Department for Environment Food & Rural Affairs

Impact pathways approach

Guidance for air quality appraisal

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1. Introduction

This document details the methodology that should be followed by analysts undertaking bespoke appraisals of air quality impacts resulting from policies or projects. This methodology is called the impact pathways approach (IPA) and is recommended for use where the air quality impacts are estimated to be significant (>£50 million) or where changes to air quality are the principle objective of the policy or project.

The methodology described in this document is also used to produce air quality damage costs – a set of pre-calculated values, expressed in £/tonne of emissions, that can be used by analysts in place of the IPA where air quality impacts are less significant. A separate guidance document provides details on how to use damage costs, while this document details the methodology underlying them.

This updated methodology is the result of a review undertaken by Defra to reflect improvements in air pollution modelling and developments in the underlying evidence base, including the addition of wider health impacts. The review was not intended as a comprehensive reassessment but was instead focused on revising specific areas of the methodology where developments in the underpinning evidence base were considered to have the most important impact on cost estimates.

2. Overview

The impact pathways approach is a systematic method for identifying and tracing the effects of air pollution, from changes in emissions through to impacts on outcomes that society values. There are three component stages:

1. Modelling the dispersion of emissions of air pollutants to understand changes in ambient pollutant concentrations in different locations

2. Estimating how those changes in concentrations affect different impact pathways related to health, economy and environment

3. Valuing those impacts using a single monetary metric

Damage costs are calculated by undertaking an impact pathways analysis for the UK as a whole using the methodology in this document. The results of this analysis are then summarised by calculating the average value associated with one tonne of emissions for different pollutants and sectors. A separate guidance document on how and when to use damage costs is available online.[1] Figure 1 illustrates the difference between the impact pathways approach and damage costs.

[1] https://www.gov.uk/guidance/air-quality-economic-analysis

The following sections provide details on how each component stage of the impact pathways approach can be undertaken.

Impact Pathways Approach	**Damage Cost Approach**
Policy Intervention	Policy Intervention
↓ (policy appraisal)	↓
Emissions Change	Emissions Change
↓ (dispersion modelling)	↓
Concentration Change	
↓ (concentration response function)	
Impacts	
↓ (valuation techniques)	
Value	Value

Figure 1. Comparison of impact pathway and damage cost approaches

3. Dispersion

The first step is to estimate how changes in emissions of air pollutants resulting from a policy or project are likely to translate into changes in concentrations. A range of dispersion models are available to do this and specialist consultancies may be able to provide this service. Defra can provide advice on the most appropriate choice of model.

In Defra, ambient concentrations of air pollutants are estimated for the country as a whole using the Pollution Climate Mapping (PCM) model. This atmospheric dispersion model takes emissions data from the National Atmospheric Emissions Inventory (NAEI) in combination with meteorological data and modelling of chemical processes to translate emissions from various sources into concentration estimates on a 1km x 1km grid across the UK. The current damage costs are based on emissions estimates from 2014. By combining the concentration estimates produced by the PCM with population data from the 2011 census, a population-weighted mean concentration for each pollutant is obtained.

For further information on the PCM model, including details of the emissions sources that are included, see Brookes et al. (2015).[2]

The average relationship between emissions and exposure to concentrations is then calculated as population-weighted mean concentration for a pollutant divided by the total annual emissions of that pollutant. This provides the basis for the 'national' damage cost estimates. Values are also provided for different sector and location types, since emissions from particular sources will differ in the number of people that are exposed to the resulting concentrations – for example, emissions in city centres will have a greater effect on exposure than emissions in rural areas. The damage costs are calculated based on the geographical locations of emissions sources in different categories, as recorded in the NAEI.

The PCM model estimates concentrations for five key pollutants – particulate matter (PM), nitrogen dioxide (NO_2), volatile organic compounds (VOCs), ammonia (NH_3) and sulphur dioxide (SO_2). There are also chemical interactions associated with some of these pollutants that should be accounted for in dispersion modelling. In particular, emissions of NO_x, NH_3 and SO_2 contribute to the formation of PM; and NO_x and VOCs affect the formation of ozone (O_3). There are, therefore, some pathways associated with O_3 included in the damage costs even though there are no damage cost values for emissions of O_3 on its own.

For the current set of damage cost values, dispersion modelling has been updated in a number of ways, including:

- the use of specific dispersion modelling for NOx
- accounting for NOx to NO_2 chemistry
- using updated relationships between NOx emissions and PM concentrations

Many of the pathways described in this methodology refer to $PM_{2.5}$ emissions. PM_{10} emissions can be converted into estimated $PM_{2.5}$ emissions based on ratios between these two pollutants from the National Atmospheric Emissions Inventory. Conversion factors for PM emissions from different sectors are available in the damage cost guidance.[3]

[2] Brookes et al (2015); 'Technical report on UK supplementary Assessment under the Air Quality Directive (2008/50/EC), the Air Quality Framework Directive (96/62/EC) and Fourth Daughter Directive (2004/107/EC) for 2014'; https://uk-air.defra.gov.uk/assets/documents/reports/cat09/1611011538_AQ0650_2014_MAAQ_technical_report.pdf
[3] https://www.gov.uk/guidance/air-quality-economic-analysis

4. Impact pathways

The next stage is to assess the changes in outcomes that result from the population-weighted concentration changes estimated through dispersion modelling. These outcomes include impacts on public health, the natural environment and the economy.

Concentration response functions (CRFs) are the main analytical concept that allow us to translate concentration changes into impacts. These are functions that express changes in outcomes per unit change in concentrations. For example, this could take the following form: a 1µg/m^3 increase in population-weighted mean concentration of particulate matter leads to a 5% increase in the incidence of a particular disease.

Each impact category is briefly discussed below and Table 4 details each of the concentration response functions that are used to estimate damage costs and recommended for use in any bespoke IPA.

The full list of impact pathways are as follows:

- Health
  - → Chronic mortality
  - → Acute mortality
  - → Respiratory hospital admissions
  - → Cardiovascular hospital admissions
  - → Coronary heart disease*
  - → Stroke*
  - → Lung cancer*
  - → Asthma*
  - → COPD (chronic bronchitis)*
  - → Diabetes*
- Environment
  - → Damage caused by sulphur dioxide to buildings
  - → Damage caused by ozone to materials
  - → Soiling of buildings due to PM
  - → Ecosystem damages*
- Economy
  - → Productivity*

Pathways marked with an asterisk are pathways that are included in this methodology for the first time.

Health impacts

The health impact pathways and CRFs that are included in this methodology are selected based on a combination of advice from the Committee on the Medical Effects of Air Pollution (COMEAP) and Public Health England (PHE). These are impacts for which there is strong or reasonable evidence of an association with exposure to air pollutant concentrations. For some impacts there is only weak or emerging evidence of an association – where possible, these impacts are included only in the high estimates of damage costs for use in sensitivity analyses. Tables 1 - 3 show the full range of primary health impact pathways that are included for each pollutant.

Table 1. PM impact pathways

Impact pathway (PM)	Low	Central	High
Chronic mortality	X	X	X
Respiratory hospital admissions	X	X	X
Cardiovascular hospital admissions	X	X	X
Coronary heart disease		X	X
Stroke		X	X
Lung cancer		X	X
Asthma (children)		X	X
COPD (chronic bronchitis)			X
Diabetes			X

Table 2. NOx impact pathways

Impact pathway (NOx)	Low	Central	High
Chronic mortality	X	X	X
Asthma (children)		X	X
Respiratory hospital admissions			X
Asthma (adults)			X
Diabetes			X
Lung cancer			X

Table 3. SO_2 impact pathways

Impact pathway (SO_2)	Low	Central	High
Acute mortality	X	X	X
Respiratory hospital admissions		X	X

There are no health impact pathways included for ammonia or VOCs except through their secondary effect on the formation of other air pollutants in the atmosphere. For example, VOCs and NOx have effects on the formation of ozone, which is associated with acute mortality and hospital admissions.

The chronic mortality pathway is a measure of all-cause mortality – in other words, this pathway is based on an estimate of the relationship between chronic exposure to air pollutants and premature deaths, regardless of the conditions (e.g. respiratory, cardiovascular) that may have preceded death. The impact of a one-year change in emissions on all-cause mortality is calculated using life tables. This is a technique that simulates changes in survival rates at different ages for the UK population and permits estimation of total life years lost due to a one year change in emissions. This approach assumes that a sustained change in emissions (i.e. greater than one year) can be approximated by the sum of consecutive one-year changes in emissions.

Acute mortality refers to loss of life due to short term impacts of air pollution. For example, a person suffering with an existing respiratory condition may be more likely to experience a fatal episode in periods of particularly poor air quality. This is in contrast to the long term effects of air pollution on human health that are captured in the chronic mortality pathway.

The morbidity pathways (i.e. all pathways except chronic and acute mortality) account for the fact that air pollution causes a reduction in the quality of life as well as a reduction in total life years lived. Concentration response functions for these pathways are recommended by COMEAP and PHE. For most of the morbidity pathways (coronary heart disease, stroke, diabetes, lung cancer and asthma) concentration response functions estimate the change in incidence of conditions related to air pollution – i.e. changes to the flow of new cases ('incidence') rather than changes to the stock of existing cases ('prevalence'). Therefore, to estimate the damage associated with a one-year change in emissions it is necessary to calculate the costs of an incident case over the lifetime of an individual. That means valuing each year of the incident case over the average number of years that a person lives with the disease. The chronic bronchitis pathway is estimated differently using a prevalence approach, following COMEAP recommendations.[4] Concentration response functions for hospital admissions are also based on COMEAP advice.

While disease-specific pathways and hospital admissions are both a form of morbidity impacts, any double counting between these impact are thought to be limited since the former represents the day-to-day suffering associated with living with a condition for a whole year, while the latter represents the disutility associated with a single hospital admission event.

Environmental impacts

Air pollutants can have a range of negative impacts on the environment and ecosystems and for any particular policy or project there may only be specific pathways that are

[4] COMEAP (2016), 'Long-term exposure to air pollution and chronic bronchitis', https://www.gov.uk/government/publications/comeap-long-term-exposure-to-air-pollution-and-chronic-bronchitis

relevant. Appraisers should ideally conduct a bespoke analysis of potential environmental and ecosystem impacts resulting from the decision being appraised.

Four environmental impact pathways are included in the impact pathway methodology used to derive damage costs:

- Damage caused by sulphur dioxide to buildings
- Damage caused by ozone to materials
- Soiling of buildings due to PM
- Ecosystem damages

Emissions of sulphur dioxide are the principle cause of acid rain. The analysis of these impacts was advanced through the work by the Europe-wide ICP Materials (2003) and quantification under various studies for the European Commission DG Research, in particular ExternE and associated projects.

Ozone can have a damaging effect on materials such as rubbers and paints. This impact is quantified and included in damage costs based on a study by Holland *et al*. (1998).[5] This pathway is a secondary mechanism included in damage costs for NOx and VOCs due to their impact on formation of ozone in the atmosphere.

Particulate matter can cause blackening on the exterior of buildings, which creates costs in the form of reduced amenity and increased cleaning. This impact is quantified and included in damage costs based on a study by Rabl *et al*. (1998).[6]

A range of impacts on ecosystems has been quantified in a study commissioned by Defra,[7] including impacts on agricultural production and recreational disamenity. This study provided national average costs associated with emissions of different pollutants. In the absence of bespoke, local information on ecosystem impacts, these values (expressed in £/tonne of emissions) can be incorporated into an impact pathway approach analysis (see Table 7).

Economic impacts

Air pollution affects the economy by reducing the ability of workers to attend the workplace and produce efficiently. This impact is included in the damage costs and quantified based

[5] Holland, M. et al (1998): 'The effects of ozone on materials'. Contract report for the Department of the Environment, Transport and the Regions
[6] Rabl, A. Curtiss, P. and Pons, A. (1998) 'Air Pollution and Buildings: An Estimation of Damage Costs in France', Environmental Impact Assessment Review
[7] Jones et al. (2014), 'Assessment of the Impacts of Air Pollution on Ecosystem Services – Gap Filling and Research Recommendations', https://uk-air.defra.gov.uk/assets/documents/reports/cat10/1511251140_AQ0827_Asessment_of_the_impacts_of_air_pollution_on_Ecosystem_Services_Final_report.pdf

on a methodology developed by Ricardo AEA (2014).[8] That work estimated the effect on productivity through a range of pathways including, for example, mortality; however, only two pathways from this research are included in this methodology to avoid double counting:

- absenteeism and work-days lost for employees, volunteers and carers ($PM_{2.5}$)
- presenteeism and minor restricted activity days for employees ($PM_{2.5}$ and O_3).

These impacts are included in the central and high scenarios.

Table 4. Concentration response functions

Pollutant	Pathway	Low	Central	High
Relative risk (% change per 10µg/m³ change in pollutant)				
$PM_{2.5}$	Chronic mortality	4	6	8
PM_{10}	Respiratory hospital admission	0.8	0.8	0.8
PM_{10}	Cardiovascular hospital admission	0.8	0.8	0.8
SO_2	Acute mortality	0.6	0.6	0.6
SO_2	Respiratory hospital admission	0.5	0.5	0.5
O_3	Acute mortality	0.12	0.34	0.56
O_3	Respiratory hospital admission	0.3	0.75	1.2
O_3	Cardiovascular hospital admission	-0.06	0.11	0.27
NO_2	Respiratory hospital admission			0.5
NO_2	Chronic mortality*	0.6	0.9	1.3

[8] Ricardo-AEA (2014): 'Valuing the Impacts of Air Quality on Productivity', https://uk-air.defra.gov.uk/assets/documents/reports/cat19/1511251135_140610_Valuing_the_impacts_of_air_quality_on_productivity_Final_Report_3_0.pdf

$PM_{2.5}$	Diabetes			10
$PM_{2.5}$	Lung cancer		9	14
NO_2	Diabetes*			5
NO_2	Lung cancer*			2
Hazard ratio (% change per 10μg/m³ change in pollutant)				
$PM_{2.5}$	CHD		19	42
$PM_{2.5}$	Stroke		6.4	10.9
Odds ratio (change in baseline odds for 10μg/m³ change in pollutant)				
PM_{10}	Chronic bronchitis			1.32
$PM_{2.5}$	Asthma (Older Children)		1.48	1.97
NO_2	Asthma (Adults)*			1.04
NO_2	Asthma (Small Children)*		1.08	1.12
NO_2	Asthma (Older Children)*		1.03	1.06

* These CRFs have been reduced to 40% of their full value, to account for confounding effects of other pollutants

Relative risk, hazard ratio and odds ratio

The estimation of the change in incidence due to a decrease of 1 μg/m³ of $PM_{2.5}$ or NO_2 is different depending on whether the CRF is based on the relative risk, hazard ratio or odds ratio. The change in incidence (ΔI_i) per 100,000 inhabitants when the CRF is based on either the relative risk or hazard ratio is estimated as the product between the change in concentration of the pollutant, the baseline incidence, the population and the relative risk or hazard ratio as in Equation 1:

$$\Delta I_i = \frac{\Delta C_{Pol}}{C_{Inc}} \cdot \frac{RR}{100} \cdot \frac{N}{10^5} \cdot I_i \qquad (1)$$

Where:

ΔC_{Pol} is the change in concentration of a given pollutant ($PM_{2.5}$, NO_2).

C_{Inc} is the concentration increment on which the CRF is based (5 or 10 μg/m^3).

RR is the Relative Risk (or Hazard Risk, if applicable).

N is the total population of the United Kingdom.

I_i is the age- and gender-weighted incidence of a disease *i*.

The estimation of the change in incidence (ΔI_i) per 100,000 inhabitants when the CRF is based on the odds ratio (OR) is more complex, as it requires an estimate of the odds of reporting the disease at the new concentration (κ_i) first, as in Equation 2:

$$\kappa_i = \exp\left(-\ln(OR) \cdot \frac{\Delta C_{Pol}}{C_{Inc}} + \ln \frac{I_i}{10^5 - I_i}\right) \quad (2)$$

The change in incidence (ΔI_i) per 100,000 inhabitants can then be estimated as a function of the odds of reporting the disease at the new concentration (κ_i) as in Equation 3:

$$\Delta I_i = \frac{N(1+\kappa_i)}{\kappa_i(I_i - 1) + I_i} \quad (3)$$

Table 5. Pathways included for each pollutant

Pollutant	Pathway	Damage cost: NO_x	Damage cost: SO_2	Damage cost: NH_3	Damage cost: VOC
$PM_{2.5}$	Chronic mortality	2	2	2	
PM_{10}	Respiratory hospital admission	2	2	2	
PM_{10}	Cardiovascular hospital admission	2	2	2	
$PM_{2.5}$	Productivity	2	2	2	
PM_{10}	Chronic Bronchitis	2*	2*	2*	
SO_2	Deaths brought forward		P		
SO_2	Respiratory hospital admission		P		
NO_2	Respiratory hospital admission	P*			
NO_2	Chronic mortality	P			
NO_2	Productivity	P*			
O_3	Deaths brought forward	2			2
O_3	Respiratory hospital admission	2			2
O_3	Cardiovascular hospital admission	2			2
O_3	Productivity	2*			2*
O_3	Material damage	2			2
PM_{10}	Building soiling				
SO_2	Material damage		P		
SO_2	Ecosystems		P		
O_3	Ecosystems	2			2
NO_2	Ecosystems	P			
NH_3	Ecosystems			P	
$PM_{2.5}$	CHD	2	2	2	
NO_2	Asthma (Adults)	P*			
$PM_{2.5}$	Stroke	2	2	2	
$PM2.5$	Diabetes	2*	2*	2*	
NO_2	Diabetes	P*			
$PM_{2.5}$	Lung Cancer	2	2	2	
NO_2	Lung Cancer	P*			
$PM_{2.5}$	Asthma (Children)	2	2	2	
NO_2	Asthma (Small Children)	P			
NO_2	Asthma (Older Children)	P			

	$PM_{2.5}$	P	P	P	P	P *											P						P		P	P *		P		P		

Key: P = primary effect; 2 = secondary effect; * = impact only included in 'high' scenario

5. Valuation

Having identified and quantified the physical impacts of unit changes in emissions of different pollutants, each of these impacts is monetised using a range of different methods.

Chronic mortality

The value of life years lost due to the chronic effects of air pollution are monetised using values estimated in a study by Chilton *et al*. (2004).[9] This research involved a bespoke contingent valuation survey of over 600 people in England, Scotland and Wales. Respondents were asked to indicate their willingness to pay for reductions in the health effects associated with air pollution, including reduced life expectancy. The value of a life year lost due to the effect of air pollution that was obtained in this study has been rebased to current prices and is used to monetise the all-cause mortality pathway in damage cost calculations. The value is £42,780 (2017 prices) and is based on life years lost being in normal health.

Acute mortality

Life years lost due to the acute effects of short term exposure to air pollution are valued at £22,110 per life year lost, also based on values estimated in a study by Chilton *et al.* (2004).[10] Each death brought forward due to acute exposure is assumed to incur 2 - 6 months of lost life (4 months in the central scenario) in poor health.

Morbidity

The standard method for monetising the loss of quality of life due to health conditions is Quality Adjusted Life Years (QALYs). In accordance with the Green Book, QALYs are valued at £60,000 in 2014 prices – this is different from the value of a life year used in the mortality pathway since the QALY must represent the value of a year lived in perfect health. On the other hand the value of a life year used in the mortality pathway is based on the quality of life of years lost that is expected by respondents to the stated preference survey.

The method for valuing morbidity involves assigning a utility weight to different conditions: a value of 1 is attached to a life year lived in perfect health and is valued at £60,000 in

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9 Chilton et al. (2004) 'Valuation of health benefits associated with reductions in air pollution. Final report' http://randd.defra.gov.uk/Document.aspx?Document=EP01006_4723_FRP.pdf

10 Chilton et al. (2004) 'Valuation of health benefits associated with reductions in air pollution. Final report' http://randd.defra.gov.uk/Document.aspx?Document=EP01006_4723_FRP.pdf

2014 prices;[11] values approaching 0 indicate increasingly poor quality of life. The utility weights used in calculating damage costs are obtained from Sullivan *et al.* (2011).[12] The product of this utility weight and the perfect health value (£60,000 in 2014 prices) yields the value attributable to the loss of quality of life for one year due to a particular condition. The total value of each morbidity pathway is, therefore, the annual cost of lost quality of life combined with the average duration of disease.

The average duration of disease measures the mean number of years that a person will experience a disease following initial incidence. Duration of the disease ends through: (i) remission; (ii) death from the disease; or (iii) death from all other causes. For calculating damage costs, the average duration values were derived using the DISMOD II model[13] and epidemiological input data from PHE's modelling of costs to the NHS from air pollution.[14] Table 6 details the average duration of diseases in years that were used to calculate damage costs.

Table 6. Estimated average duration of diseases

Disease	Duration (years)
Asthma in Adults	9.5
Asthma in Children	23.6
CHD	36.2
Stroke	14.8
Diabetes	9.1
Lung cancer	1.8

Hospital admissions are treated differently, since they are single events rather than a year lived with a particular condition. The research conducted by Chilton et al. (2004),[15] cited above, also asked respondents about their willingness to pay to avoid hospitalisation and these values are used in damage cost pathways, rebased to current prices. The values are

[11] HMT (2018), Green Book, https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent
[12] Sullivan et al. (2011) 'Catalogue of EQ-5D scores for the United Kingdom', https://www.ncbi.nlm.nih.gov/pubmed/21422468
[13] With thanks to Yong Yi Lee and Queensland Centre for Mental Health Research for the bespoke research they undertook to provide these values
[14] Public Health England (2018), 'Air pollution: a tool to estimate healthcare costs', https://www.gov.uk/government/publications/air-pollution-a-tool-to-estimate-healthcare-costs
[15] Chilton et al. (2004) 'Valuation of health benefits associated with reductions in air pollution. Final report' http://randd.defra.gov.uk/Document.aspx?Document=EP01006_4723_FRP.pdf

£8,296 for a respiratory hospital admission and £8,471 for a cardiovascular admission (2017 prices).

Productivity

Productivity impacts of air pollution are valued following the approach adopted in Ricardo AEA (2014).[16] This essentially involves calculating the product of working time lost due to air pollution related illness and an estimate of marginal productivity. Values for marginal productivity are taken from the Confederation of British Industry's (CBI) 'Workplace Health and Absence' survey,[17] which accounts for wage and non-wage costs. For further detail on this valuation approach see Section 5 of Ricardo AEA (2014).[18]

Damage caused by sulphur dioxide to buildings

Damage to building materials covers limestone, sandstone, mortar and zinc used in galvanised steel. Quantification covers utilitarian buildings and infrastructure, but not cultural heritage. Response functions were taken from a major international research effort and are based on 8 years of exposure of material specimens across Europe. These demonstrate SO_2 to be the most harmful of the pollutants under conditions up to the mid-2000s, so analysis has focused on this pollutant. Valuation is performed using repair cost data from the architecture and building sector, with repair assumed necessary once a critical loss of material (defined in relation to each material, taking account of how they are used) has occurred. Value is calculated via the change in frequency of repair operations. Full account of the methods used is provided in the reports of the European Commission funded ExternE Project.[19] The value is estimated, on a national average basis, at £237 per tonne of SO_2 emitted (2017 prices).

Damage caused by ozone to materials

Holland *et al.* (1998)[20] estimated that the effect of a population weighted 1ppb change in ozone was £3.7m per annum (2005 prices). This relationship has been used in the

[16] Ricardo-AEA (2014), 'Valuing the Impacts of Air Quality on Productivity'; https://uk-air.defra.gov.uk/assets/documents/reports/cat19/1511251135_140610_Valuing_the_impacts_of_air_quality_on_productivity_Final_Report_3_0.pdf
[17] CBI (2013): 'Fit for purpose: Absence and workplace health survey 2013'
[18] Ricardo-AEA (2014): 'Valuing the Impacts of Air Quality on Productivity'; https://uk-air.defra.gov.uk/assets/documents/reports/cat19/1511251135_140610_Valuing_the_impacts_of_air_quality_on_productivity_Final_Report_3_0.pdf
[19] http://www.externe.info/externe_d7/sites/default/files/vol2.pdf, p.300, http://www.externe.info/externe_d7/sites/default/files/vol7.pdf, p. 381, http://www.externe.info/externe_d7/sites/default/files/methup05a.pdf, p 109.
[20] Holland, M. et al (1998): 'The effects of ozone on materials'. Contract report for the Department of the Environment, Transport and the Regions

damage cost estimates with an update to the price base and conversion to be expressed in terms of population-weighted ozone concentration (1ppb to 2µg/m^3) to gain the impact per tonne of NOx or VOC emitted via this ozone pathway in current prices.

Soiling of buildings due to PM

Rabl *et al*. (1998)[21] estimated the disamenity impacts of soiling due to PM by inferring the value from expenditure on renovation of buildings in France. The values obtained in this research are used in the damage costs and equate to £565 (2017 prices) per tonne of PM_{10} emissions (and £881 per tonne when converted to emissions of $PM_{2.5}$).

Ecosystem damages

Drawing on the Jones et al. (2014) study commissioned by Defra,[22] Table 7 details the valuation for different ecosystem pathways associated with key pollutants that are used to produce damage costs.

Total contribution of pathways to overall impact

Following the impact pathway approach methodology set out on this document, damage costs are produced for more proportionate analysis where air quality impacts are less significant. Table 8 shows the breakdown of the damage cost for each pollutant by impact pathway. This also gives a sense of the most significant impacts in terms of value to society.

[21] Rabl, A. Curtiss, P. and Pons, A. (1998) 'Air Pollution and Buildings: An Estimation of Damage Costs in France', Environmental Impact Assessment Review

[22] Jones et al. (2014), 'Assessment of the Impacts of Air Pollution on Ecosystem Services – Gap Filling and Research Recommendations', https://uk-air.defra.gov.uk/assets/documents/reports/cat10/1511251140_AQ0827_Asessment_of_the_impacts_of_air_pollution_on_Ecosystem_Services_Final_report.pdf

Table 7. Ecosystem pathway values

			Provisioning services		Regulating services				Cultural services	
Pollutant	**Unit**	**Sensitivity**	**Crop production**	**Timber production**	**Livestock production**	**CO_2 GHG Emissions**	**N_2O GHG Emissions**	**CH_4 GHG Emissions**	**Recreational fishing**	**Biodiversity**
NO_2	£/tonne (2014 prices)	Central	-	-4.30	-8.80	-54.00	11.80	-	0.10	102.80
		Low	-	*-2.30*	*-5.60*	*-22.80*	*6.20*	-	*0.10*	*33.30*
		High	-	*-8.00*	*-11.80*	*-94.00*	*18.70*	-	*0.10*	*237.40*
NH_3	£/tonne (2014 prices)	Central	-	-93.10	-294.10	-1,267.10	338.40	-	2.20	413.80
		Low	-	*-49.70*	*-186.60*	*-535.40*	*179.10*	-	*2.20*	*139.10*
		High	-	*-170.70*	*-395.90*	*-2,204.00*	*537.40*	-	*2.20*	*1,021.50*
SO_2	£/tonne (2014 prices)	Central	-	-	-	-	-	-5.30	-	-
		Low	-	-	-	-	-	*-1.60*	-	-
		High	-	-	-	-	-	*-9.50*	-	-
O_3	£/ppb (7-month 24-hour mean) (2014 prices)	Central	-	-	-1,051,000	-5,740,000	-	-	-	-
		Low	-	-	*-427,000*	*-3,866,000*	-	-	-	-
		High	-	-	*-1,705,000*	*-7,939,000*	-	-	-	-
O_3	£/POD (2014 prices)	Central	-100,555,000	-	-	-	-	-	-	-
		Low	*-83,421,000*	-	-	-	-	-	-	-
		High	*-118,970,000*	-	-	-	-	-	-	-

Table 8. Contribution of different impact pathways to overall national damage costs

Pollutant Emitted	NOx	SO_2	NH_3	VOC	$PM_{2.5}$
Damage Cost (£/t in 2017 prices)	6,199	6,273	6,046	102	105,836
PM2.5 Chronic mortality	593	2,305	2,528	-	40,238
PM10 Respiratory hospital admission	5	16	19	-	393
PM10 Cardiovascular hospital admission	3	10	12	-	240
SO2 Deaths brought forward	-	14	-	-	-
SO2 Respiratory hospital admission	-	26	-	-	-
O3 Deaths brought forward	-9	-	-	4	-
O3 Respiratory hospital admission	-47	-	-	18	-
O3 Cardiovascular hospital admission	-4	-	-	2	-
NO2 Chronic mortality	2,223	-	-	-	-
PM2.5 Productivity	52	201	221	-	3,515
O3 Productivity	-56	-	-	22	-
O3 Material damage	-18	-	-	5	-
PM10 Building soiling	-	-	-	-	881
SO2 Material damage	-	237	-	-	-
SO2 Ecosystems	-	-6	-	-	-
O3 Ecosystems	-18	-	-	11	-
O3 Ecosystems	-19	-	-	40	-
NO2 Ecosystems	63	-	-	-	-
NH3 Ecosystems	-	-	-539	-	-
PM2.5 CHD	417	1,620	1,777	-	28,282
PM2.5 Stroke	157	610	669	-	10,642
PM2.5 Lung Cancer	10	39	43	-	687
PM2.5 Asthma (Children)	309	1,201	1,317	-	20,959
NO2 Asthma (Small Children)	1,958	-	-	-	-
NO2 Asthma (Older Children)	580	-	-	-	-

6. Analytical considerations

Overlap of NO_x and PM

Air pollutants are often emitted in mixtures – for example, road transport will typically produce emissions of both NO_x and PM simultaneously. As such, it can be difficult for epidemiological studies to isolate the health impacts of just one type of pollutant. Coefficients derived from studies that look at one pollutant only (‘single pollutant models’) may also capture the effects of other pollutants and, therefore, be biased. Nonetheless, some measures will affect emissions of one type of pollutant more than another and so we require a method to estimate the damage associated with each pollutant individually.

In order to correct for this potential bias, COMEAP have recommended a reduction in the CRF associated with single pollutant NO_x models:

> To assess pollution reduction measures which are specific to NO_x/NO_2 reduction, we have decided to recommend use of the summary estimate from a meta-analysis from the single pollutant models but we have used expert judgement to reduce this coefficient to account for confounding by both PM mass (in the light of the results of the two pollutant models) and for the possible effects of other pollutants which correlate more strongly with NO_2 than PM. The majority view of the Committee is to recommend use of 25-55% (mid-point of range 40%) of the unadjusted coefficient 1.023 (95% CI: 1.008, 1.037) per 10 µg/m3 annual average NO_2. This yields coefficients of 1.006 per 10 µg/m3 annual average NO_2 and 1.013 per 10 µg/m3 annual average NO_2 respectively.[23]

This 40% adjustment factor is, therefore, applied to the CRF in the NO_2 chronic mortality pathway and NO_2 morbidity pathways.

No such adjustment factor is available for PM emissions. This means that the PM chronic mortality pathway does not account for the potential confounding effect of other correlated pollutants and, as such, is likely to be overestimated. **Analysts should clearly acknowledge this limitation and examine its potential effect on results through sensitivity analysis.**

Conversion of PM_{10} to $PM_{2.5}$

Damage costs for particulate matter are expressed in terms of emissions of $PM_{2.5}$ (that is, particles of diameter 2.5µm or less). However, some of the pathways included in those

[23] COMEAP (2018), ‘Associations of long-term average concentrations of nitrogen dioxide with mortality’, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/734799/COMEAP_NO2_Report.pdf

costs relate to PM_{10} (that is, particles of diameter 10μm or less) and for some activities it is more common for emissions to be expressed in terms of PM_{10}.

Typically, for any given source of PM emissions there will be a range of particle sizes. The National Atmospheric Emissions Inventory (NAEI) provides an estimate of emissions of both $PM_{2.5}$ and PM_{10} for most sources, which allows calculation of the expected ratio of these emission categories for different sectors and emission sources. These ratios allow the appraiser to convert estimates of PM_{10} emissions to estimates of $PM_{2.5}$ emissions and to monetise the latter using damage costs. The damage costs that are applied to $PM_{2.5}$ emissions contain all of the relevant impact pathways for PM_{10}.

Sensitivities

Impact pathways should be calculated for low, central and high scenarios, to capture the key uncertainties associated with the analysis. For NOx and PM, the scenarios differ in which impact pathways they incorporate. Tables 1 - 3 show which impact pathways are incorporated into the sensitivities. Table 9 below shows the other variations that the low and high sensitivities take into account. Table 4 details the concentration response functions that are used in the low, central and high scenarios for each pathway.

Table 9. Sensitivity scenarios

Variable	Pollutants affected	Sensitivity scenarios		
		Low	**Central**	**High**
CRF sensitivity	All	Low CRFs (and small adjustment of NO_2 chronic mortality effect)	Central CRFs (and central adjustment of NO_2 chronic mortality effect)	High CRFs (and large adjustment of NO_2 chronic mortality effect)
Value of health impacts	All	Low impact values	Central impact values	High impact values
Proportion of acute deaths valued at good health VOLY	NOx, SO_2, VOC	0%	0%	15%
Life-years-lost for acute deaths	NOx, SO_2, VOC	2 months	4 months	6 months

NO_2 hospital admission impact pathway included?	NOx	No	No	Yes
Productivity impacts included?	NOx, VOC, PM	No	Yes	Yes
Less certain morbidity pathways included?	NOx, SO_2, VOC, PM	No	No	Yes

Overall uncertainty

The sensitivities and caveats covered above provide analysts with a means of capturing the key identified uncertainties. However, there remains a large degree of unquantifiable uncertainty throughout the impact pathways process. This includes but is not limited to:

- A large degree of uncertainty involved in the dispersion modelling that underpins the calculation of impacts – this will depend on the specific model employed.
- Potential impacts caused by exposure to air pollutants that have not yet been identified and quantified by the research community.
- The valuation of PM emissions have not been adjusted to account for potential confounding effects of other pollutants.