schwartz (1994a) Location: Birmingham, AL Other pollutants in model: none
hospital admissions – pneumonia	$\Delta pneumonia\,admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{10}} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for pneumonia per person = 5.18 E-5 β = PM_{10} coefficient = 0.00115 Δ PM_{10} = change in daily average PM_{10} concentration pop = population age 65 and older σ_β = standard error of β = 0.00039	Study: Schwartz (1994b) Location: Detroit, MI Other pollutants in model: O_3

Health Endpoint	C-R Function	Source of C-R Function
hospital admissions – COPD	$$\Delta COPD\ admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{10}} - 1)\right] \cdot pop,$$ where: y_0 = daily hospital admission rate for COPD per person = 3.05 E-5 β = PM_{10} coefficient = 0.00202 Δ PM_{10} = change in daily average PM_{10} concentration pop = population age 65 and older σ_β = standard error of β = 0.00059	Study: Schwartz (1994b) Location: Detroit, MI Other pollutants in model: O_3
hospital admissions – all respiratory	$$\Delta\ all\ respiratory\ admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{10}} - 1)\right] \cdot pop,$$ where: y_0 = daily hospital admission rate for all respiratory per person 65 or older = 1.187 E-4 β = PM_{10} coefficient = 0.00163 Δ PM_{10} = change in daily average PM_{10} concentration pop = population age 65 and older σ_β = standard error of β = 0.000470	Study: Schwartz (1996) Location: Spokane, WA Other pollutants in model: none
hospital admissions – all respiratory	$$\Delta all\ respiratory\ admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{10}} - 1)\right] \cdot pop,$$ where: y_0 = daily hospital admissions for all respiratory per person 65 and older = 1.187 E-4 β = PM_{10} coefficient = 0.00172 Δ PM_{10} = change in daily average PM_{10} concentration pop = population age 65 and older σ_β = standard error of β = 0.000930	Study: Schwartz (1995) Location: New Haven, CT Other pollutants in model: O_3
hospital admissions – all respiratory	$$\Delta all\ respiratory\ related\ admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{10}} - 1)\right] \cdot pop,$$ where: y_0 = daily hospital admissions for all respiratory conditions per person 65 and older = 1.187 E-4 β = PM_{10} coefficient = 0.00227 Δ PM_{10} = change in daily average PM_{10} concentration pop = population age 65 and older σ_β = standard error of β = 0.00145	Study: Schwartz (1995) Location: Tacoma, WA Other pollutants in model: O_3
hospital admissions – asthma	$$\Delta Asthma\ Admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{2.5}} - 1)\right] \cdot pop,$$ where: y_0 = daily hospital admission rate for asthma per person = 4.52 E-6 β = $PM_{2.5}$ coefficient = 0.0027 $\Delta PM_{2.5}$ = change in daily average $PM_{2.5}$ concentration pop = population of ages < 65 σ_β = standard error of β = 0.000948	Study: Sheppard et al. (1999) Location: Seattle, WA Other pollutants in model: CO

Health Endpoint	C-R Function	Source of C-R Function
hospital admissions – cardiac	$\Delta cardiac = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{2.5-10}} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for cardiac per person = 3.81 E-5 β = $PM_{2.5-10}$ coefficient = 0.00704 $\Delta PM_{2.5-10}$ = change in daily average $PM_{2.5-10}$ concentration pop = population of all ages σ_β = standard error of β = 0.00215	Study: Burnett et al. (1997b) Location: Toronto, Canada Other pollutants in model: O_3
hospital admissions – dysrhythmias	$\Delta Dysrhythmias\ Admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{2.5}} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for dysrhythmias per person = 6.46 E-6 β = $PM_{2.5}$ coefficient = 0.00136 $\Delta PM_{2.5}$ = change in daily average $PM_{2.5}$ concentration pop = population of all ages σ_β = standard error of β = 0.000910	Study: Burnett et al. (1999) Location: Toronto, Canada Other pollutants in model: CO, O_3
hospital admissions – ischemic heart disease	$\Delta Ischemic\ Heart\ Disease\ Admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{10}} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for ischemic heart disease per person 65 and older = 9.96 E-5 β = PM_{10} coefficient= 0.000496 ΔPM_{10} = change in daily average PM_{10} concentration pop = population age 65 and older σ_β = standard error of β = 0.000220	Study: Schwartz and Morris (1995) Location: Detroit, MI Other pollutants in model: CO
hospital admissions – congestive heart failure	$\Delta Congestive Heart\ Failure\ Admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{10}} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for congestive heart failure per person 65 and older = 5.82 E-5 β = PM_{10} coefficient = 0.000741 ΔPM_{10} = change in daily average PM_{10} concentration pop = population age 65 and older σ_β = standard error of β = 0.000311	Study: Schwartz and Morris (1995) Location: Detroit, MI Other pollutants in model: CO
hospital admissions – cardiovascular	$\Delta cardiovascular\ admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{10}} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for cardiovascular disease per person 65 and older = 2.23 E-4 β = PM_{10} coefficient = 0.000737 ΔPM_{10} = change in daily average PM_{10} concentration pop = population age 65 and older σ_β = standard error of β = 0.000170	Study: Schwartz (1999) Location: eight U.S. counties Other pollutants in model: CO

Health Endpoint	C-R Function	Source of C-R Function
hospital admissions – cardiovascular	$$\Delta cardiovascular\ admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{10}} - 1)\right] \cdot pop,$$ where: y_0 = daily hospital admission rate for cardiovascular disease per person 65 and older = 2.23 E-4 β = PM_{10} coefficient = 0.00102 ΔPM_{10} = change in daily average PM_{10} concentration pop = population age 65 and older σ_β = standard error of β = 0.000423	Study: Schwartz (1997) Location: Tucson, AZ Other pollutants in model: CO
emergency room visits	$$\Delta\ asthma\ visits = -\left[y_0 \cdot (e^{-\beta \cdot \Delta PM_{10}} - 1)\right] \cdot pop,$$ where: y_0 = daily ER visits for asthma per person under 65 years old = 7.69 E-6 β = PM_{10} coefficient (Schwartz et al., 1993, p. 829) = 0.00367 ΔPM_{10} = change in daily average PM_{10} concentration pop = population ages 0-64 σ_β = standard error of β (Schwartz et al., 1993, p. 829) = 0.00126	Study: Schwartz (1993) Location: Seattle, WA Other pollutants in model: none
acute bronchitis	$$\Delta Acute\ Bronchitis = -\left[\frac{y_0}{(1-y_0)\cdot e^{\Delta PM_{2.5}\cdot\beta} + y_0} - y_0\right]\cdot pop,$$ where: y_0 = annual bronchitis incidence rate per person = 0.044 β = estimated $PM_{2.5}$ logistic regression coefficient = 0.0272 $\Delta PM_{2.5}$ = change in annual average $PM_{2.5}$ concentration pop = population ages 8-12 σ_β = standard error of β = 0.0171	Study: Dockery et al. (1996) Location: 24 U.S. and Canadian cities Other pollutants in model: none
lower respiratory symptoms (LRS) defined as cough, chest pain, phlegm, and wheeze	$$\Delta Lower\ Respiratory\ Symptoms = -\left[\frac{y_0}{(1-y_0)\cdot e^{\Delta PM_{2.5}\cdot\beta} + y_0} - y_0\right]\cdot pop.$$ where: y_0 = daily lower respiratory symptom incidence rate per person = 0.0012 β = estimated $PM_{2.5}$ logistic regression coefficient = 0.01823 $\Delta PM_{2.5}$ = change in daily average $PM_{2.5}$ concentration pop = population ages 7-14 σ_β = standard error of β = 0.00586	Study: Schwartz, et al. (1994) Location: six U.S. cities Other pollutants in model: none

Health Endpoint	C-R Function	Source of C-R Function
Shortness of breath, days	$$\Delta Shortness\,of\,Breath = -\left[\frac{y_0}{(1-y_0)\cdot e^{\Delta PM_{10}\cdot\beta}+y_0} - y_0\right]\cdot pop,$$ where: y_0 = daily shortness of breath incidence rate per person = 0.056 β = estimated PM_{10} logistic regression coefficient = 0.00841 ΔPM_{10} = change in daily average PM_{10} concentration pop = asthmatic African-American population ages 7 to 12 σ_β = standard error of β = 0.00363	Study: Ostro et al. (1995) Location: Los Angeles, CA Other pollutants in model: none
URS, defined as runny or stuffy nose, wet cough, burning, aching, or red eyes	$$\Delta Upper\,Respiratory\,Symptoms = -\left[\frac{y_0}{(1-y_0)\cdot e^{\Delta PM_{10}\cdot\beta}+y_0} - y_0\right]\cdot pop,$$ where: y_0 = daily upper respiratory symptom incidence rate per person = 0.3419 β = estimated PM_{10} logistic regression coefficient = 0.0036 ΔPM_{10} = change in daily average PM_{10} concentration pop = asthmatic population ages 9 to 11 = 6.91% of population ages 9 to 11 σ_β = standard error of β = 0.0015	Study: Pope et al. (1991) Location: Utah Valley Other pollutants in model: none
presence of any of 19 acute respiratory symptoms	$$\Delta ARD2 \cong \beta^*_{PM_{10}}\cdot\Delta PM_{10}\cdot pop,$$ where: β^* = first derivative of the stationary probability = 0.000461 ΔPM_{10} = change in daily average PM_{10} concentration pop = population ages 18-65 σ_β = standard error of β^* = 0.000239	Study: Krupnick et al. (1990) Location: Glendora-Covina-Azusa, CA Other pollutants in model: SO_2, O_3 Comments: COH used in estimation of model. The estimated COH coefficient is used with PM_{10} data.
moderate or worse asthma status	$$\Delta Days\,Moderate\,/\,Worse\,Asthma = -\beta\cdot\ln\left(\frac{PM_{2.5,\,after}}{PM_{2.5,\,before}}\right)\cdot pop,$$ where: β = estimated $PM_{2.5}$ coefficient for year i = 0.0006 $PM_{2.5}$ = change in daily average $PM_{2.5}$ concentration pop = asthmatic population of all ages = 5.61% of the population of all ages σ_β = standard error of β = 0.0003	Study: Ostro et al. (1991) Location: Denver Other pollutants in model: none Comments: The estimated coefficient is applied to populations of all ages.

Health Endpoint	C-R Function	Source of C-R Function
asthma attacks	$$\Delta asthma\,attacks = -\left[\frac{y_0}{(1-y_0)\cdot e^{\Delta PM_{10}\cdot\beta} + y_0} - y_0\right]\cdot pop,$$ where: y_0 = daily incidence of asthma attacks = 0.027 β = PM_{10} coefficient = 0.00144 ΔPM_{10} = change in daily PM_{10} concentration pop = population of asthmatics of all ages = 5.61% of the population of all ages σ_β = standard error of β = 0.000556	Study: Whittemore and Korn (1980) Location: Los Angeles, CA Other pollutants in model: O_3
Restricted Activity Days (RADs)	$$\Delta RAD = \Delta y \cdot pop = -\left[y_0 \cdot (e^{-\beta\cdot\Delta PM_{2.5}} - 1)\right]\cdot pop,$$ where: y_0 = daily RAD incidence rate per person = 0.0177 β = inverse-variance weighted $PM_{2.5}$ coefficient = 0.00475 $\Delta PM_{2.5}$ = change in daily average $PM_{2.5}$ concentration pop = adult population ages 18 to 65 σ_β = standard error of β = 0.00029	Study: Ostro (1987) Location: U.S. metropolitan areas Other pollutants in model: none Comments: An inverse-variance weighting used to estimate the coefficient, based on Ostro (1987, Table III)].
respiratory and nonrespiratory conditions resulting in a minor restricted activity day (MRAD)	$$\Delta MRAD = \Delta y \cdot pop = -\left[y_0 \cdot (e^{-\beta\cdot\Delta PM_{2.5}} - 1)\right]\cdot pop,$$ where: y_0 = daily MRAD daily incidence rate per person = 0.02137 β = inverse-variance weighted $PM_{2.5}$ coefficient = 0.00741 $\Delta PM_{2.5}$ = change in daily average $PM_{2.5}$ concentration pop = adult population ages 18 to 65 σ_β = standard error of β = 0.0007	Study: Ostro and Rothschild (1989b) Location: U.S. Other pollutants in model: O_3 Comments: An inverse-variance weighting used to estimate the coefficient, based on Ostro and Rothschild (1989b, Table 4)
work loss days (WLDs)	$$\Delta WLD = \Delta y \cdot pop = -\left[y_0 \cdot (e^{-\beta\cdot\Delta PM_{2.5}} - 1)\right]\cdot pop,$$ where: y_0 = daily work-loss-day incidence rate per person = 0.00648 β = inverse-variance weighted $PM_{2.5}$ coefficient = 0.0046 $\Delta PM_{2.5}$ = change in daily average $PM_{2.5}$ concentration pop = population ages 18 to 65 σ_β = standard error of β = 0.00036	Study: Ostro (1987) Location: U.S. metropolitan areas Other pollutants in model: none Comments: An inverse-variance weighting used to estimate the coefficient, based on Ostro (1987, Table III).

Sulfur Dioxide

The C-R functions used to estimate the impact of sulfur dioxide are summarized in Table D-19.

Table D-19
Summary of C-R Functions for Sulfur Dioxide

Health Endpoint	Concentration-Response Function	Source of C-R Function
hospital admissions – all respiratory	$\Delta All\ respiratory = -\left[y_0 \cdot (e^{-\beta \cdot \Delta SO_2} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for all respiratory per person = 2.58 E-5 β = SO_2 coefficient = 0.00446 ΔSO_2 = change in daily one-hour maximum SO_2 concentration (ppb) pop = population of all ages σ_β = standard error of β = 0.00293	Study: Burnett et al. (1997b) Location: Toronto, Canada Other pollutants in model: $PM_{2.5-10}$, NO_2, O_3
hospital admissions – pneumonia	$\Delta pneumonia\ admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta SO_2} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for pneumonia per person = 5.30 E-5 β = SO_2 coefficient = 0.00143 ΔSO_2 = change in daily average SO_2 concentration (ppb) pop = population age 65 and older σ_β = standard error of β = 0.00290	Study: Moolgavkar et al. (1997) Location: Minneapolis, MN Other pollutants in model: O_3, NO_2 PM_{10}
hospital admissions – ischemic heart disease	$\Delta Ischemic\ Heart\ Disease\ Admissions = -\left[y_0 \cdot (e^{-\beta \cdot \Delta SO_2} - 1)\right] \cdot pop,$ where: y_0 = daily hospital admission rate for ischemic heart disease per person = 2.23 E-5 β = SO_2 coefficient = 0.00177 ΔSO_2 = change in daily average SO_2 concentration pop = population of all ages σ_β = standard error of β = 0.000854	Study: Burnett et al. (1999) Location: Toronto, Canada Other pollutants in model: NO_2
chest tightness, shortness of breath, or wheeze	$\Delta symptoms = \left[\frac{1}{1+e^{-\alpha - SO_{2,pre-CAAA} \cdot \beta - \gamma}} - \frac{1}{1+e^{-\alpha - SO_{2,post-CAAA} \cdot \beta - \gamma}}\right] \cdot pop,$ .where: α = constant = -5.65 β = SO_2 coefficient = 0.00589 γ = status coefficient (used for moderate asthmatics only) = 1.10 SO_2 = peak five minute SO_2 concentration (ppb) in an hour = hourly SO_2 concentration (ppb) multiplied by 2.5 peak to mean ratio of 2.5 pop = exercising asthmatics = population of asthmatics of all ages (5.61% of the population of all ages (Adams et al., 1995 Table 57)) of whom 1.7% are exercising. Moderate asthmatics compose one third of exercising asthmatics; mild asthmatics compose the other two thirds (U.S. EPA, 1997, p. D-39). σ_β = standard error of β = 0.00247	Study: Linn et al. (1987; 1988; 1990) and Roger et al. (1985) Location: Chamber study Other pollutants in model: none Comments: The results of four chamber studies were combined to develop this C-R function. Moderate asthmatics compose one third of exercising asthmatics; mild asthmatics compose the other two thirds.

Modeling Results

This section presents the results of the health effects modeling resulting from improvements in air quality between the Pre-CAAA and Post-CAAA scenarios for the years 2000 and 2010. Tables D-20 and D-21 summarize the health effects for each study included in the analysis, presenting the mean, as well as the estimated credible interval (5^{th} and 95^{th} percentiles) of the number of avoided cases of each endpoint. Table D-20 presents these results for the subpopulation living within 50 kilometers of an air quality monitor. Table D-21 presents results for the entire population of the 48 contiguous states. Table D-22 summarizes the life-years lost by age group; Tables D-23 and D-24 present illustrative calculations of the impact of air pollution on mortality; and Figure D-2 presents the results of using alternative effect thresholds in the calculation of mortality.

The ranges of estimates presented in Tables D-20 and D-21 reflect the measured uncertainty inherent in the estimated C-R coefficients used in calculating the avoided incidence for each endpoint. These ranges are only a partial measure of the total uncertainty associated with the estimation of the avoided incidence of each health effect. There are other potentially important sources of uncertainty in this benefits analysis that would likely lead to a wider uncertainty range. For example, some of the analytical components are point estimates that do not incorporate information about the uncertainty inherent in the estimates, such as the emissions and air quality estimates. A complete depiction of the uncertainty of the estimates would include the uncertainty in these important analytical components. Incorporating quantitative uncertainty estimates into each of these components is not feasible for this current analysis. Therefore, the range of estimates presented herein is only a partial reflection of the total uncertainty range.

Uncertainty

The stated goal of this study is to provide a comprehensive estimate of the benefits of the Clean Air Act Amendments of 1990. To achieve this goal, information with very different levels of confidence must be used. The analysis presents information on the plausible range of estimates through the use of two approaches. The first approach is to reflect the measured uncertainty in estimating the avoided incidence of health effects by using an estimated probability distribution for each C-R coefficient used in the analysis. The second approach is to present analysis using different key assumptions. The threshold choice, the time between PM exposure and mortality, the choice of studies, and whether to estimate mortality using statistical life years or statistical lives lost are important assumptions that are examined in this analysis.

To capture the variation in the C-R function coefficient estimates used to estimate the avoided incidence of health effects, this analysis uses a Monte Carlo procedure to generate distributions of estimated effects by randomly sampling the distribution of coefficients (given by the mean coefficient and standard deviation reported in the literature) and then evaluating the C-R function with the randomly selected coefficient. This yielded an estimate of avoided incidence for the given effect and was repeated many times to generate distributions of avoided incidence. Both the mean estimates and the 5^{th} and 95^{th} percentile estimates of the resulting distributions of avoided incidence estimates are presented here for each health effect.

The second type of uncertainty considered here addresses the fact that different published results reported in the scientific literature typically do not report identical findings; in some instances the differences are substantial. For this analysis, some health endpoints used more than one concentration-response function, each representing a different study. The alternative concentration-response functions provide differing measures of the effect air quality reductions have on changes in particular health endpoints. This between-study variability is captured by considering the range of estimates for a given endpoint, and can be used to derive a range of possible results. For example, concentration-response functions for developing chronic bronchitis from three different studies are used to estimate the range of avoided cases of chronic bronchitis.

Another important source of uncertainty that is considered as an alternative analysis is the estimation of statistical life years lost. Table D-22 presents the percentage of lives lost for each age group considered and the average number of life years lost. The majority of the estimated deaths occur in people over the age of 65 (due to their higher baseline mortality rates), and this group has a short life expectancy relative to other age groups.

Sensitivity Analyses

One particularly important uncertainty is the impact that alternative threshold assumptions have on both the estimates of specific health effects and ultimately on monetary benefits. The available evidence has failed to identify thresholds – or safe levels of air pollution – for any of the effects associated with criteria pollutants, so this analysis assumes that there are no effective thresholds and that air pollution has effects down to zero ambient levels. Nevertheless, thresholds may exist and their potential impact on the overall benefits analysis could be substantial. Any of the health effects estimated in this analysis could have a threshold; however a threshold for PM-related mortality would have the greatest impact on the overall benefits analysis. Figure D-2 shows the effect of incorporating a range of possible thresholds, using 2010 PM levels and the Pope et al. (1995) study.

Pope et al. (1995) did not explicitly include a threshold in their analysis. However, if the true mortality C-R relationship has a threshold, then Pope et al.'s slope coefficient would likely have been underestimated for that portion of the C-R relationship above the threshold. This would likely lead to an underestimate of the incidences of avoided cases above any assumed threshold level. It is difficult to determine the size of the underestimate without data on a likely threshold and without re-analyzing the Pope et al. data.

The quantitative results of several other sensitivity analyses are also presented. As discussed above, there is information suggesting a possible relationship between ozone and premature mortality, and between PM and infant mortality. However, there is considerable uncertainty about these relationships at this time, so quantitative estimates of these effects are not included in the aggregated results. The possible magnitude of these health effects are explored as sensitivity analyses, reported in Tables D-23 (for the population within 50 kilometers of a monitor) and D-24 (for the entire population of the 48 contiguous states). In addition, the results of an alternative estimate of the premature adult mortality associated with long-term PM exposure based on Dockery et al. (1993) are also presented in Tables D-23 and D-24. The Dockery et al. study used a smaller sample of individuals from fewer cities than the study by Pope et al., although it features improved exposure estimates, a slightly broader study population, and a follow-up period nearly twice as long as that of Pope et al. The results based on Dockery are presented only as sensitivity calculation for this important health effect; the Pope et al. (1995) estimate is used in the primary analysis.

Finally, this study includes a sensitivity analysis illustrating the effect of alternative assumptions about a potential lag between PM exposure and premature mortality on monetized benefit estimates. As discussed earlier, a change in the assumed lag period will have no effect on the total estimate of avoided mortality presented in Table D-21; it will only affect the distribution of those avoided deaths through time. Changes to this distribution will, however, affect monetized benefit estimates if the values of the avoided future deaths are discounted. Therefore, although we discuss the various lag scenarios here, the results of this sensitivity analysis are presented in the valuation appendix, Appendix H.

Before describing the lag scenarios, we emphasize that no scientific evidence currently exists to support the assumption of a significant lag (i.e., several years or more) between PM exposure and premature mortality. The prospective cohort study design of long-term epidemiological studies of PM exposure (including Pope et al., 1995) provides no information about whether a lag exists or whether a particular length of exposure is required to elicit an effect. Further, we have identified no studies specifically designed to test for such a PM/mortality lag. However, we have incorporated a lag into our primary analysis and conducted this sensitivity analysis for two reasons. First, other similar types of exposures, such as cigarette smoking, do show evidence of a lag. Studies of reductions in cigarette smoking suggest that the benefits of smoking cessation occur over a several year period. Second, differences between the relative risk estimates of short-term studies of PM exposure and those of long-term (i.e., cohort) studies may suggest the presence of a lag for some portion of the overall mortality effect of PM exposure.

Short-term epidemiological studies linking daily measures of PM exposures with daily mortality rates show statistically significant increases in mortality within days of increased PM exposure. However, the appropriate lag period for the portion of deaths that do not occur immediately is unclear. Some interpret the analysis by Brunekreef (1997) as indicative of a much longer mortality lag of 15 years; however, it appears that Brunekreef simply employed assumptions consistent with the cohort design of the Dockery et al., 1993 study, which examined the relative risk for a cohort aged 25 to 74 over a 15-year period. The selection of such a follow-up period by Dockery et al. was not based on biological or epidemiological evidence of a 15-year lag, and Brunekreef cites no evidence supporting a lag of this length. Therefore, we do not find the Brunekreef (1997) study to be convincing evidence of a fifteen-year lag.

Table D-25 compares the distribution of avoided mortality benefits assumed in the primary analysis with each of the sensitivity analysis scenarios. In the primary analysis, we apply the same lag structure used as a sensitivity analysis in the draft RIA for the proposed Tier 2 motor vehicle emission standards (U.S. EPA, 1999). Under this scenario, the avoided mortality occurs over a five year period, with fifty percent of the avoided mortality occurring within the first two years (i.e. 25 percent per year), and the remainder of avoided deaths distributed evenly across the last three years (approximately 16.7 percent per year). As mentioned above, the appropriate length of the lag period is highly uncertain, and so is the distribution of deaths over that period, although evidence from short-term studies suggests weighting the distribution toward the first couple of years following exposure. The assumptions of the Tier 2 lag structure reflect the best judgment of the Agency on this issue; however, they do not represent any known lag structure for PM mortality.

We evaluate three lag scenarios for the sensitivity analysis. The first scenario assumes no lag; that is, all avoided mortality occurs in the same year as exposure (Year 1 in Table D-25). The second distributes avoided mortality evenly across eight years; this scenario is based on the eight-year cohort follow-up period of the Pope et al., 1995 study. The third scenario is based on the Dockery et al., 1993 follow-up period of 15 years, with avoided mortality distributed evenly across that period. As discussed earlier, we find the 15-year lag to be an extremely conservative assumption.

The effect of these different lag assumptions on our estimate of monetary benefits depends on the discount rate used. Given the discount rate used in the primary analysis, five percent, the no lag scenario would increase the primary mortality reduction benefits estimate by nine percent; the Pope-based lag estimate would decrease the estimate by eight percent; and the Dockery-based lag estimate would decrease the estimate by 21 percent. The actual monetary benefit estimates generated by this sensitivity analysis are presented in Appendix H.

Table D-20
Change in Incidence of Adverse Health Effects Associated with Criteria Pollutants (Pre-CAAA minus Post-CAAA) – 48 State U.S. Population within 50 km of a Monitor (avoided cases per year)

		2000			2010			% of Baseline Incidences for the mean estimates [a]	
Endpoint	**Pollutant**	**5th %**	**mean**	**95th %**	**5th %**	**mean**	**95th %**	**2000**	**2010**
Mortality									
ages 30 and older	PM	7,900	13,000	18,000	13,000	20,000	28,000	0.67%[b]	0.95%[b]
Chronic Illness									
chronic bronchitis	PM	2,300	11,000	20,000	4,300	18,000	30,000	2.05%	3.09%
chronic asthma	O_3	910	4,900	8,300	1,100	5,500	8,700	3.46%	3.59%
Hospitalization									
respiratory admissions	PM, CO, NO_2, SO_2, O_3	7,300	12,000	17,000	12,000	19,000	29,000	0.52%	0.76%
cardiovascular admissions	PM, CO, NO_2, SO_2, O_3	5,400	19,000	41,000	9,400	38,000	90,000	0.59%	1.10%
emergency room visits for asthma	PM, O_3	200	1,300	6,600	310	2,000	10,000	0.19%	0.27%
Minor Illness									
acute bronchitis	PM	0[c]	25,000	49,000	0[c]	40,000	79,000	3.19%	4.71%
upper respiratory symptoms	PM	170,000	570,000	970,000	260,000	870,000	1,500,000	0.61%	0.86%
lower respiratory symptoms	PM	130,000	270,000	420,000	210,000	440,000	670,000	2.19%	3.30%
respiratory illness	NO_2	24,000	110,000	180,000	63,000	270,000	450,000	7.62%	17.29%
moderate or worse asthma[d]	PM	32,000	210,000	370,000	48,000	310,000	570,000	0.15%	0.21%
asthma attacks[d]	O_3, PM	520,000	960,000	1,400,000	800,000	1,500,000	2,100,000	0.74%	1.06%

Endpoint	Pollutant	2000			2010			% of Baseline Incidences for the mean estimates [a]	
		5th %	mean	95th %	5th %	mean	95th %	2000	2010
chest tightness, shortness of breath, or wheeze	SO_2	200	80,000	370,000	270	100,000	470,000	0.003%	0.004%
shortness of breath	PM	16,000	57,000	95,000	25,000	88,000	150,000	1.25%	1.79%
work loss days	PM	1,900,000	2,200,000	2,500,000	3,100,000	3,500,000	4,000,000	0.60%	0.87%
minor restricted activity days / any of 19 respiratory symptoms[e]	O_3, PM	14,000,000	17,000,000	20,000,000	22,000,000	27,000,000	32,000,000	1.47%	2.16%
restricted activity days[d]	PM	5,500,000	6,200,000	6,800,000	9,000,000	10,000,000	11,000,000	0.61%	0.91%

[a] The baseline incidence generally is the same as that used in the C-R function for a particular health effect. However, there are a few exceptions. To calculate the baseline incidence rate for respiratory-related hospital admissions, we used admissions for persons of all ages for ICD codes 460-519; for cardiovascular admissions, we used admissions for persons of all ages for ICD codes 390-429; for emergency room visits for asthma, we used the estimated ER visit rate for persons of all ages; for chronic bronchitis we used the incidence rate for individuals 27 and older; for the pooled estimate of minor restricted activity days and any-of-19 respiratory symptoms, we used the incidence rate for minor restricted activity days.

[b] Calculated as the ratio of avoided mortality to the projected baseline annual non-accidental mortality for adults aged 30 and over. Non-accidental mortality was approximately 95% of total mortality for this subpopulation in 2010.

[c] Monte Carlo modeling returned a negative value for the fifth percentile estimate of this endpoint. However, we believe the negative result represents an artifact of the statistical methods employed in the uncertainty analysis, since none of the studies used in the health benefits analysis suggest a negative correlation between criteria air pollutant exposure and this health endpoint. We therefore truncate this value at zero for presentation. The full distribution of estimates, including negative values, is used in all aggregations of benefits estimates presented in this document.

[d] These health endpoints overlap with the "any-of-19 respiratory symptoms" category. As a result, although we present estimates for each endpoint individually, these results are not aggregated into the total benefits estimates.

[e] Minor restricted activity days and any-of-19 respiratory symptoms have overlapping definitions and are pooled.

Table D-21
Change in Incidence of Adverse Health Effects Associated with Criteria Pollutants (Pre-CAAA minus Post-CAAA) – 48 State U.S. Population (avoided cases per year)

		2000			2010			% of Baseline Incidences for the mean estimates [a]	
Endpoint	**Pollutant**	**5th %**	**mean**	**95th %**	**5th %**	**mean**	**95th %**	**2000**	**2010**
Mortality									
ages 30 and older	PM	8,800	14,000	19,000	14,000	23,000	32,000	0.66%[b]	1.00%[b]
Chronic Illness									
chronic bronchitis	PM	3,100	13,000	22,000	5,000	20,000	34,000	2.21%	3.14%
chronic asthma	O_3	1,300	5,600	9,600	1,800	7,200	12,000	3.22%	3.83%
Hospitalization									
respiratory admissions	PM, CO, NO_2, SO_2, O_3	8,100	13,000	20,000	13,000	22,000	34,000	0.40%	0.62%
cardiovascular admissions	PM, CO, NO_2, SO_2, O_3	5,800	22,000	48,000	10,000	42,000	100,000	0.49%	0.86%
emergency room visits for asthma	PM, O_3	260	3,100	8,900	430	4,800	14,000	0.39%	0.55%
Minor Illness									
acute bronchitis	PM	0[c]	29,000	59,000	0[c]	47,000	94,000	3.39%	5.06%
upper respiratory symptoms	PM	180,000	620,000	1,000,000	280,000	950,000	1,600,000	0.61%	0.86%
lower respiratory symptoms	PM	150,000	320,000	480,000	240,000	520,000	770,000	2.38%	3.57%
respiratory illness	NO_2	31,000	130,000	220,000	76,000	330,000	550,000	4.46%	10.44%
moderate or worse asthma[d]	PM	52,000	260,000	460,000	80,000	400,000	720,000	0.17%	0.24%
asthma attacks[d]	O_3, PM	590,000	1,100,000	1,600,000	920,000	1,700,000	2,500,000	0.73%	1.04%

Endpoint	Pollutant	2000 5th %	2000 mean	2000 95th %	2010 5th %	2010 mean	2010 95th %	% of Baseline Incidences for the mean estimates [a] 2000	% of Baseline Incidences for the mean estimates [a] 2010
chest tightness, shortness of breath, or wheeze	SO_2	220	88,000	410,000	290	110,000	520,000	0.002%	0.003%
shortness of breath	PM	16,000	59,000	98,000	26,000	91,000	150,000	1.19%	1.69%
work loss days	PM	2,200,000	2,500,000	2,900,000	3,600,000	4,100,000	4,600,000	0.62%	0.94%
minor restricted activity days / any of 19 respiratory symptoms[e]	O_3, PM	16,000,000	19,000,000	23,000,000	25,000,000	31,000,000	37,000,000	1.43%	2.15%
restricted activity days[d]	PM	6,400,000	7,200,000	7,900,000	10,000,000	12,000,000	13,000,000	0.65%	1.00%

[a] The baseline incidence generally is the same as that used in the C-R function for a particular health effect. However, there are a few exceptions. To calculate the baseline incidence rate for respiratory-related hospital admissions, we used admissions for persons of all ages for ICD codes 460-519; for cardiovascular admissions, we used admissions for persons of all ages for ICD codes 390-429; for emergency room visits for asthma, we used the estimated ER visit rate for persons of all ages; for chronic bronchitis we used the incidence rate for individuals 27 and older; for the pooled estimate of minor restricted activity days and any-of-19 respiratory symptoms, we used the incidence rate for minor restricted activity days.

[b] Calculated as the ratio of avoided mortality to the projected baseline annual non-accidental mortality for adults aged 30 and over. Non-accidental mortality was approximately 95% of total mortality for this subpopulation in 2010.

[c] Monte Carlo modeling returned a negative value for the fifth percentile estimate of this endpoint. However, we believe the negative result represents an artifact of the statistical methods employed in the uncertainty analysis, since none of the studies used in the health benefits analysis suggest a negative correlation between criteria air pollutant exposure and this health endpoint. We therefore truncate this value at zero for presentation. The full distribution of estimates, including negative values, is used in all aggregations of benefits estimates presented in this document.

[d] These health endpoints overlap with the "any-of-19 respiratory symptoms" category. As a result, although we present estimates for each endpoint individually, these results are not aggregated into the total benefits estimates.

[e] Minor restricted activity days and any-of-19 respiratory symptoms have overlapping definitions and are pooled.

Table D-22
Mortality Distribution by Age in Primary Analysis, Based on Pope et al. (1995)

Age Group	Proportion of Premature Mortality by Age [a]	Life Expectancy (years)
Infants	not estimated	--
1-29	not estimated	--
30-34	1%	48
35-44	4%	38
45-54	6%	29
55-64	12%	21
65-74	24%	14
75-84	30%	9
85+	24%	6

[a] Percentages sum to 101 percent due to rounding.

Table D-23
Illustrative Estimates of the Impact of Criteria Pollutants on Mortality – 48 State U.S. Population within 50 km of a Monitor (cases per year)

		2000			2010			% of Baseline Incidences for the mean estimates	
Endpoint	**Pollutant**	**5th %**	**mean**	**95th %**	**5th %**	**mean**	**95th %**	**2000**	**2010**
ages 30 and older (Pope et al., 1995)	PM	7,900	13,000	18,000	13,000	20,000	28,000	0.67%	0.95%
ages 25 and older (Dockery et al., 1993)*	PM	12,000	29,000	46,000	20,000	47,000	73,000	1.35%	2.19%
all ages *	O_3	81	1,100	2,200	130	1,600	3,400	0.06%	0.08%
post-neonatal *	PM	39	81	120	59	120	180	0.93%	1.39%

*The Dockery et al. (1993), ozone mortality, and post-neonatal mortality estimates are not aggregated into total benefits estimates.

Table D-24
Illustrative Estimates of the Impact of Criteria Pollutants on Mortality – 48 State U.S. Population (cases per year)

		2000			2010			% of Baseline Incidences for the mean estimates	
Endpoint	**Pollutant**	**5th %**	**mean**	**95th %**	**5th %**	**mean**	**95th %**	**2000**	**2010**
ages 30 and older (Pope et al., 1995)	PM	8,800	14,000	19,000	14,000	23,000	32,000	0.66%	1.00%
ages 25 and older (Dockery et al., 1993)*	PM	15,987	34,860	54,677	26,000	56,000	88,000	1.60%	2.39%
all ages *	O_3	0†	1,400	2,800	0†	2,200	4,600	0.07%	0.09%
post-neonatal *	PM	45	88	130	69	130	200	1.02%	1.38%

*The Dockery et al. (1993), ozone mortality, and post-neonatal mortality estimates are not aggregated into total benefits estimates.

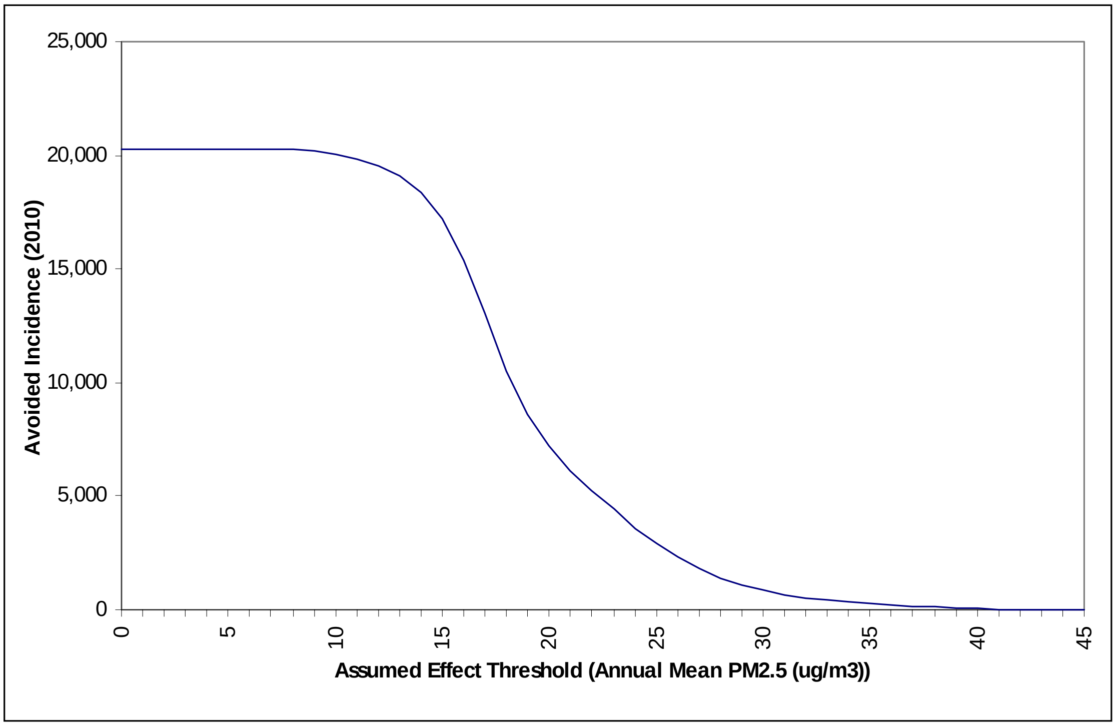
†Monte Carlo modeling returned a negative value for the fifth percentile estimate of this endpoint. However, we believe the negative result represents an artifact of the statistical methods employed in the uncertainty analysis, since none of the studies used in the health benefits analysis suggest a negative correlation between criteria air pollutant exposure and this health endpoint. We therefore truncate this value at zero for presentation. The full distribution of estimates, including negative values, is used in all aggregations of benefits estimates presented in this document.

Table D-25
Comparison of Alternative Lag Assumptions for Premature Mortality Associated with PM Exposure

Year	Percent of Avoided Mortality By Year														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Tier II SA Lag (Primary Estimate)	25	25	16.67	16.67	16.67	0	0	0	0	0	0	0	0	0	0
No Lag	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lag Distributed Evenly Over the Period Covered by Pope et al., 1995	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	0	0	0	0	0	0	0
Lag Distributed Evenly Over the Period Covered by Dockery et al., 1993	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67

Totals may not sum to 100 percent due to rounding.

Figure D-2
Long-Term Mortality Based on Pope (1995): National Avoided Incidence Estimates (2010) at Different Assumed Effect Thresholds, Based on a 50 Km Maximum Distance



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