The contribution of shipping emissions to pollutant concentrations and nitrogen deposition across the UK

Contract Report

Defra Contract ECM_53210: Support for National Air Pollution Control Strategies (SNAPCS) 2018-2020 (lot 1)

December 2019 (updated Feb 2021)

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Report to Defra under SNAPCS contract

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Acknowledgments: We are grateful to Ricardo Energy and Environment for providing maps of shipping emissions in 2016 based on their analysis of AIS data, and associated information. Also to Mike Holland of EMRC who provided guidance on damage costs (as described in Appendix C)

This is a slightly updated version of the report produced in December 2019 using UKIAM5 to incorporate updates in UKIAM version 6 in modelling nitrate aerosol, leading to slightly higher estimates of the contribution from shipping.

Terminology

AIS Automatic Identification System

CH4 Methane

CO Carbon Monoxide

CO2 Carbon Dioxide

ECA Emission Control Area

EGR Exhaust Gas Recirculation

FRAME Fine Resolution Atmospheric Multi-pollutant Exchange

IMO International Maritime Organization

LNG Liquefied Natural Gas

NAEI National Atmospheric Emission Inventory

NECD National Emission Ceilings Directive

NHy Reduced nitrogen

N20 Nitrous Oxide

NOx Nitrogen Oxides (NO and NO2)

PM2.5 Particulate Matter with a diameter of 2.5 micrometers or less

PM10 Particulate Matter with a diameter of 10 micrometers or less

PWMC Population Weighted Mean Concentration

SCR Selective Catalytic Reduction

SIA Secondary Inorganic Aerosol (includes aerosol sulphate, nitrate and ammonium)

SO2 Sulphur Dioxide

SOx Sulphur Oxides

UKIAM UK Integrated Assessment Model

VOC Volatile Organic Compounds

WHO World Health Organization

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1. Introduction

The rapid growth of shipping and associated emissions of atmospheric pollutants raises questions about the effect on air pollution in the UK. European countries are committed to reducing their emissions of NOx, SO2, PM2.5 and other pollutants to comply with strict emission ceilings by 2030 in a major effort to reduce transboundary air pollution. However control of maritime emissions in Europe has been much more limited, and restricted to specific areas of the North Sea and the Baltic. New estimates of pollutant emissions from shipping have been undertaken by Ricardo Energy & Environment using Automatic Identification System (AIS) data from shipping as received at coastguard stations (Ricardo 2017). These are more comprehensive than previous estimates, and indicate substantially higher emissions from UK domestic shipping than earlier data reported in the UK National Atmospheric Emissions Inventory, NAEI. The new AIS data also indicate emissions in 2016 of 665 kt of NOx from UK international shipping and in-transit shipping in sea areas surrounding the UK. This compares with current NOx emissions from the whole of the UK of 870kt, with a commitment for future reduction to 468 kt by 2030 (a 73% reduction relative to emissions of 1735 kt in 2005 for compliance with the National Emission Ceiling Directive, NECD).

The purpose of this report is therefore to investigate more thoroughly the future role of shipping with respect to air pollution in the UK. The aim is to investigate future scenarios to 2030, and assess the contribution of UK domestic shipping, and of UK international shipping plus in-transit shipping, to exposure of the UK population to PM2.5 and NO2 and associated health impacts; and also the contribution to deposition of nitrogen and effects on natural ecosystems. In this work we have used new modelling by the UK Centre for Ecology and Hydrology (UKCEH) of the dispersion and deposition of the marine emissions.

2. Emissions

The new data provided by Ricardo Energy and Environment is based on AIS data supplied by the Maritime and Coastguard Agency for the year 2014, as described in the Ricardo report (Ricardo 2017). These 1x1 km gridded data span the important sea areas surrounding the UK that are modelled in UKIAM, which include the Channel and North Sea, and the Irish Sea: and distinguish the Emission Control Areas (ECA) for International Maritime Organization (IMO) regulations on SOx and NOx. The emission data provided from Ricardo had been adjusted to emissions in 2016 as the base year reflecting changes due to the control of SOx within the ECA, and fleet projections.

The data covers emissions of the pollutants covered under the NECD (NOx, SO2, PM10 and VOCs, since current and historic emissions of NH3 from shipping are negligible) and also CH4, CO, and N2O, with estimated consumption of fuel oil and gas oil determining CO2 emissions. Emissions are broken down to distinguish UK domestic shipping emissions, UK international shipping emissions for trips either starting or ending at UK ports, and in-transit emissions from vessels passing the UK at sea but which do not call at a UK port. Because of the importance of emissions in ports, emissions at berth have also been separated out. More details of these categories are given in the Ricardo report.

To avoid any confusion it should be noted that the gridded data provided by Ricardo were from their AIS-based ship model at 1km resolution, and although they played an important part in a revised methodology for the NAEI to follow, they differ from the data now included in the NAEI for several reasons which have been highlighted in the following report:
https://uk-air.defra.gov.uk/assets/documents/reports/cat07/1812061112_MappingMethodology-for-NAEI-2016.pdf
These differences include the following:

In the AIS data provided Ricardo had excluded AIS messages with gaps greater than 24 hours between consecutive messages, which would otherwise show up as erroneous hot-spots in the grid (erroneous for their location, not magnitude). These are, for example, cases where fishing vessels that had called at the UK went beyond the range of the AIS receivers: the emissions from the vessels were included within the NAEI for the entirety of the voyage until the vessel returned back to the UK, even though the geographic representation of the vessel movement was missing from the gridded data.

The UKIAM model covers a different geographic area as shown in the maps in this report, from the geographic scope covered by the NAEI

The UK international and transit emission estimates are based on the AIS model, whereas the NAEI reported data are based on fuel sales and not on AIS fuel use.

2.1 UK Domestic Shipping emissions

As explained above emissions have been mapped from the 1x1 km gridded data provided by Ricardo across the sea area covered in detail by the UK Integrated Assessment Model (UKIAM) developed by Imperial College London (Oxley et al 2013), and by the underlying modelling of dispersion with the FRAME model of UKCEH (Dore et al 2007, Dore et al 2015). A summary of the emissions of each pollutant is given in table 1, distinguishing emissions from fuel oil and from gas oil, where those emissions classified as at berth are separated out for specific consideration of ports. As explained above the total emissions in table 1 are not always identical to those reported in the NAEI, where additional emissions are included outside the map area modelled in UKIAM, for example for fishing, and where naval emissions are also added. The distinction between fuel oil and gas oil is important because fuel oil is restricted to use outside the ECA (see later in this report), and can not be used in ports where S content is restricted to 0.1% in fuel for marine use. Note that these emissions are generally much higher than previous estimates for UK domestic shipping emissions, and reflect the more complete coverage. For example, UK domestic shipping emissions of NOx within the map area including at berth emissions are now 75 kt, whereas the estimate used in UKIAM taken from older NAEI estimates (based on fuel data) was 30.8 kt.

Table 1. Emissions from UK domestic shipping in 2016

	CH4 tons	CO tons	N2O tons	NOx tons	SO2 tons	VOC tons	PM10 tons	CO2 ktons
Fuel oil	9	492	26	12416	4614	437	452	531
Gas oil	33	3120	143	56426	6157	1660	1013	1945
At berth	4	410	22	5911	309	179	159	383
Total	**46**	**4022**	**191**	**74750**	**11080**	**2276**	**1624**	**2859**

These emissions are also broken down by vessel type as illustrated in figure 1 for NOx and CO2.

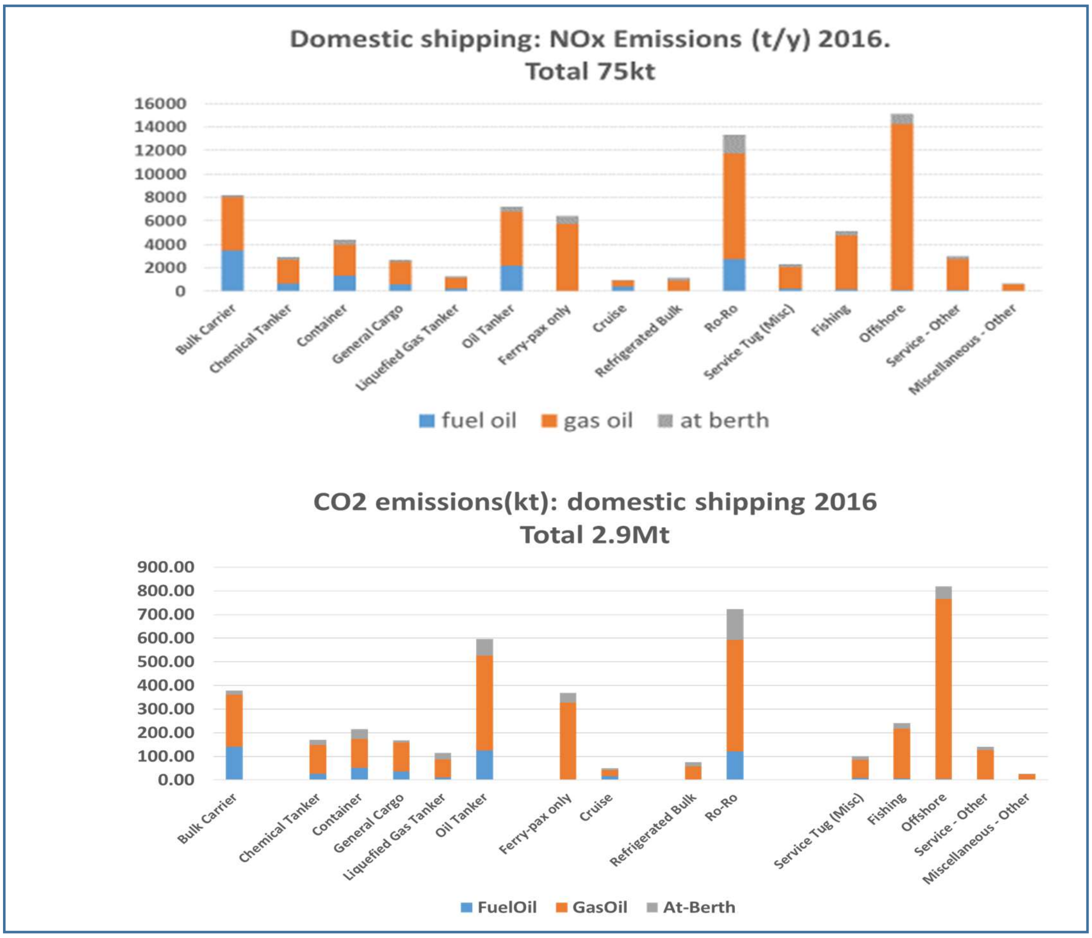
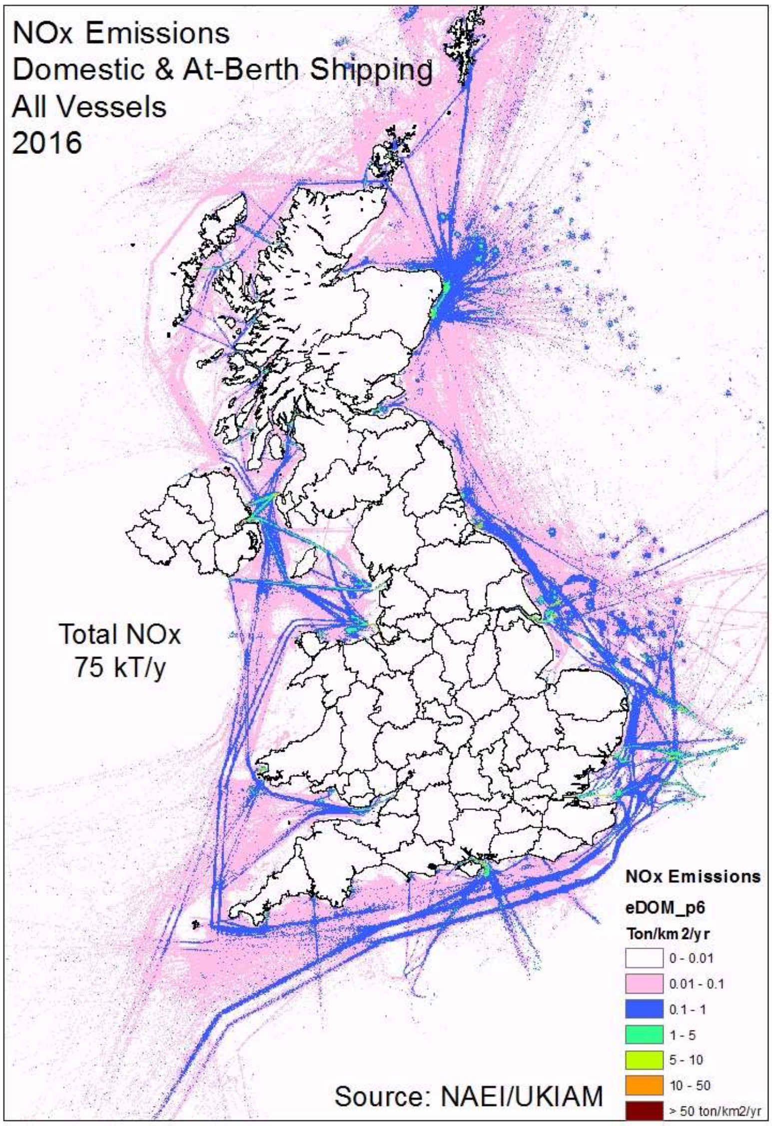


Figure 1 Break down of NOx and CO2 emissions from UK domestic shipping in 2016 by vessel type (NB At berth emissions are gas oil)

The spatial distribution of emissions is also important for air quality, where NOx is of most concern together with SO2 and PM10. Figure 2 shows the spatial distribution of NOx emissions from UK domestic shipping (including at berth). There are big differences in the spatial pattern for different vessel types contributing to this total, for which individual maps are given in Appendix B. These indicate that the oil industry and fishing account for the high values on the east coast of Scotland; and highlight the contribution of ferries in the English Channel.

Also important for future emissions and concentrations is the distribution between ECAs, in which IMO regulations apply, and non-ECA areas. This is discussed below under emission projections based on a more detailed break down between ECA and non-ECA areas of emissions of SO2, NOx and PM10 as the main pollutants of concern.

Figure 2: Map of NOx emissions from UK domestic shipping in 2016 (includes at berth)



2.2 UK International Shipping and In-transit Shipping emissions

There are two other categories of shipping, the UK international shipping to and from UK ports (but with all at berth emissions included in UK domestic emissions), and in-transit shipping, which is shipping passing the UK at sea which does not call at a UK port. These are combined in table 2.

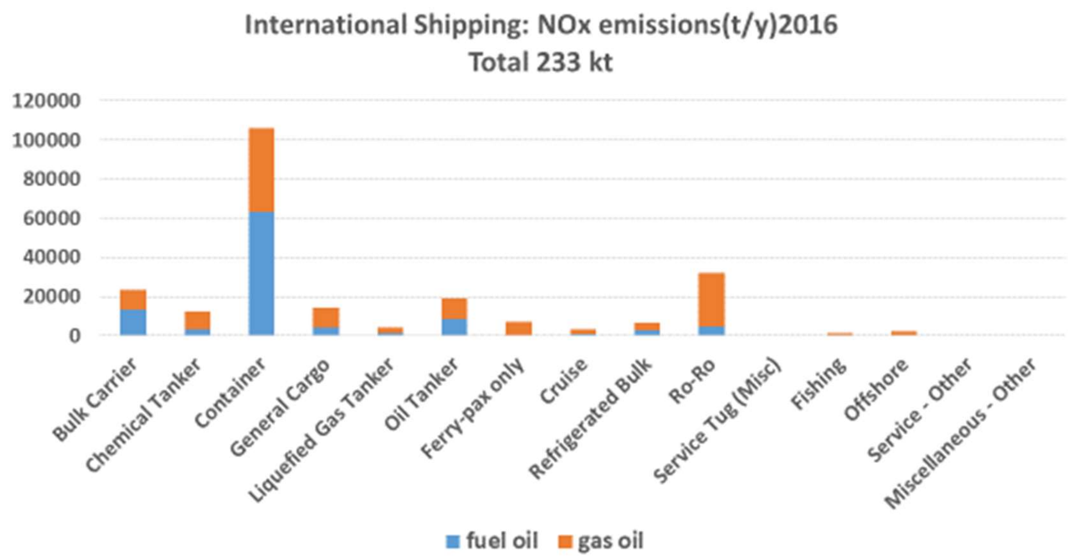
Table 2: Emissions from UK international shipping and in-transit shipping in 2016].

	CH4	CO	N2O	NOx	SO2	VOC	PM10	CO2
UK international	tons	tons	tons	tons	tons	tons	tons	ktons
fuel oil	72	3610	187	102708	33862	3615	3439	4043
gas oil	64	6498	281	130422	9826	3230	1881	6053
total	**136**	**10108**	**469**	**233130**	**43689**	**6845**	**5320**	**10096**
In Transit								
fuel oil	113	5698	299	162534	53820	5669	5459	6346
gas oil	138	12739	573	270150	18112	7034	3781	10613
Total	**251**	**18437**	**872**	**432684**	**71933**	**12703**	**9240**	**16959**
TOTAL	**387**	**28540**	**1341**	**665000**	**115000**	**19548**	**14500**	**27050**

The total emissions from UK international shipping and in-transit shipping are also larger than previous estimates. For example, 233kt of NOx from UK international shipping plus 432kt from in-transit shipping, gives a total of 665kt (compared with a total of 430 kt based on earlier work by ENTEC – ENTEC 2010). Disaggregated emissions of NOx by vessel type are shown separately in figure 3 for UK international shipping, where container ships are by far the largest source: and for in-transit shipping emissions, where as well as container ships, tankers and bulk carriers are important sources too.

Figure 3. Emissions of NOx by type of vessels from UK international shipping plus in-transit shipping in 2016

a) UK international shipping



b) In-transit shipping

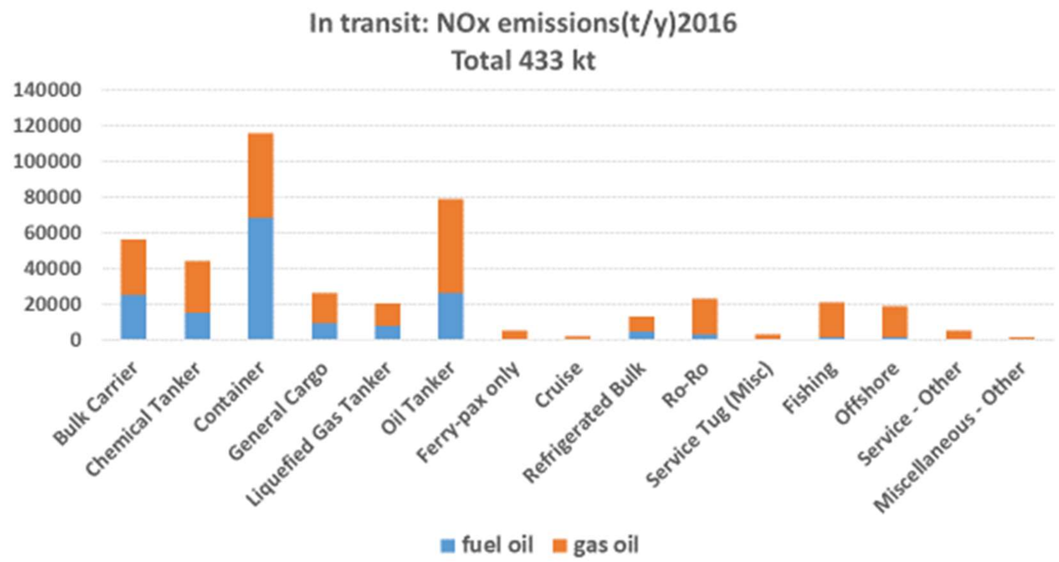
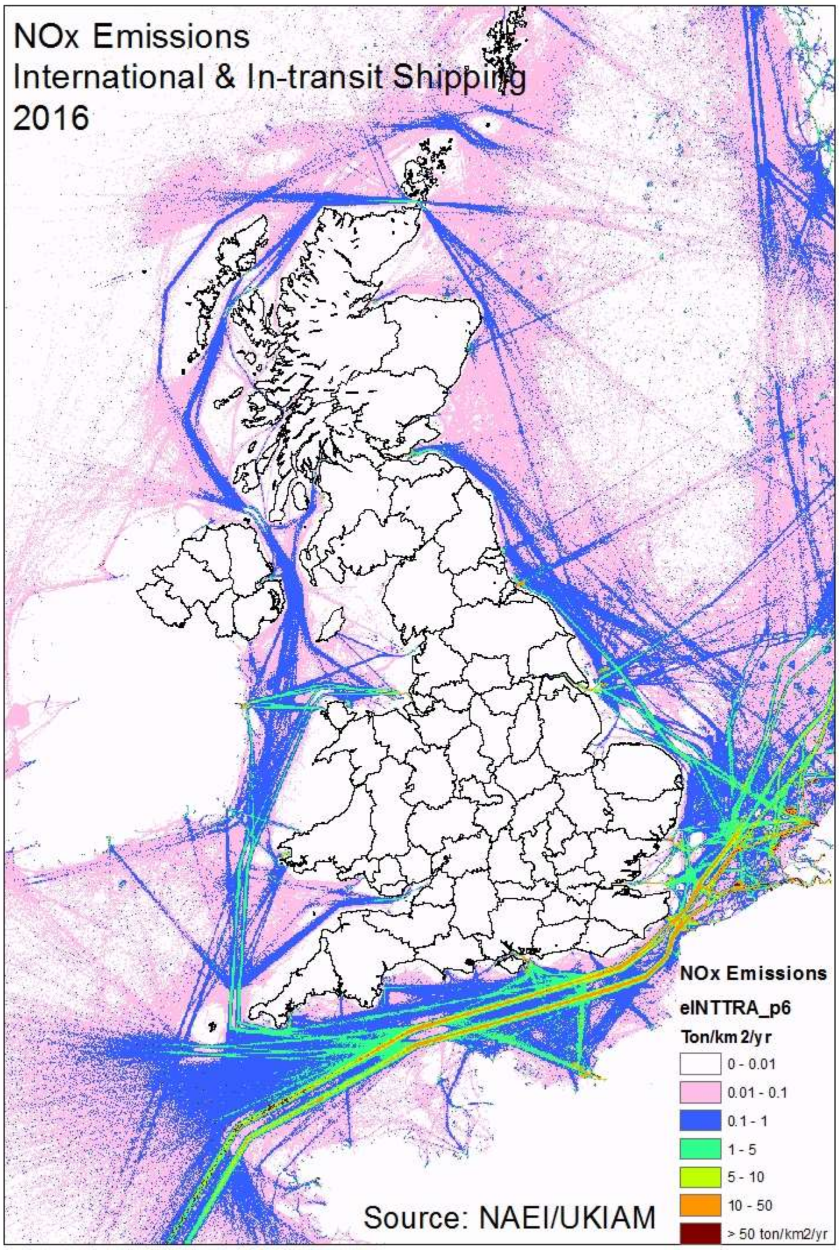


Figure 4 shows a map of the total emissions from UK international shipping and in-transit shipping in 2016, with the high values concentrated along shipping lanes through the English Channel and into the North Sea. Note that the ECA covers the Channel and sea areas to the east of the UK; but not the Irish sea and areas to the west of the UK.

Figure 4: Total NOx emissions from UK international shipping and in-transit shipping in 2016



2.3 Emission projections to 2030

Emission projections to 2030 depend on projected rates of change of shipping activities, and improved efficiencies and control of emissions. These are dependent on international regulation by the IMO within the ECA covering the English Channel and the North Sea for both SOx and NOx. With respect to SOx, outside the ECA the sulphur content of fuel will be limited to 0.5% from 2020, whilst within the ECA and for ships at berth and in ports the sulphur content is limited to 0.1% which means that fuel oil is not used. With respect to NOx for ships operating within the ECA, new ships constructed from 1 January 2021 will need to meet the tier III requirements. This is likely to require technologies such as Exhaust Gas Recirculation (EGR) and Selective Catalytic Reduction (SCR), or use of alternative fuels like Liquefied Natural Gas (LNG).

The projection of emissions from 2016 to 2030 has been based on estimates by Wood Plc as described in Appendix A for UK domestic emissions, distinguishing between ECA and non-ECA areas and with different projection factors for each vessel type and pollutant. We have used the projection factors derived as the ratio of future emissions in 2030 to those in 2016, summing over the different vessel types to get total UK domestic emissions distinguishing between within the ECA and outside it. This has been extrapolated to UK international and in-transit emissions within and outside the ECA, assuming the same projection factors apply for the ratio of emissions in 2030 to those in 2016 for each vessel type and pollutant as for the UK domestic emissions. It should be noted that this is a significant assumption, and that the activity change from 2016 to 2030 associated with UK international and the transiting vessels is likely to be much higher than for domestic. For example, the IMO (2014) estimates suggest that emissions of CO2 will increase from global shipping under BAU scenarios, suggesting a substantial activity increase up to 2050. However, the lack of UK-specific data on this means it is difficult to estimate the likely change in activity for international shipping in UK waters, and the uncertainty around these values are within the uncertainty levels of the assessment. However the assumption made is a conservative one tending towards underestimation of the future impact of international shipping.

Table 3 gives the calculated total emissions in 2030 compared with those for 2016, distinguishing emission in ECA and non-ECA areas. These reflect different growth rates for different types of shipping; and a more detailed disaggregation by type of vessel is given in appendix A. It is assumed that emission reduction of NOx in the ECA is achieved by an equal split between EGR, SCR and LNG. The SO2 emissions reflect the sulphur content of the fuel, which also affects the emissions of primary PM10. It is assumed that almost all the PM10 is emitted as the finer fraction PM2.5 (factor 0.947).

Table 3: Shipping emissions (kt) in 2016 and 2030

a) UK domestic shipping emissions

	Fuel Oil		Gas-oil at sea		Gas-oil at berth		Total
	Non ECA	ECA	Non ECA	ECA	Non ECA	ECA	
2016							
SO2	4.61	0	4.65	1.50	.109	.199	11.08
NOx	12.1	0	12.56	43.86	2.03	3.87	74.75
PM10	.452	0	.419	.593	.086	.072	1.623
2030							
SO2	1.85	0	2.12	1.33	.109	.194	5.61
NOx	12.21	0	11.36	32.23	2.01	3.05	60.87
PM10	.230	0	.224	.547	.091	.073	1.17

b) Emission from UK international shipping plus in-transit shipping

	UK International Fuel Oil		UK International Gas Oil		In Transit Fuel Oil		In Transit Gas Oil		Total
	Non ECA	ECA	Non ECA	ECA	Non ECA	ECA	Non ECA	ECA	
2016									
SO2	33.77	0	6.58	3.25	53.68	0	11.17	6.94	115.4
NOx	102.43	0	18.16	112.3	162.13	0	33.41	236.8	665.2
PM10	3.43	0	.601	1.28	5.44	0	1.05	2.73	14.54
2030									
SO2	16.59	0	3.47	3.53	24.01	0	5.36	6.74	59.73
NOx	122.57	0	19.07	102.0	176.73	0	31.83	191.51	643.8
PM10	2.13	0	.371	1.45	3.09	0	.591	2.77	10.4

3.0 Modelling environmental impacts of shipping

Shipping contributes to air pollution in the UK in three ways. First there is the contribution to concentrations of fine particulate PM2.5. This is mainly a long-range effect as gaseous emissions give rise to secondary inorganic aerosol during atmospheric transport. Then there is a more localised contribution to NO2 concentrations, where in-port emissions may be important. Thirdly the NOx emissions from shipping give rise to nitrogen deposition across the UK, contributing to eutrophication of ecosystems and loss of biodiversity.

The modelling of concentrations and deposition has been modelled with UKIAM (Oxley et al 2013), based on atmospheric modelling of source footprints for UK domestic, at-berth, and UK international shipping plus in-transit shipping emissions, distinguishing ECA and non-ECA areas. The FRAME model of UKCEH (Dore et al 2007, Dore et al 2015) has been used to model the concentrations of secondary particulates and deposition of nitrogen across the UK for the situation in 2016, and the component contributions are scaled in UKIAM in accordance with changes in emissions to match emission projections and abatement scenarios. Concentrations of NOx and NO2, and primary PM2.5, which are dominated by local scale dispersion, are modelled with the Gaussian PPM model of Imperial College. In a similar way, using scaling of source footprints, the UKIAM model combines the contribution imported from other countries (based on European scale modelling of atmospheric dispersion with the EMEP model (Simpson et al 2012) incorporated in the ASAM sub-model of UKIAM), with that from UK international shipping plus in-transit shipping as described in this report; and with contributions from UK sources including UK domestic shipping and at berth emissions. The combined totals are used in assessing future air quality in the UK for Defra to support development of abatement strategies.

3.1 Contribution of shipping to total PM2.5 concentrations and population exposure in the UK

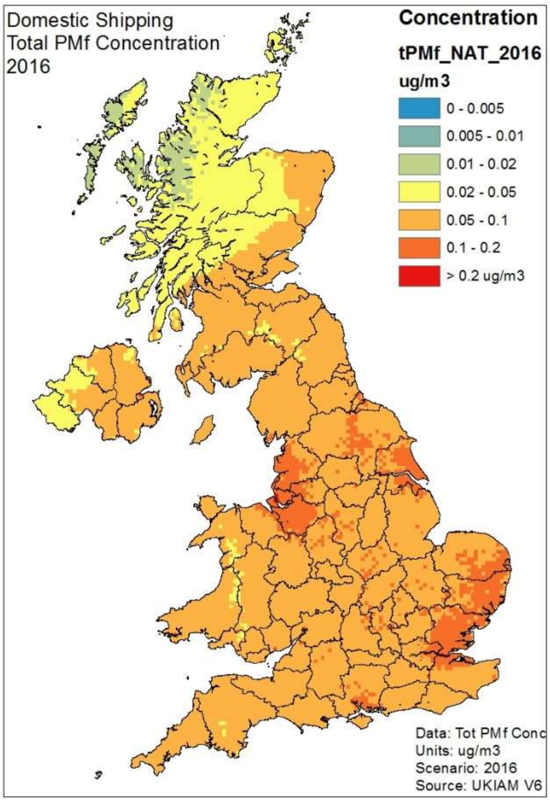
The contribution of primary PM emissions from shipping to population exposure in the UK is small, but the large NOx emissions give rise to particulate nitrate with additional contributions from SO2 emissions to secondary inorganic aerosol, SIA. These secondary contributions dominate the contribution of shipping to PM2.5 exposure in the UK. Note that because of interactive chemistry reducing SO2 or NOx emissions affects the chemical composition of all the SIA components (sulphate (SO4), nitrate (NO3) and ammonium (NH4)). The total PM2.5 concentration is the combination of the primary PM2.5 with these secondary components.

a) UK domestic shipping

Figure 5 shows maps of the total PM2.5 concentrations due to UK domestic shipping including at berth emissions in 2016, and in 2030 for the Business as Usual scenario. The overall contribution from at-berth emissions is small but concentrated in port areas. Overall the contribution of UK shipping emissions to combined primary and secondary PM2.5 concentrations across most of the UK is close to or below 0.1 ug.m^{-3}. This is a modest contribution compared with the World Health Organization (WHO) guideline for PM2.5 exposure of 10ug.m^{-3}. Figure 5 also shows the further reduction by 2030, reflecting control of NOx, and to a lesser extent SO2 emissions from UK domestic shipping. Although there are potentially effective measures for reducing shipping emissions, the effect of further abatement of UK domestic shipping therefore has a limited effect on overall PM2.5 concentrations, although it may be important in other contexts- in particular for at berth emissions with respect to NOx concentrations in ports- see next section. Table 5 illustrates this, comparing population weighted mean concentrations for different areas of the UK in 2016, 2030, and for a “Central scenario” provided by Defra and based on work by Wood Plc. aimed at achieving the NECD emission ceilings for UK emissions overall in 2030. This last scenario includes UK domestic shipping as one of the component UK sources abated to achieve the required reduction of overall UK emissions. In this central scenario a significant additional reduction (~30kt of NOx) is made to UK domestic shipping emissions in 2030 towards achieving the UK ceiling for NOx, and incurs only a low cost. But the benefit in reducing exposure to PM2.5 and associated health impacts by addressing just these UK domestic shipping emissions is limited compared with international and in transit shipping discussed in the next section (with measures in the central scenario reducing population weighted mean exposure in the UK by 0.026 ug/m3- see table 5 , equivalent to a monetised health benefit of ~ £87 million per year).

Figure 5.Total PM2.5 concentration (ug/m3) due to UK domestic shipping emissions in (a) 2016 and in (b) the 2030 Business as Usual scenario

a) 2016



b) 2030 Business as Usual

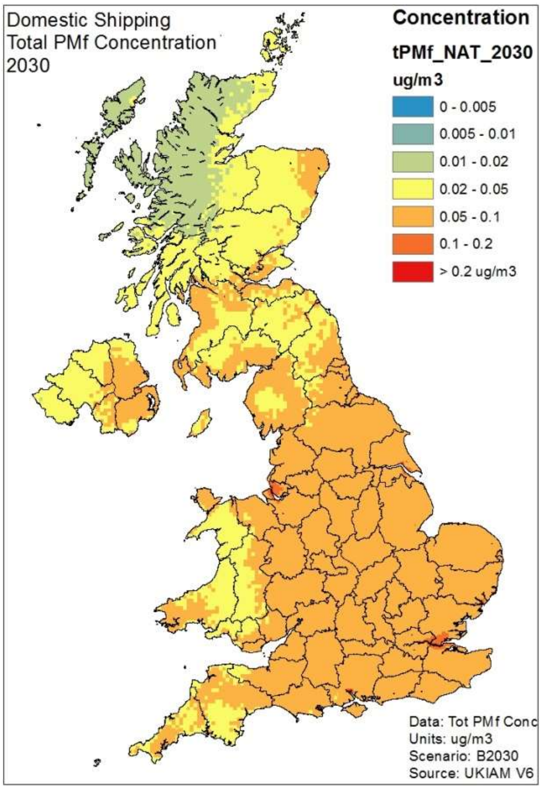


Table 5: population weighted mean concentrations of PM2.5 ($ug.m^{-3}$) in different regions due to UK domestic shipping in 2016, 2030 Business as Usual (BAU) and for a 2030 'Central Scenario'

	National	London	England	Scotland	Wales	N Ireland
2016	0.094	0.099	0.097	0.076	0.077	0.071
2030 BAU	0.073	0.079	0.076	0.058	0.057	0.056
2030 Central	0.047	0.043	0.047	0.044	0.042	0.049

b) UK International shipping and in-transit shipping

The emissions of 665 kt of NOx in 2016 from UK international shipping and in-transit shipping in sea areas surrounding the UK are nearly an order of magnitude greater than the UK domestic shipping emissions; and larger than the ceiling for UK total NOx emissions in 2030 of 470 kt. Not surprisingly secondary PM2.5 from these NOx emissions has a bigger effect on concentrations of PM2.5 across the UK than secondary PM2.5 from UK domestic shipping. The contribution from primary PM2.5 emissions from shipping is very small, and dwarfed by the secondary PM2.5 contribution. Figure 6 shows maps of PM2.5 across the UK attributed to UK international shipping plus in-transit shipping, both for 2016 and for projected emissions in 2030. The latter reflect IMO legislation to reduce emissions from shipping within the ECA area, and figure 7 shows a break down of the separate contributions from shipping within and outside the ECA in 2030.

Table 6 gives the contributions from ECA and non-ECA areas to population weighted mean concentrations of PM2.5 in different regions of the UK. It can be seen how the contribution from the non-ECA area increases between 2016 and 2030: but that from the ECA reduces, though by a moderate amount as increases in shipping volume counteract the effect of legislation to reduce emissions- which for NOx only applies to new ships built from 2021 onwards. Overall the change between 2016 and 2030 is small, and the SIA is dominated by the NOx emissions with SO2 emissions only playing a small part even from the non-ECA areas in 2030.

In terms of monetised health effects an average contribution to exposure of the 67 million people in the UK of 0.44 $ug.m^{-3}$ (the slightly lower figure for 2030) is approximately £1.5 billion per year. This is based on a cost of £50 per $ug.m^{-3}$ per person per year corresponding to 2017 prices, and in line with recent revision of Defra damage costs (see Appendix C). This is a substantial sum, and the contribution of 0.6 $ug.m^{-3}$ to exposure of the London population is important in the context of attaining the WHO guideline of 10 $ug.m^{-3}$ in the UK.

Table 6 Population weighted mean concentrations of PM2.5 ($ug.m^{-3}$) due to UK international shipping plus in-transit shipping

	National	London	England	Scotland	Wales	N Ireland
2016						
ECA	0.270	0.384	0.302	0.073	0.181	0.056
Non-ECA	0.215	0.239	0.227	0.100	0.244	0.158
Total	**0.485**	**0.623**	**0.530**	**0.173**	**0.425**	**0.213**
2030						
ECA	0.229	0.327	0.257	0.062	0.153	0.047
Non-ECA	0.215	0.245	0.228	0.098	0.234	0.157
Total	**0.444**	**0.573**	**0.484**	**0.160**	**0.387**	**0.204**

Figure 6: Total PM2.5 concentrations (ug.m^{-3}) due to UK international shipping plus in-transit shipping in a) 2016 and b) 2030

a)2016 b) 2030

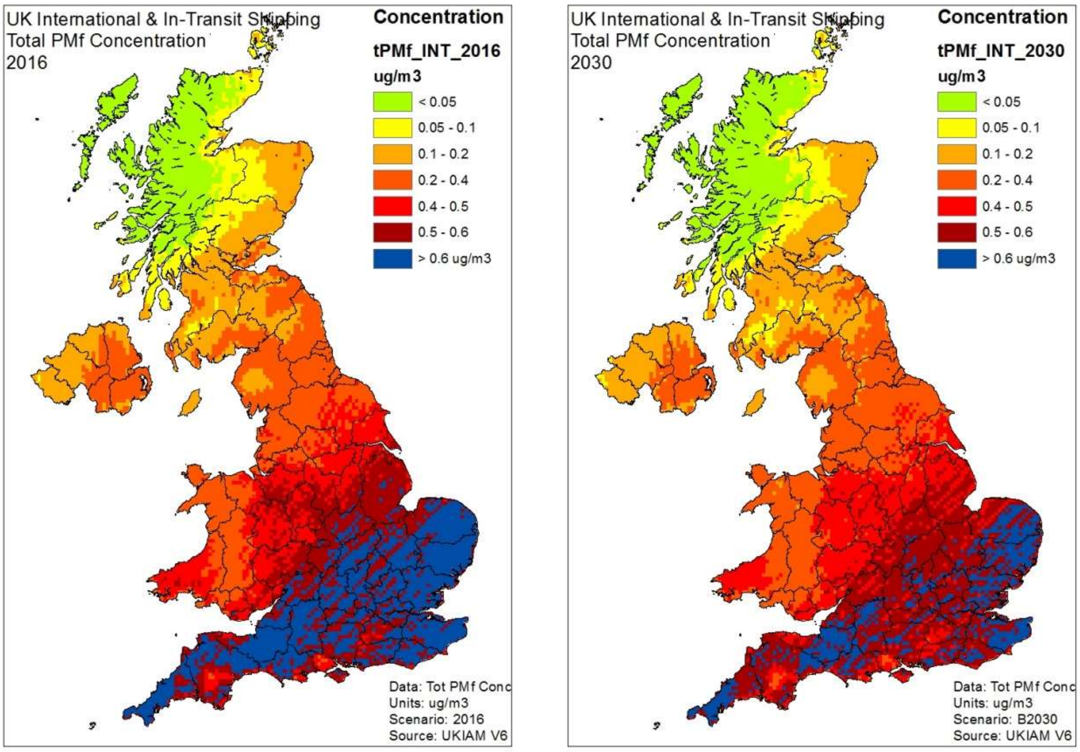
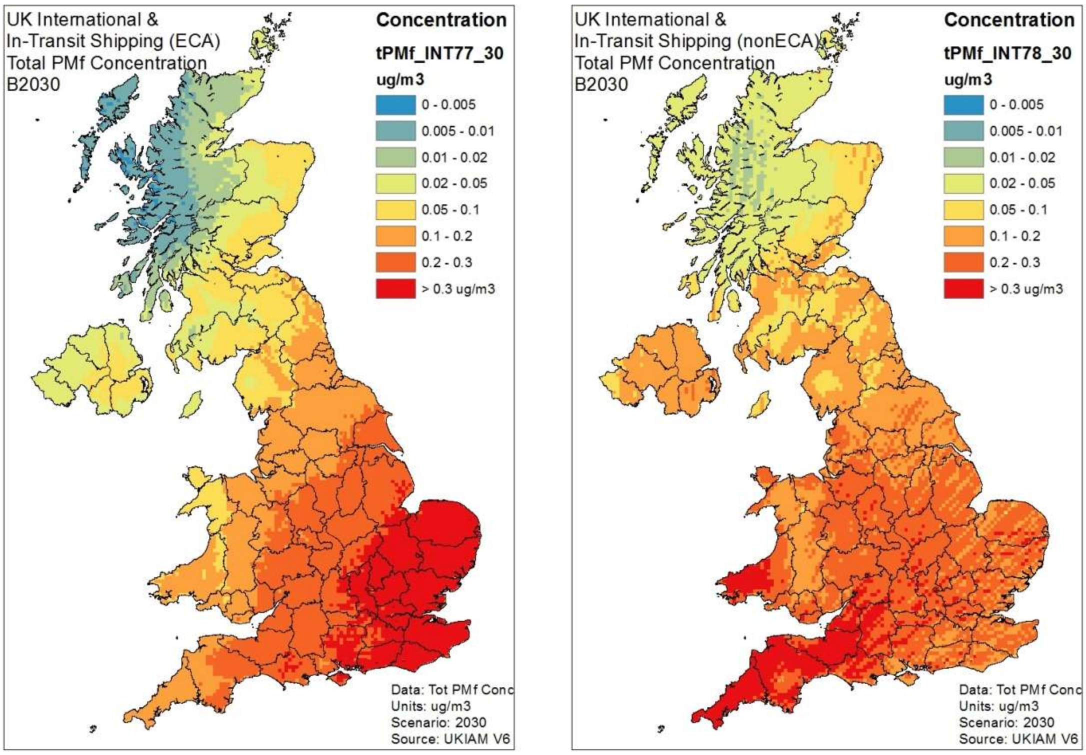


Figure 7: Total PM2.5 concentration (ug.m^{-3}) from UK international shipping plus in-transit shipping from a) ECA and b) non-ECA areas in 2030

a) ECA b) non-ECA



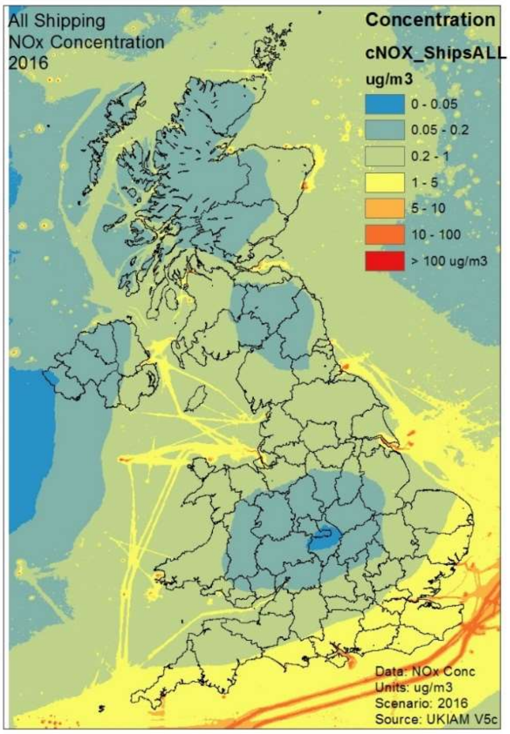
3.2 Contribution to NOx concentrations

The contribution of shipping to atmospheric NOx concentrations falls off rapidly with distance from the point of emission, and is dominated by local sources. Figure 8 shows maps of the combined contributions of UK domestic shipping(including at berth) plus UK international shipping and in-transit shipping emissions in 2016 and 2030. This illustrates that the combined effect exceeds 1ug.m^{-3} in localised areas round ports, and over southern and south-eastern coastal areas close to the main shipping lanes through the Channel. There are also very small areas in orange/red above 5ug.m^{-3} which are limited to port areas, and it is these areas where contributions to NOx may be significant. Here the at-berth emissions can be important, and will be superimposed on traffic, freight and other operational sources associated with ports. A proper study of such areas requires detailed modelling with higher spatial resolution that can reflect where the ships and other sources are relative to populated areas on shore.

Figure 9 gives a break down of the contributions to NOx concentrations in 2030 from UK domestic shipping (excluding at berth emissions), at berth emissions, and UK international shipping plus in-transit shipping broken down between emissions in the ECA and non-ECA areas. The latter illustrates the spatial extent of the ECA zone. Most of the more diffuse NOx concentrations over the southern and south eastern coasts come from UK international shipping and in-transit shipping.

Figure 8: Combined contributions of shipping (UK domestic, UK international and in-transit) to atmospheric NOx concentrations (ug.m^{-3}) in a) 2016 and b) 2030

a) 2016



b) 2030

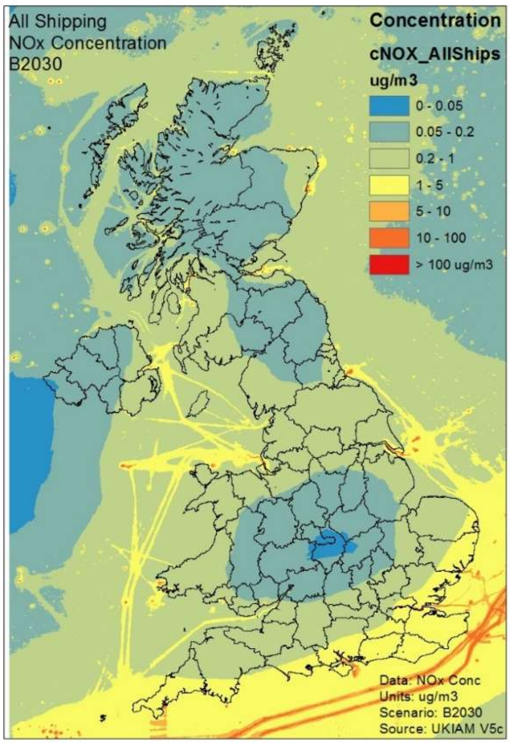
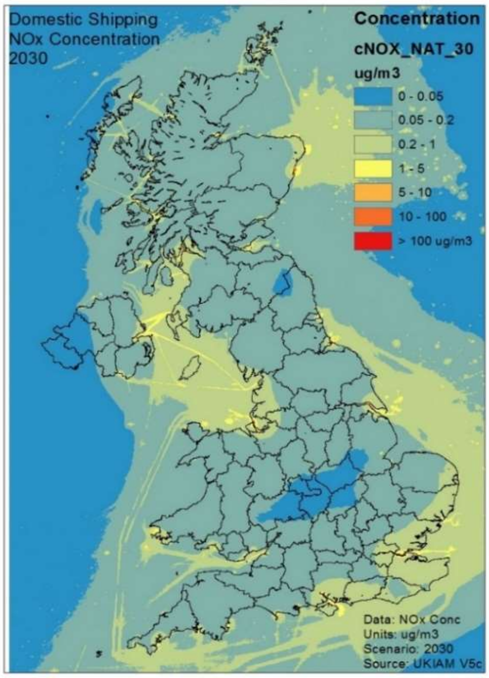
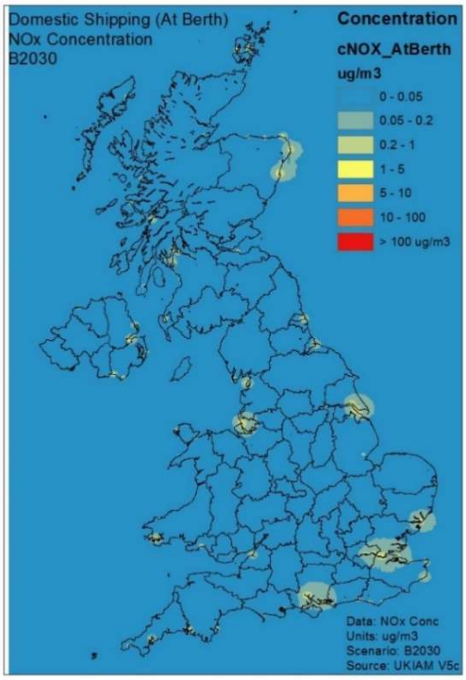


Figure 9: Contributions to NOx concentrations (ug.m^{-3}) in 2030 of emissions from a) UK domestic shipping excluding at berth, b) at berth emissions, c) UK international shipping and in-transit shipping in the ECA, and d) UK international shipping and in-transit shipping in non-ECA areas.

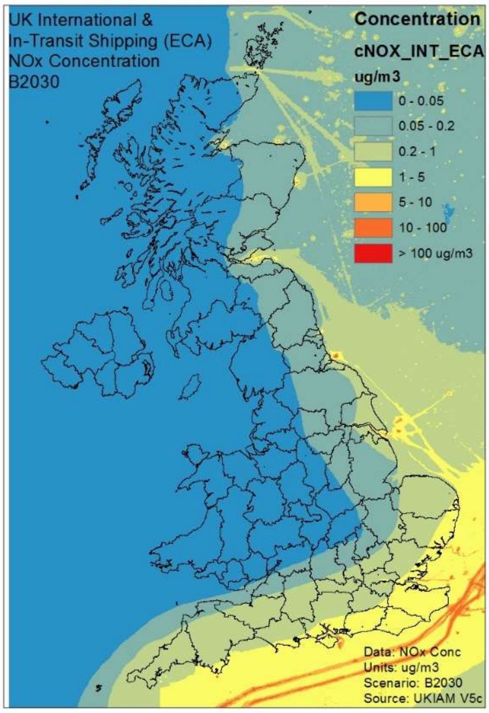
a)



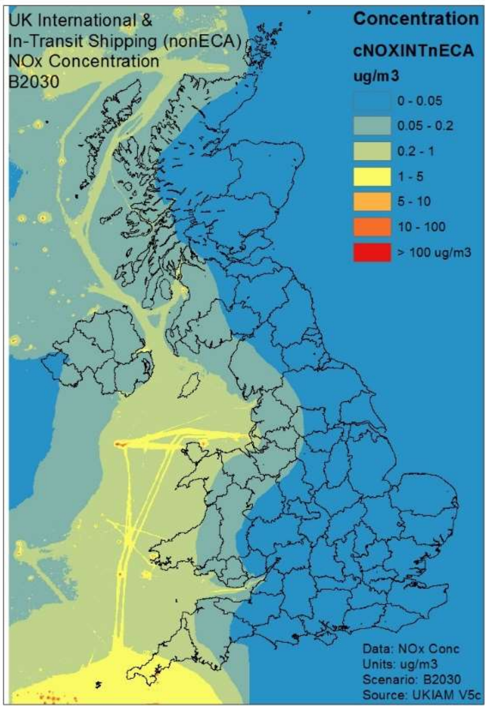
b)



c)



d)



3.3 Deposition

The third consideration is the contribution from shipping to nitrogen deposition, and eutrophication of natural ecosystems in the UK. With stricter control of SO2 emissions from ships the deposition of sulphur is small, and overall problems of acidification are much reduced in the UK. But excess nitrogen deposition and protection of ecosystems and biodiversity is a more difficult problem to solve, including control of ammonia emissions from agricultural sources to cut nitrogen deposition in reduced form (NHy).

New data has been provided from the FRAME model by UKCEH to estimate deposition of nitrogen from shipping across the UK, with the deposition of nitrogen in precipitation ('wet deposition') being the greater part and subject to enhanced deposition over higher land where many sensitive ecosystem areas are located (Kryza. M et al 2012). It is thought that the new data from the FRAME model might overestimate wet removal of nitrogen over the sea, and hence underestimate the amount of nitrogen transported to land. Hence the results reported in this section may tend to underestimate the amounts of nitrogen deposited from shipping.

Table 7 summarises the estimated nitrogen deposition to the UK in kilo-tonnes per year, both nationally and broken down by region. This is for both UK domestic shipping including at berth, and for UK international shipping plus in-transit shipping, distinguishing ECA and non-ECA emission areas to indicate the relative changes between 2016 and 2030 with and without the emission controls operating in the ECA. It can be seen that increased emissions in the non-ECA areas almost cancel out the emission reductions in the ECA, and there is thus a shift spatially of emissions towards the west of the UK. This effect shows in the maps of deposition in figures 10(b) and 10(d), where a reduction in nitrogen deposition from UK international shipping and in-transit shipping can be seen over Kent between 2016 and 2030, but no corresponding improvement is indicated for sensitive areas in Wales and south west England.

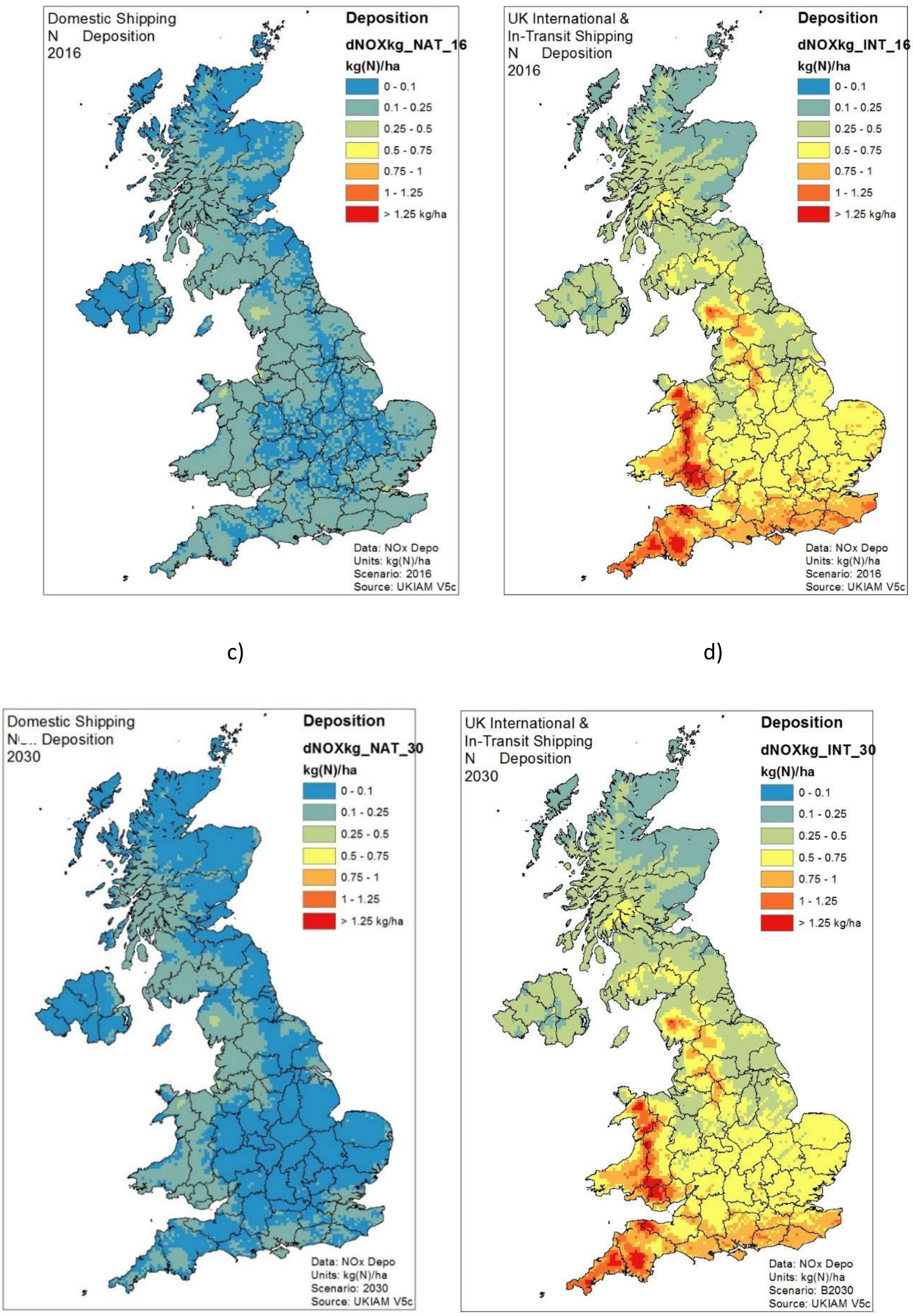
Deposition of oxidised nitrogen from combustion sources, alongside deposition of reduced nitrogen coming mainly from agriculture, have important effects on UK ecosystems, particularly from eutrophication where excess nitrogen affects competitiveness of plant species and biodiversity. To put the contribution from shipping to nitrogen deposition in perspective total deposition of oxidised nitrogen from UK sources in 2016 is estimated at about 47 kt, reducing to around 23 kt in 2030 for the central scenario aimed at compliance with the NECD. In this context deposition of 13 kt of nitrogen from international shipping plus in-transit shipping is an important additional source of nitrogen deposition which is not reducing over time.

Table 7: Deposition of nitrogen (kt of N) from shipping in 2016 and projected to 2030

	National	England	Scotland	Wales	N Ireland
2016 UK domestic	2.90	1.57	0.88	0.33	0.13
2016 UK international plus in-transit					
ECA	7.29	5.22	1.08	0.86	0.12
Non-ECA	6.09	3.57	1.24	0.97	0.29
Total	**13.4**	**8.79**	**2.33**	**1.85**	**0.42**
2030 UK Domestic	2.44	1.30	0.75	0.28	0.11
2030 UK international plus in-transit					
ECA	6.13	4.39	0.91	0.73	0.10
Non-ECA	6.75	3.95	1.38	1.09	0.33
Total	**12.9**	**8.35**	**2.29**	**1.82**	**0.43**

Figure 10. Maps of nitrogen deposition (kgN/ha) due to NOx emissions from a) UK domestic shipping in 2016, b) UK international shipping plus in-transit shipping in 2016, c) UK domestic shipping in 2030, and d) UK international shipping plus in-transit shipping in2030.

a) b)



4. Summary and future work

This report has used new shipping emissions data compiled by Ricardo using AIS. This gives more complete coverage and higher emissions than previous estimates in the NAEI, and covers UK domestic emissions including at-berth emissions in port, and UK international shipping plus in-transit shipping in sea areas round the UK. Emissions for 2016, broken down by type of vessel, have been used as the basis for projections to 2030, taking account of growth in future shipping activity and distinguishing shipping within the Emission Control Area where IMO regulations will apply to reduce SOx and NOx.

UK domestic shipping emissions in 2016 of ~75 kt of NOx (more than twice previous estimates) show a modest reduction to 61 kt in 2030, whereas emissions of SO2 are halved from 11 kt to 5.6 kt with associated reductions in primary PM10 from 1.6 to 1.2 kt in 2030. Total UK international shipping and in-transit shipping emissions of NOx at 665 kt in 2016 from the sea areas surrounding the UK are large, and show only a small reduction to 644 kt in 2030 (compare with 870 kt as the current total NOx emissions from the UK, and 470kt as the NECD UK ceiling to be attained by 2030). As for UK domestic shipping, SO2 emissions are nearly halved from 115 kt to 60 kt, and PM10 comes down from 14.5 kt in 2016 to 10kt in 2030.

These shipping emissions data have been used in Imperial College's UKIAM model, to investigate the potential environmental effects from shipping. Three aspects have been considered. The first is the contribution of shipping to exposure of the UK population to fine particulates PM2.5, including secondary PM2.5 where emissions of NOx and SO2 are converted to SIA particles during atmospheric transport and dispersal. This is a longer range effect, where emissions of NOx from UK international shipping and in-transit shipping are particularly important. Overall UK international shipping plus in-transit shipping contributes an average of .48 ug.m^{-3} to PM2.5 concentrations and exposure averaged over the UK population. Unlike imported contributions from other countries in Europe, who like the UK are making big reductions in their national air pollutant emissions, this imported contribution from UK international shipping and in-transit shipping reduces only marginally to .44 ug.m^{-3}in 2030. The corresponding monetised health costs for the UK population, derived as described in Appendix C) , are approximately £1.5 billion per year in 2017 prices

The contribution of shipping to NOx and NO2 atmospheric concentrations is less of an issue, except for ports where at-berth and other emissions including traffic and freight and port operations may lead to combined local problems. This would require more detailed local scale modelling of a port area, and the proximity of local populations.

The third issue considered was the contribution of shipping to deposition of nitrogen across the UK with respect to eutrophication and protection of natural ecosystems. Here the modelling may tend to underestimate the deposition, but ~13 kt of N deposited per year across the UK from UK international shipping and in-transit shipping, and a further up to 3kt from UK domestic shipping is substantial. This compares with deposition of 47 kt of nitrogen from all UK sources of NOx in 2016, reducing to around 23 kt in 2030 for the Central scenario. Moreover there is little or no reduction of nitrogen deposition from international and in-transit shipping between 2016 and 2030.

The current study has not looked at how emissions of air quality pollutants from shipping might be reduced more effectively. Future work could explore such scenarios, and look in more detail at emission control options for specific types of shipping vessel and activity. It is also noted that there are large uncertainties in the future growth of shipping, particularly in international shipping; and that the conservative assumptions made in this report may tend to underestimate future emissions and impacts. There may also be synergies and conflicts for air quality impacts from measures to reduce green-house gas emissions, such as the potential use of NH3 as a marine fuel.

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APPENDIX A : Shipping Emissions and Emission Projections

This appendix describes the method used to derive projected shipping emissions in 2030, followed by tables giving a break down by vessel type for 2016 as the base year, and the calculated projected emissions in 2030.

Calculation of emission projections by Wood PLc

The main NAEI emissions projections do not distinguish between ECA and non-ECA, which influences business as usual technologies. However, the UK shipping inventory has recently been overhauled (Ricardo E&E, 2017). Imperial College has taken the Ricardo inventory data for 2016 and mapped disaggregated emissions between inside and outside Emission Control Area (ECA) for each pollutant, fuel type and 14 vessel categories, differentiating between at berth and at sea. These detailed data have been used (by Wood) to develop emission projections for 2025 and 2030, adjusting for growth and technology changes. These detailed projections have been calibrated against the main NAEI shipping emission projections. A set of projections using the categorisation consistent with the NAEI projections with the additional differentiation between inside and outside ECAs has been produced and used as the input for the MPMD.

The estimated projections were derived using assumptions of i) improvements in overall efficiency of the fleet resulting from fleet turnover with newer, more efficient vessels replacing older ones, ii) changes in emission factors for each pollutant across the fleet (i.e. based on fleet turnover rate), and iii) projected changes in the average annual rates of activity (i.e. fuel consumption) for each vessel type. The projected emissions were also split between those occurring inside and outside the emissions control areas (ECAs) . For consistency, as far as possible we have designed the methodology for deriving these projections to align with that used in the Ricardo (2017) report, as far as possible from the information provided. In some cases there was some uncertainty as to what the exact approach was in this study. The results are calibrated with the separate NAEI projections, the added value being that the emissions projections are broken down and mapped geographically to distinguish the ECA and non-ECA areas for each pollutant.

To derive an 'efficiency index' for 2025 and 2030, following the approach used by Ricardo (2017), it is assumed that the efficiency of sea transport improves by 1% per year from 2014 to account for lower fuel consumption per unit transported and more fuel efficient new vessels compared to old vessels. The efficiency index can therefore be descried by the equation:

$Efficiency\ Index = 0.99^{(y-Start\ Year)}$.

To align with the approach of the Ricardo E&E (2017) study, the UK fleet is disaggregated into 15 vessel type categories[1], whereas the NAEI only distinguishes fishing vessels. It can be expected that each of these categories will experience different rates of annual growth. Therefore, 'activity index' values for each vessel type were derived. For ten[2] of the vessel types, the activity indices were obtained directly from the Ricardo (2017) study. For the remaining six vessel types, following the approach used in Ricardo E&E (2017), the activity index was derived from fuel consumption data from the NAEI Activity projections.

Another difference between the data provided from the Ricardo E&E (2017) shipping inventory and the NAEI is that emissions are disaggregated between "at sea" and "at berth". The "at sea" emissions have been provided only for vessels operating on UK to UK movements. The "at berth" emissions include all vessels; those operating domestically and internationally, and it is not possible to distinguish. A further difference, particularly significant for fishing vessels, is in the geographical boundary captured by the two different datasets; the shipping inventory covers up to 200 nautical miles from land, whereas the NAEI covers full movements.

For NO_X, an emissions split of 78% ECA, 22% non-ECA was derived for the 2016 NAEI data. Emission factor indexes were derived for each of the individual pollutants. Emission factor indexes are expected to differ for NO_X emissions inside and outside the ECA. Outside the ECA, the changes in emission factor

[1] Bulk carrier ; Chemical tanker Container; General cargo; Liquefied gas tanker ; Oil tanker; Ferry- pax only ; Cruise ; Refrigerated bulk ; Ro-Ro; Service - tug ; Miscellaneous - fishing ; Offshore ; Service – other ; Miscellaneous - other

[2] ; Service - tug ; Miscellaneous - fishing ; Offshore ; Service – other ; Miscellaneous - other

are expected to result only from the turnover of new vessels into the fleet. An annual reduction factor of 0.7% is applied, in line with that used by Ricardo (2017).

Inside the ECA, the changes to emission factor will be caused by both the fleet turnover (see above) and the emission reduction required to meet the Tier III standards (i.e. the emission saving from Tier I to Tier III). Ricardo E&E (2017) estimate an emissions reduction of 80% between Tier I and Tier III. Taking into account that the ECA would apply only to vessels in the North Sea and English Channel rather than all new vessels, we derive an emissions reduction value of 64% based on the NO_X emission split from the 2016 NAEI data. However, it should be noted that some vessels will adapt to comply with ECA and also operate and achieve a saving outside of the NECA, which is not taken into account in the current approach.

For SO_2, emission factor indexes for fuel oil and gas oil emissions both inside and outside the ECA were derived. For emission factor indexes inside the ECA, a value of 1 is used, as the S-fuel content limit of 0.1% was implemented in 2015 so no additional SO_2 emission reduction is expected.

Outside the ECA, for fuel oil, the estimated emission factor index is based on a reduction from current sulphur fuel content in the UK (estimated to be 1.34% in 2015 by the UKPIA) to the general global cap on sulphur content of marine fuel of 0.5% from 2020 onwards. For gas oil, outside the ECA, the emission factor index is set at 0.5 for all years, assuming S-content of fuel from 2020 onwards complied with the global cap on sulphur content of marine fuel (0.5%), reduced from the current legislative limit of 1.0%, as used in the Ricardo E&E (2017) study.

$PM_{2.5}$ emissions are proportional to the SO_2 emissions. Ricardo (2017) report using specific reference factors for the conversion of SO_2 to $PM_{2.5}$ emission factors, dependent on the S-content of the fuel. A factor of 0.38 is used here, corresponding to the difference between 1.0% and 0.1% S content of the fuel. The derived split in PM emissions is 57% ECA, 43% non-ECA.

It should be noted that no change in VOC emission factor is expected, and changes in emission are only expected to result from changes in activity and efficiency.

The projected emissions for 2025 and 2030 (and the corresponding split of ECA and non-ECA) were found to differ from the main NAEI projections, partly due to differences in the geographical scope of the Imperial College mapped data and the main NAEI projections. Furthermore, the approach taken by Ricardo in developing the NAEI projections from the detailed inventory is not transparent, and although the method, values and assumptions adopted have been aligned as far as possible there may be differences in our approach. Therefore, the calculated projections were compared against the NAEI projections to derive calibration factors, which were then applied to the calculated emissions projections split by ECA and non-ECA in 2025 and 2030. This ensures alignment with the total emissions based on our projections with the total emissions in the NAEI projections.

It should be noted that the activity change from 2016 to 2030 associated with UK international and the transiting vessels is likely to be much higher than for domestic. For example, the IMO (2015) estimates suggest that emissions of CO2 will increase from global shipping under BAU scenarios, suggesting a substantial activity increase up to 2050. However, the lack of UK-specific data on this means it is difficult to estimate the likely change in activity for international shipping in UK waters, and the uncertainty around these values are within the uncertainty levels of the assessment.

Activity data:

Using the UK average annual rate of activity change 2014-2035, used in Ricardo (2017), Activity index values for 2030 were derived. For the vessel categories where this was not available, the activity index was based on NAEI Activity projections 2016-2030.

Vessel Category	UK average annual rate of activity change 2014-2035 (%)	Activity Index (2030)	Source
Bulk carrier	0	1.00	Ricardo(2017)
Chemical tanker	0	1.00	Ricardo(2017)
Container	+4%	1.73	Ricardo(2017)
General cargo	0	1.00	Ricardo(2017)
Liquefied gas tanker	+2%	1.32	Ricardo(2017)
Oil tanker	+1%	1.15	Ricardo(2017)
Ferry- pax only	-1%	0.87	Ricardo(2017)
Cruise	+1%	1.15	Ricardo(2017)
Refrigerated bulk	+2%	1.32	Ricardo(2017)
Ro-Ro	+3%	1.51	Ricardo(2017)
Service - tug	na	0.95	Based on NAEI Activity projections 2016-2030
Miscellaneous - fishing	na	0.89	Based on NAEI Activity projections 2016-2030
Offshore	na	0.95	Based on NAEI Activity projections 2016-2030
Service – other	na	0.95	Based on NAEI Activity projections 2016-2030
Miscellaneous - other	na	0.95	Based on NAEI Activity projections 2016-2030

Ricardo 2017. A review of the NAEI shipping emissions methodology. Report for BEIS December 2017

ENTEC 2010 UK Shipping emissions inventory. Final report November 2017

SO2, NOx and PM10 shipping emissions in 2016, by vessel and sea area

	SO2 Emissions from Domestic Shipping (2016) - Tons/year						
	At Sea				At-Berth		
Vessel Type	Fuel Oil		Gas Oil (Marine Diesel)				TOTAL
	Non-ECA	ECA	Non-ECA	ECA	Non-ECA	ECA	
Bulk Carrier	1177	0	99	128	2	9	1414
Chemical Tanker	215	0	159	61	6	8	449
Container	435	0	53	71	5	21	585
General Cargo	309	0	203	56	2	5	575
Liquefied Gas Tanker	85	0	130	35	11	6	268
Oil Tanker	1033	0	476	203	14	31	1757
Ferry-pax only	16	0	966	108	11	14	1115
Cruise	133	0	61	10	2	3	209
Refrigerated Bulk	9	0	193	16	6	5	230
Ro-Ro	1008	0	1083	187	36	45	2359
Service Tug (Misc)	70	0	127	36	3	7	242
Fishing	60	0	427	88	5	10	591
Offshore	34	0	443	432	5	28	942
Service - Other	28	0	192	58	3	6	288
Miscellaneous - Other	1	0	43	11	0	1	57
All Vessels (Total)	4614	0	4655	1502	109	200	**11080**

	SO2 Emissions from International & In-Transit Shipping (2016) - Tons/year								
	International				In-Transit				
Vessel Type	Fuel Oil		Gas Oil		Fuel Oil		Gas Oil		TOTAL
	Non-ECA	ECA	Non-ECA	ECA	Non-ECA	ECA	Non-ECA	ECA	
Bulk Carrier	4206	0	113	247	7983	0	317	767	13633
Chemical Tanker	1006	0	168	228	4849	0	446	758	7456
Container	20826	0	151	1128	22434	0	168	1260	45967
General Cargo	1574	0	478	298	3487	0	794	499	7129
Liquefied Gas Tanker	401	0	56	79	2463	0	905	298	4201
Oil Tanker	2980	0	869	253	9017	0	3033	1432	17585
Ferry-pax only	106	0	603	179	3	0	526	140	1558
Cruise	290	0	49	67	139	0	46	30	622
Refrigerated Bulk	776	0	162	105	1410	0	458	238	3150
Ro-Ro	1441	0	3720	567	973	0	2206	439	9345
Service Tug (Misc)	4	0	10	9	14	0	126	59	221
Fishing	50	0	139	13	417	0	1616	370	2605
Offshore	106	0	54	62	429	0	388	504	1542
Service - Other	2	0	6	10	50	0	102	114	283
Miscellaneous - Other	0	0	2	2	15	0	41	34	94
All Vessels (Total)	33769	0	6579	3247	53681	0	11170	6943	**115390**

Vessel Type	NOx Emissions from Domestic Shipping (2016) - Tons/year						TOTAL
	At Sea				At-Berth		
	Fuel Oil		Gas Oil (Marine Diesel)				
	Non-ECA	ECA	Non-ECA	ECA	Non-ECA	ECA	
Bulk Carrier	3458	0	253	4315	27	160	8213
Chemical Tanker	656	0	297	1751	92	130	2926
Container	1369	0	126	2468	87	368	4418
General Cargo	621	0	486	1414	40	113	2674
Liquefied Gas Tanker	238	0	367	550	105	41	1300
Oil Tanker	2193	0	949	3642	129	279	7191
Ferry-pax only	54	0	2640	3058	279	375	6405
Cruise	419	0	147	343	26	48	983
Refrigerated Bulk	31	0	454	420	123	107	1135
Ro-Ro	2744	0	2812	6169	710	895	13331
Service Tug (Misc)	233	0	479	1362	72	175	2321
Fishing	201	0	1449	3092	133	267	5142
Offshore	107	0	1332	12796	120	735	15090
Service - Other	92	0	601	2063	86	145	2987
Miscellaneous - Other	2	0	170	420	7	37	637
All Vessels (Total)	12416	0	12563	43863	2036	3875	**74753**

Vessel Type	NOx Emissions from International & In-Transit Shipping (2016) - Tons/year								TOTAL
	International				In-Transit				
	Fuel Oil		Gas Oil		Fuel Oil		Gas Oil		
	Non-ECA	ECA	Non-ECA	ECA	Non-ECA	ECA	Non-ECA	ECA	
Bulk Carrier	13302	0	383	9728	25248	0	1050	30214	79925
Chemical Tanker	3133	0	513	8662	15098	0	1370	27853	56629
Container	63297	0	507	42096	68184	0	605	47140	221829
General Cargo	4259	0	1360	8720	9434	0	2212	14527	40512
Liquefied Gas Tanker	1220	0	155	2661	7502	0	2494	9975	24009
Oil Tanker	8561	0	2381	8023	25901	0	8821	43950	97635
Ferry-pax only	355	0	1713	5014	11	0	1507	3297	11897
Cruise	867	0	155	2335	416	0	155	1086	5014
Refrigerated Bulk	2550	0	504	3726	4633	0	1219	7044	19674
Ro-Ro	4430	0	9764	18001	2990	0	5831	13986	55003
Service Tug (Misc)	12	0	38	349	49	0	498	2308	3254
Fishing	161	0	496	485	1347	0	5905	13630	22025
Offshore	275	0	165	2032	1111	0	1204	16438	21225
Service - Other	7	0	19	382	155	0	372	4273	5209
Miscellaneous - Other	1	0	7	63	49	0	162	1082	1364
All Vessels (Total)	102430	0	18161	112278	162127	0	33406	236803	**665204**

	PM10 Emissions from Domestic Shipping (2016) - Tons/year						
Vessel Type	At Sea				At-Berth		TOTAL
	Fuel Oil		Gas Oil (Marine Diesel)				
	Non-ECA	ECA	Non-ECA	ECA	Non-ECA	ECA	
Bulk Carrier	118	0	9	50	1	3	181
Chemical Tanker	22	0	13	23	4	3	65
Container	45	0	5	27	4	8	87
General Cargo	27	0	17	21	1	2	69
Liquefied Gas Tanker	9	0	12	11	7	2	40
Oil Tanker	94	0	39	73	10	9	225
Ferry-pax only	2	0	89	45	9	6	151
Cruise	14	0	5	4	1	1	25
Refrigerated Bulk	1	0	16	6	5	2	30
Ro-Ro	101	0	96	73	29	16	315
Service Tug (Misc)	8	0	13	16	2	3	42
Fishing	6	0	41	39	5	4	95
Offshore	3	0	41	177	4	11	237
Service - Other	3	0	18	25	3	2	51
Miscellaneous - Other	0	0	4	5	0	1	10
All Vessels (Total)	452	0	419	593	87	72	**1624**

	PM10 Emissions from International & In-Transit Shipping (2016) - Tons/year								
Vessel Type	International				In-Transit				TOTAL
	Fuel Oil		Gas Oil		Fuel Oil		Gas Oil		
	Non-ECA	ECA	Non-ECA	ECA	Non-ECA	ECA	Non-ECA	ECA	
Bulk Carrier	433.6928	0	10.91288	106.2663	823.187	0	30.46268	330.1914	1734.713
Chemical Tanker	102.9823	0	15.80969	92.24711	496.2719	0	41.79208	298.007	1047.11
Container	2113.966	0	14.19036	427.8097	2277.188	0	17.33893	478.7533	5329.2461
General Cargo	151.683	0	43.02122	113.7161	336.0119	0	71.0254	189.642	905.09965
Liquefied Gas Tanker	41	0	5	27	253	0	80	99	506
Oil Tanker	299	0	80	101	905	0	284	554	2223
Ferry-pax only	11	0	57	74	0	0	50	50	241
Cruise	30	0	5	27	14	0	4	12	92
Refrigerated Bulk	81	0	15	42	147	0	41	81	406
Ro-Ro	149	0	335	230	100	0	199	178	1191
Service Tug (Misc)	0	0	1	4	2	0	13	27	48
Fishing	5	0	14	6	43	0	163	165	396
Offshore	10	0	5	26	42	0	37	208	328
Service - Other	0	0	1	4	5	0	11	49	70
Miscellaneous - Other	0	0	0	1	2	0	4	14	21
All Vessels (Total)	3429	0	601	1280	5445	0	1048	2734	**14537**

SO2, NOx and PM10 Shipping emissions in 2030 by vessel and sea area

Vessel Type	SO2 Emissions from Domestic Shipping (2030) - Tons/year						TOTAL
	At Sea				At-Berth		
	Fuel Oil		Gas Oil (Marine Diesel)				
	Non-ECA	ECA	Non-ECA	ECA	Non-ECA	ECA	
Bulk Carrier	386	0	39	102	1	7	535
Chemical Tanker	70	0	63	48	5	6	193
Container	247	0	37	97	7	30	417
General Cargo	101	0	81	44	1	4	232
Liquefied Gas Tanker	37	0	68	37	12	6	160
Oil Tanker	389	0	217	186	13	28	834
Ferry-pax only	5	0	333	75	7	10	430
Cruise	50	0	28	10	1	3	92
Refrigerated Bulk	4	0	101	17	6	6	134
Ro-Ro	500	0	651	225	43	54	1473
Service Tug (Misc)	22	0	48	27	2	5	104
Fishing	22	0	200	83	5	10	319
Offshore	11	0	167	327	4	21	529
Service - Other	9	0	73	44	3	4	132
Miscellaneous - Other	0	0	16	8	0	1	26
All Vessels (Total)	1853	0	2123	1330	110	195	**5610**

Vessel Type	SO2 Emissions from International & In-Transit Shipping (2030) - Tons/year								TOTAL
	International				In-Transit				
	Fuel Oil		Gas Oil		Fuel Oil		Gas Oil		
	Non-ECA	ECA	Non-ECA	ECA	Non-ECA	ECA	Non-ECA	ECA	
Bulk Carrier	1379	0	45	196	2618	0	126	610	4974
Chemical Tanker	330	0	67	181	1590	0	177	602	2948
Container	11828	0	104	1552	12741	0	115	1734	28074
General Cargo	516	0	190	237	1144	0	315	397	2798
Liquefied Gas Tanker	173	0	29	83	1066	0	474	313	2138
Oil Tanker	1124	0	397	232	3399	0	1385	1308	7845
Ferry-pax only	30	0	208	124	1	0	182	97	641
Cruise	109	0	23	61	53	0	21	27	294
Refrigerated Bulk	336	0	85	110	610	0	240	250	1631
Ro-Ro	715	0	2236	682	482	0	1326	527	5968
Service Tug (Misc)	1	0	4	7	4	0	47	45	108
Fishing	18	0	65	12	152	0	755	346	1348
Offshore	33	0	20	47	134	0	146	381	761
Service - Other	1	0	2	8	15	0	38	86	150
Miscellaneous - Other	0	0	1	1	5	0	16	26	48
All Vessels (Total)	16594	0	3475	3532	24014	0	5365	6748	**59728**

NOx Emissions from Domestic Shipping (2030) - Tons/year

Vessel Type	At Sea				At-Berth		TOTAL
	Fuel Oil		Gas Oil (Marine Diesel)				
	Non-ECA	ECA	Non-ECA	ECA	Non-ECA	ECA	
Bulk Carrier	2759	0	201	2838	21	105	5925
Chemical Tanker	523	0	237	1151	73	86	2070
Container	1891	0	174	2811	120	420	5415
General Cargo	496	0	387	930	32	74	1919
Liquefied Gas Tanker	251	0	385	477	111	35	1259
Oil Tanker	2011	0	868	2753	118	211	5961
Ferry-pax only	37	0	1825	1747	193	214	4016
Cruise	384	0	135	259	24	36	838
Refrigerated Bulk	32	0	477	365	129	92	1096
Ro-Ro	3313	0	3385	6137	855	891	14580
Service Tug (Misc)	177	0	363	852	54	109	1555
Fishing	179	0	1338	2359	123	204	4202
Offshore	81	0	1008	8002	91	460	9642
Service - Other	69	0	455	1290	65	91	1970
Miscellaneous - Other	2	0	129	263	5	23	422
All Vessels (Total)	12206	0	11365	32234	2014	3051	**60871**

NOx Emissions from International & In-Transit Shipping (2030) - Tons/year

Vessel Type	International				In-Transit				TOTAL
	Fuel Oil		Gas Oil		Fuel Oil		Gas Oil		
	Non-ECA	ECA	Non-ECA	ECA	Non-ECA	ECA	Non-ECA	ECA	
Bulk Carrier	10616	0	304	6398	20150	0	836	19871	58174
Chemical Tanker	2500	0	409	5697	12049	0	1091	18318	40063
Container	87477	0	698	47942	94231	0	834	53686	284867
General Cargo	3399	0	1083	5735	7529	0	1760	9554	29059
Liquefied Gas Tanker	1285	0	163	2309	7900	0	2619	8656	22933
Oil Tanker	7853	0	2178	6065	23760	0	8069	33225	81149
Ferry-pax only	246	0	1184	2865	7	0	1042	1884	7228
Cruise	795	0	142	1765	382	0	142	821	4046
Refrigerated Bulk	2685	0	529	3233	4878	0	1280	6112	18717
Ro-Ro	5347	0	11753	17907	3609	0	7019	13913	59549
Service Tug (Misc)	9	0	29	218	37	0	377	1444	2113
Fishing	143	0	458	370	1200	0	5452	10399	18022
Offshore	209	0	125	1271	843	0	911	10280	13639
Service - Other	5	0	15	239	118	0	282	2672	3331
Miscellaneous - Other	1	0	5	40	37	0	123	677	882
All Vessels (Total)	122572	0	19075	102053	176730	0	31834	191511	**643774**

	PM10 Emissions from Domestic Shipping (2030) - Tons/year						
Vessel Type	At Sea				At-Berth		TOTAL
	Fuel Oil		Gas Oil (Marine Diesel)				
	Non-ECA	ECA	Non-ECA	ECA	Non-ECA	ECA	
Bulk Carrier	49	0	4	41	1	3	98
Chemical Tanker	9	0	6	19	4	2	40
Container	32	0	4	38	6	11	91
General Cargo	11	0	8	18	1	1	40
Liquefied Gas Tanker	5	0	7	12	8	2	33
Oil Tanker	45	0	21	69	9	9	154
Ferry-pax only	1	0	36	32	7	4	80
Cruise	7	0	3	4	1	1	15
Refrigerated Bulk	1	0	10	7	5	2	25
Ro-Ro	63	0	68	91	36	21	280
Service Tug (Misc)	3	0	6	13	2	2	26
Fishing	3	0	24	39	5	4	74
Offshore	1	0	18	140	3	9	171
Service - Other	1	0	8	20	2	2	33
Miscellaneous - Other	0	0	2	4	0	0	7
All Vessels (Total)	231	0	224	548	91	73	**1167**

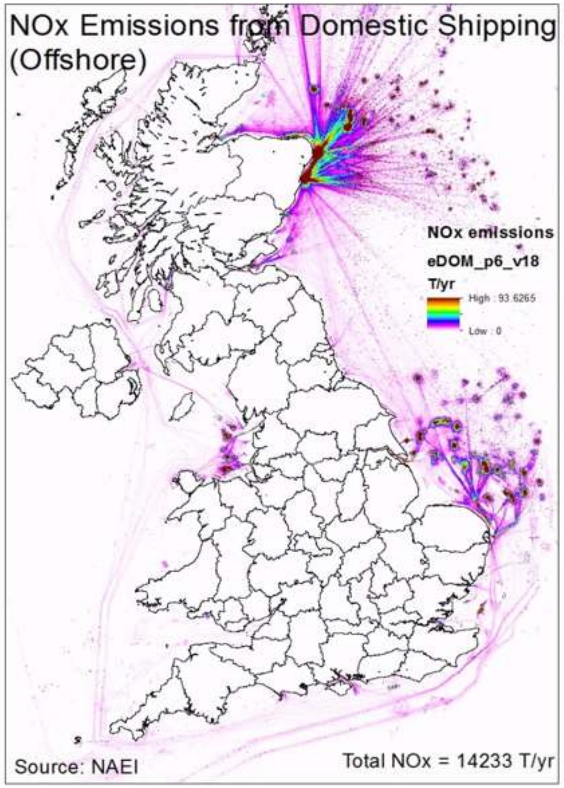
	PM10 Emissions from International & In-Transit Shipping (2030) - Tons/year								
Vessel Type	International				In-Transit				TOTAL
	Fuel Oil		Gas Oil		Fuel Oil		Gas Oil		
	NONECA	ECA	NONECA	ECA	NONECA	ECA	NONECA	ECA	
Bulk Carrier	180	0	5	88	342	0	14	275	905
Chemical Tanker	43	0	7	77	206	0	19	248	600
Container	1521	0	11	616	1638	0	14	690	4491
General Cargo	63	0	20	95	140	0	33	158	508
Liquefied Gas Tanker	23	0	3	29	139	0	49	109	352
Oil Tanker	143	0	43	96	432	0	152	529	1396
Ferry-pax only	4	0	23	53	0	0	20	36	136
Cruise	14	0	3	26	7	0	2	12	63
Refrigerated Bulk	44	0	9	46	81	0	25	89	294
Ro-Ro	93	0	236	289	63	0	141	224	1046
Service Tug (Misc)	0	0	0	3	1	0	6	21	32
Fishing	2	0	8	6	20	0	93	167	295
Offshore	4	0	2	20	16	0	16	165	224
Service - Other	0	0	0	3	2	0	5	39	49
Miscellaneous - Other	0	0	0	1	1	0	2	11	14
All Vessels (Total)	2135	0	372	1449	3087	0	592	2772	**10407**

APPENDIX B

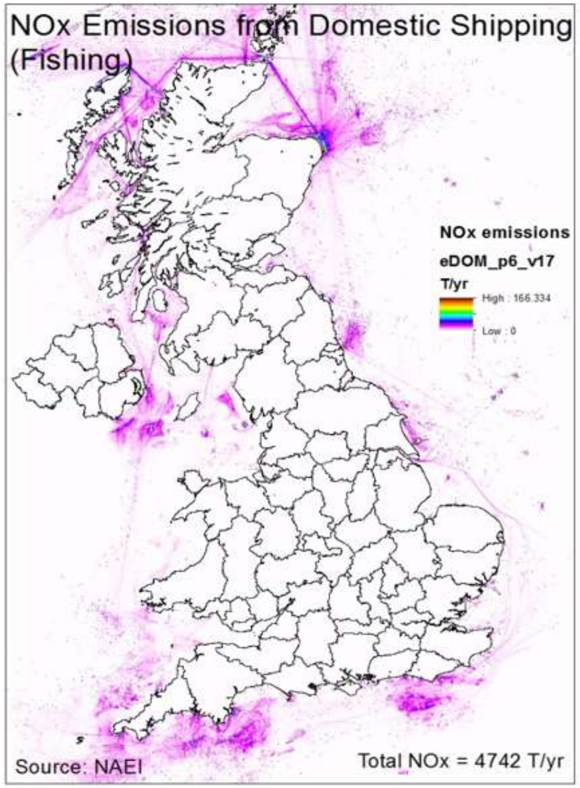
Additional maps of UK shipping emissions by vessel type and categ

Spatial distributions of domestic emissions by vessel type

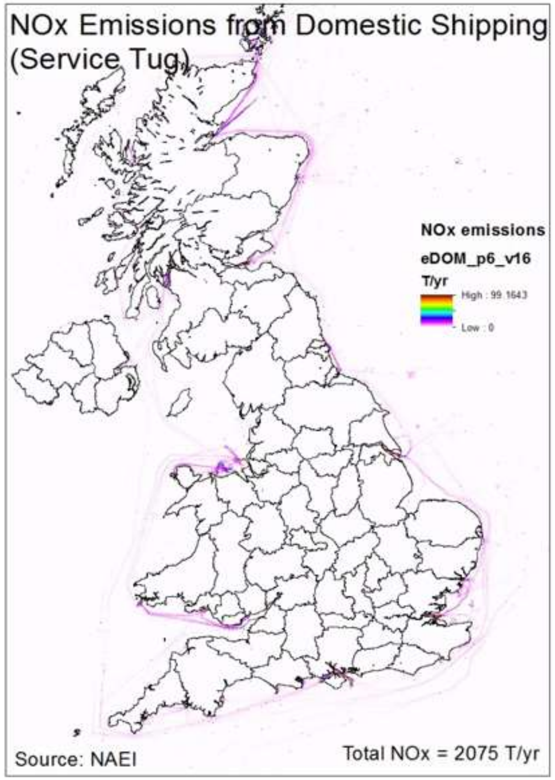
NB on different mapping scales; see total emissions below figures



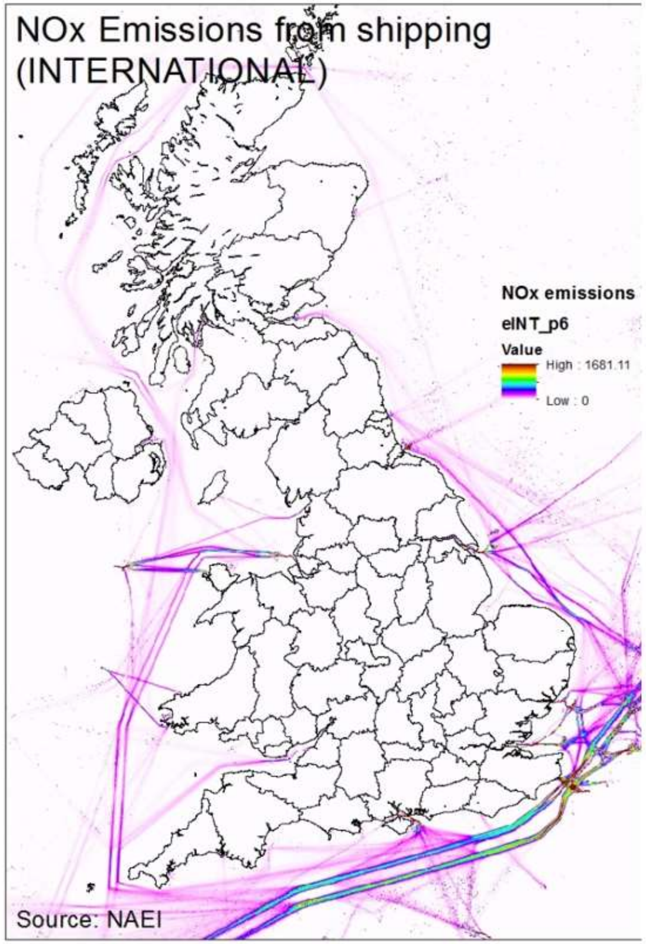
14 kt

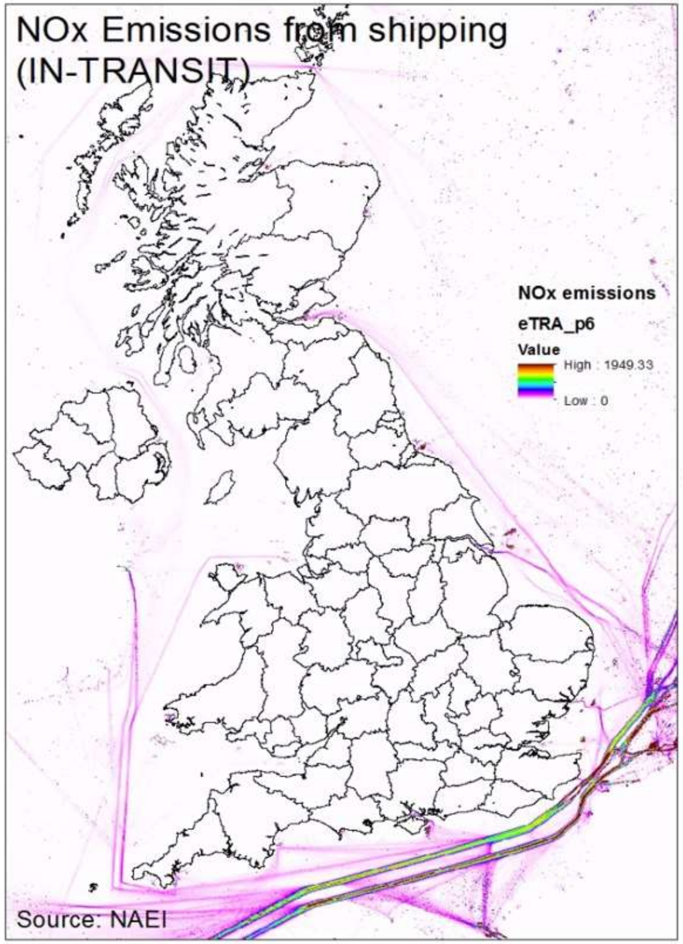


4.7kt



2.0kt





UK International : 233 kt NOx **In transit: 433 kt NOx**

APPENDIX C

Estimation of health costs of exposure to air pollution

The estimation of health costs based on pollutant concentrations and exposure of the UK population derived from UKIAM is based on the attached note produced by Mike Holland of EMRC within the SNAPCS Defra contract.

Derivation of damage costs per unit pollutant exposure for UKIAM

Mike Holland, 19/6/2019, mike.holland@emrc.co.uk

The general methodology used to derive the damage costs is the impact pathway approach (IPA) developed originally in the ExternE Project of the European Commission in the early 1990s (ExternE, 1995; 1997; 2005). This approach describes a logical sequential pathway from emission, through pollutant dispersion and chemistry to exposure of the population and other sensitive receptors (buildings, ecosystems, etc.) to impact assessment and monetary valuation. Defra adopted this approach for damage assessment in the late 1990s. Whilst the overall approach has not changed since that time, details of the method (dispersion models, response functions and valuation data) have been updated to reflect developments in the scientific literature.

For UKIAM health costs are required per person per ug/m3. Results are presented in the following table giving low-high ranges as well as central estimates. Prices are correct for the year 2017. Being expressed per person, and assuming that there is not significant demographic change, quantification of underlying impacts on health etc. should be reliable for the foreseeable future, subject to adjusting prices for other years in line with Green Book guidance.

Table 1

	Direct health impacts - (£2017 per pop. weighted mean 1μg/m^3 change per person)		
Pollutant	**Low**	**Central**	**High**
NOx	£0.6	£6.3	£19.1
SO_2	£0.1	£0.1	£0.1
NH_3	£0.0	£0.0	£0.0
VOC	£0.0	£0.0	£0.0
$PM_{2.5}$	£13.8	£50.1	£119.7

The table deals with health impacts linked to direct exposure to pollutants in the form that they are emitted (NO_2, SO_2 and $PM_{2.5}$). In the case of UKIAM where exposure to secondary inorganic aerosol (SO4,NO3 and NH4) is calculated directly including imported contributions from outside the UK, the value for PM2.5 may also be applied to this, since no distinction is made for the chemical form of the PM2.5. A lack of exposure-response functions prevents quantification of the direct impacts of NH_3 and VOCs.

Note also that in UKIAM health costs are only applied to health effects on the UK population, although UKIAM can also calculate the exposure in other countries outside the UK in which case the health costs in table 1 may be extrapolated (as has been done in reporting benefits of UK emission reductions in other countries for the NAPCP).

Low, central and high values of costs

The ranges shown in the tables reflect variation in three elements of the analysis:

- The health impacts for which quantification is performed
- Variability in the response functions used for analysis
- Variability in valuation data.

The low, central and high ranges are composed of the following impacts, with the items in italics not included in table 1 of health costs:

Low:

- **NO_2, $PM_{2.5}$: Chronic mortality**
- **O_3, SO_2: Deaths brought forward**
- **NO_2, O_3, PM_{10}, SO_2: Respiratory hospital admissions**
- **O_3, PM_{10}: Cardiovascular hospital admission**
- *O_3, $PM_{2.5}$, PM_{10}: Productivity*
- *PM_{10}: Building soiling*
- *O_3, SO_2: Material damage*
- *NH_3, NO_2, O_3, PM_{10}, SO_2: Ecosystems*

Central: As low, but including also

- $PM_{2.5}$: Coronary Heart Disease
- $PM_{2.5}$: Stroke
- NO_2, $PM_{2.5}$: Asthma in children
- $PM_{2.5}$: Lung cancer morbidity

High: As central, but including also

- NO_2**:** Respiratory hospital admissions
- PM_{10}: Productivity
- **PM_{10}: Chronic Bronchitis**
- NO_2: Asthma in adults
- NO_2, $PM_{2.5}$: Diabetes
- NO_2: Lung cancer morbidity

Analysis is based on the recommendations of COMEAP for the effects shown in bold in this list. For other effects, alternative sources have been used, as documented by Ricardo (2019). Mortality is valued using a value of life year (VOLY) of £42,780.

COMEAP's updated guidance (COMEAP, 2018) on quantification of NO_2 effects on mortality suggests alternative approaches depending on the scope of the appraisal. In particular, this focuses on the scope of emissions assessed. The guidance suggests:

- For interventions that primarily target emissions of NOx: Use 25-55% of unadjusted coefficient (mid-point of range 40%) 1.023 (95% CI: 1.008, 1.037) per 10 $\mu g/m^3$ annual average NO_2.
- For interventions that reduce all traffic related air pollutants: use the unadjusted NO_2 coefficient 1.023 (95% CI: 1.008, 1.037) per 10 $\mu g/m^3$ annual average NO_2.

In order to maintain simplicity in the interpretation and implementation of the damage costs, IGCB agreed that it was preferable to have one method of estimating the effects that applies to all policy measures. Hence IGCB's guidance will be to apply, in all circumstances, the adjusted NOx coefficient (for interventions that primarily target emissions of NOx) to estimate damages associated with NOx emissions, alongside the unadjusted PM coefficient to estimate damages associated with PM emissions. The update to the damage costs and values in the above tables has been undertaken in accordance with this direction.

It may be asked by how much life is shortened as a result of exposure to air pollution. There is no simple answer to this. At the level of the individual it could be a minimum of a few days (in the case of someone for example having a heart attack where exposure to air pollution pushes them over the edge) to many years (when air pollution is active in development of disease).

With respect to an average loss of life expectancy across the population, COMEAP (2010) provides the following information, starting with a possible range for average loss of life expectancy per person affected by air pollution:

It is not known how this population-wide burden is spread across individuals in the population, but we can speculate between various possibilities. Our results are consistent with an average loss of life ranging at one extreme from 11.5 years if air pollution was solely responsible for 29,000 deaths to, at the other extreme, six months if the timing of all deaths was influenced by air pollution.

This statement recognises that air pollution is one of several stresses (alongside smoking, poor diet, lack of exercise, occupational exposures, etc.) that will act synergistically on the body. The estimated number of 'air pollution deaths' (in this case, 29,000) is a statistical construct representing the effects on mortality described by COMEAP as 'equivalent attributable deaths'. The number of people for whom air pollution has played some role in the timing of death may be very much greater than the figures suggest at first sight.

COMEAP (2010) continues:

We believe both of these extremes [6 months to 11.5 years] *to be extremely unlikely. Given that much of the impact of air pollution on mortality is linked with cardiovascular deaths, it is more reasonable to consider that air pollution may have made some contribution to the earlier deaths of up to 200,000 people in 2008, with an average loss of life of about two years per death affected, though that actual amount would vary between individuals. However, this assumption remains speculative.*

This position (that the assumption remains speculative) has not changed. Outside of COMEAP I am aware of no group that has investigated this question. Table 8.1 from the COMEAP (2010) report illustrates variation in the average loss of life expectancy according to different assumptions:

Table 8.1: Hypothetical average years of life expectancy lost in 2008 due to the contribution of anthropogenic particulate air pollution, averaged over different sections of the UK population

Hypothetical population affected	Number affected	Hypothetical average loss of life expectancy
Whole population (ages 30+)	38,348,000	3 days
All deaths (ages 30+)	569,000	½ year
50% of deaths (30+)	290,000	1 year
Deaths from CV causes (30+)	191,000	2 years
20% of deaths (30+)	116,000	3 years
10% of deaths (30+)	58,000	6 years
7% of deaths (30+)	40,000	8½ years
'Attributable' deaths (30+)	29,000	11½ years

This discussion should not give the impression that there is great uncertainty in estimates of air pollution mortality. The expression of an effect on mortality in terms of life years lost is most robust, followed by estimates of equivalent attributable deaths. The problem comes in thinking how the life years lost are distributed across the population, but that does not affect the valuation.

References

COMEAP (2010) https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/304641/COMEAP_mortality_effects_of_long_term_exposure.pdf

COMEAP (2018) https://www.gov.uk/government/publications/nitrogen-dioxide-effects-on-mortality

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