Chief Medical Officer's
Annual Report 2022

Air pollution

Front cover image: Emissions from Hope Cement Works, Hope Valley, Derbyshire, England
Source: Wesley Kristopher Photography.

Executive summary

Introduction

Air pollution affects us all. It is associated with impacts on lung development in children, heart disease, stroke, cancer, exacerbation of asthma and increased mortality, among other health effects. Except for air quality in our own homes, we have little control as individuals over the level of pollution that we and our families breathe – this must be seen as a societal problem to solve. Government has therefore had a central role in tackling air pollution in the UK going back at least to King Edward I in the 1280s, and does now. Many industries and sectors also have to be part of the solution.

Outdoor air quality in this country, and most high-income countries, has improved significantly since the 1980s. Some air pollutants such as sulphur dioxide from coal, and lead from petrol, are fractions of their previous levels.

As this report lays out, we can and should go further to reduce air pollution – and it is technically possible to do so. Improvements in engineering for transport and industry, modifications to agricultural practice and improvements in the built environment are examples that should, once a change is made, be self-sustaining and allow us to reap health benefits for the foreseeable future. Many of the changes to improve outdoor air pollution have significant co-benefits. For example, reducing the use of fossil fuels for energy reduces both air pollution and carbon emissions; improving active travel reduces air pollution emissions from vehicles and has direct health benefits to those who are walking, wheeling or cycling.

In particular, we need to concentrate on the places where people live, work and study; the same air pollution concentration in a densely populated area will lead to greater accumulated health effects than in a sparsely populated area as more people will be affected.

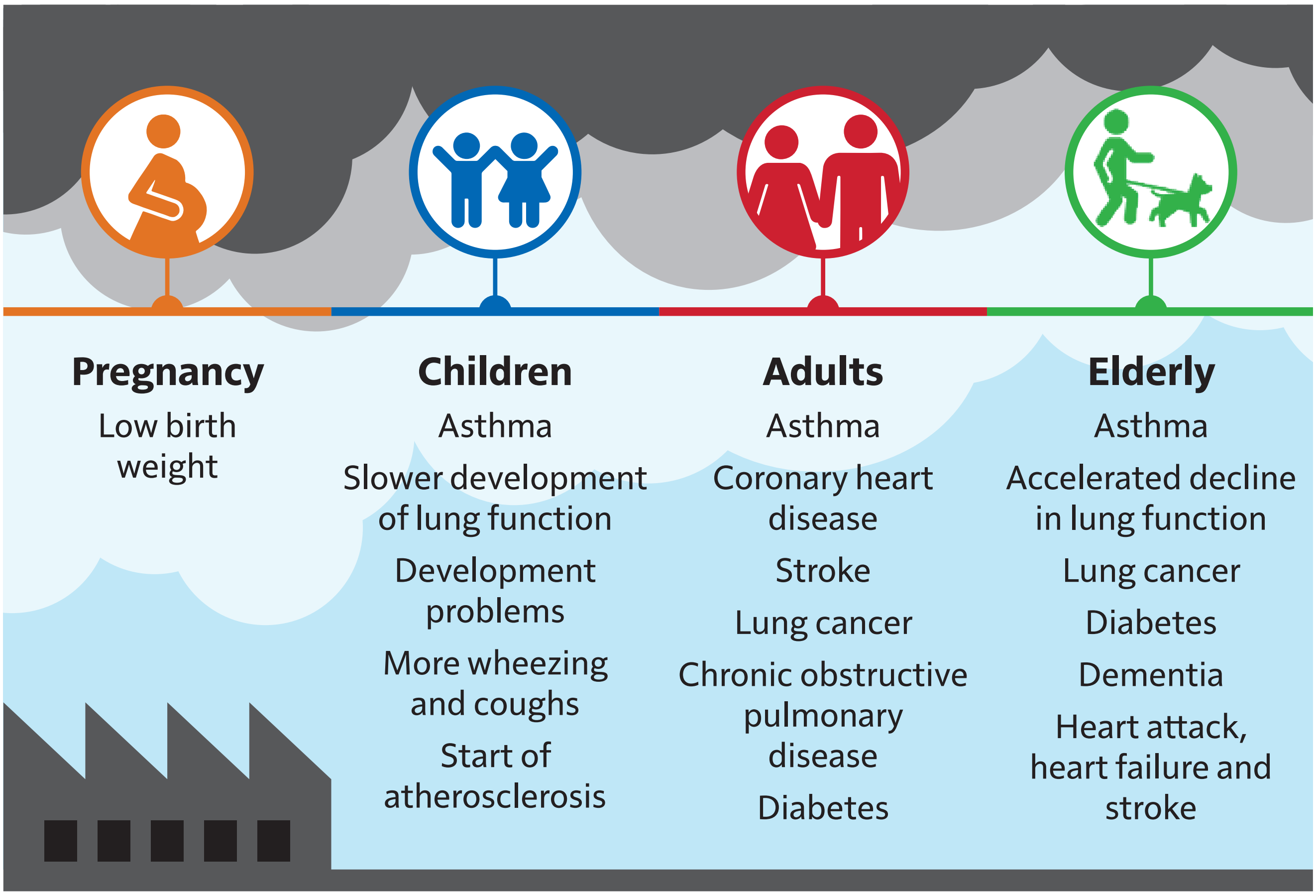
The path to better outdoor air quality is clear, and we now need to go down it. Indoor air pollution is becoming an increasing proportion of the problem as improvements in outdoor air pollution occur. Most of our days are spent indoors whether for work, study or leisure, yet indoor air quality has been studied much less than outdoors. While there are some spaces such as owner-occupied houses that are fully private, many indoor spaces are public, including health facilities, schools, other public buildings, and also shops and workplaces. As with outdoor spaces, people in public buildings are exposed to air pollution but can do little about it, so society needs to act. A better understanding of how we can prevent and reduce indoor air pollution should now be a priority.

This report is about air pollution and its solutions in England, but it is also an international problem. There is a lot we can learn from best international practice. Many air pollutants travel long distances, so emissions and air quality in continental Europe affect the UK and vice versa. It is important to acknowledge that the improvements in air quality we are seeing in high-income countries are yet to be felt in many middle-income countries, but many of the technologies and techniques will be transferable.

The first chapters of this report lay out the health problems of air pollution, but most of the report is about achievable solutions. Air pollution is everybody's problem, but it has improved, and will continue improving provided we are active in tackling it.

Chapter 1 – Air pollution and health

Chapter 1 covers the effects of air pollution on health, including inequalities. Air pollution has negative effects on health throughout the life course, from pre-birth to old age, summarised in Figure 1.



Source: Adapted from Public Health England (2018)[1]

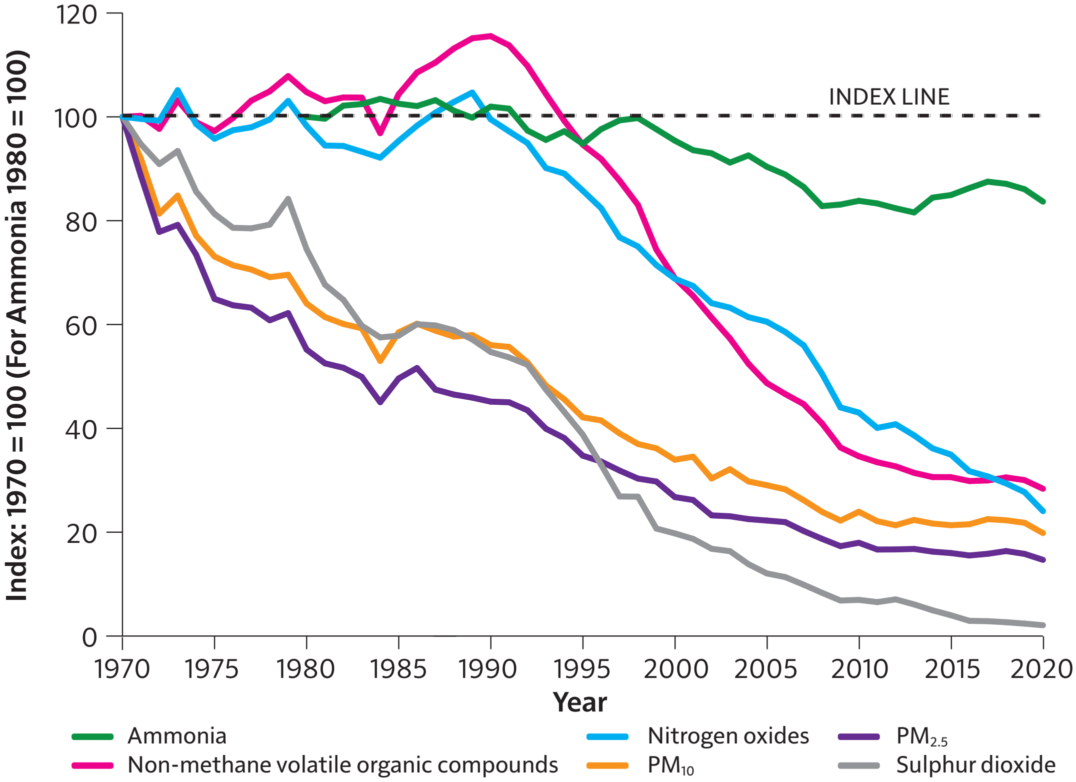
Figure 1: Health effects of air pollution throughout life

Some individuals such as those with pre-existing respiratory or cardiovascular disease are particularly susceptible, but the effects of air pollution can be seen across the population. The mortality burden of air pollution in England is estimated to be between 26,000 and 38,000 a year, but in addition many people suffer avoidable chronic ill health as a result of it. Improvements in air quality have been associated with improved health outcomes – for example, reductions in air pollution in London have led to reduced childhood asthma hospital admissions. Further reductions in air pollution will lead to significant reductions in coronary heart disease, stroke and lung cancer, among others.

The chapter discusses and summarises evidence for the short- and long-term health effects of the main outdoor air pollutants, including particulate matter (PM) especially fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), ozone (O_3), sulphur dioxide (SO_2) and others. It then considers additional indoor air pollutants such as volatile organic compounds (VOCs). Air pollution does not affect everyone equally and the chapter has a further section on disparities in air pollution including by age, socio-economic gradient and ethnicity. These disparities are both by air pollution exposure and by vulnerability – for example pregnant women, children and those with health conditions are more vulnerable to harm, even if their exposure is the same as other population groups.

Chapter 2 – Outdoor air pollution emissions and recent trends

Chapter 2 considers recent trends in outdoor air pollution emissions. There has been a steady decline in emissions of most outdoor air pollutants, with some dropping substantially, such as SO_2. Others such as ammonia (NH_3) have been largely static, as shown in Figure 2. In the last decade improvements in $PM_{2.5}$ have stalled, and these especially need attention.



Note: The figure shows trends in annual emissions of particulate matter (PM_{10} and $PM_{2.5}$), nitrogen oxides, ammonia, non-methane volatile organic compounds, and sulphur dioxide, 1970 to 2020, expressed as a percentage change from the base year of 1970 (for ammonia the base year is 1980).

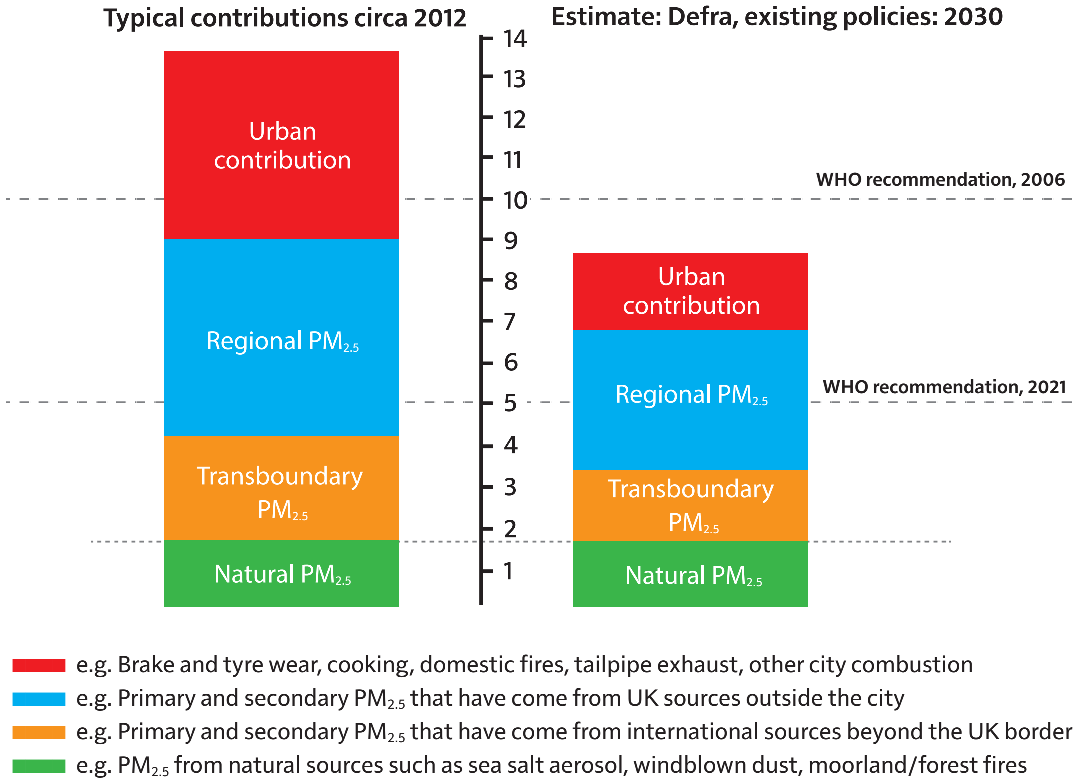
Source: Ricardo Energy & Environment. Defra (2022)[2]

Figure 2: Trends in UK emissions of air pollutants 1970 to 2020

Chapter 3 – How air pollution is changing

Chapter 3 explains how air pollution is changing and how it is expected to change in the future. It considers UK and international trends that will affect the UK, and likely changes in population-weighted exposure to outdoor air pollution. It also considers some of the interactions between air pollution and climate change, and the implications of net zero policies.

Outdoor $PM_{2.5}$ is changing in its nature, and to address it we need to differentiate between primary $PM_{2.5}$ (emitted direct from source) and secondary $PM_{2.5}$ (formed by combining chemicals in the atmosphere). For example, NH_3 from agriculture contributes to secondary $PM_{2.5}$ in cities as well as having negative effects on rural ecosystems. Air pollutants vary in how long they persist in the atmosphere, and this has implications on how far away from source they can have an effect on health. The relative importance of these sources will vary over the next decade, and Figure 3 shows estimates of the contributions to $PM_{2.5}$ for an urban background location circa 2012 and estimated for 2030.

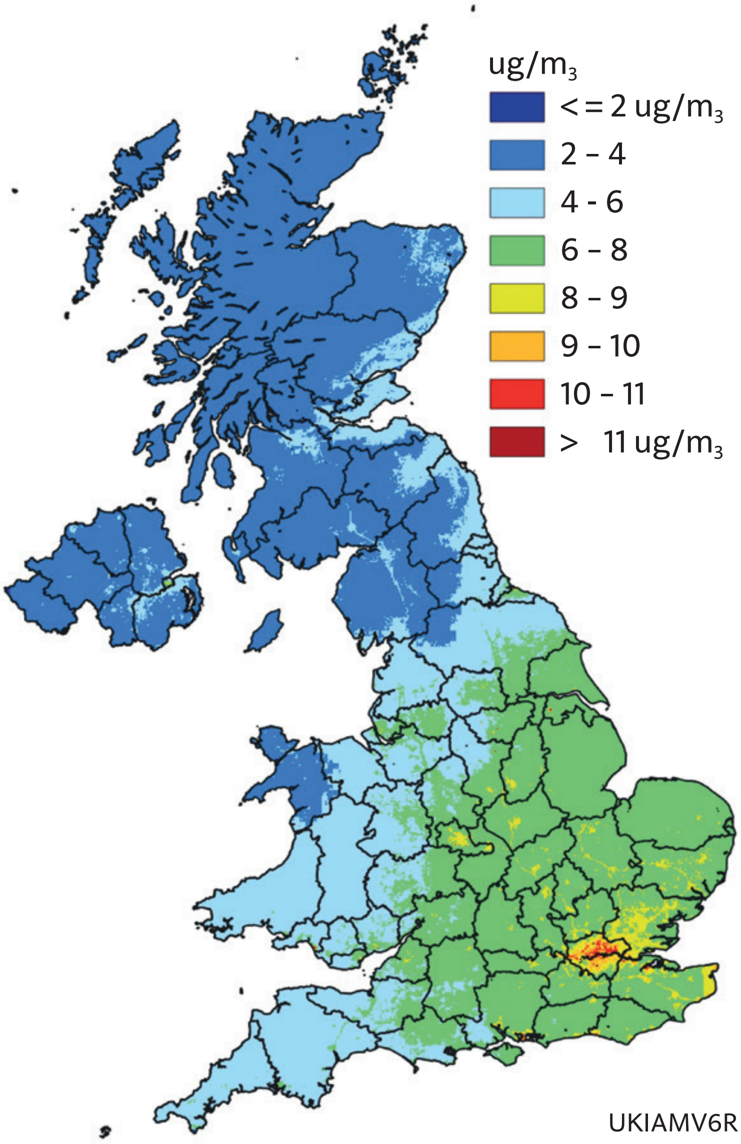


Left: the period circa 2012 (based on materials in reference 3). Right: contributing sources that might be anticipated in 2030 based on the author’s evaluation of impacts arising from likely emissions reduction by 2030. Y-axis is atmospheric concentration in units of µg/m^3.

Source: AQEG (2015)[3] and ApSimon et al. (2022)[4]

Figure 3: A qualitative representation of the different contributing sources to $PM_{2.5}$ that might be experienced in a typical urban centre (England)

The chapter also shows how, with existing policies, outdoor air quality will have improved right across the UK by 2030, however some areas will still experience annual average concentrations of $PM_{2.5}$ higher than the government's target of 10 micrograms/m^3, particularly in South-East England, as shown in Figure 4. It then goes on to consider changes, or lack of them, in indoor air pollution in the future. Changes to behaviour, such as more working from home, may have an important impact on people's exposures.



Source: Air Quality $PM_{2.5}$ Targets: Detailed Evidence Report. Department for Environment, Food & Rural Affairs, 2022[5]

Figure 4: Modelled annual average concentrations of $PM_{2.5}$ in 2030 based on a 'baseline' (existing agreed government policies) emission reduction scenario[6]

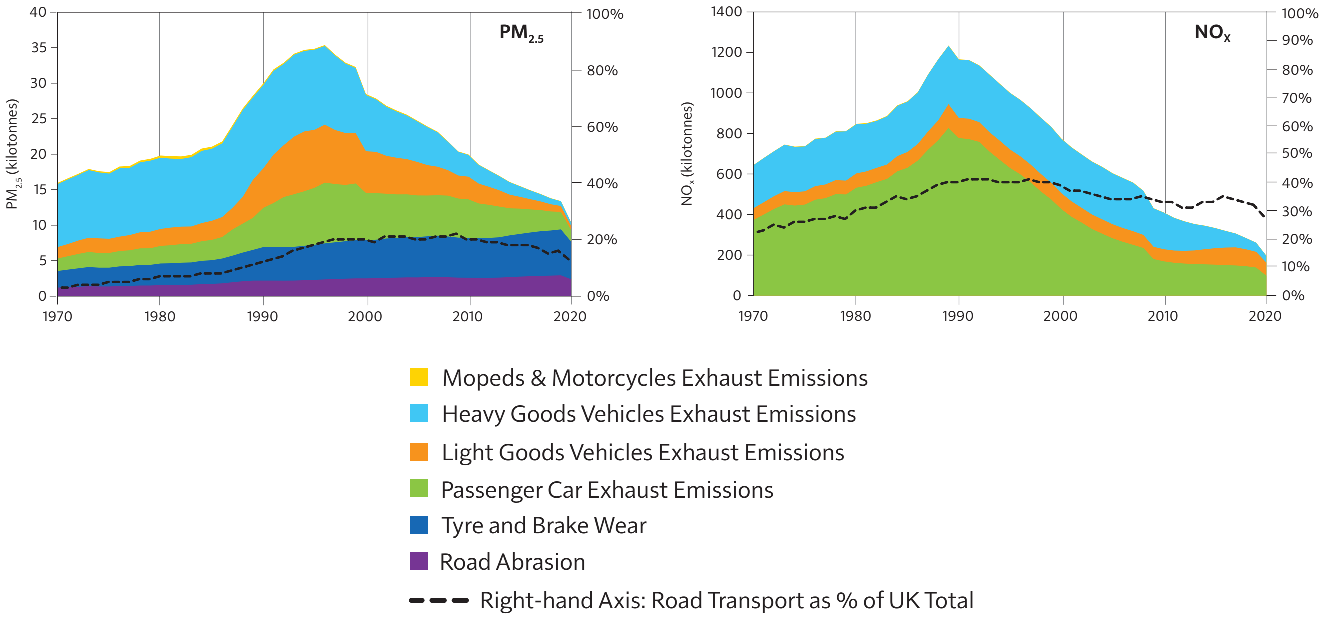
Chapter 4 – Outdoor and indoor air pollution solutions

Chapter 4 is the largest chapter of the report, and it covers major sectors that emit outdoor air pollution and what can be done to reduce these emissions. The sections within the chapter cover areas including transport, urban planning, industry, agriculture and a specific section on the NHS. Chapter 4 also discusses indoor air quality.

4.1 Transport

Road vehicles

Road vehicles have been sources of some of the most important air pollutants, especially $PM_{2.5}$ and NO_2, which are of health concern, particularly in urban areas where there is large population exposure. NO_2 is a gas that is produced along with nitric oxide (NO) by combustion processes, and together they are often referred to as nitrogen oxides (NO_x). There have been considerable reductions in road vehicle emissions, as successive tightening of regulations on Euro engineering standards for road vehicles have been met, as shown in Figure 5.



Note: The dashed black line indicates the contribution of road transport to the overall emissions on the right-hand axis .

Source: National Atmospheric Emissions Inventory[7] analysed by Air Quality Consultants Ltd

Figure 5: $PM_{2.5}$ and NO_x emissions from road vehicle sources since 1970

Tailpipe emissions from petrol and diesel engines are now much lower than they were two decades ago, and they are expected to fall further as zero tailpipe emission electric vehicles are adopted. Maintaining or accelerating this switch is important for air pollution. $PM_{2.5}$ emissions from brakes are also likely to fall, but not to zero, as the regenerative braking in electric vehicles takes over. This will leave tyre wear emissions and resuspension of road dust – novel low emission tyre materials and methods for capturing these particles, without reducing road safety, will become increasingly important. The section considers the relative merits of petrol, diesel, electric and hydrogen vehicles for air pollution reduction. The move to electric vehicles will take longer for heavy goods vehicles and may provide a need for other engineering solutions, and there may be some interim solutions. Some specific vehicle types are also considered, for example refrigerated vehicles can currently emit significant air pollution from diesel refrigeration units.

Rail

In many areas, rail transport has moved from fossil fuel combustion to electrification as its main power source, and this can lead to reduced air pollution emissions, which is of particular importance in urban areas and enclosed spaces such as train stations. While further electrification is the ideal, there are several technical solutions that would improve air quality as an interim or permanent solution to air pollution, including power by bi-mode (with the option of diesel or electric), battery and hydrogen fuel cells. There are air pollution emissions from other rail sources including friction from brakes, the interface between the wheel and rail, and pantographs. Air pollution in stations is a particular problem and should be a priority.

Underground railways and metros often have significant $PM_{2.5}$ due to limited ventilation, with the London Underground having the highest measured concentrations in European subway systems. Improvements in braking, ventilation and/or filtration are possible solutions.

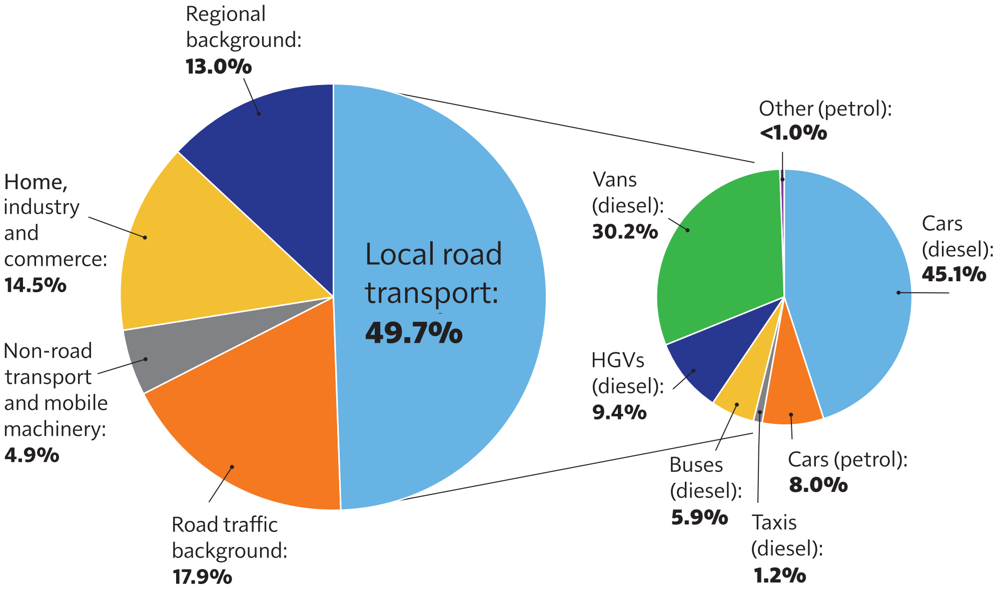
Aviation and shipping

Both aviation and shipping emit substantial air pollution that can affect the population, especially around ports and airports. While fuels for road transport have progressively reduced their sulphur content, jet fuel and bunker fuel for ships both still contain appreciable amounts of sulphur containing compounds, which leads to SO_2 emissions on combustion. Further reducing the sulphur content of ship and aviation fuels will reduce air pollution.

Using electrical power and tugs while aircraft are on the ground in airports would reduce some of the local air quality effects of aircraft engines, along with low or zero combustion airport vehicle fleets. For ships, more use of shore electricity and electrification of cranes and harbour craft would lead to improvements in air quality.

4.2 Reducing roadside NO_2 – an example of central and local government action

For all vehicle types, government action can have a significant impact on air pollution. Central and local government can both change local air pollution, including through regulation and the purchasing of cleaner vehicles for public transport, and the effect on NO_x can be substantial. Figure 6 shows the UK average NO_x roadside concentrations, by different sources.



Note: NO_x is the sum of nitrogen dioxide (NO_2) and nitric oxide (NO).

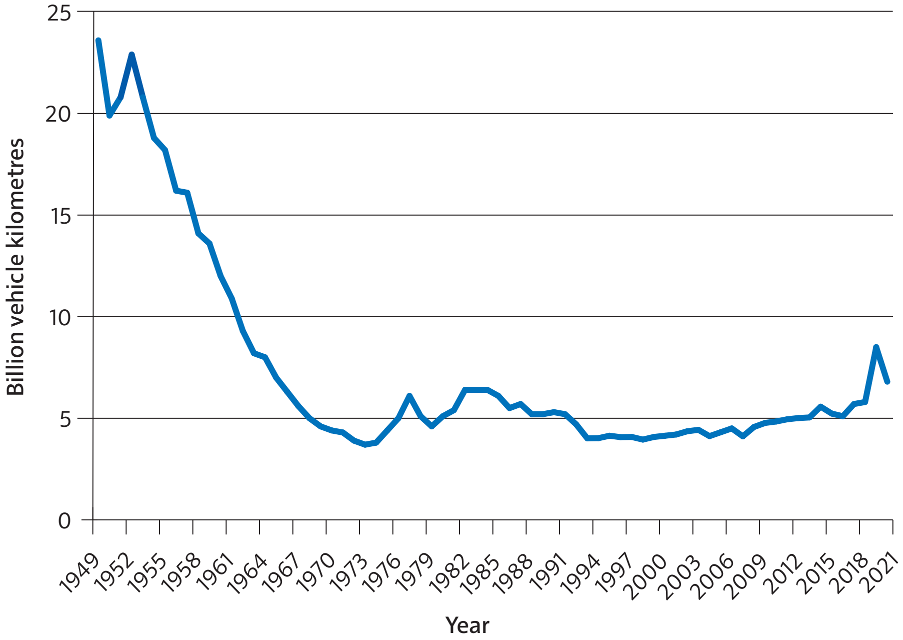
Source: Defra (2021)[8]

Figure 6: UK national average NO_x roadside concentration apportioned by source of NO_x emissions, 2020

Clean air zones are, if well designed, potentially a way of reducing tailpipe air pollution, although they can have a mixed reception from the public. Clean air zones are designated in areas with high air pollution concentrations and high population density, and mainly target older vehicles with higher tailpipe emissions in areas of high risk and population vulnerability.

4.3 Urban planning and 4.4 Active travel

Urban planning can have a major impact on how much people use active forms of transport, compared to transport that emits air pollution. It can also influence the concentration of pollutants in areas of high building density and the impact of urban greening. Active travel, walking, wheeling and cycling has fallen a long way since the 1950s, and Figure 7 shows kilometres travelled by bicycle in Great Britain from 1949 to 2021. Reversing this decline would have substantial additional health benefits due to physical activity being built into the normal day, in addition to reductions in air pollution. Improving the infrastructure for active travel is a necessary, although not sufficient, step towards more active trips taken safely by all ages.

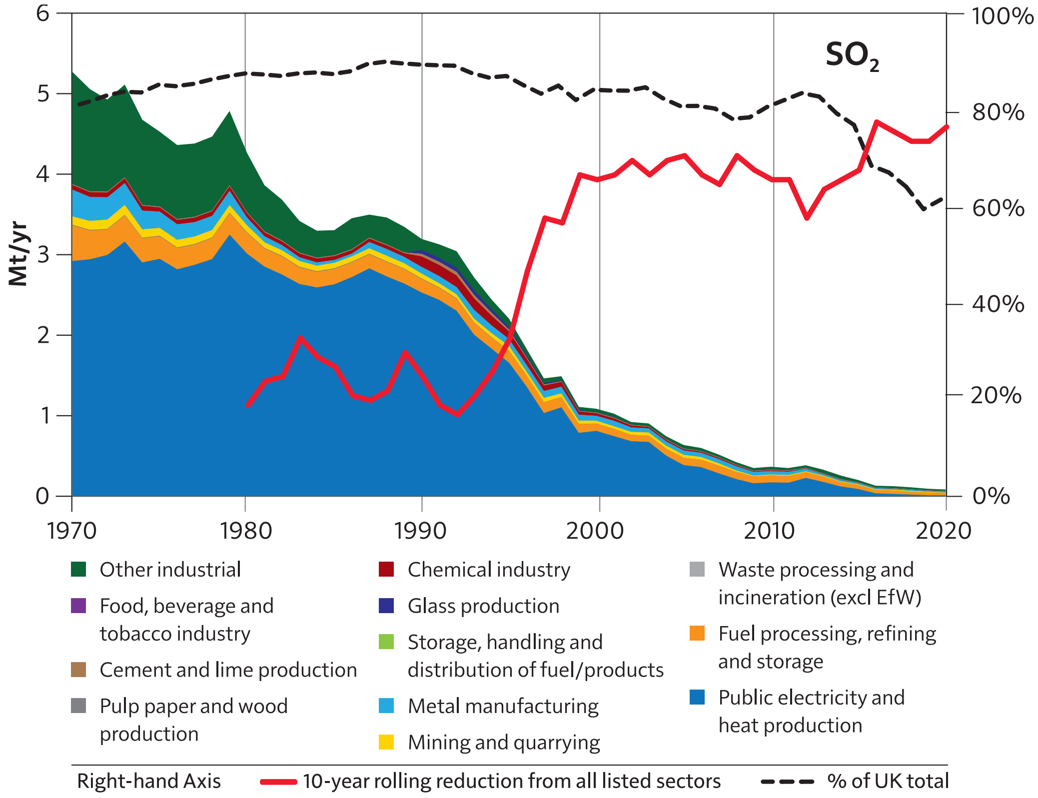


Source: Department for Transport (2022)[9]

Figure 7: Kilometres travelled by bicycle in Great Britain from 1949 to 2021

4.5.1 – 4.5.3 Industry

Many types of industry have reduced their emissions of air pollutants very substantially over recent decades. The major improvement in SO_2 is the most striking success, with the move away from coal and engineered solutions. $PM_{2.5}$ and NO_2 have also been reduced, or where they cannot be reduced, moved away from areas of high population density. Figures 8a, b, and c show the changes in total emissions from industrial processes of SO_2, NO_x and $PM_{2.5}$ from 1970 to 2020. Reductions in emissions or mitigations for many chemicals which can cause harm through air pollution have been achieved in multiple sectors.



Notes: Also showing the contribution of these sectors to the total reported UK emissions (black dashed line). Red line shows the % change over the preceding 10 years.

Source: National Atmospheric Emissions Inventory[10]

Figure 8a: Total UK emissions of SO_2 from industrial sectors reported in the NAEI

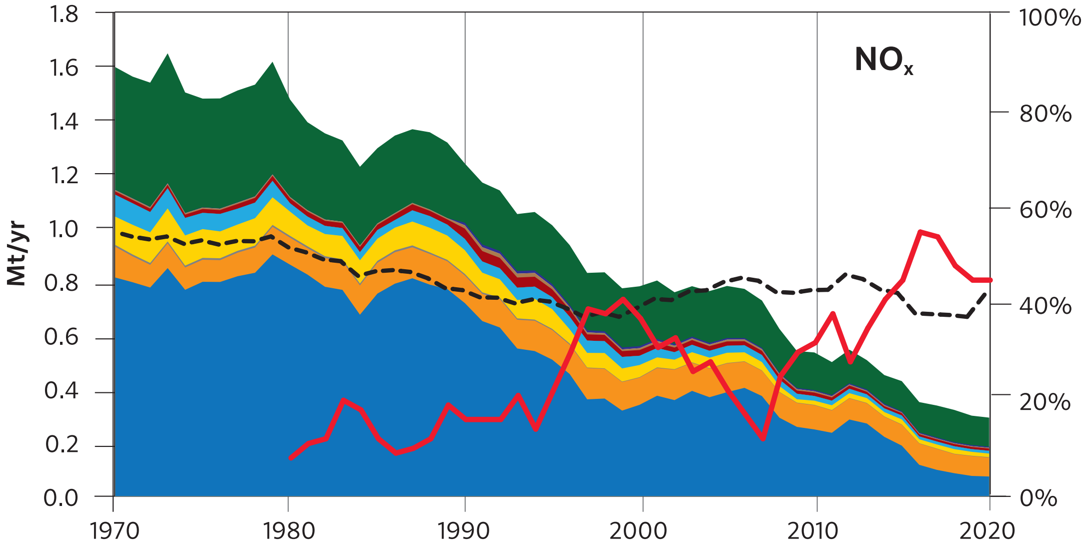
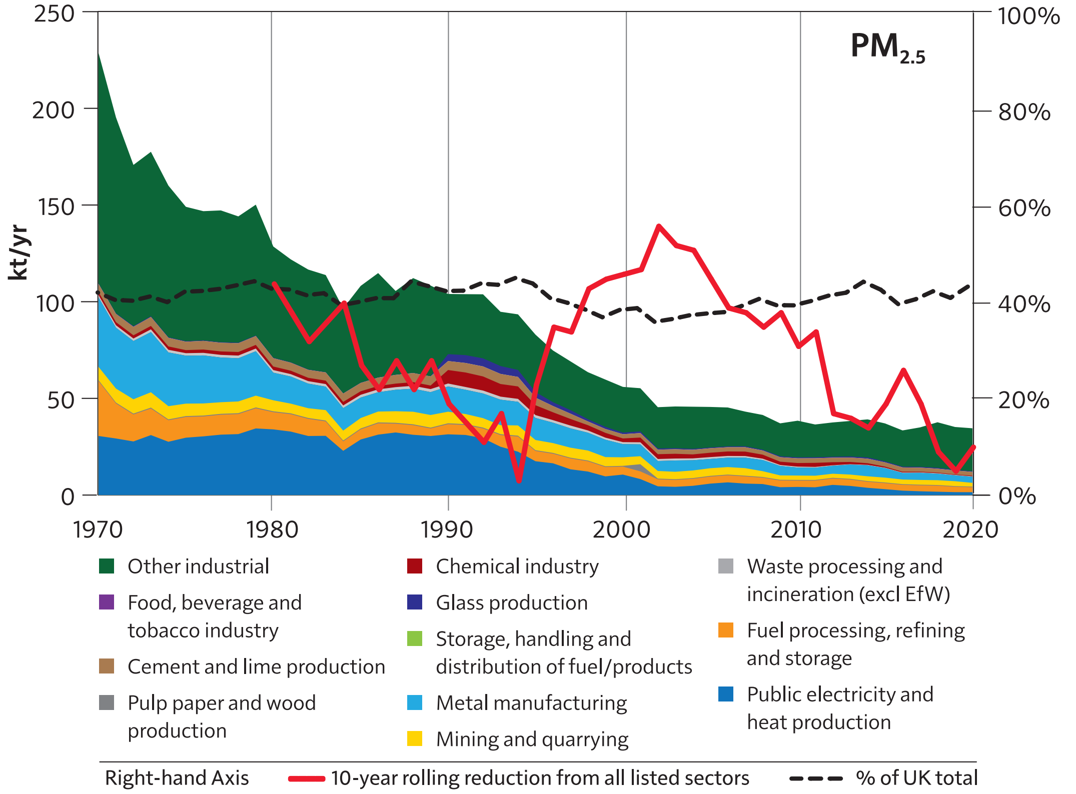


Figure 8b: Total UK emissions of NO$_x$ from industrial sectors reported in the NAEI



Notes: Also showing the contribution of these sectors to the total reported UK emissions (black dashed line). Red line shows the % change over the preceding 10 years.

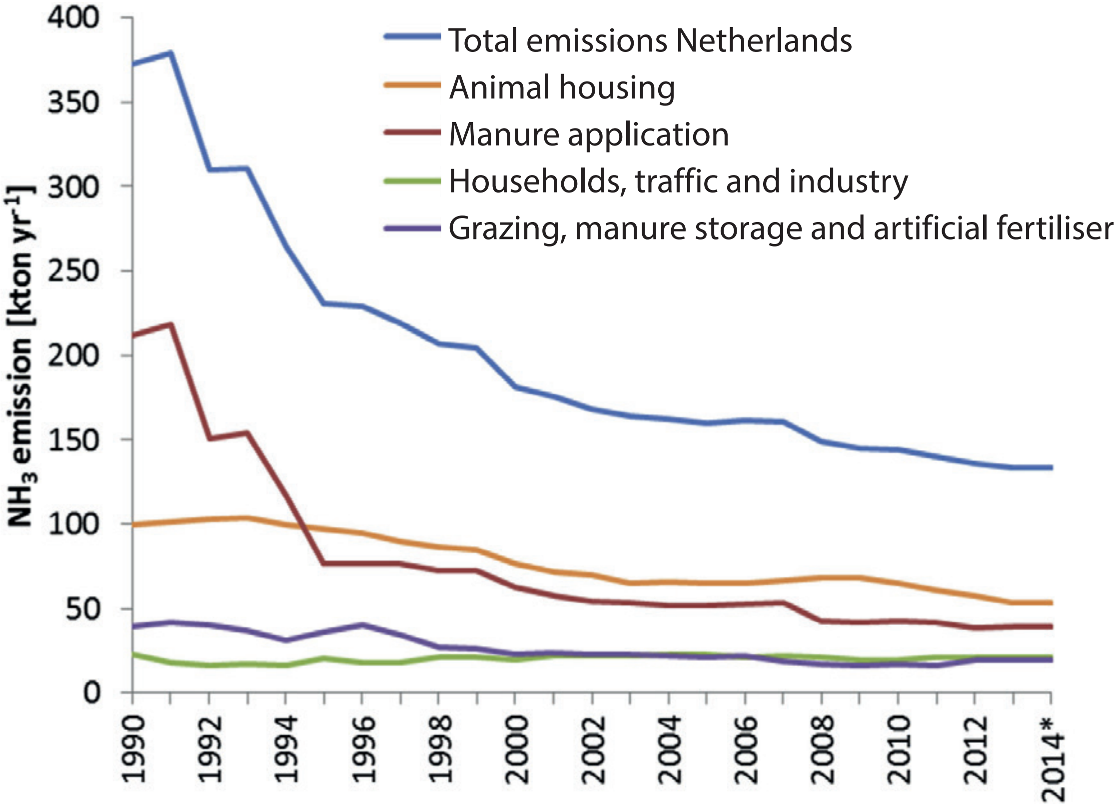
Source: National Atmospheric Emissions Inventory[10]

Figure 8c: Total UK emissions of PM$_{2.5}$ from industrial sectors reported in the NAEI

Regulations have supported a level playing field for industries and encouraged a transition away from processes which gave rise to significant air pollution emissions to those that were either intrinsically cleaner, or had much improved abatement. Some industries will inevitably cause particulate emissions and other air pollution in areas of human habitation, including the construction industry. However, even for these industries, air pollution emissions can be reduced substantially.

4.6 Agriculture

Agriculture is a sector that could, using existing technology, significantly reduce its contribution to air pollution. Ammonia (NH_3) is the most important air pollutant emitted from agriculture. NH_3 has negative effects on ecosystems, but importantly leads also to the creation of secondary $PM_{2.5}$ which can have an effect on health over wide areas. NH_3 emissions have changed very little over the last decades, in contrast to all other major outdoor pollutants. Some countries have demonstrated it is possible to significantly reduce NH_3 by a combination of liquid manure (slurry) covering and changing techniques to apply slurry to fields. Moving from broadcast (splash plate) slurry spreading, where much of the NH_3 ends up in the air, to more direct methods including narrow band spreading, trailing shoe or injection significantly reduces emissions, and can contribute to a reduced need for chemical fertiliser. The Netherlands is an example of where this has been successful, as shown in Figure 9.



Note: *The emissions in 2014 are assumed to be the same as in 2013 in this study as final numbers were not yet available

Source: Reproduced from Wichink-Kruit et al. 2017,[11] © 2017 The Authors. Published by Elsevier Ltd. Licensed under CC BY-NC-ND 4.0

Figure 9: Estimated contributions to the changes in NH_3 emissions from agriculture in the Netherlands, 1990 to 2014

4.7 The NHS

The health sector, and specifically the NHS, needs to contribute to the effort to improve outdoor air quality and is taking steps to do so. It has a large workforce and estate, and a substantial fleet of vehicles, second only to the Royal Mail nationally. Reducing the combustion of fossil fuels used to heat hospitals and other buildings reduces NO_x emissions. Electrification of the vehicle fleet and minimising unnecessary trips reduces NHS transport related air pollution emissions. The example of Great Ormond Street Hospital, working to improve local air quality is described in Section 4.7.2.

4.8 Indoor environments

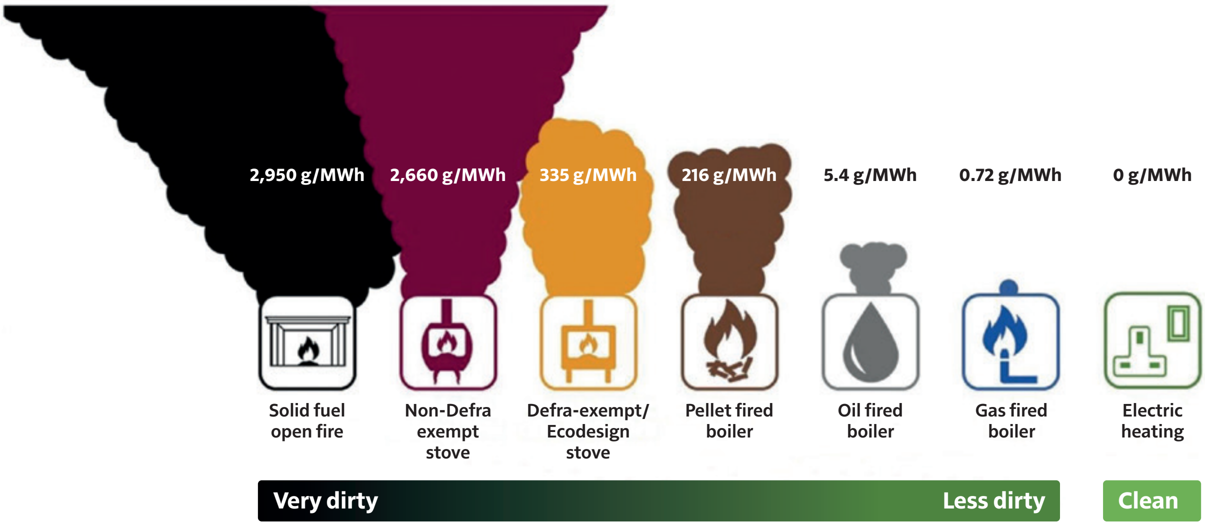
Indoor air pollution is important because over 80% of a typical adult day is spent indoors. Despite this we have much less knowledge about the sources and people's exposure to indoor air pollution, and a less well-developed plan for reducing it. As outdoor air pollution decreases in many environments, indoor air pollution will become the more important opportunity to improve health. Reducing emissions of health harming pollutants is clearly the best option.

Some pollutants may enter buildings from outdoors, and there are also indoor sources of PM and NO_x. Other pollutants such as volatile organic compounds and carbon monoxide are emitted indoors and tend to have higher concentrations indoors. Reducing emissions and concentrations of known pollutants and identifying other chemical indoor pollutants with significant health harms is important.

The role of ventilation is central to reducing unavoidable indoor air pollution, and this is an important difference from addressing outdoor air pollution. A critical engineering challenge is getting the best solution for maximising ventilation, while keeping buildings warm in winter and cool in summer, and minimising energy and therefore carbon use. This is likely to be different in large multi-occupier buildings compared to individual houses, and solutions may vary by season. The role of regulation may well be important in buildings which are public spaces, and in individual products and appliances that are used indoors.

4.9 Domestic space heating, including burning of solid fuels

The heating of buildings presents an important source of indoor as well as outdoor air pollution. Some historically important forms of indoor air pollution have largely gone, such as domestic coal burning. There is a substantial difference between the least and most polluting methods of domestic heating, as shown in Figure 10.



Note: The air pollution emissions will also depend on the age of the appliance, how it is maintained and used and the fuel burned (for example, dry or wet wood).

The following definitions were used: *Solid fuel open fire*: wood burned in an open fire. *Non-Defra-exempt stove*: wood in a conventional stove. *Defra-exempt/Ecodesign **stove***: wood in an advanced/ecolabelled stove. *Pellet fired boiler*: wood in pellet stoves and boilers. *Oil fired boiler*: fuel oil in a medium (>50KWth <1MWth) boiler. *Gas fired boiler*: natural gas in a small (≤50kWth) boiler.

Source: Emission factors taken from EMEP 2019 Guidebook[12] (1A4 small combustion tables). Adapted from the Clean Air Strategy[13] with updated data

Figure 10: The relative $PM_{2.5}$ emissions from domestic heating methods

Solid fuels are by far the most polluting method of domestic heating, and wood burning has increased in popularity over recent years. Reasons for burning wood and other solid fuels vary, and include aesthetic as well as practical, ecological or economic reasons. For air pollution emissions, there is substantial difference between the different open fire and stove designs, the age of the appliance and how well maintained it is, and the moisture content of the wood, for those who want to burn wood. In urban areas, burning wood has the potential to worsen local air quality significantly.

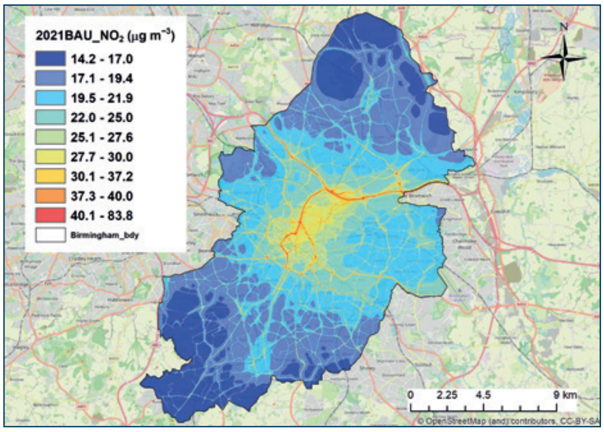
Chapter 5 – Air pollution chemistry, monitoring, forecasting and information

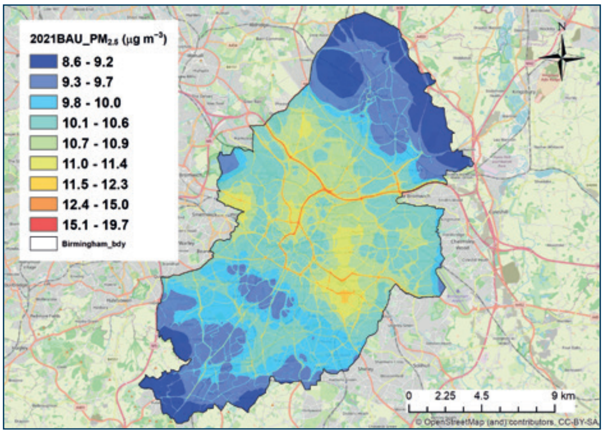
Section 5.1 covers a more detailed examination of where air pollution comes from, and where it goes to. This includes the transport of different pollutants, and how some can transform to secondary pollutants. Broadly the more persistent the pollutants are, the wider their effect geographically. Air pollution also varies by time of day and by season.

Section 5.2 turns to air pollution monitoring, forecasting and alerting – with alerting being particularly helpful for people who are medically vulnerable to harm from air pollution. Section 5.3 covers patient and public information about air pollution. This is especially useful when healthcare workers are giving simple, practical advice to potentially vulnerable children and adults.

Chapter 6 – City examples – work to reduce air pollution

Chapter 6 presents interventions to reduce outdoor air pollution at a city-wide level, considering the examples of Birmingham, Bradford and London. Each of these cities have had significant challenges around air pollution and have taken slightly different approaches to tackle it. These integrate actions including around transport, urban planning and design, reducing pollution around schools and monitoring at a city level. Figures 11 and 12 show maps of NO_2 and $PM_{2.5}$ air pollution across Birmingham.





Source: Zhong et al. (2019)[14] as part of the West Midlands Air Quality Improvement (WM-Air) programme[15]

Figure 11: Annual air quality map of mean NO_2 over Birmingham for 2021

Figure 12: Annual air quality map of mean $PM_{2.5}$ over Birmingham for 2021

Chapter 7 – Air pollution research and innovation

Chapter 7 turns to air pollution research and innovation. For some air pollutants, knowledge of sources, impacts and potential solutions already exists, and it should now be a matter of getting on and doing what we know works. There are however some significant research gaps, both in understanding how certain pollutants are generated, transformed and interact with the human body, and in designing countermeasures and mitigations. These include the health effects of different components of PM, a better understanding of indoor air pollution, and economic analyses of air pollution interventions. Countermeasures that need further development range from tyre design to research on energy-efficient and heat-retaining building ventilation.

Appendix

The report's Appendix lays out the range of publicly funded research on air pollution, currently being undertaken, funded by UK Research and Innovation, National Institute for Health and Care Research, government departments and some international research funded by the Wellcome Trust.

We hope that those reading this CMO Report will come away both with a sense of the scale of the challenge, but also the substantial progress that has been, and will be, made. Air pollution is an environmental risk to health that can, and should, be solved systematically.

Christopher Whitty, Chief Medical Officer for England

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Recommendations

Overall

Outdoor air pollution

1. Outdoor air pollution is falling and will fall further, provided we continue and accelerate the things we know work. This requires action in many sectors, but the interventions are all realistic. We need to focus on areas where people live, study, work and have leisure.

Indoor air pollution

2. As outdoor air pollution falls, indoor air pollution becomes a greater proportion of the problem. Ventilation and reducing emissions are important. Several interventions are highlighted in the report. However, the path to improvement is not as clear as for outdoors, and further research will be needed.

Specific recommendations

Transport

3. The electrification of light vehicles and public transport is important for reducing air pollution from vehicle tailpipes – momentum must be maintained, and accelerated wherever possible. Emissions from tyres and road wear will not be improved by electrification, and this is a key research and innovation need.
4. A greater range of options for reducing air pollution emissions from heavy vehicles is needed. Some specialised vehicles such as refrigerated units need to be addressed, especially in urban areas.
5. The electrification of railways can significantly reduce air pollution emissions from trains and improve air quality for travellers, staff and those living nearby. Where this is not possible, bi-mode or other low-pollution technologies should be used. Closed spaces are important, for example we should look to end diesel trains being left running in enclosed stations.

Urban planning

6. With national government, local authorities are central in the response to air pollution. Urban planning should support reducing air pollution concentrations locally – such as reducing air pollution near schools and healthcare settings. Shifting to active travel where possible has direct health wins as well as reducing air pollution from vehicles – planning should support this.

Industry

7. The substantial improvements from industrial processes over recent years are impressive. Wherever possible remaining industries that emit pollution should be sited away from densely populated areas. Where they cannot, such as construction, mitigations can significantly reduce the impact and they should be adhered to.

Agriculture

8. Ammonia emissions from agriculture contributes to secondary particulate matter air pollution, which can travel large distances and affect populated areas. Significant reductions in ammonia air pollution could be achieved by precision application of slurry to, or into soil, and covering slurry-stores. There would be capital costs, but these changes could be self-sustaining afterwards.

The NHS

9. The NHS is committing to halving its contribution to poor air quality within a decade while reducing health inequalities.
10. The training of healthcare staff should include the health effects of air pollution and how to minimise these, including communication with patients.

Indoor air pollution

11. People spend large periods of time indoors and many indoor places are public, where individuals have little control over the quality of air they breathe. These two factors should be recognised in the planning and development of public indoor spaces.
12. Effective ventilation, while minimising energy use and heat loss, is a priority for reducing air pollution, respiratory infections and achieving net zero. This is a major engineering challenge which needs solving.
13. While there is co-ordination across government, the ownership of indoor air quality policy within government needs to be clarified.

Wood stoves and other solid fuel heating

14. The use of wood stoves is increasing and can impact air quality significantly in urban areas. Air pollution emissions can be reduced, but not fully eliminated, by using modern, less polluting stoves and burning wood that is dry. In smoke control areas, the rules should be adhered to.

Research

15. Research priorities are highlighted in the research section. Indoor air pollution in particular needs greater research interest. Policies should be evaluated once implemented.

There are other recommendations in the different sections of the report.

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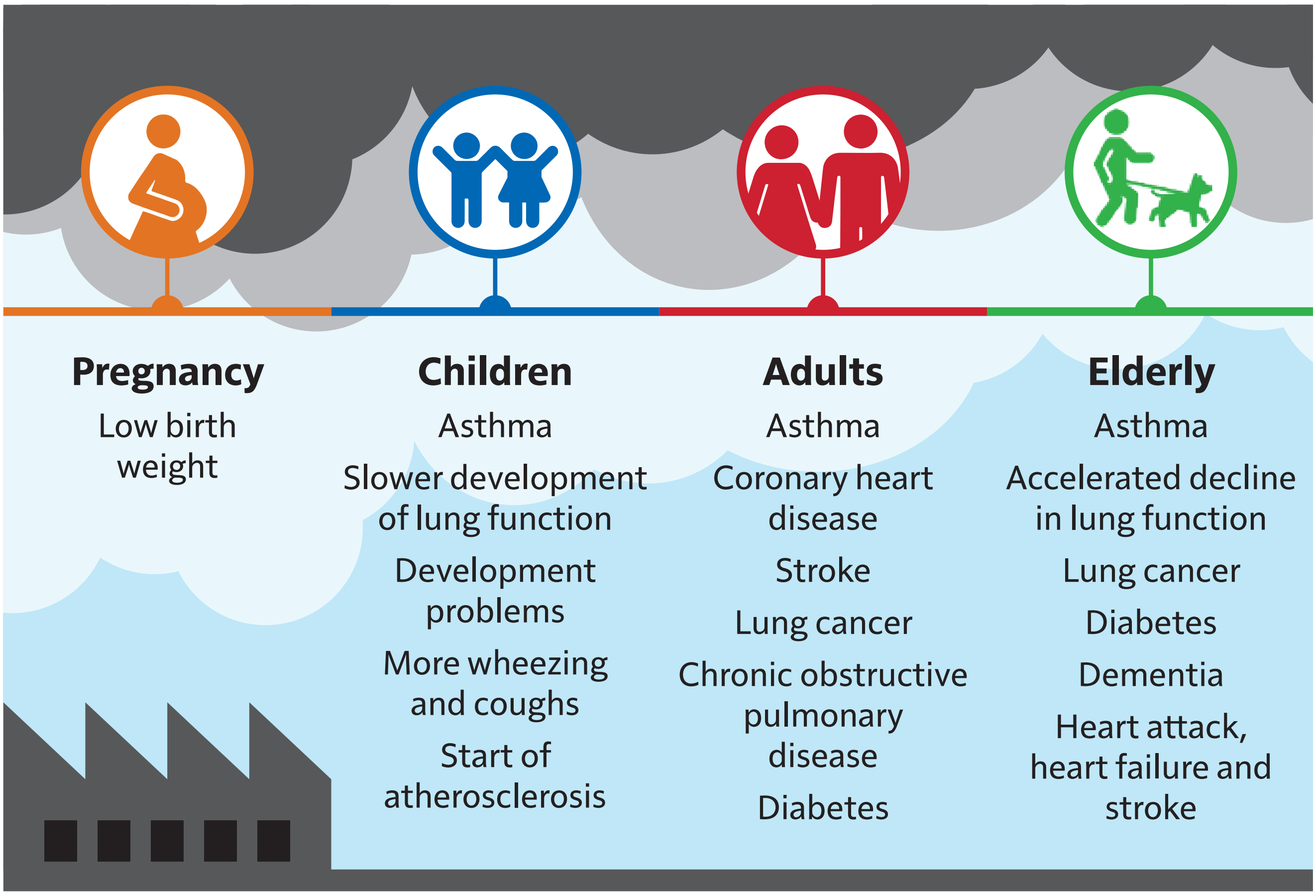
Air pollution – a modifiable risk factor for disease

People's environments have important influences on their physical and mental health. Appreciation of the health effects of air pollution is easier when it is visible, such as during the London smogs in the 1950s, but now in England, most of the time air pollution is not visible. Each year we experience several episodes of elevated air pollution concentrations that cause acute health harms. However regular long-term exposures to air pollution at lower concentrations is also of significant public health concern.

Air pollution affects people's health throughout their lives, including before birth, in the very young, through to older adults. Exposure to air pollution, indoors and outdoors, over a long period of time, reduces people's life expectancy. There is clear evidence that air pollution contributes to the initiation and development of cardiovascular and respiratory diseases, and can cause lung cancer.

Evidence of links between exposure to air pollution and a wider range of health effects, such as intra-uterine impacts, adverse birth outcomes, poor early life organ development, diabetes, reduced cognitive performance, and increased dementia risk continues to build, with varying strengths of evidence.[1] Recent research has suggested that long-term exposure to raised concentrations of outdoor air pollution may increase susceptibility to more severe health outcomes, including the risk of hospitalisation due to COVID-19.[2,3,4,5] Figure 1 shows the many diseases and health effects linked to air pollution exposure.



Source: Adapted from Public Health England (2018)[6]

Figure 1: Health effects of air pollution throughout life

The mortality burden of long-term exposure to outdoor air pollution in England in 2019 was estimated to be equivalent to 26,000 to 38,000 deaths a year.[7] The figure is noted as 'equivalent to' because air pollution is considered to be a contributory factor to mortality. This estimate was calculated by the UK Health Security Agency (UKHSA), based on recommendations from the Committee on the Medical Effects of Air Pollutants (COMEAP)[8], which provides independent advice to government departments and agencies on how air pollution impacts on health.

The public health burden due to air pollution is likely to be even higher than the estimate above, as it does not consider all outdoor air pollutants, or the morbidity impacts, and it does not include exposure to indoor air pollution. It has been estimated that more than 550,000 deaths in the World Health Organization (WHO) European region in 2016 were due to the effects of exposure to household and outdoor air pollution.[9]

There is less information about typical indoor exposure to pollutants and the quantified health effects, apart from the well-studied pollutants carbon monoxide and radon. This is mainly due to the challenges of conducting large-scale monitoring or exposure assessment studies in people's homes. Added to this is the complexity and variability of indoor spaces, which include both public and private spaces – places of work, education, leisure, inside transport and homes. These challenges are discussed further in Section 4.8.

Pollution that affects indoor air quality is not just from indoor sources, such as cooking and stoves, it may also be due to ingress of outdoor pollutants. Some indoor sources emit pollutants that are also found outdoors, such as particulate matter (PM) and nitrogen dioxide (NO_2).[10] Despite this, we do know that those with pre-existing respiratory or cardiovascular conditions or allergies are particularly affected by poor indoor air quality, and children are particularly at risk from respiratory problems, such as wheezing and asthma, eye and skin complaints and reduced cognitive performance.[11,12,13]

Benefits to health of improving air quality

Concentrations of air pollution have decreased considerably over the last 100 years and a study over recent years estimated that childhood asthma admissions due to air pollution in London have reduced by 30% since 2016.[14] However, there are still significant health gains to be made from improving air quality further.

Reductions in air pollution have been found to have positive effects on the development of children's lung function. For example, in a study in California, long-term reductions in PM and NO_2 (median declines of 12.6 $\mu g/m^3$ and 14.1 ppb respectively) were associated with measurable improvements in the development in the lung function of children with and without asthma between the ages of 11 and 15, compared with those growing up earlier when pollution levels were higher.[15] While small changes in lung function might not seem significant on an individual level, it is important on a population level when we consider that even a small change in average lung function leads to a far greater number of people falling below the disease threshold.[2]

While some improvements in health are likely to be seen quite quickly following improvements in air quality, it is unlikely that the full health benefits would be realised immediately. Modelling estimates suggest that a reduction of one $\mu g/m^3$ of $PM_{2.5}$ in 2017 in England could prevent 50,900 cases of coronary heart disease, 16,500 strokes, 4,200 lung cancers and 9,300 cases of asthma in people aged over 18 years by 2035.[16]

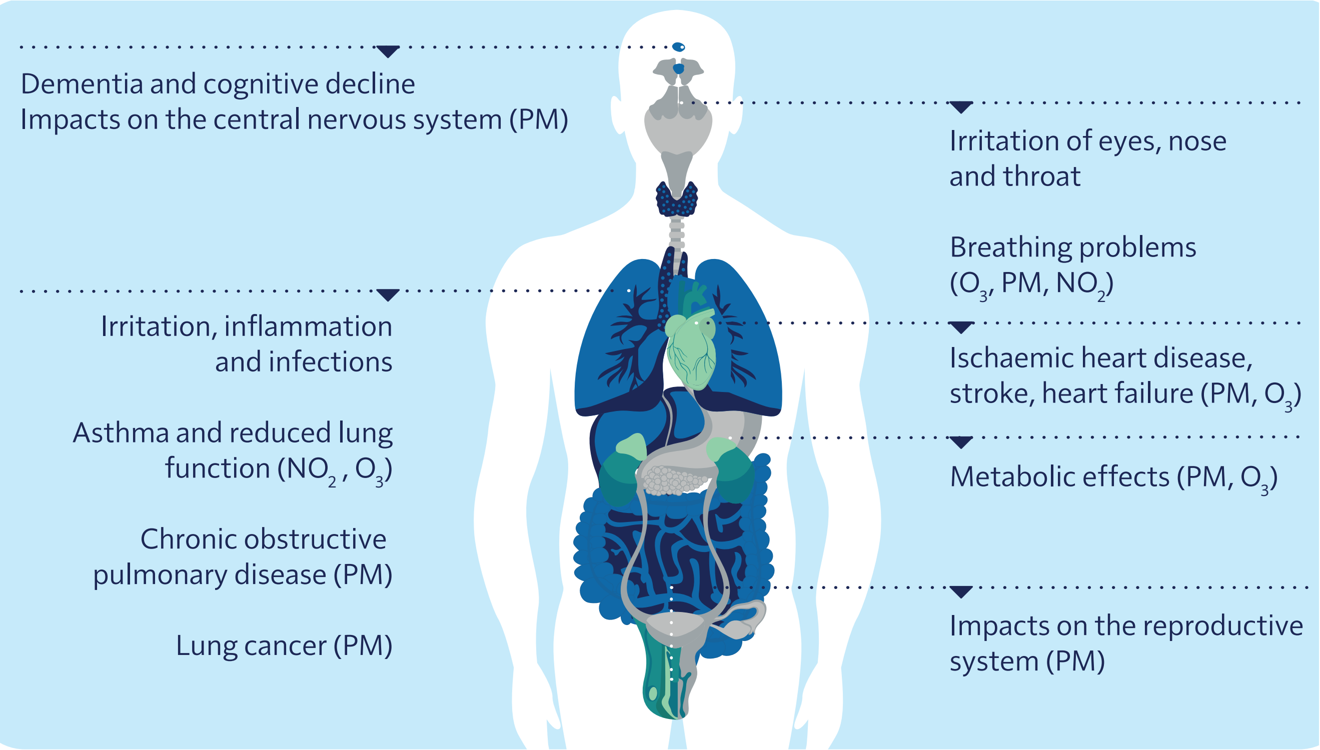
When estimating the benefits of reducing air pollution, COMEAP has assumed that: 30% of the reduction in risk of mortality occurs in the first year after pollution reduction; 50% occurs across years 2 to 5; and the remaining 20% of the risk reduction is distributed across years 6 to 20. These 3 components of the distribution reflect short-term, cardiovascular and lung cancer effects, respectively.[17]

There is also increasing evidence showing health effects of exposure to lower levels of pollutants, and no obvious thresholds have been detected for the effects for air pollution at a population level. This evidence has been reflected by the updated WHO Global Air Quality Guidelines published in 2021.[18] WHO's annual average air quality guidelines were reduced from 10 to 5 $\mu g/m^3$ for fine particulate matter ($PM_{2.5}$) and 40 to 10 $\mu g/m^3$ for NO_2.[18] The absence of thresholds of effect for common air pollutants is likely to be partly due to variability between individuals' sensitivity to the pollutants studied.[19] This and other reasons for the disparities in the health effects of air pollution are described further in Section 1.2.

Key air pollutants and health harms

While 'air pollution' is often used as a general term, the pollution that people breathe is a mixture of gases and particulates – all of which may interact and have greater health effects if combined. There are numerous sources of indoor and outdoor air pollution, so understanding the risks from air pollution is complex in determining people's exposures and their health outcomes. Most evidence on the health effects from air pollutants comes from population-based epidemiological studies, controlled human exposure studies and toxicological studies in animal models or in-vitro cell studies. The health evidence for some of the key pollutants in outdoor and indoor environments is discussed below.

Figure 2 presents an overview of some of the health effects of different air pollutants.



Source: Adapted from EEA (2020)[20]

Figure 2: Health effects of air pollutants

Outdoor environments

The UK government's Clean Air Strategy covers emissions of 5 of the most damaging air pollutants: fine particulate matter; nitrogen oxides; ammonia; sulphur dioxide; and non-methane volatile organic compounds.[21] Some of the other outdoor air pollutants that can affect health include particulate matter associated metals (arsenic, cadmium, nickel, lead and mercury), polycyclic aromatic hydrocarbons, ozone and bioaerosols. An overview of the most important pollutants, their sources and health effects can be found in Table 1 at the end of this section. The following section covers the 3 outdoor air pollutants that are of particular public health concern: particulate matter, nitrogen dioxide, and ozone.

Particulate matter (PM)

PM is a generic term used to describe a complex mixture of solid and liquid particles of varying size, shape, and composition. Some particles are emitted directly (primary PM); others are formed in the atmosphere through complex chemical reactions (secondary PM). The composition of PM varies greatly and depends on many factors, such as geographical location, emission sources and meteorology. Further information about the outdoor sources of PM can be found in Chapter 2, and detail about the transformation of primary to secondary PM in Section 5.1.

PM is often classified according to aerodynamic size.

PM_{10} particles are generally less than 10 microns (μm) in diameter and includes the following fractions:

- coarse particles, $PM_{10\text{-}2.5}$ (particles that are between 10 and 2.5 μm in diameter)
- fine particles, $PM_{2.5}$ (particles that are less than 2.5 μm in diameter)
- ultrafine particles $PM_{0.1}$ (particles that are less than 0.1 μm in diameter)

Particles larger than 10 μm are mainly deposited in the nose or throat, whereas particles smaller than 10 μm pose the greatest risk because they can be drawn deeper into the lung. $PM_{2.5}$ can reach the terminal bronchioles and ultrafine particles can enter the alveoli, with a small proportion able to cross into the blood stream and reach other organs.[22]

Much of the research, particularly the epidemiological studies, has investigated the effects of $PM_{2.5}$. As the Environment Act, for air quality, is focused on developing targets specifically for $PM_{2.5,}$ the main evidence discussed here on particulate matter will concentrate on $PM_{2.5}$.[23]

Short-term exposure to $PM_{2.5}$

Mortality – There is a substantial evidence base linking short-term (daily, for example) variations in PM concentrations with variations in mortality risk, on the same or subsequent days. Short-term exposure to $PM_{2.5}$ is associated with cardiovascular, respiratory, and cerebrovascular mortality.[24]

Respiratory effects – There is evidence that short-term exposure to PM is associated with hospital admissions for respiratory conditions. The US Environmental Protection Agency (US EPA) has an Integrated Science assessment for PM which concluded that short-term exposures to $PM_{2.5}$ are likely to be causally associated with respiratory effects, particularly exacerbations of asthma and chronic obstructive pulmonary disease (COPD) and respiratory-related diseases. This is supported by evidence from animal toxicological studies providing biological plausibility for asthma and COPD exacerbations. Evidence from animal studies also shows that PM can cause greater susceptibility to bacterial infection, allergic sensitisation, and airway irritant effects. There is some evidence for altered host defence, pulmonary injury, inflammation, and oxidant stress.[25]

Cardiovascular effects – Short-term exposure to $PM_{2.5}$ causes cardiovascular effects, with the strongest evidence from epidemiological studies for ischaemic heart disease, stroke and heart-failure emergency department and hospital admissions, along with cardiovascular-related mortality.[101]

Controlled human exposure, animal toxicological, and panel studies support the evidence demonstrating small increases in blood pressure and small changes in endothelial function, reduced heart rate variability, arrhythmias (abnormal rhythms of the heart), progression of atherosclerotic disease (thickening or hardening of the arteries) and promotion of blood clotting.[25,26] The health effects are thought to be possibly due to the passage of inflammatory mediators from the lung into the blood leading to systemic inflammation, effects on the autonomic nervous system altering the regulation of cardiac function and direct effects on vascular function.[26]

Other health outcomes – Emerging evidence linking short-term $PM_{2.5}$ exposure with metabolic and nervous system effects was considered suggestive of, but not sufficient to infer, causality by the US EPA.[25]

Long-term exposure to $PM_{2.5}$

Mortality –There is strong epidemiological evidence of the link between long-term exposure to $PM_{2.5}$ and mortality and it is possible to quantify estimates of the effect at a population level.[17,7,27] $PM_{2.5}$ is also causally associated with specific causes of mortality from cardiovascular and respiratory disease and from lung cancer.[17,25,28,29] It is estimated that the fraction of mortality attributable to long-term exposure to $PM_{2.5}$ in England is 5.6% but this varies across different parts of the country.[30]

Recent large epidemiological cohort studies investigating mortality and health effects at low levels of air pollution report effects below the current air pollution standards and guidelines. For example, the Effects of Low-Level Air Pollution: A Study in Europe (ELAPSE) multicentre project found effects on mortality following long-term exposure to $PM_{2.5}$ at 5 $\mu g/m^3$. Also, a large American cohort study reported that in populations where some individuals' exposure to $PM_{2.5}$ was as low as 2.8 $\mu g/m^3$ there was evidence of increased risk of mortality.[31,32]

Respiratory effects – Long-term exposure to $PM_{2.5}$ is associated with effects on lung development and asthma in children. In adults, it is associated with an acceleration of lung function decline and respiratory mortality.[2,25] In 2016, COMEAP found some epidemiological evidence of an association between the incidence and prevalence of chronic bronchitis and long-term exposure to air pollution (mainly measured as PM_{10}) but the evidence was not sufficient to infer a causal relationship in the UK today.[33] A large cohort study in 2021 found associations with black carbon particles and NO_2 and prevalence and incidence of chronic bronchitis, but did not demonstrate significant associations with $PM_{2.5}$.[34]

Cardiovascular effects – Long-term exposure to $PM_{2.5}$ is causally related to cardiovascular effects.[35] There is good evidence of an association between long-term exposure to $PM_{2.5}$ and cardiovascular mortality[36] but more limited epidemiological evidence on cardiovascular morbidity. Fewer studies have been conducted to investigate this. COMEAP considers that the epidemiological and mechanistic evidence for the associations between long-term average concentrations of $PM_{2.5}$ and ischaemic heart disease and cerebrovascular disease (stroke) suggests a causal relationship.[37]

COMEAP found that most of the available mechanistic evidence linking air pollutants with cardiovascular effects comes from studies considering short-term exposure to air pollution.[26] Both COMEAP and the US EPA noted that these effects (such as atherosclerotic plaque progression, increased coronary wall thickness, decreased cardiac contractility and output, and changes in blood pressure) seen in animal studies[38] provide further evidence to that observed in epidemiological studies, indicating a likely causal role of $PM_{2.5}$ on cardiovascular health.

Cancer – The link between air pollution and lung cancer has been recognised for many years. In 2013, WHO's International Agency for Research on Cancer (IARC) listed PM in outdoor air pollution as carcinogenic to humans (Group 1 carcinogen), as well as outdoor air pollution generally.[28,39] The US EPA found that the already strong epidemiological evidence linking long-term $PM_{2.5}$ exposure with increases in lung cancer incidence and mortality is now supported by additional experimental and epidemiological evidence indicating genotoxicity, epigenetic effects, and carcinogenic potential.[25] There is an increasing number of studies investigating associations with other types of cancer, such as breast cancer, but the evidence is not supportive of an association.[40]

Metabolic effects – The US EPA noted consistent findings in epidemiological studies of diabetes-related mortality and indicators of metabolic syndrome, but inconsistent findings from epidemiological studies of the incidence of type 2 diabetes and concluded that the evidence was suggestive of, but not sufficient to infer, causality.[25] The evidence continues to build such that the Global Burden of Disease analysis[41] found it sufficient to quantify the effect, estimating that in 2019, a fifth of the global burden of type 2 diabetes was attributable to exposure to $PM_{2.5}$ pollution.[42]

Nervous system effects – There is also increasing evidence on long-term exposure to $PM_{2.5}$ and effects on the nervous system. Animal studies suggest a range of effects including neuroinflammation and oxidative stress, neurodegeneration, and effects on cognitive function and neurodevelopment.[25] Most of the available epidemiological studies have investigated effects in older adults (brain morphology, cognitive decline, and dementia).[25,43,44] Some studies have investigated Parkinson's disease, anxiety, depression, and psychosis.[45,46,47,48] Limited epidemiological evidence related to neurodevelopmental effects is also reported.[25] Of these outcomes, the evidence seems strongest for $PM_{2.5}$ and dementia.[44]

COMEAP recently concluded that air pollution does contribute to a decline in mental ability and dementia in older people, but more research is needed before the size of the effect can be quantified.[49] The associated review concluded that there is strong evidence of a causal association between air pollutants and study endpoints relevant to cognitive decline and dementia. However, the studies are not consistent in which pollutant they report as being most closely associated with these adverse effects.[43]

A more recent review notes that the weight of the evidence suggests an adverse association between $PM_{2.5}$ and cognitive decline.[50] Associations with dementia are thought to be due to air pollution causing cardiovascular effects, which affect blood supply to the brain, leading to vascular dementia. However, a direct effect of particles on the brain may also be possible, and particles have been identified within the brain in animals and in human cerebrospinal fluid.[51,52] Another review found associations for dementia outcomes, even after adjustment for the presence of other cardiovascular comorbidities, which may suggest an independent $PM_{2.5}$ dementia pathway.[44]

Birth outcomes and fertility – There is evidence that air pollution might affect people's health before they are born, and could be linked to premature birth and low birth weight.[1] Currently, the US EPA's view is that the evidence for long-term exposure to $PM_{2.5}$ with pregnancy and birth outcomes is considered suggestive of but, not sufficient to infer, a causal relationship. The same conclusion applies to male and female reproduction and fertility.[25] However, a 2021 report by the Royal College of Obstetricians and Gynaecologists[53] noted the growing body of evidence – such as Hansell et al (2019)[54] – on adverse pregnancy outcomes and childhood lung function affected due to prenatal and early life exposure. The 2019 Global Burden of Disease analysis of the effect of ambient and household $PM_{2.5}$ on perinatal outcomes, low birth weight, pre-term birth and reduced birth weight and gestational age, estimated that low birth weight and over 5.9 million pre-term birth infants worldwide could be attributable to $PM_{2.5}$ air pollution exposure during pregnancy.[55]

Differential toxicity of components and sources of particulate matter

It is unlikely that all the chemicals and their sources associated with ambient PM are equally harmful to human health. Some components and/or sources of particulate air pollution are almost certainly more detrimental to health than others, but studies trying to identify which are the most toxic particles are challenging. Ultrafine particles, diesel particles, black carbon particles (soot and a tracer of vehicle exhausts), secondary sulphates, metal content of particles and chemicals on the surface of particles have all been suggested as particularly important.

Specific sources of particulate matter – The different sources of PM are discussed in Chapter 2. Much of the health research has concentrated on traffic-related emissions as this is a significant contribution to poor air quality. PM, elemental carbon and NO_2 are often considered as markers of traffic-related air pollution exposure (depending on the study setting and exposure assessment). Following a large systematic review, the Health Effects Institute reported an overall high or moderate to high level of confidence in an association between long-term exposure to traffic-related air pollution and all-cause mortality, circulatory disease, ischaemic heart disease and lung cancer mortality, asthma onset in children and adults, and acute lower respiratory infections in children.[56] Associations with Parkinson's disease have also been reported, especially for NO_2 and traffic-related air pollutants.[57,58] IARC also found an association between long-term exposure to air pollution and urinary bladder cancer, largely based on evidence from studies on traffic-related air pollution.[28]

Other studies have specifically considered the health effects from diesel exhaust. Animal and cell-based studies have demonstrated oxidative stress and inflammation. Studies in human controlled exposures and in real-world studies have shown evidence of cardiovascular effects.[38,59] IARC concluded that diesel engine exhaust causes lung cancer in humans.[60,61]

Particle metrics and size – Particle mass concentration, the total mass of particles per unit volume of air (for example $\mu g/m^3$) is the common metric used to evaluate and regulate PM. There is evidence to suggest that particle number concentrations (total number of particles per unit volume of air, for example cm^3) might be of greater significance than particle mass concentrations in the determination of certain health effects. This is particularly relevant for ultrafine particles.[62]

Ultrafines make up a small fraction of the PM mass because of their small size, but the particle number concentration is higher. Based on toxicological studies, it has been hypothesized that ultrafine particles may be an especially toxic component of $PM_{2.5}$ because of their small size, large numbers, and large surface area-to-mass ratio, which increases the potential to carry other harmful chemicals.

Recent reviews of epidemiological and toxicological studies suggest that short-term exposures to ultrafines are linked with inflammation and cardiovascular changes such as endothelial dysfunction, vascular inflammation, and atherosclerosis.[62,63] Ultrafine particles have been identified in the placenta[64] and the brain[62] but there is insufficient epidemiological evidence of associated health effects. For other health outcomes, the evidence of independent effects of ultrafine particles is limited and inconsistent.[62,63,65] The WHO Air Quality Guidelines published in 2021 considered that there was insufficient epidemiological data to recommend air quality guidelines, but provided good practice statements with recommendations on increased monitoring, mitigation and future research.[18]

While PM studies show effects from different sources and components, the epidemiological evidence does not clearly indicate that any one source or component is more strongly related with health effects than $PM_{2.5}$ mass. Therefore, current recommendations are that the focus should be on reducing PM mass as a whole.[25,66] However, it is recognised that better understanding of the health effects of various components of PM is needed. As well as recommendations for ultrafines, WHO also produced good practice statements identifying black carbon/elemental carbon, and particles associated with sand and dust storms as components of particular concern needing more monitoring and research.[18]

Nitrogen dioxide (NO_2)

Nitrogen oxides (NO_x) are a group of gases that are predominantly formed during combustion and emitted in the form of nitric oxide (NO). The main sources are power generation, industrial combustion and road transport. When NO reacts with other gases present in the air, it can form nitrogen dioxide (NO_2), which is harmful to health.

A notable source of NO_2 is road traffic – which has made it difficult to distinguish the effects seen in epidemiological studies for NO_2 from those of particulate matter. However, the evidence associating NO_2 with health effects continues to grow.

Short-term exposure to high concentrations of NO_2

Mortality – Since the US EPA concluded in 2016 that the evidence was not strong enough to show a causal association, the evidence has increased for an association between NO_2 and mortality. A recent review for WHO found a high level of confidence in the evidence of a positive association with short-term exposure (24-hour average) to NO_2 and all-cause mortality, and moderate strength of evidence associated with 1-hour average exposures.[24]

Respiratory effects – In recent years, the growing evidence for direct effects of NO_2, particularly for acute respiratory effects following short-term exposure, has been recognised.[18,67,68] At high concentrations, NO_2 is a respiratory irritant that can cause decreases in lung function and inflammation of the airways, which can lead to, for example, cough, production of mucus and shortness of breath.[19]

Epidemiological and controlled human exposure studies demonstrate the effects of NO_2 on the airway responsiveness of individuals with asthma, and increases in allergic responses, which are part of the proposed mechanisms linking NO_2 and asthma exacerbation. A recent systematic review of studies found high certainty from the epidemiological evidence that 24-hour average exposure to NO_2 is associated with emergency department visits or hospital admissions due to asthma (but less certainty with a 1-hour exposure metric).[69]

Evidence from controlled human exposures to NO_2 provides plausibility that the effects seen in these epidemiological studies are actually due to NO_2 rather than it acting as a marker for other pollutants.[68,70]

Cardiovascular effects – There is consistent epidemiologic evidence for increases in hospital admissions and emergency department visits for myocardial infarction and ischaemic heart disease, and cardiovascular mortality. The strongest evidence is for effects related to triggering myocardial infarction. There are limited findings from human and animal experimental studies that identify markers of inflammation and oxidative stress. The US EPA concluded that the evidence is suggestive of, but not sufficient to infer, a causal relationship. This is mainly because associations do not always remain after adjustment for $PM_{2.5}$ and other pollutants.[68] In 2022, COMEAP also noted that there was uncertainty regarding whether associations between NO_2 and cardiovascular hospital admissions were causal, suggesting that associations are seen because NO_2 is acting as a marker for emissions of other pollutants.[70]

Other health outcomes – There is suggestive evidence for a range of effects similar to particulate air pollution, such as metabolic effects, fertility, birth outcomes and nervous system effects. However, in most cases, the evidence is less strong for NO_2 than for particulate pollution.[68]

Long-term exposure to NO_2

Mortality effects – Evidence of effects on mortality following long-term exposure to NO_2 have been found in populations exposed to concentrations as low as 10 $\mu g/m^3$ in the European ELAPSE multicentre study.[32] However, when COMEAP reviewed the evidence for a link between long-term exposure to NO_2 and mortality they concluded that, while the association represents some effect from NO_2 itself, it is likely to be an over-estimate because of confounding by other pollutants such as $PM_{2.5}$ and other traffic pollutants such as ultrafine particles, black carbon and volatile organic chemicals.[71] A review found associations between NO_2 and mortality for all-cause, respiratory, COPD and Acute Lower Respiratory Infection (ALRI). The authors noted heterogeneity in the studies for outcomes, suggesting moderate certainty of the evidence for the associations with all-cause, respiratory and ALRI mortality but high certainty for the evidence linking long-term average concentrations of NO_2 and COPD mortality.[72] WHO noted the increase in studies supporting associations of long-term exposure to NO_2 with all cause and respiratory mortality.[18]

Respiratory effects – Epidemiological and experimental evidence indicate a likely causal relationship between long-term exposure to NO_2 and respiratory effects, with the evidence strongest for asthma development. Evidence for other respiratory effects, such as respiratory disease severity, lung function changes, and respiratory infection, is more uncertain because the combined epidemiologic and/or experimental evidence does not clearly demonstrate an independent effect of long-term NO_2 exposure.[68]

Cancer – There is evidence of associations of long-term average concentrations of NO_2 with lung cancer, but in this context it is regarded as a proxy for traffic-related air pollution.[73] There is increasing evidence for associations with breast cancer.[40]

Nervous system effects – There is epidemiological evidence of an association with dementia and cognitive decline[43,49] and emerging evidence of an association with Parkinson's disease.[57,58]

Other health outcomes – While there are increasing studies suggesting associations with cardiovascular effects, metabolic effects, fertility, and birth outcomes, the evidence is not consistent, and potential confounding from other pollutants is not always ruled out.[68]

Ozone (O_3)

O_3 at ground-level is an irritant gas with known impacts on health. Ground-level, or tropospheric, O_3 is not emitted directly into the air but is created by photochemical reactions involving the precursor pollutants nitrogen oxides (NO_x) and volatile organic compounds (VOCs). The reactions can take place over long distances and timescales. It is mainly a problem in the UK in summer months when the temperature is high enough to stimulate chemical reactions that form O_3. Concentrations of O_3 tend to be higher in rural areas than in urban and suburban areas. However, increases in suburban and urban O_3 are occurring due to the reductions in primary emissions of NO_x.[74] As well as locally generated O_3, much of the O_3 experienced in England is due to emissions of its precursor pollutants in other areas of the world.

Epidemiological studies of O_3 can be difficult to interpret due to the complex temporal and spatial correlations with other pollutants that can change with temperature, season and pollutant concentrations.[75]

Short-term exposures to high concentrations of O_3

Mortality – There is evidence of a causal association of mortality with short-term exposure to ozone (measured as the maximum daily 8-hour running mean). There is evidence from a smaller number of studies for associations with cardiovascular mortality and respiratory mortality.[75] More recent epidemiological studies continue to support this.[76]

Respiratory effects – The strongest evidence in relation to short-term exposures is respiratory effects such as wheezing, coughing, throat irritation, chest tightness, shortness of breath and reduction in lung function. Epidemiological and human exposure evidence suggests that O_3 exposure can make asthma symptoms worse and can increase sensitivity to asthma triggers. A recent review for WHO found strong evidence of an association with 8-hour and 24-hour exposure to O_3 with emergency department visits and hospital admissions for asthma.[69] Epidemiological studies found associations between exposure to O_3 and markers of respiratory tract inflammation, lung function decrements, and emergency department visits and hospital admissions for asthma and respiratory infection. There is also sufficient evidence of the impacts of short-term exposure to O_3 (measured as the maximum daily 8-hour running mean) on respiratory hospital admissions.[75]

Based on animal and controlled human exposure studies, it is proposed that effects may occur via activation of sensory nerves in the respiratory tract leading to lung function reduction and increased airway responsiveness and/or via injury to respiratory tract, inflammation and oxidative stress, leading to morphologic changes and altered host defence.[77]

Metabolic effects – It was recently concluded that there is a likely causal association between exposure to O_3 and metabolic health impacts.[77] The US EPA based this on strong and consistent evidence from animal toxicological studies, epidemiological studies and one controlled human exposure study. Short-term O_3 exposure has been shown to consistently impair glucose and insulin homeostasis and increase triglycerides and fatty acids.[77]

*Other health effect*s – adverse effects on the cardiovascular and nervous systems following short-term exposures to O_3 have also been reported. The US EPA considered the evidence insufficient to demonstrate a causal association.[77] However, although more uncertain than the respiratory effects, COMEAP considered the evidence sufficient to recommend quantification of cardiovascular hospital admissions associated with short-term exposure to O_3.[75]

Long-term exposure to O_3

The evidence for associations between long-term exposure to O_3 and impacts on human health is less clear.

Mortality effects – No evidence of associations between long-term annual O_3 concentrations and the risk of death from all causes, cardiovascular or respiratory diseases, or lung cancer were found in a comprehensive systematic review in 2016.[78] In 2020, the US EPA supported the conclusion noting that the evidence for long-term exposure to annual concentrations of O_3 and all-cause mortality was suggestive of, but not sufficient to infer, a causal relationship.[77] This was supported by a recent review which found a high level of heterogeneity in the evidence of associations with all cause and respiratory mortality associated with annual averages or peak (warm season) average O_3 metrics. They concluded that there was a low certainty of the evidence for metrics and outcomes, except for peak exposure and all-cause mortality where there was moderate certainty of the evidence.[72]

Respiratory effects – The recent US EPA review notes a likely causal relationship between long-term exposure to O_3 and respiratory effects.[77] This is based on limited but consistent epidemiological studies of asthma development in children, bronchitic symptoms, hospital admissions and emergency department visits for asthma and studies of allergic response. It is supported by consistent animal toxicological evidence relating to O_3 causing morphological changes, compromising airway growth and development, promoting the development of an allergic phenotype and increased airway responsiveness, and causing persistent alterations to the immune system.[77]

Other health outcomes – metabolic and cardiovascular, fertility and birth outcomes were considered suggestive but not sufficient to infer causality.[77] There are few studies on associations with cancer, and the evidence is regarded as inadequate to assess causality.[77]

For the health impacts of other outdoor air pollutants, see Table 1 at the end of this section.

Indoor environments

People's activities, the locations and conditions of the buildings where they live, learn and work influence their exposure and ultimately their risk of health harms from indoor air pollution. Outdoor air pollutants, from vehicle traffic exhausts and industrial activities, may penetrate the indoor environment. Indoor sources of PM, $NO_{2,}$ carbon monoxide (CO), biological particles such as mould and pet dander, and VOCs include occupant activities, such as cooking, heating and poorly maintained fuel-burning appliances.[11,13]

Use of wood and coal to heat homes causes poor indoor and outdoor air quality, and there is much evidence in lower-income countries of the effects of exposure to solid fuel burning on respiratory health. There are fewer studies in higher-income countries, such as the UK. There is some limited evidence for indoor exposure to wood burning being associated with asthma and respiratory infections in children.[79] For adults, indoor exposure to solid fuels was associated with an increased risk of lung cancer and COPD in adults. Inconsistent results were found with other respiratory outcomes.[80] Domestic burning accounted for 25% of the UK's total primary $PM_{2.5}$ emissions in 2020, with wood alone accounting for 17% of primary $PM_{2.5}$ emissions in 2020.[81] Domestic solid fuel burning is discussed further in Section 4.9.

Compared with outdoors, people indoors are likely to be exposed to higher concentrations of volatile and semi-volatile organic compounds, including the known carcinogen, formaldehyde. These pollutants can be emitted from construction products, building materials for home building projects, paints and solvents, personal care products, cleaning products, carpets and furniture. Exposure to high concentrations may cause irritation of the eyes and respiratory tract, allergies and asthma, central nervous system symptoms, liver and kidney damage, as well as cancer risks.[82,83]

For CO, while deaths due to unintentional non-fire related CO poisoning in England and Wales have decreased over time – to around 20 deaths per year[84] – a recent review of coroner reports found that fatalities still occur, especially in more deprived populations, males working in outbuildings or garages and among the elderly.[85] Cases of CO poisoning are regularly dealt with by the National Poisons Information Service, with 663 patient-related CO exposures reported in 2020, of which most cases were due to poorly maintained or faulty boilers at home.[86] Long-term exposure to low levels of CO concentrations may also have a significant public health impact by causing neurological symptoms.[87]

The health effects of other indoor pollutants, such as bioaerosols, radon and asbestos, are described in Table 1, at the end of this section.

Improving assessments of health effects

While there is a need to better understand which outdoor and indoor sources and components of pollutants are associated with health effects,[88] research into personal exposures and total exposures is also required.

To date most health studies have used the outside air pollution concentration near a person's home as the measure of their air pollution exposure. This has provided strong epidemiological evidence that air pollution adversely affects health. However, this does not account for personal exposures – for example, on the commute or school run, or from pollution indoors, where people spend most of their time. Modelling studies have estimated how the distribution of personal exposures within a city will change in response to policies to reduce emissions both indoors and outdoors. These studies need information on personal exposures to validate and refine the results.[89]

There are studies underway that, rather than using central site air pollution monitoring or modelled air pollution exposure, use personal monitors to see if they can help improve predictions of health outcomes. However, there are technical engineering challenges to developing personal monitors that are small and produce accurate data, and which are also low-cost and low-maintenance so that large numbers of people can wear them. Human biomonitoring (using samples of blood, urine, exhaled breath), can also help to assess personal exposures and effects of chemicals from air pollution sources. For example, DNA adducts have been proposed as biomarkers of exposure to ambient air pollution. Early biological and epigenetic effects such as DNA methylation can be used as biomarkers of early biological change,[90] but more work is needed in this area.

For understanding total exposure to indoor air pollution, WHO recently developed a tool to assess the cumulative risks from exposure to indoor air pollutants at schools.[13] The interest in understanding people's total combined exposure to indoor and outdoor air pollution has led to projects funded under the UK Research and Innovation (UKRI) Strategic Priorities Fund Clean Air Programme.[91]

Table 1 – Summary of air pollutants and their health effects[7,13,35,68,77,92,93,94,95,96,97,98,99,100]

Pollutant	Description and health effects
Particulate matter (PM)	PM is a generic term used to describe a complex mixture of solid and liquid particles of varying size, shape, and composition. Some particles are emitted directly (primary PM); others are formed in the atmosphere through complex chemical reactions (secondary PM). The composition of PM varies greatly and depends on many factors, such as geographical location, emission sources and weather. The size of the particles and the duration of exposure are the main determinants of the potential adverse health effects. Particles larger than 10 μm are mainly deposited in the nose or throat, whereas particles smaller than 10 μm pose the greatest risk because they can be drawn deeper into the lung. The strongest evidence for effects on health is associated with fine particles ($PM_{2.5}$). Exposure to PM increases mortality and morbidity from cardiovascular and respiratory diseases and can cause cancer. It is also causally linked to dementia and decline in cognitive function. There is growing evidence for associations with adverse birth outcomes and diabetes.
Nitrogen dioxide (NO_2)	NO_2 is a gas that is produced along with nitric oxide (NO) by combustion processes, such as by road transport vehicles, power generation and industry. Together they are often referred to as nitrogen oxides (NO_x). Sources indoors include heating and cooking with carbon-containing fuels (coal, coke, gas, kerosene and wood). Outdoor exposure to NO_2 is associated with respiratory disease and mortality. There is growing evidence for associations with nervous system effects. NO_2 as a marker of traffic emissions is associated with lung cancer. There is suggestive but not sufficient evidence linking with cardiovascular, metabolic effects and adverse birth effects. Exposure to indoor NO_2 is associated with irritative cough, wheezing, increased prevalence of allergic asthma (exercise induced, past year and lifetime) and increased respiratory infections in children.

Pollutant	Description and health effects
Ozone (O_3)	O_3 is a gas and occurs in the earth's upper atmosphere and at ground level. Ground level, or tropospheric O_3, is not emitted directly into the air but is created by photochemical reactions involving the precursor pollutants NO_x and volatile organic compounds (VOCs). Several epidemiological studies have reported adverse associations between short-term exposure to O_3 and human health. The effects of exposure to O_3 are predominantly respiratory, but likely causal metabolic effects from short-term exposure have been identified. There is insufficient evidence for cardiovascular and nervous system effects. For long-term exposure, there is a likely causal association with respiratory effects such as asthma development, but for other health outcomes the evidence is less clear.
Sulphur dioxide (SO_2)	SO_2 is produced when sulphur-containing fuels, such as coal, are burned. It is an invisible gas with a distinctive smell and can dissolve in water. Chemical reactions of SO_2 can also produce sulphates, which remain in the air as secondary particles, contributing to the PM mix. SO_2 has an irritant effect on the lining of the nose, throat and airways, and the effects are often felt very quickly. It can exacerbate asthma and cause respiratory effects. It is also associated with cardiovascular effects. Due to the increased use of natural gas and electricity, coal-burning is now relatively uncommon, and levels of SO_2 have steadily declined over the last 50 years.
Ammonia (NH_3)	NH_3 is a gas released into the atmosphere from natural and man-made sources. Once emitted into the atmosphere, the subsequent deposition of NH_3 can be a major source of pollution, causing nitrogen (N) enrichment (eutrophication) and acidification of soil and water sources. Atmospheric NH_3 also reacts with acid gases, such as sulphuric and nitric acid, to form secondary $PM_{2.5}$. The main health impacts of NH_3 arise through its role in secondary $PM_{2.5}$ formation and health effects associated with exposure to PM, as described above. Thus, NH_3 plays a role in acidification and eutrophication and also contributes to the overall PM burden. Agricultural emissions of NH_3 have been reported to be a key contributor to some short-term episodes of high PM pollution in recent years.

Pollutant	Description and health effects
Carbon monoxide (CO)	CO is a colourless, odourless, and tasteless gas, emitted when fuels such as gas, oil, coal and wood burn without enough oxygen. These are fuels used in many household appliances, including boilers, central heating systems, gas fires, water heaters, cookers and open fires. Burning charcoal, running cars and the smoke from cigarettes also produce CO gas. Exposure to high indoor levels of CO can be fatal, while exposure to lower levels can result in symptoms that resemble flu, viral infections or food poisoning.
Volatile organic compounds (VOCs)	VOCs consist of a large variety of chemically different compounds. In the environment, they come from natural and anthropogenic sources. VOCs are emitted from a wide variety of products and processes, including industrial processes and agriculture, and they also form a significant component of indoor air pollution emitted from household products. Indoor exposure can come from cleaning and personal care products, building materials and household consumer products (paints, carpets, laminate, furniture, cleaning products, air fresheners, polishing). In the atmosphere, non-methane VOCs (NMVOCs) react with NO_x in the presence of sunlight to form tropospheric O_3, known to be harmful to health and the environment. Chemical reactions also occur indoors. Indoors, VOCs emitted from consumer products are not thought be to a significant public health issue when homes are well ventilated and when the products are used according to the manufacturers' instructions. But some people may suffer irritation of the upper airway system (eyes, nose and throat), respiratory effects, headaches and dizziness if they are exposed. A growing body of research links indoor air pollutants and carcinogenicity risk.
Radon	Radon is a naturally occurring radioactive gas that arises due to the radioactive decay of radium-226, associated with igneous and metamorphic rocks such as granite and limestone. There is an increased risk of lung cancer if exposed to high levels of radon for a long time, and it is the second highest cause of lung cancer after smoking in the UK. It is generally not a problem in the outside air, but it can accumulate in buildings. More than 1,000 lung cancer deaths occur each year in the UK due to exposure to radon gas at home.

Pollutant	Description and health effects
Polycyclic aromatic hydrocarbons	Polycyclic aromatic hydrocarbons (PAHs) are a large class of chemicals produced due to incomplete combustion of organic sources. Sources include motor vehicles, biomass burning and wildfires. Most data on the health effects of PAHs is based on benzo[a]pyrene (BaP). Inhalation of BaP can cause lung cancer.
Metals and metalloids	Arsenic, cadmium, chromium, cobalt, copper, iron, manganese, nickel, lead, selenium, vanadium and zinc are measured in the PM_{10} fraction of air pollution. Lead was once a significant contributor to outdoor air pollution, and its health harms include neurological damage. With the introduction of unleaded petrol, it is no longer a major contributor to poor air quality. Background concentrations of lead are 0.01 $\mu g/m^3$ or less over most of the UK. There are some higher concentrations, particularly near industrial areas, but these are at concentrations well below the UK limit value of 0.5 $\mu g/m^3$ annual mean. In a domestic environment, lead exposure is most likely to come from paint or water pipes. Lead may also originate from contaminated soil, flaking external house paint, nearby industrial processes and roads, or through previous use of the land the property was constructed on.
Asbestos	Asbestos was previously used in building materials. It can enter the lungs when the materials containing it are damaged or disturbed, resulting in a release of fibres into the air. It is mainly of concern for construction workers. Inhalation of these fibres can lead to mesothelioma (cancer affecting the lining of the lungs and the lower digestive tract), asbestos-related lung cancer, asbestosis (scarring of the lung) and thickening of the lung lining. In Great Britain, the average number of mesothelioma deaths is 2,523 per year, and there are around 2,500 asbestos-related lung cancer deaths each year.
Silica	Silica is a natural substance found in varying amounts in most rocks, sand and clay, and it can be released during drilling and grinding, causing a fine dust to penetrate deep into the lungs. It is mainly of concern for construction workers, and long-term exposure can cause lung cancer, silicosis (which causes breathing problems) and chronic obstructive pulmonary disease. Another source is Saharan dust storms, which occasionally reach the UK and cause episodes of high air pollution.

Pollutant	Description and health effects
Bioaerosols	Liquid or solid particles in the air may be of biological origin and are referred to as bioaerosols. They can include fungi, bacteria, viruses as well as plant and animal matter, such as pollen and pet dander. Levels in the outdoor air are strongly influenced by the weather, but also by human activity. These include agricultural practices (for example, growing rapeseed, and intensive livestock farming), small and large-scale composting, and the type of trees planted in towns. Exposure may occur indoors due to damp, leading to the build-up of mould, cleaning activities and from pets. Those susceptible can experience respiratory effects such as allergic rhinitis and worsening of asthma or chronic obstructive pulmonary disease. Up to 70% of people with asthma demonstrate sensitisation to at least one fungus.

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1.2 Disparities in air pollution exposure and its health impacts

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Introduction

Air pollution does not affect everyone equally. Some population groups have physiological susceptibility to the health impacts of air pollution, including those at the extremes of age and people with a wide range of underlying health conditions, such as respiratory and cardiovascular diseases. In addition, people's exposure is likely to be greater if they live, work or study in places with high concentrations of air pollution. These factors of physiological susceptibility and greater risk of exposure can overlap. This section discusses evidence for disparities in air pollution exposure and health harms in different population groups. These disparities are important considerations when designing and evaluating interventions to reduce or remove the effects of air pollution in the population.

Air pollution and different population groups

Socio-economic groups

Areas of high deprivation frequently have higher levels of traffic or industrial activities, and these more heavily polluted areas may be more affordable to live in.[1,2] People in lower socio-economic groups are more likely to have pre-existing health conditions earlier in life, and the higher exposures to air pollution may add to the greater burden of poor health.[2,3,4] Studies of hospital admissions and mortality show increased health risks associated with exposure to air pollution among those living in areas of higher socio-economic deprivation.[5]

Children

Children are particularly susceptible to the health effects of air pollution, as their lungs and other organs are still developing, and they inhale more air per body weight than adults.[6] Children also experience socio-economic inequalities in air pollution exposure in the places where they live, play and learn.[7] For example, a study of Greater London in 2016, found that the closest play spaces for more than 250,000 children under 16 years old had nitrogen dioxide (NO_2) concentrations above the UK annual air quality limit of 40 $\mu g/m^3$. This represented 14% of all children in Greater London. Of these, two-thirds (165,000 children) lived in the most deprived areas of the city.[8]

A modelling study reported that, in 2017, around one-third of schools in England, representing around 3.4 million pupils, were located in areas with fine particulate matter ($PM_{2.5}$) levels exceeding the guideline for $PM_{2.5}$ of 10 µg/m^3 set by the World Health Organization (WHO).[9] This 2005 WHO guideline level was reduced to an annual mean concentration of 5 µg/m^3 in 2021. Schools in areas with high $PM_{2.5}$ tended to be more ethnically diverse and claimed more free school meals (this is used as a metric of deprivation).

Pregnant women

There is growing evidence worldwide that the health of pregnant women and their babies could be affected by air pollution.[10,11,12,13,14] In the UK, the Avon Longitudinal Study of Parents and Children found links between prenatal, early-life and childhood exposure to particulate matter (PM) from road traffic and reductions in lung function during childhood.[15] The same group also found that the risk of term low birth weight increases as maternal exposure to PM increases. Other research found a corresponding link to socio-economic status.[16,17]

Ethnicity

The association between air pollution exposure, area level deprivation and ethnicity is complex. A 2015 study compared exposure to air pollution across communities in England and the Netherlands.[18] The most deprived 20% of neighbourhoods in England had higher air pollution levels than the least deprived neighbourhoods, after adjusting for other factors. The highest levels of pollution were seen in ethnically diverse neighbourhoods, defined as those where more than 20% of the population were not white. This difference persisted after adjusting for deprivation for both PM_{10} and NO_2.

Analysis of air pollution in London in 2019 found that communities with higher levels of deprivation, or a higher proportion of people from a non-white ethnic background, were more likely to be exposed to higher levels of air pollution. This disparity in exposure between different ethnic groups in London reduced between 2013 and 2019,[19] as discussed in Section 6.3.

Disparities in exposure to air pollution

Analysis at different geographical scales

The findings of an association between deprivation and exposure to air pollution depends on the scale of the analysis (neighbourhoods, city, regional or national scales, and fine or coarse resolution of the air pollution data).

Analysis at the national scale in England found a correlation between higher levels of PM_{10}, $PM_{2.5}$ and NO_2 concentrations and deprivation, with higher concentrations of pollutants in the most deprived 20% of neighbourhoods. However, in a postcode-level analysis across London, a more complex relationship was observed. While air pollution concentrations were generally higher in areas with higher deprivation, there were marked exceptions and a reversal of this association in the most central areas of the city.[18,20]

Proximity to air pollution sources

Factors that influence people's exposures to air pollution include: the proximity to traffic or to industrial sites; whether the location is urban or rural; and indoor air pollution, which can be affected by the building quality.

Traffic-related particulate air pollution (primary and total $PM_{2.5}$, 2010 data) has been shown to be higher in more deprived areas. On the contrary, ozone (O_3) concentrations generally decrease as socio-economic deprivation increases.[21]

Commuters from low-income areas rely more on public transport, which can have high pollution exposure (depending on the type of public transport) but can generate fewer emissions per person.[22] Evidence suggests that pollutant exposure is particularly high in public transport hubs.[23]

Inverse patterns in inequalities in air pollution in London were observed when exposure was estimated at residence versus personal exposure with respect to household income;[24] the highest income group had lower residential exposure to NO_2 but higher overall personal NO_2 exposure, mainly due to the duration and type of transport used. For $PM_{2.5}$, differences in residential exposure and personal exposure across income groups were small, due to limited spatial variation in ambient $PM_{2.5}$ in the city.

Urban areas tend to have high population exposure to outdoor air pollution, due to high population density. However, people in rural areas may also be exposed to harmful air pollution – for example, exposure to indoor air pollution when homes are not connected to the gas grid and are reliant on solid fuel burning to heat the home (see Section 4.9).

Indoor air pollution

Much of the existing literature has focused on inequalities in exposure to outdoor air pollution, but a recent review by Ferguson and others[25] considered indoor air pollution. This review found that households in more deprived areas experienced higher levels of indoor PM, NO_2, and volatile organic compounds (VOCs) (and environmental tobacco smoke, which has clear health harms but is outside the scope of this report).

Air pollution indoors can be split into: ingress of outdoor pollutants into the indoor environment; and air pollutants that are emitted indoors. Inequality in indoor exposure to pollutants is linked to the quality of housing (new build or retrofitted) as well as location – whether the housing is located near busy or congested roads, or industrial sites. Indoor activities of cooking, heating and use of building materials, cleaning and personal care products can emit NO_2, carbon monoxide (CO), PM and VOCs indoors.

Concentrations of these indoor pollutants can be increased by higher occupancy levels, and lack of adequate ventilation. Measures that seek to improve energy efficiency – such as increased insulation and double glazing, reduced infiltration and reliance on mechanical ventilation systems – may reduce the ingress of outdoor pollutants from nearby industry and traffic. However, these measures can increase indoor pollution concentrations from indoor sources if there is not also adequate ventilation for indoor pollutants to leave the building. Significant increases in indoor concentrations of $PM_{2.5}$, NO_2 and VOCs have been observed in low-income housing following a retrofit of the building envelope that increased the airtightness.[26]

Housing in areas of deprivation can also be affected by multiple occupants in a household, resulting in greater resuspension of particles. Security concerns can also mean restricted window opening.[25] In homes that are not owner-occupied, residents may have less agency to improve indoor air quality, for example, through interventions to reduce damp and mould. There is evidence that children growing up in homes with mould are between 1.5 and 3 times more prone to coughing and wheezing.[27]

Radon is an indoor air pollutant that is governed by geological variables, so it is concentrated in particular parts of the country. Higher radon concentrations have been found in homes in high socio-economic areas.[28]

Evidence from Europe and the USA of air pollution disparities

Exposure to air pollution

In Europe, there is evidence of similar disparities in air pollution exposure and risks of health effects and findings of associations also depend on the scale of air pollution data analysis. At the European regional level, those areas with high levels of deprivation and lack of higher education tend to have higher exposure to particulate matter ($PM_{2.5}$ and PM_{10}) and O_3.[1,2,29] As with evidence from the UK, the relationship with NO_2 exposure is more complex.[1,30]

European cities show a variability in exposure to air pollution, depending on the characteristics of each city. For instance, lower-income areas had higher exposure to air pollution outside the Brussels city centre,[31] whereas, as for central London, wealthier populations can be exposed to high levels of traffic-related pollutants, such as NO_2 in the city centre of Paris[32] and NO_2, $PM_{2.5}$, and Black Carbon in the city centre of Barcelona.[33]

As with findings from the UK, the level and size of spatial analysis affects results, indicating that there is the potential for residual socio-economic confounding in epidemiological studies of area-level exposure to air pollution. At the neighbourhood level, those with either ethnically diverse populations or higher unemployment rates, have the highest NO_2 levels, as shown in 16 cities from 8 Western European countries.[34]

In the USA, inequalities in exposure to air pollution were larger by race or ethnicity than by other characteristics such as income, education or age.[35,36] The reduction over recent years in transport-related NO_2 exposure differed between non-white and white participants in the USA. Exposure to the key pollutants except O_3 (CO, NO_2, $PM_{2.5}$, PM_{10}) was generally higher for lower-income than for higher-income households.[36] Hispanic and black residents were more likely to live in neighbourhoods with higher on-road air pollution exposure.[37]

Health effects of air pollution

An early review[38] concluded that, although deprived European populations are not always more exposed to air pollution, they experience greater health effects of air pollution. A systematic review with most of the studies from the USA and Europe[39] found some evidence to suggest that lower education, income or employment status groups are at higher risk of death due to short-term exposure to particulate matter (PM_{10} and $PM_{2.5}$). In a recent study of 380,000 Europeans, there was a tendency for greater effects of air pollution among people with lower overall levels of education.[40]

Evidence suggests that pregnant women in lower socio-economic groups who are exposed to air pollution have an increased risk of having a child with low birth weight, as shown by a review of published literature[17] and recent evidence from France.[41]

Public engagement and air pollution disparities

Addressing inequalities in air pollution exposure and health harms requires engagement with the public, and in particular those who are most affected by air pollution. An example is the Environment Agency, leading work to understand and reduce air pollution and health-related inequalities through a collaborative network of individuals, community groups, non-governmental organisations, academics, third sector, and international, national, and local governments and public sector bodies. Early findings highlighted the importance of meaningful engagement with those people most affected by both poor air quality and inequalities, listening to and understanding their experiences. For air pollution interventions, data and information needs to be accessible, and the preferred interventions were those that focus on those most disadvantaged by poor air quality. Focus groups also noted that air pollution sources are often outside of an individual's control, so a cross-sector approach is needed to reduce air pollution and the associated disparities.

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2 Outdoor air pollution emissions and recent trends

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Introduction

Air pollution is a local, regional, national and international problem caused by emissions of pollutants and chemical reactions in the atmosphere. The short-term and long-term health effects of different air pollutants, with a summary table, are described in Section 1.1. Air pollution can also have harmful effects on the environment.

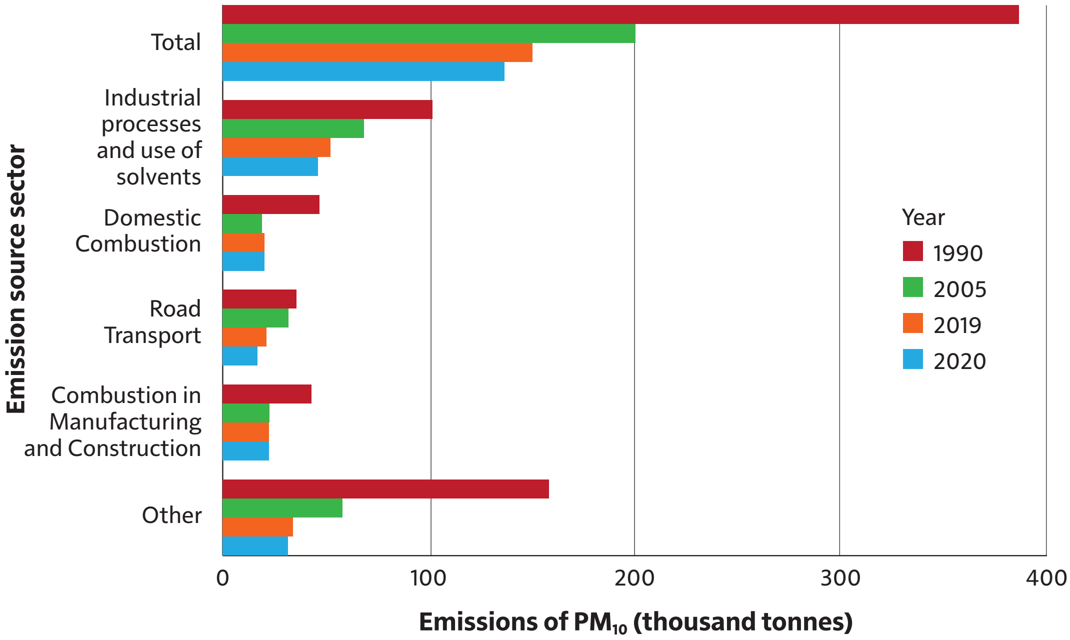
This section examines outdoor air pollutants, and explains the major emissions sources and long-term and recent trends in emissions and concentrations. The expected future trends for air pollution are discussed in Chapter 3. Air pollutants in indoor environments are discussed in Sections 4.8 and 5.1.

Outdoor air pollutants

Particulate matter

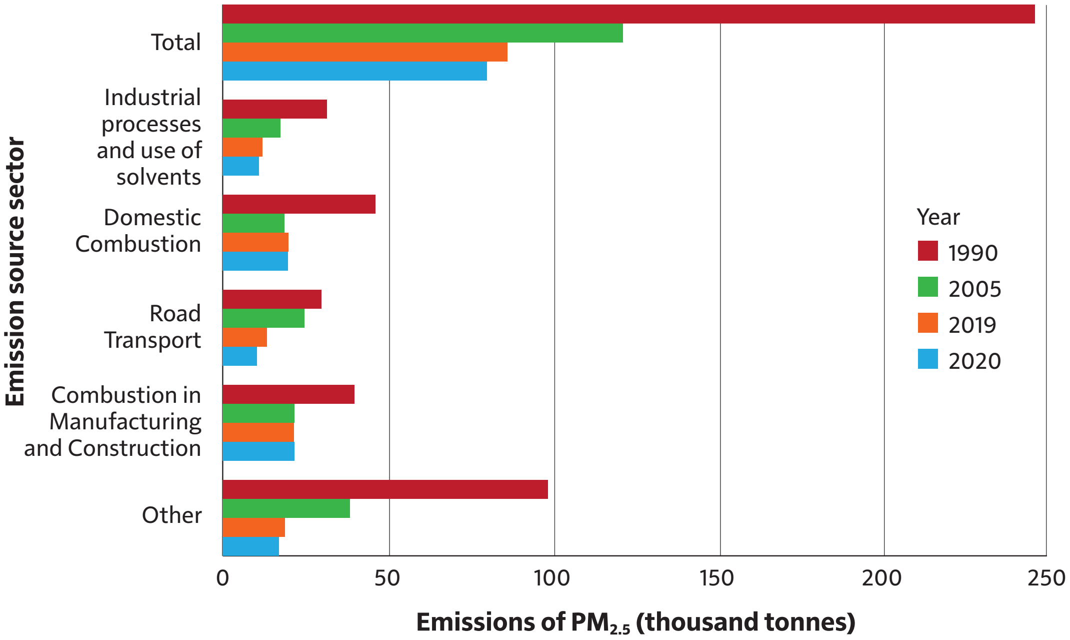
Particulate matter (PM) can exist in the form of many different chemical compounds and materials. These particulates can be classified according to size, into either a coarse fraction, PM_{10}, or a fine fraction, $PM_{2.5}$. PM can be 'primary', emitted directly to the atmosphere, or 'secondary', formed by the chemical reaction of other pollutants in the air, such as the reactions of sulphur dioxide (SO_2) or nitrogen dioxide (NO_2) with ammonia to form ammonium sulphate and nitrate aerosol respectively.

The main source of primary particulate emissions is combustion, such as from vehicles, domestic combustion and power stations. Other man-made sources include quarrying and mining, industrial processes and tyre and brake wear. Natural sources include wind-blown dust, sea-salt and soil particles. Emissions sources of primary PM_{10} and $PM_{2.5}$ over time are presented in Figures 1 and 2.



Source: Ricardo Energy & Environment. Defra (2022)[1]

Figure 1: UK annual emissions of PM$_{10}$ by major emissions sources in 1990, 2005, 2019 and 2020



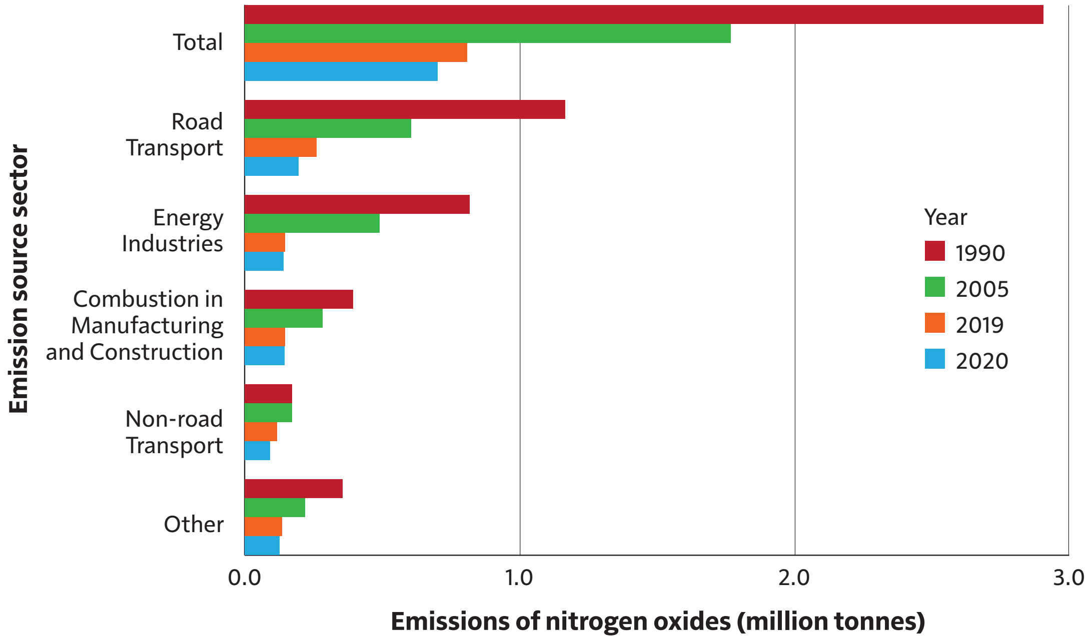
Source: Ricardo Energy & Environment. Defra (2022)[1]

Figure 2: UK annual emissions of PM$_{2.5}$ by major emissions sources in 1990, 2005, 2019 and 2020

Nitrogen oxides

Nitrogen oxides (NO_x) are gases that are predominantly formed during combustion. Most NO_x emitted as a result of combustion is in the form of nitric oxide (NO), with the main sources being power generation, industrial combustion and road transport. The major sources of NO_x emissions over time are presented in Figure 3.

When NO reacts in the air, it can form nitrogen dioxide (NO_2), which is harmful to health. It is also a precursor to the formation of ozone. NO converts to NO_2 very quickly, and vice versa. It is therefore often scientific practice to refer to the two gases together as NO_x.



Source: Ricardo Energy & Environment. Defra (2022)[2]

Figure 3: UK annual emissions of NO_x by major emissions sources in 1990, 2005, 2019 and 2020

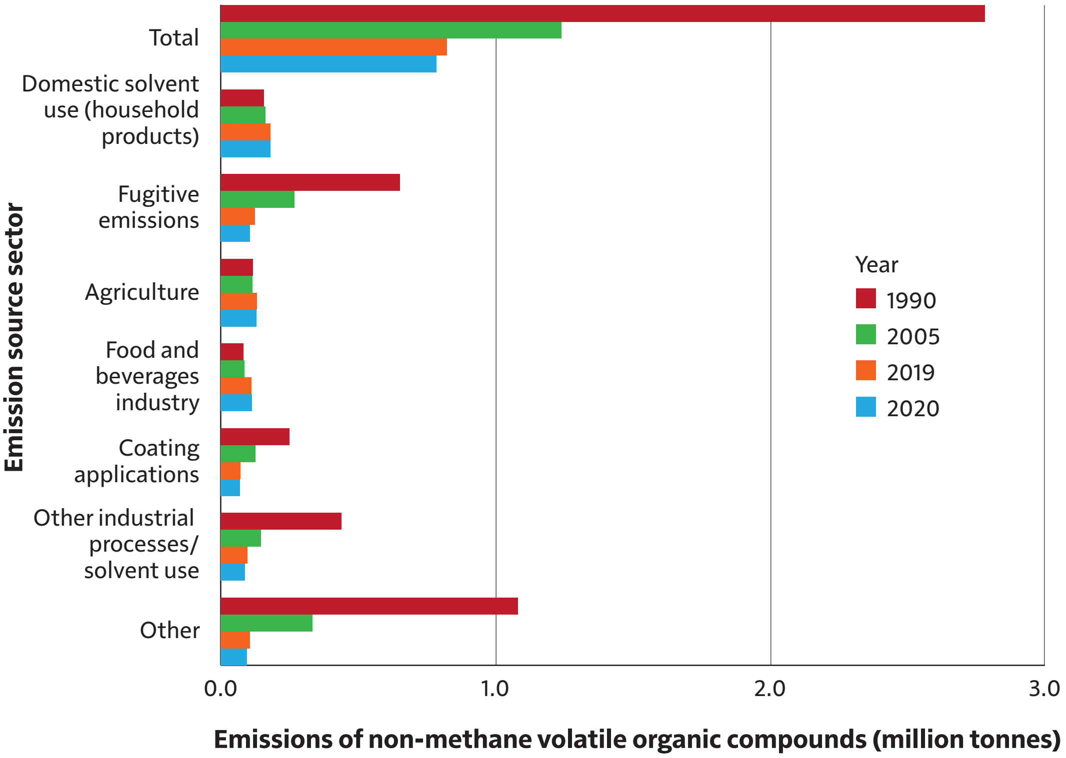
Non-methane volatile organic compounds

Volatile organic compounds (VOCs) are a very large and diverse group of organic compounds. One of the most abundant and common of these is methane. However, methane is relatively non-toxic and poses little direct harm to human health (although it does pose notable environmental concerns as a greenhouse gas, and it contributes to the formation of ozone).

Non-methane VOCs (NMVOCs) arise either as combustion products or as vapour from fuels, solvents, paints, air fresheners, cleaning products, perfumes and many other sources, including natural sources such as vegetation. Anthropogenic emissions tend to come from chemical and petroleum industries and from organic solvents in small stationary sources such as dry cleaners. Major emissions sources of NMVOCs are presented in Figure 4.

While NMVOCs differ widely in their chemical composition, they can display similar behaviour in the atmosphere as a result of commonalities in terms of chemical and physical structure.

Interest in NMVOC emissions has grown as the understanding of their role in the photochemical production of ozone has developed. NMVOCs can also contribute to the formation of secondary PM.



Source: Ricardo Energy & Environment. Defra (2022)[3]

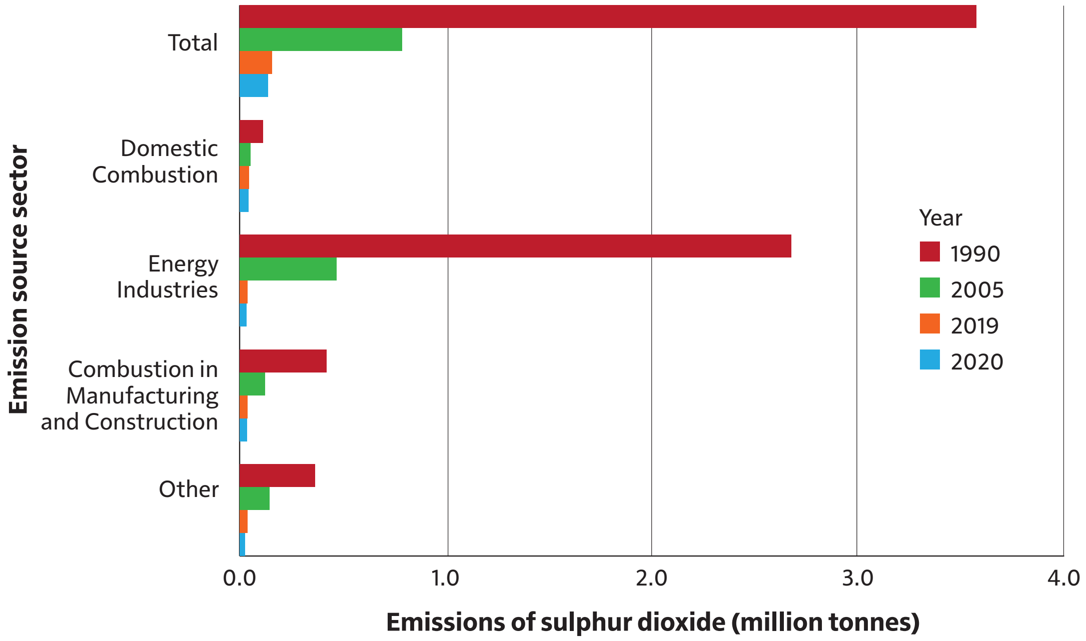
Figure 4: UK annual emissions of NMVOCs by major emissions sources in 1990, 2005, 2019 and 2020

Ozone

Ozone (O_3) is a gas that is not emitted directly, but is formed in the air, and is therefore a secondary pollutant. O_3 is a very reactive gas and so is an irritant that is harmful to human health in addition to having detrimental effects on plant and crop health. Ground level, or tropospheric, O_3 can be formed by the photochemical reactions (that is, driven by sunlight) of NO_x and NMVOCs from various natural and man-made sources. O_3 formation is often at large distances from the original source of emissions. As the formation of O_3 is heavily influenced by the presence of sunlight, its concentrations commonly build up and spike during hot summer days. Methane also plays a role in the formation of O_3 and contributes to regional background concentrations of the gas in the troposphere.[4]

Sulphur dioxide

Sulphur dioxide (SO_2) is a gas that is formed when fuels containing sulphur impurities are burned. It is a toxic gas that is harmful to human health. Along with PM, SO_2 used to contribute to the formation of winter-time smogs and was a major component of acid rain through the formation of sulphuric acid in the atmosphere. SO_2 can be transported far from its emission source. Natural sources include decomposing organic molecules, volcanic activity and geothermal vents. SO_2 can be a significant component of PM. The major emissions sources of SO_2 over time are presented in Figure 5.

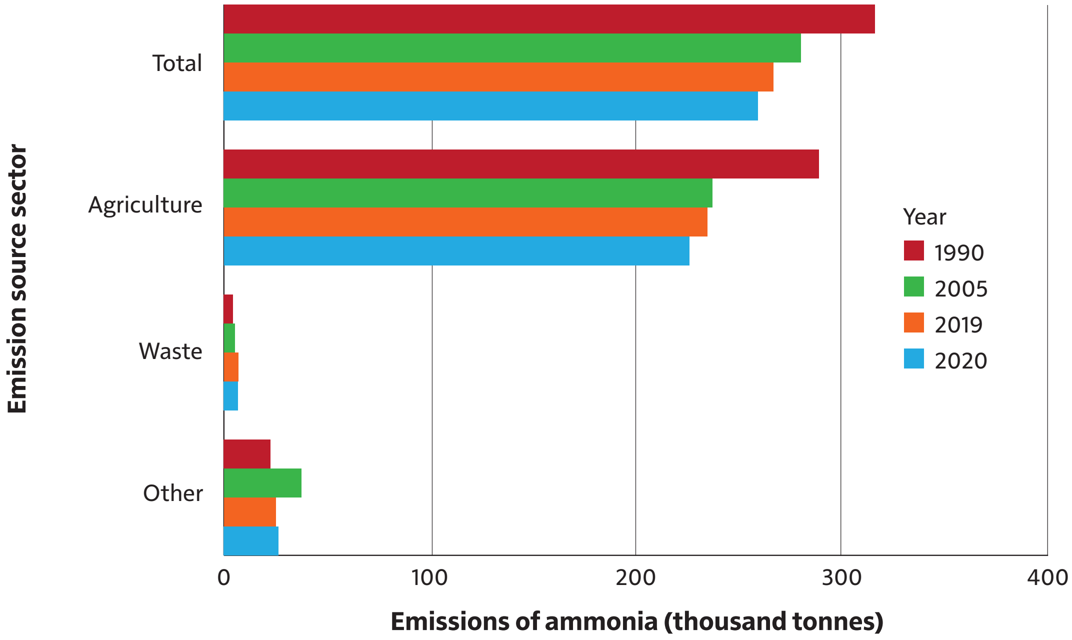


Source: Ricardo Energy & Environment. Defra (2022)[5]

Figure 5: UK annual emissions of SO_2 by major emissions sources in 1990, 2005, 2019 and 2020

Ammonia

Ammonia (NH_3) is a reactive form of nitrogen in the atmosphere that can transform readily to other compounds and can affect ecosystems. Most emissions of NH_3 come from agriculture, such as the spreading of manures, slurries and fertilisers, discussed in Section 4.6, although waste-related sources are also significant. The major emission sources of NH_3 over time are presented in Figure 6.



Source: Ricardo Energy & Environment. Defra (2022)[6]

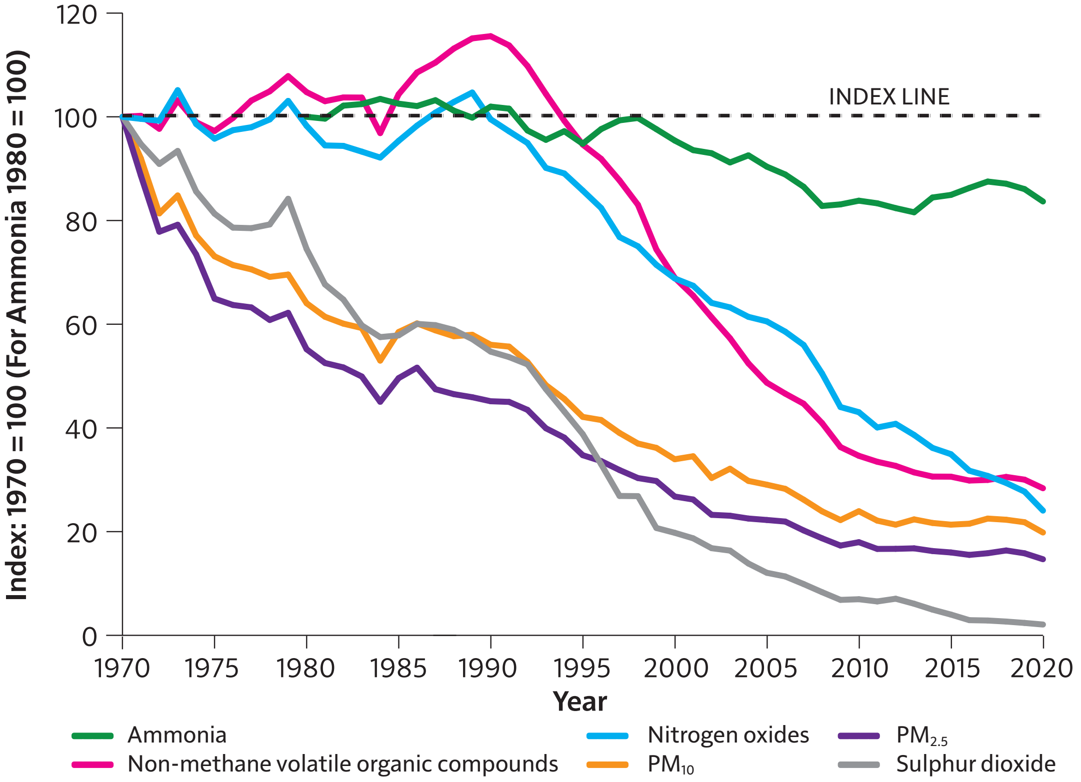
Figure 6: UK annual emissions of NH_3 by major emissions sources in 1990, 2005, 2019 and 2020

NH_3 only remains in the atmosphere for a few hours in gaseous form; however, when it reacts with other gases in the atmosphere, such as NO_2 and SO_2, it can form PM which can persist for several days and be transported large distances across continents. This can be removed from the atmosphere by rain. As a result, NH_3 emissions can have highly localised effects, as well as contributing to effects from long-range pollutant transport.

Trends over time

Emissions

Emissions of most outdoor air pollutants are at the lowest they have been since measurements began. The reduction in UK emissions of air pollutants over the last 5 decades is shown in Figure 7.



Note: The figure shows trends in annual emissions of particulate matter (PM_{10} and $PM_{2.5}$), nitrogen oxides, ammonia, non-methane volatile organic compounds, and sulphur dioxide, 1970 to 2020, expressed as a percentage change from the base year of 1970 (for ammonia the base year is 1980).

Source: Ricardo Energy & Environment. Defra (2022)[7]

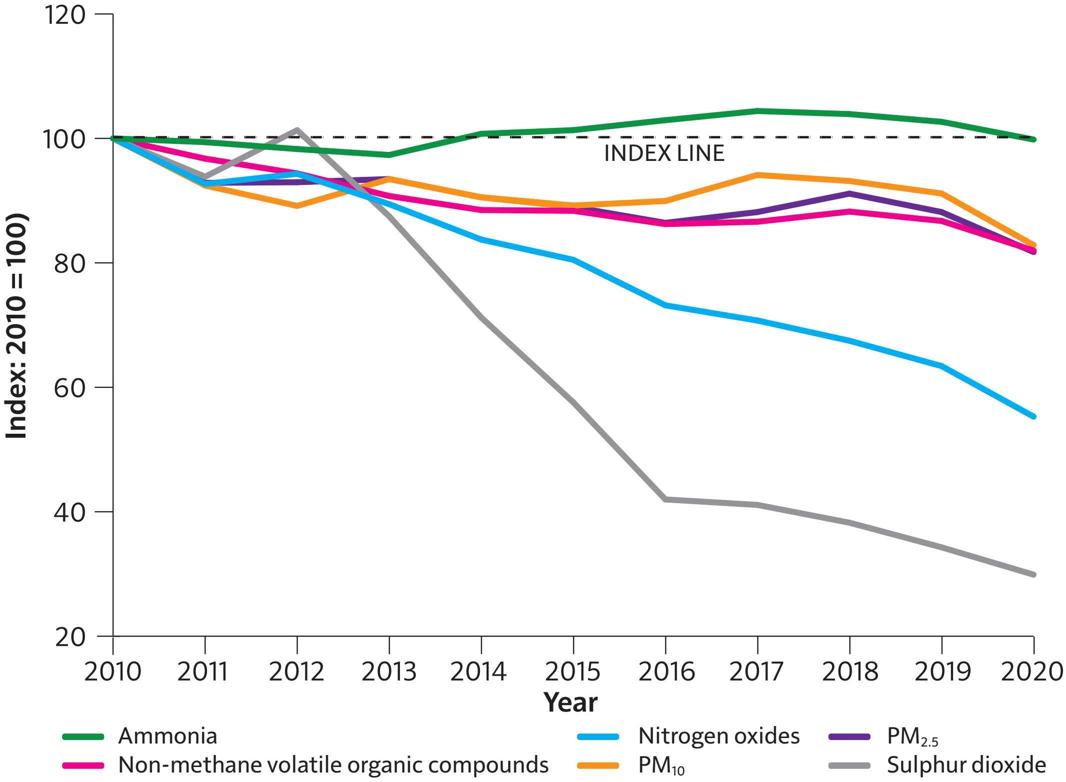
Figure 7: Trends in UK emissions of air pollutants, 1970 to 2020

Since 1970, there has been a decrease in emissions of the main pollutants presented above. SO_2 emissions have decreased most substantially to around 5% of their 1970 levels. There were also significant decreases in NO_x, $PM_{2.5}$ and NMVOCs, and a relatively limited decrease in NH_3. O_3 is not included here as it is formed in the air through secondary reactions rather than being emitted directly.

Figure 7 shows a noticeable peak in emissions of NMVOCs, $PM_{2.5}$, PM_{10} and NO_x around 1990. This can be attributed to an increase in road traffic without suitable pollution abatement technology.

A combination of domestic, European and international legislation has been introduced over the past 70 years. The long-term decrease in emissions of air pollutants can be linked to changes to technology, urban planning and behaviour, and broader socio-economic changes.

Figure 8 shows recent trends between 2010 and 2020, where there has been mixed progress in reducing emissions of air pollutants. Emissions of SO_2 and NO_x have continued to fall in line with the long-term trend, and much of this reduction is due to decreasing dependence on burning coal for energy. Total emissions of NMVOCs and PM have also decreased, although more gradually over the last 10 years. Annual emissions of NH_3 have remained broadly stable. The results from interventions to reduce or remove air pollution in different sectors is discussed in Chapter 4.



Note: The figure shows trends in annual emissions of particulate matter (PM_{10} and $PM_{2.5}$), nitrogen oxides, ammonia, non-methane volatile organic compounds and sulphur dioxide, 2010 to 2020 expressed as a percentage change from the base year of 2010.

Source: Ricardo Energy & Environment. Defra (2022)[7]

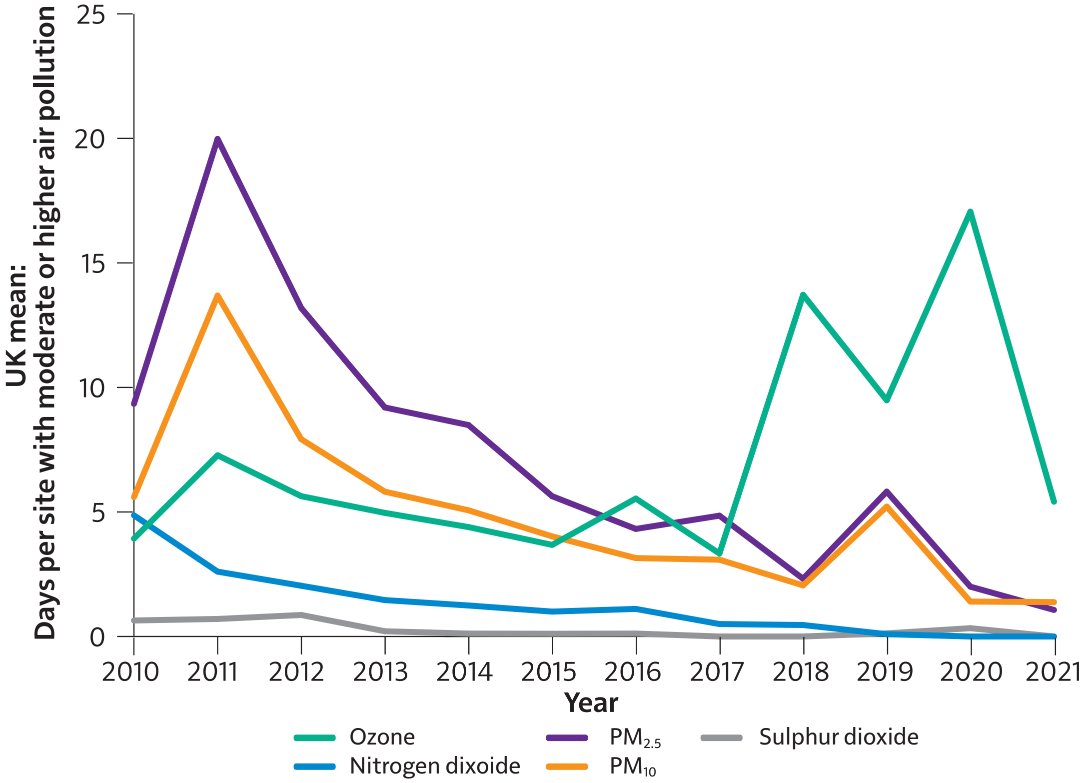
Figure 8: Recent trends in UK emissions of air pollutants, 2010 to 2020

Concentrations

Long-term concentration measurements have not been monitored for as long as emissions measurements. However, the data available shows that concentrations of most air pollutants are also at their lowest level since records began. Depending on their lifetime in the atmosphere, some pollutants, such as PM, are transported far from their origin. The relationship between locally measured concentrations and local, regional and international emissions is complex. This is due to a number of factors, including the long-range transport of pollutants, atmospheric chemistry changing pollutants in the air, and the local, regional and international scale meteorology.

To examine short-term trends in concentrations, Figure 9 converts measured data from Defra's national monitoring networks and expresses them using the Daily Air Quality Index (DAQI).[8] The DAQI represents concentration levels for individual pollutants at urban sites in the UK on a 10-point scale in 4 bands (low, moderate, high and very high). Using the DAQI scale means that estimating the health effect is more intuitive than using concentrations taken directly from measurements. It shows that concentrations of the main pollutants have decreased over the short-term and long-term, with the exception of O_3 and PM.

As a secondary pollutant, concentrations of O_3 can be influenced by the relative abundance of its precursors in the atmosphere as well as meteorological conditions. The emission trends in Figures 7 and 8 show that NO_x emissions are falling at a faster pace than NMVOCs, and this imbalance can lead to periodic O_3 elevations. The period from 2010 to the present has had several years with particularly high summer temperatures, which also contributed to increased O_3, as shown in Figure 9 where 2011, 2018 and 2020 are notable for an increased number of days with elevated O_3 because of their high summer temperatures. Further discussion of secondary pollutants can be found in Section 5.1.



Note: The rankings 'moderate', 'high' and 'very high' are on the Daily Air Quality Index that expresses air pollutant concentrations based on a 10-point scale with bandings that also include 'very low' and 'low'. Where more than one pollutant exceeds the 'moderate' threshold on any given day, it is counted for each pollutant – that is, there is double counting.

Source: Ricardo Energy & Environment. Defra (2022)[9]

Figure 9: Average number of days when levels of O_3, PM_{10}, $PM_{2.5}$, NO_x and SO_2 were 'moderate' or higher at urban sites in the UK, 2010 to 2021

The increased number of days with elevated PM in 2011 and 2019 could be linked to a combination of stable weather conditions preventing the dispersion of emitted PM, in addition to easterly winds transporting pollutants from mainland Europe. An eruption from the Grímsvötn volcano in Iceland was a further source of elevated PM in 2011.

Geographical and cyclical variations in air pollution

In addition to long and short-term trends over time, air pollution also varies between different places in England, from day to day, and with the seasons.

The spatial distribution of air pollutant concentrations varies greatly depending on the pollutant. For example, concentrations of NO_2 can be higher within urban areas due to their proximity to the main sources of traffic and industry. NO_2 is a pollutant that is short-lived, so is not affected by transboundary air pollution. SO_2 concentrations are also strongly influenced by proximity to sources. PM is longer lived and therefore affected by pollution from outside the UK. While elevated concentrations are seen around urban areas, concentrations of PM also tend to be higher in the southern and eastern areas of the UK due to the influence of pollution sources from mainland Europe. O_3 concentrations are also affected by the transport of O_3 precursors and so concentrations tend to be higher in southern and eastern areas.

Concentrations of air pollutants vary on a seasonal, weekly and daily basis, and such variation can be due to meteorological factors and human activity. These differences, and the implications for air pollution monitoring and forecasting are discussed in Section 5.2.

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3 How air pollution is changing

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Introduction

Air pollution is a complex mixture of chemicals and biological materials which reflects, among other things, the activities we undertake in our homes, the systems used for transport, and the energy sources that supply our heat and power, and these change over time. This section provides an overview, and several areas are explained in further technical detail in subsequent sections.

The UK atmosphere of the 1950s and 60s had high levels of sulphur dioxide (SO_2) pollution arising from coal combustion. Today, SO_2 is so reduced that it is often difficult to detect. The 1980s and 1990s saw high concentrations of volatile organic compounds (VOCs) from evaporating petrol, and VOCs and nitrogen oxides (NO_x) emissions from the tailpipe, subsequently reduced with the highly effective three-way catalytic converter. Vehicles at that time also gave rise to harmful emissions of lead, a problem that was ultimately resolved through reformulation of the fuel itself. NO_x emissions were also reduced through controls on large combustion plants. Most recently, the urban atmosphere has been affected by nitrogen dioxide (NO_2) from diesel vehicle exhaust. (For a global chronology of air pollution, see Fowler and others[1]). Air pollution in the 2030s, 2040s and 2050s will be a different mixture to the recent or distant past; it will change as energy supplies and transport systems are decarbonised, lifestyles and working practices evolve, and as novel materials, products and processes are adopted.

The future of air pollution in England will depend on other countries, as well as what happens domestically. Our atmosphere does not exist in isolation from the rest of the world, so changes in emissions, regulation, agriculture and industry in near neighbours in Europe, and further afield in North America and Asia, will play a role in determining the concentrations of outdoor pollution. Overlaying pollutant emissions are the physical and chemical behaviours of the atmosphere itself. Concentrations are also controlled by dilution and atmospheric removal of pollutants, including wet and dry deposition and photochemistry. Wetter, windier weather tends to reduce air pollution concentrations, while stable conditions with low wind speeds can exacerbate them.

These meteorological factors are not fixed, and climate change over the next 50 years will alter how pollution is dispersed and removed. Air pollution and climate change are linked in other ways too, not least because they are both driven by emissions to the atmosphere. Some emissions are important for both issues, particularly the greenhouse gas methane, which contributes to the formation of photochemical ozone, a potent air pollutant with links to human and ecosystems health. Ozone is also a greenhouse gas in its own right.

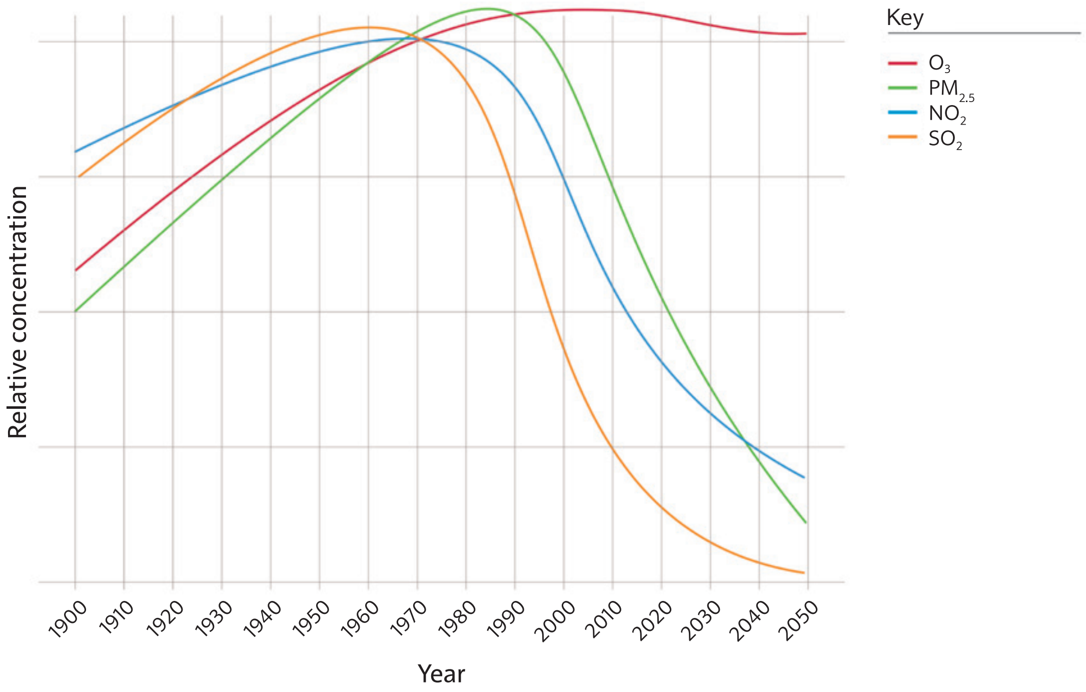
Anticipating future trends in air pollution requires foresight of emissions and the changing regional climate. Actions and interventions that have worked successfully in the past may not necessarily secure optimal air quality in the future, and there are risks that interventions focus on previous problems, rather than the most pressing ones of the day. The easy wins in emissions reductions have largely been addressed, so future action needs to be well-targeted where health and wider environmental co-benefits (such as reduced nitrogen deposits to ecosystems) will be greatest. Emergent pollutant threats – for example, from new technologies, materials, or processes – should be identified and quickly intercepted.

Significant for the future is the avoidance of unintended negative consequences for air quality from decisions taken in other areas of society, for example, around achieving net zero greenhouse gas emissions, food production, buildings design, or use of future fuels. More positively, when large shifts in technology and society are planned, they can be designed to have air quality benefits built in, and are often easier to implement from new, rather than via retrofitting.

3.1 Changes to outdoor air pollution

The big picture outdoors

The definition of good or bad air quality is often expressed through a small number of metrics associated with the concentrations of pollutants, including fine particulate matter ($PM_{2.5}$), NO_2, SO_2 and ozone (O_3). This is undoubtedly a simplification, and many other airborne chemicals have health or ecosystem effects, or are precursors to other pollutants. Nonetheless these 4 continue to be of most direct interest to regulators and health professionals. An illustrative evolution of air pollution over the last 100 years, and pathway for next 30 in the UK, has been described by Carslaw and others (2021), part of a Royal Society report on Climate Change and Air Quality.[2] This is reproduced in Figure 1 below.



Note: The trends are scaled from zero to maximum value for each pollutant individually.

Source: Effect of net zero policies and climate change on air quality, Royal Society (2021)[2]

Figure 1: Trends in population-weighted concentrations of 4 significant air pollutants in the UK

The peaks in UK concentrations of different pollutants have occurred at different times, and their future trajectories are also likely to differ. For example, SO_2 peaked earliest and may all but disappear from the pollution mixture in the coming decades. Its few remaining sources are from fossil fuel combustion – in a UK context, from the last remaining coal-fired power stations, and heavy fuel oil used in shipping. These sources are set to fall further in the short to medium term through power station closures and international controls on sulphur content in marine fuel. Long-term, anthropogenic SO_2 emissions could be almost eliminated as a consequence of global decarbonisation, although some point sources may remain from industries such as smelting.

Further substantial reductions in outdoor concentrations of NO_2 are anticipated from vehicle electrification, although the trajectory from the 2030s onwards will be sensitive to the degree that combustion is replaced by electrification in other sectors. This will depend on which low-carbon technologies are adopted for other transport modes and for space heating, and the extent to which there is retention of high temperature combustion appliances in either. Burning of green fuels such as bio-ethanol, bio-butanol, biodiesel, bio-kerosene, hydrogen or ammonia, while potentially compatible with a net zero commitment, still lead to emissions of NO_x produced via the formation of nitrogen oxides from molecular nitrogen and oxygen in the air at high temperatures. This is known as the Zel'dovich mechanism and is intrinsic to combustion.[3] The fine details of how net zero is technically implemented will ultimately control the medium- and long-term concentrations of NO_2.

With current measures, outdoor concentrations of $PM_{2.5}$ are anticipated to further decline in the coming decades, although improvements will inevitably begin to slow, reflecting that many of the largest and most readily abated sources have already been addressed. What is left is a diverse mix of sometimes diffuse emissions, many of which have a more limited scope for reduction. As UK emissions reduce, transboundary particulate matter (PM) – which is not directly reducible through national action – and natural emissions become a larger fraction of the PM that remains. In the long-term however, $PM_{2.5}$ must inevitably reach a non-zero plateau in concentration that cannot be practically reduced further through reasonable technical or policy interventions. That value will depend on willingness to abate the remaining controllable emissions and external factors relating to natural emissions, geography and weather. This point is expanded on in later sections of this chapter. The complex contributions to future $PM_{2.5}$ make this the most difficult pollutant to forecast long term with confidence.

Background and rural tropospheric ozone (O_3) is anticipated to change relatively little over the next 30 years, but concentrations in urban areas – and hence exposure among urban populations – are likely to rise as UK NO_x emissions fall further.[4] O_3 is a secondary pollutant formed through photochemical reactions in the atmosphere, and its future concentration will depend on future emissions of NO_x and VOCs at the local and regional scale, as well as the global concentration of the greenhouse gas, methane. The reductions in travel seen during the COVID-19 pandemic have already given some foresight of future O_3, demonstrating that increases in urban O_3 occur when primary nitric oxide (NO) emissions are reduced.[5,6] Close to roads, the direct emission of NO from vehicle exhaust reacts rapidly (within a few seconds) to titrate O_3, removing it from the air, albeit only temporarily. Downwind of cities, the O_3 can be regenerated through photolysis of NO_2 which acts as a short-term reservoir. Currently, vehicle exhaust emissions of NO act to deplete O_3 by roads in cities, but as this emission source declines, O_3 concentrations in urban centres are predicted to increase. This effect was widely observed during periods of reduced travel during the COVID-19 pandemic.

The changing nature of outdoor $PM_{2.5}$

At the national scale, $PM_{2.5}$ is considered currently to be the air pollutant that leads to the most significant effects on public health.[18] Its effects are often quantified against an annual mean concentration in micrograms/m^3, although this simple number hides considerable complexity.

While O_3 and NO_2 are pure chemicals, $PM_{2.5}$ is defined as a mass of all particles smaller than 2.5 microns diameter. This measure of $PM_{2.5}$ says nothing about the chemical composition, or distribution of sizes and shapes. Particles are exceptionally complex, with urban PM likely containing more than 10,000 individual chemical species.[7]

The origin of $PM_{2.5}$ can be usefully categorised as being 'primary' or 'secondary'. Primary $PM_{2.5}$ is pollution released directly from a source, such as a tailpipe, the abrasion from a brake pad, or wear of a tyre on the road. Secondary $PM_{2.5}$ are particles generated in the atmosphere from chemical reactions, typically occurring over hours to days, and are formed from gaseous precursor pollutants such as NO_x, ammonia, and VOCs. Secondary PM is further sub-classified as secondary inorganic aerosols (SIA) and secondary organic aerosols (SOA), both of which give rise to adverse health effects.[8,9]

The relative contributions made by primary and secondary $PM_{2.5}$ to the overall amount that is typically inhaled outdoors depends on the location. As direct controls on emissions at source have become more stringent, particularly those associated with combustion and tailpipe emissions, primary $PM_{2.5}$ in cities has declined.[10]

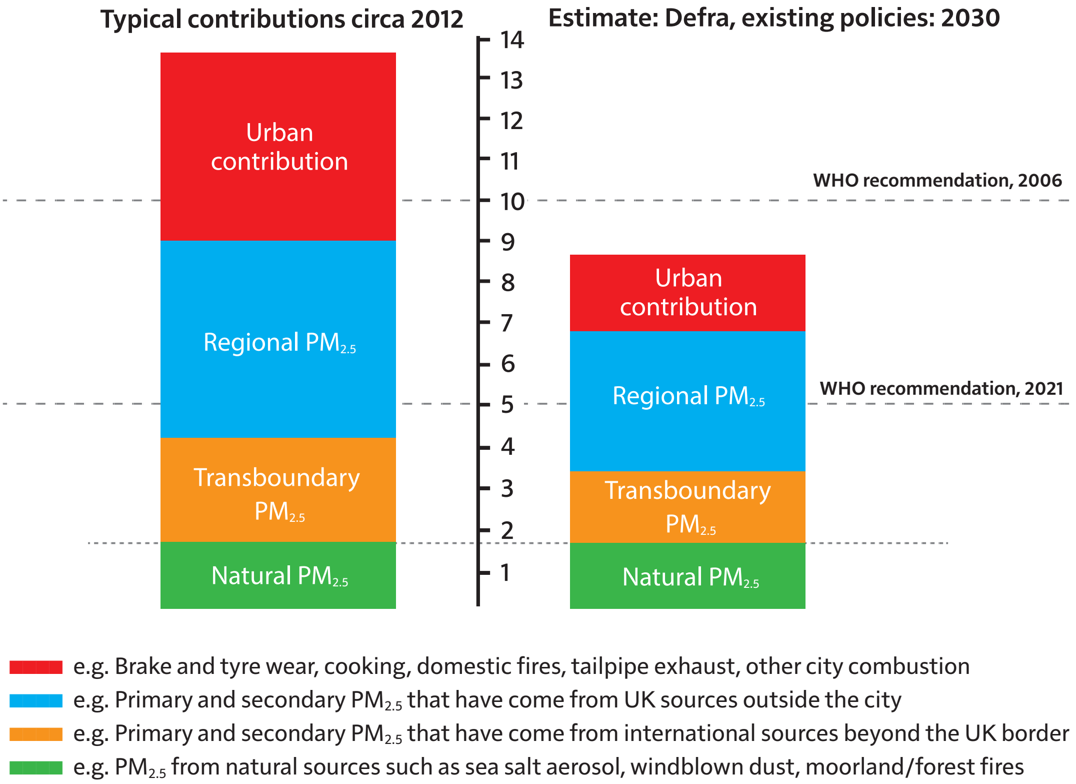
Progress on reducing the precursor pollutants that contribute to secondary $PM_{2.5}$ has been variable. Of particular note there has been rather limited success in reducing emissions of ammonia, which react with acids in the atmosphere to create ammonium nitrate and sulphate, which in turn make up a substantial fraction of $PM_{2.5}$ (see Section 4.6).[11]

In many locations, urban and rural ambient $PM_{2.5}$ concentrations have declined over the last 20 years, with secondary particles now frequently making up a large fraction of the $PM_{2.5}$ that is experienced. This has implications for future policy and action. Primary $PM_{2.5}$ is a source of pollution that is potentially under direct and local control, while secondary $PM_{2.5}$ is a by-product from cumulative emissions of precursors from multiple sources and over large geographic areas, including those accumulated from transboundary movement of pollution between countries. Secondary $PM_{2.5}$ is harder to control as it depends on the chemical and physical interaction of pollutants, which can produce complex, non-linear responses to reductions in precursor emissions.

The future trajectory of ammonia emissions, a critical gaseous precursor to secondary $PM_{2.5}$, will depend on several policy decisions that are yet to be made. Ammonia is the regulated pollutant that has seen the smallest reduction in emissions over recent decades. While policies are being developed to reduce emissions, as laid out in the Clean Air Strategy,[12] it is projected that the current trajectory in the UK will still not meet the emissions reductions committed to by 2030 under the Gothenburg Protocol. There are several current and future policy options with the potential to influence ammonia emissions. The use of anaerobic digestion to meet the target of zero food waste to landfill and for biogas production may increase emissions, while the choice and scale of use of energy crops may change the amount of fertiliser used nationally. Ammonia may be used as a hydrogen 'carrier' and as a fuel, although whether fugitive losses would occur is uncertain. Improved agricultural practices and incentives alongside dietary change and reduction in meat consumption would likely reduce emissions. Further reductions in NO_x emissions should have a secondary benefit in also reducing $PM_{2.5}$, but this is dependent on emissions of ammonia being reduced in tandem.

Managing primary emissions, including interventions enacted at local scale, will continue to be a central policy pillar for reducing exposure to outdoor $PM_{2.5}$. Limiting regional and transboundary emissions will become increasingly important. Air pollution is often viewed as a problem that can be solved through actions of local authorities, or through unilateral policies and interventions introduced by the UK government. This remains the case for short-lived pollutants such as NO_2 which do not travel far from their point of emission. These can be addressed through town or city-level initiatives such as low emissions zones, or national legislation on targeted vehicle emissions standards. However, $PM_{2.5}$ and O_3 travel much further and have atmospheric lifetimes of many days. This makes the challenge more like greenhouse gases and climate change. For longer-lived air pollutants, a combination of local, national and international actions are required to act in concert.

Contributions to the $PM_{2.5}$ experienced in cities come from 4 broad categories, shown illustratively in Figure 2 for an urban background location in circa 2012, and estimated for 2030 with existing Defra policies. For an example of a more detailed breakdown of PM composition, see for example Yin and others (2015).[13] In the UK there is a natural background concentration of between 1–3 μg/m^3 depending on geographical location (with concentrations being highest in South East England and lowest in North West Scotland). Natural $PM_{2.5}$ derives from sources such as seaspray, windblown soils and dust, and organic aerosols or bioaerosols derived from trees and plants. This $PM_{2.5}$ would be present irrespective of human activity.



Left: the period circa 2012 (based on materials in reference 16). Right: contributing sources that might be anticipated in 2030 based on the author's evaluation of impacts arising from likely emissions reduction by 2030. Y-axis is atmospheric concentration in units of μg/m^3.
Source: AQEG (2015)[16] and ApSimon et al. (2022)[44]

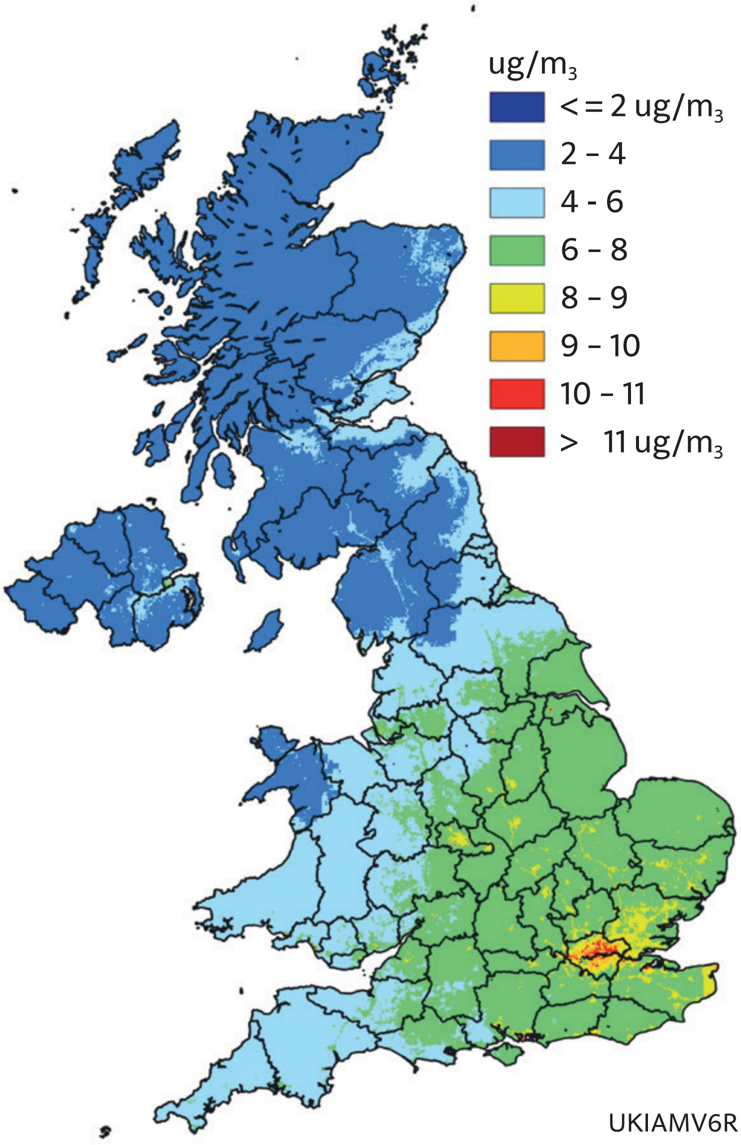
Figure 2: A qualitative representation of the different contributing sources to $PM_{2.5}$ that might be experienced in a typical urban centre (England)

There is also a contribution from international transboundary $PM_{2.5}$, mostly from near-European neighbour countries, but with some small amounts from North America – these are often secondary particles.[14,15] Added to this are regional contributions of $PM_{2.5}$ from other UK-based sources, beyond the city itself. These would include pollutants arising from agriculture, power generation and industry, as well as from adjacent towns and cities.

A fraction of regional $PM_{2.5}$ is still primary in nature, including from remaining industrial sources. These affect their nearby communities and contribute to wider regional pollution – for example, from steel and refining industries in places such as Port Talbot, South Yorkshire and Teesside. The final contribution to the $PM_{2.5}$ concentrations experienced in a city comes from within the city itself and its immediate periphery. There are a multiplicity of primary sources in cities, including tailpipes, vehicle friction and abrasion, construction dust, combustion heating systems, cooking and so on. Historically substantial benefits to $PM_{2.5}$ air quality could be achieved through tackling these urban sources (sometimes referred to as the 'urban increment') and thus reducing the height of the column.

A review by the Air Quality Expert Group in 2015 concluded that around 50–55% of UK total annual average $PM_{2.5}$ in the UK derived from UK anthropogenic emissions.[16] As primary emissions have reduced in cities, the increment experienced in urban areas has reduced and, in the 2020s, is now often rather small, perhaps only around 1 $\mu g/m^3$ higher than the concentrations found outside the city.[17] There are also now only small differences in $PM_{2.5}$ between the roadside and urban backgrounds.

To drive further reductions in $PM_{2.5}$ concentrations, regional and transboundary sources also need to be reduced. Defra modelling indicates that implementing a range of already agreed policies would result in extensive areas of the UK outside of central London experiencing concentrations of $PM_{2.5}$ that are below the 2006 World Health Organization (WHO) guideline annual mean limit value of 10 $\mu g/m^3$ by 2030 (see Figure 3). However, much of the UK population would still experience outdoor air quality that was above the revised 2021 WHO recommendation of 5 $\mu g/m^3$ annual average.[18] The Environment Act (2021) proposed new targets for $PM_{2.5}$, committing to meeting an annual average 10 ug/m^3 limit value everywhere in the UK by 2040.[19]



Source: Air Quality $PM_{2.5}$ Targets: Detailed Evidence Report. Department for Environment, Food & Rural Affairs, 2022.[45]

Figure 3: Modelled annual average concentrations of $PM_{2.5}$ in 2030 based on a 'baseline' (existing agreed government policies) emission reduction scenario[18]

The future for natural sources of $PM_{2.5}$ is difficult to predict, but may possibly increase due to climate change, notably due to more frequent UK wildfires. As a minimum, it seems unlikely that the natural contribution in 2050 would be less than it is today. The transboundary contributions to $PM_{2.5}$ should continue to fall, at least until 2030, because of international commitments made under the Gothenburg Protocol and Convention on Long-Range Transboundary Air Pollution (CLRTAP) agreements. Existing policy measures already agreed in the UK should also deliver a reduction in contributions from UK regional sources.

It is anticipated that there will be a further overall reduction in primary emissions of $PM_{2.5}$ from within cities over the coming decades. There will undoubtedly be a further decline in tailpipe emissions of $PM_{2.5}$ as older and poorer performing vehicles leave the fleet to be replaced by cleaner, or fully electrified vehicles. Benefits will also derive from other city-scale interventions such as Clean Air Zones. It should be noted, however, that battery electric vehicles (EVs) are not 'zero emission' with respect to air quality, and continue to emit $PM_{2.5}$ (and PM_{10}) from road and tyre wear and from braking. There are many uncertainties in how these non-exhaust emissions will develop. EVs may be heavier than the internal combustion engine vehicles they replace, something that may *increase* friction-rated emissions. These vehicles may also be driven *more frequently* since cost-per-mile (perceived or actual) may be lower (known as the rebound effect).[20] They are also likely to be perceived as being a clean or green option for travel. Counterbalancing that, regenerative braking and autonomous driving may *reduce* emissions through smoother driving and less brake wear.[21] Despite the uncertainties, over the next decade the removal of tailpipe emissions from older internal combustion engine vehicles, including buses, vans and heavy goods vehicles, should lead to a net benefit for $PM_{2.5}$. Beyond that, effects on air quality become more uncertain.

Urban reductions in primary $PM_{2.5}$ emissions will arise due to action being taken on solid fuel burning and stove appliances, enhanced controls on tailpipe emissions from off-road construction vehicles, plant and the wider construction sector, and also from improved abatement from back-up electrical generators. This leaves, by the mid-2030s, an ambient outdoor $PM_{2.5}$ mixture with relatively few primary sources of emissions that could be reduced further, and hence limited scope for actions targeting the sources shown at the top of Figure 2.

3.2 Impact of current air pollution policies

Air quality is already managed through a complex array of policies, guidance, and regulation. These apply at multiple scales: they address the problem bottom-up through limiting emissions sector-by-sector, and top-down through setting national targets for ambient air quality and a maximum ceiling on national emissions. No single sector can deliver clean air in isolation; instead, controls must work across the spectrum of sources. Bespoke emission regulations exist for a wide range of individual sources and appliances, too numerous to exhaustively list here. There are standards for vehicle emissions through the Euro scheme; for gas boilers and wood stoves via the Ecodesign Directive; rules on the content of paints (EC Paints Directive); outgassing from building products; and many others. Industrial emissions are managed at the installation level through Environment Agency permitting and local authority permitting systems. Other highly specialised sources, from crematoria to chainsaws, have regulations associated with their permitted emissions.

Much of this sectoral emissions regulation derives from European Directives. The process by which new emission standards might be delivered for individual sources post-Brexit remains unclear, although the UK is now able to set its own standards for individual appliances and deviate from those in the EU. At city level, interventions exist to specifically target road transport as an air pollution source, often designed to address outstanding problems of excess NO_2 at the roadside. London's large Ultra Low Emission Zone is perhaps the best-known example, but smaller interventions such as school streets can also work to reduce NO_2 hotspots arising from traffic, and low traffic neighbourhoods (LTNs), which have mixed evidence.

The government's Clean Air Strategy set out ambitions and possible technical approaches for a range of pollutants, with the aim (when it was published in 2019) to bring ambient air quality within EU limit values, and to ensure that the UK would be compliant with its obligations concerning transboundary pollution under the National Emissions Ceiling Directive and the Gothenburg Protocol. The Environment Act (2021) required the introduction of new standards for Air Quality and specifically for $PM_{2.5}$, to go beyond those that were transposed from EU law. As part of their target-setting process, Defra has explored the likely effectiveness of existing measures in meeting new and lower limit values for $PM_{2.5}$ in the future. Modelling has indicated that existing actions do considerable heavy lifting in improving air quality to 2040, but to reach a limit value of $PM_{2.5}$ of 10 $\mu g/m^3$ in all regions of the UK, additional policy measures would be needed. A future government Clean Air Strategy may further define those policies.

3.3 Climate change and net zero policies

Future changes in air quality due to climate change

Climate change is likely to significantly affect the UK over the next 30 years, and this will inevitably have effects on air quality, separate to the policy pathway taken on emissions reduction. The mixture of climate effects is broad and there is considerable uncertainty over the net impact on air quality from multiple competing factors. Climate change may lead to a broad shift in mean conditions alongside more frequent extremes of weather.[22] Anticipated hotter and drier summers will lead to a range of effects that could reduce air quality, from an increase in high-pressure stagnation events, increased emissions of VOCs from temperature-dependant biogenic sources (leading to ozone and $PM_{2.5}$), lower ozone removal rates through dry deposition, and increases in the frequency and extent of forest and moorland fires.[23] A warmer climate may also lead to increases in ammonia emissions since its release as a gas has a positive temperature dependency. There may also be increased emissions of NO_x from soils.

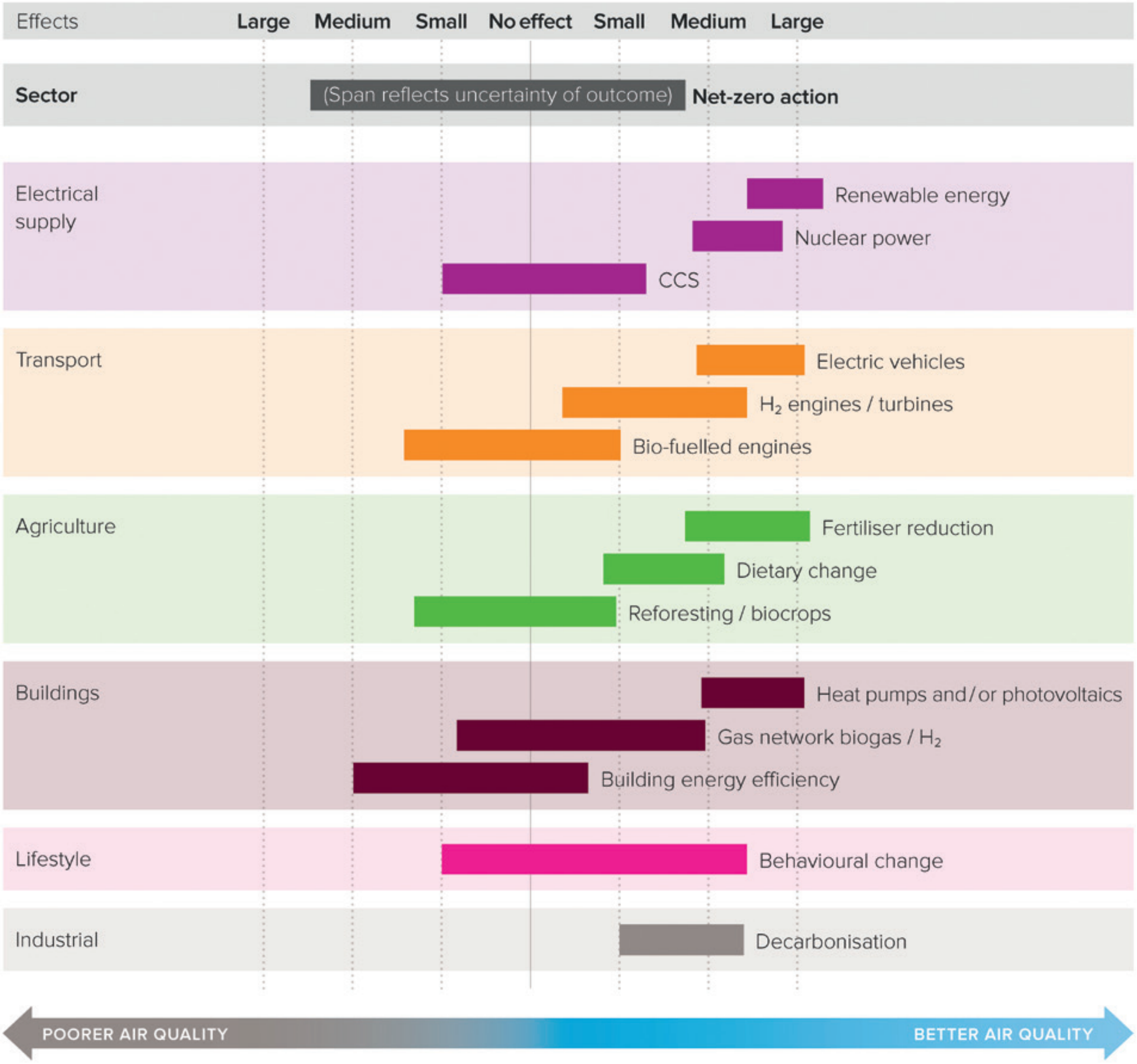
At the other meteorological extreme, winters in the UK are forecast to become stormier, windier and wetter. In combination, these factors tend to improve ambient air quality, increasing atmospheric mixing and the wet deposition of pollution. It might be envisaged that wintertime air quality would on balance improve due to climate change should this occur. There are, however, other factors where climate predictions remain too uncertain to draw conclusions on air quality. It is possible that large-scale circulation patterns may shift and, as a result, bring air to the UK more frequently from mainland Europe,[24] which generally has a negative influence on air quality.

There are also some less well defined, but possibly significant indirect impacts of climate change that are worth considering for the future. For example, a shift to hotter summers may lead to an increase in the use of air conditioning in homes and businesses. This would reduce buildings' air exchange, potentially worsening indoor air quality, since buildings would have been previously cooled via open windows and ventilation alone.

The impact of implementing net zero in the UK

Beyond existing or planned agreements and policy measures, a major factor that will affect the long-term future of air quality in the UK is the implementation of the national commitment to a net zero greenhouse gas budget by 2050.[25,26] The potential for climate-motivated greenhouse gas emissions reductions to also achieve improved air quality was articulated before net zero became a widely understood concept.[27] Many interventions to reduce greenhouse gas emissions also improve air quality. Particularly positive for air quality are those decarbonisation actions that lead to the replacement of combustion systems with non-combustion alternatives. Action to mitigate the scale of climate change and its effects are essential for the health of the planet and the population, and net zero has a pivotal role in delivering the UK's contribution to that. It has the potential to also bring large co-benefits for other environmental issues, including air quality, resulting in even greater gains for public and environmental health.

While slowing and reducing the impacts of greenhouse gases is a long-term multigenerational effort with benefits accruing over decades, air quality improvements can be delivered more quickly. Integrating the public health benefits from reduced air pollution can enhance the economic argument for taking climate change actions.[28] Delivering a national net zero greenhouse gas budget is hugely complex and relies on systemic technological and behavioural change. A high-level overview summary of the likely effects of net zero interventions on air quality are given in Figure 4. There is a balance of anticipated effects, mostly lying on the positive side of the figure for air quality, but not in every case. Sometimes the outcomes for air quality remain uncertain since the policy or technological pathway is yet to be fully defined.



Note: The bar length indicates the range of uncertainties.

Source: Effect of net zero policies and climate change on air quality, Royal Society (2021)[2]

Figure 4: Estimated effects of different net zero decarbonisation measures on ambient air quality

Many net zero policies, such as the phase out of fossil fuel electricity power generation and increase in use of solar and wind power, are unequivocally positive for air quality. Other interventions and pathways lead to more uncertain outcomes. For example, within the energy supply mix, the air quality effects arising from a large increase in carbon capture and storage (CCS) is unclear.[29] Existing combustion boilers would be retained, inevitably leading to some NO_x and PM emissions.[30] Additionally, there could be the potential for chemical stripping processes to lead to fugitive emissions of new harmful pollutants such as nitrosamines, if not well abated.

Some approaches to delivering net zero may improve air quality for some pollutants more than others. In the road transport sector, electrification of the passenger fleet will lead to the complete elimination of tailpipe NO_x from those vehicles – a huge benefit. However, battery EVs still give rise to emissions of particles from brake, tyre and road wear. Non-exhaust emissions of PM already comprise the majority of $PM_{2.5}$ and PM_{10} emissions from road transport.[31] Future policies that encourage and invest in other approaches to low-carbon transportation in cities, particularly active travel, would improve air quality for $PM_{2.5}$ as well.

While the electrification of passenger cars is well underway, other components of the transport system are in their early phases of decarbonisation. For example, the Clean Air Strategy identified the importance of phasing out older diesel trains, however, the timescale for completing this could be into the 2040s. Electrification of heavy goods vehicles and buses in cities could also follow a battery-electric or hydrogen fuel cell pathway, but low-carbon, non-combustion propulsion systems for long-distance haulage are not yet competitive when factors such as cost, range, and re-fuelling infrastructure are combined. The most difficult components of transport decarbonisation include international shipping and aviation, where some combination of synthetic organic fuels, hydrogen or ammonia may be needed. All these options could potentially be designed to deliver some air quality benefits. For example, synthetic fuels made via the Fischer–Tropsch process have very low levels of sulphur impurities, so greatly reduced SO_2 emissions.[32] However, the fundamental retention of high temperature combustion inevitably leads to some NO_x (and likely some PM) as a by-product. Friction-related PM emissions would also remain and would likely prove difficult to fully abate.

A major component of net zero must involve decarbonising homes and businesses, which in the UK are heavily reliant on fossil methane (natural gas) combustion for heating and cooking. The exact policy choices made, and technologies supported, potentially result in different effects on air quality. For example, decarbonising homes through better insulation and the adoption of heat pumps, solar, and direct electric heating/cooking, removes significant combustion sources of air pollution from the home. Alternatives being considered, such as combustion of hydrogen or biogas methane in place of fossil methane, retains emissions of NO_x. At this level of policy granularity, decisions about exactly how net zero is achieved within a sub-sector can lead to notable differences in air quality outcomes.

More broadly, the choices society makes around future fuels and the extent to which combustion remains significant, will be a defining factor in determining the air quality that will be feasible in future decades. Swapping fuels such as methane, diesel or kerosene, for carbon-neutral equivalents can deliver on net zero objectives but lead to the retention of processes and appliances that still emit air pollution.

Commercial aviation and shipping stand out as sectors where electrification is difficult and use of alternative fuels derived from waste or biomass, such as Sustainable Aviation Fuel (SAF), or hydrogen or ammonia from electrolysis is likely. The resulting combustion emissions may then occur near cities. Other sectors such as off-road vehicles and back-up power provision, could also face choices between electrification and combustion, possibly using hydrogen or biofuels. Given the relative technological ease with which such fuels can be retrofitted to existing infrastructure, the future regulatory limits that are set for emissions arising from biofuel and hydrogen/ammonia use may become critical in determining which pathway becomes the most viable.[33]

Suitable regulation of emissions from net zero processes will play a critical role in providing co-benefits. Substantial technological and regulatory failures of the kind that occurred with diesel passenger cars would undo many of the benefits anticipated in Figure 4.

During the 2000s, changing from petrol to diesel passenger vehicles resulted in increased NO_x emissions from diesel vehicles. This change was supported by government to reduce greenhouse gas emissions, but it had a harmful effect on air quality. It was well-understood at the time this policy choice was made that increased NO_x from diesel could be a potential disbenefit. However, there was confidence that abatement was possible using exhaust gas after-treatment technologies. In practice, European vehicle testing regimes were not representative of real-world driving conditions, with a number of manufacturers deliberately manipulating emissions control systems to perform well while under test, but not on the road. This highlights the importance of considering the air quality implications of other policies, including net zero, and also making sure that there are effective regulatory mechanisms to ensure that air pollution abatement, where it is needed, is working effectively.

Care is needed in messaging to ensure that net zero is not misconstrued as being an all-encompassing answer to air pollution. Although many net zero interventions also reduce air pollution emissions, some aspects do not improve air quality: some present new air pollution challenges, and some air quality issues have no connection to greenhouse gas emissions. There are risks that effective communication campaigns that aim to increase the uptake and support for measures needed to achieve net zero could lead to unanticipated or undesirable outcomes. While EVs are an important part of a decarbonised, cleaner transport system, the term ‘zero emission’ is widely used and even displayed as badges on some vehicles, without clearly defining what the ‘zero emissions’ are. Although these vehicles emit neither carbon dioxide (CO_2) nor other air pollutants from their exhausts, there are still emissions of $PM_{2.5}$ and PM_{10} from the brakes and tyres, and from wear of the road surface and agitation of road surface dust. The total air pollution emissions also depend on how the electricity to charge the batteries is generated. While the small print may include a caveat that ‘zero emission’ refers only to tailpipe emissions, the message is that these are clean vehicles. Alongside perceived cheaper running costs, this has the potential to encourage more private car use by removing the environmental arguments for seeking an alternative. The public may become disengaged or angered, much as they were by the change in narrative around diesel vehicles, to hear that they need to invest in additional technology or use their cars less to limit the emissions of $PM_{2.5}$. There are similar risks around use of the terms ‘green’ and ‘renewable’ energy – marketed as no-regrets, environmentally-friendly options – when some, such as biomass burning or anaerobic digestion, may have significant air pollution emissions and consequential influence on human or ecosystems health.

The net zero transition period and effects on air quality

Figure 4 presents a positive picture for the long-term effects of achieving net zero. However, there are areas where actions during the transition to 2050 may be less beneficial for air quality. The Committee on Climate Change estimates a doubling in electricity demand by 2050 (2018: 300TWh, 2050: 610 TWh), partially due to electrification across various sectors. An increasing market share represented by renewable sources will require actions in the short to medium term to ensure reliable supply, particularly at peaks of demand. If this requires the intermittent use of polluting technologies, such as diesel or biodiesel generators or gas engines, then the air pollution impact, particularly in areas close to source, will be less positive. Also, many existing UK gas and nuclear power plants are due to be retired, so there will be periods of sustained large-scale construction activity across the UK, creating emissions from machinery and contributions to PM from dust. To enable net zero policy, there are likely to be other infrastructure developments associated with, for example, transport and storage of CO_2, transmission of electricity from more remote generating locations, new manufacturing plants supporting the offshore wind sector, all of which may contribute temporarily to elevated emissions of air pollution. While only transitory (although possibly for many years), and geographically distributed, local communities could be significantly affected.

Transitory negative effects on air quality from decarbonisation of the transport sector are also possible. Long-term, perhaps by 2050, aviation may be able to use non-polluting energy sources such as battery electric or fuel cells. Over the intervening period, however, synthetic liquid fuels may be the preferred option; the aviation sector could experience increased passenger demand if the negative environmental connotations associated with air travel and climate change seem to have been solved. The use of transitionary fuels may lock in investment in transport systems that would continue to emit air pollutants, much as today. Adoption of carbon-neutral transitionary combustion fuels may need to be accompanied by more ambitious limits on exhaust emissions, particularly if a growth in demand is anticipated once the social climate change 'brakes' are removed.

All of this discussion highlights the need to consider the effect of net zero policy on wider systems to determine where co-benefits can be delivered and how they can be fully realised. There is a need to identify areas that might require mitigation to limit or avoid negative consequences on other areas of the environment or society.

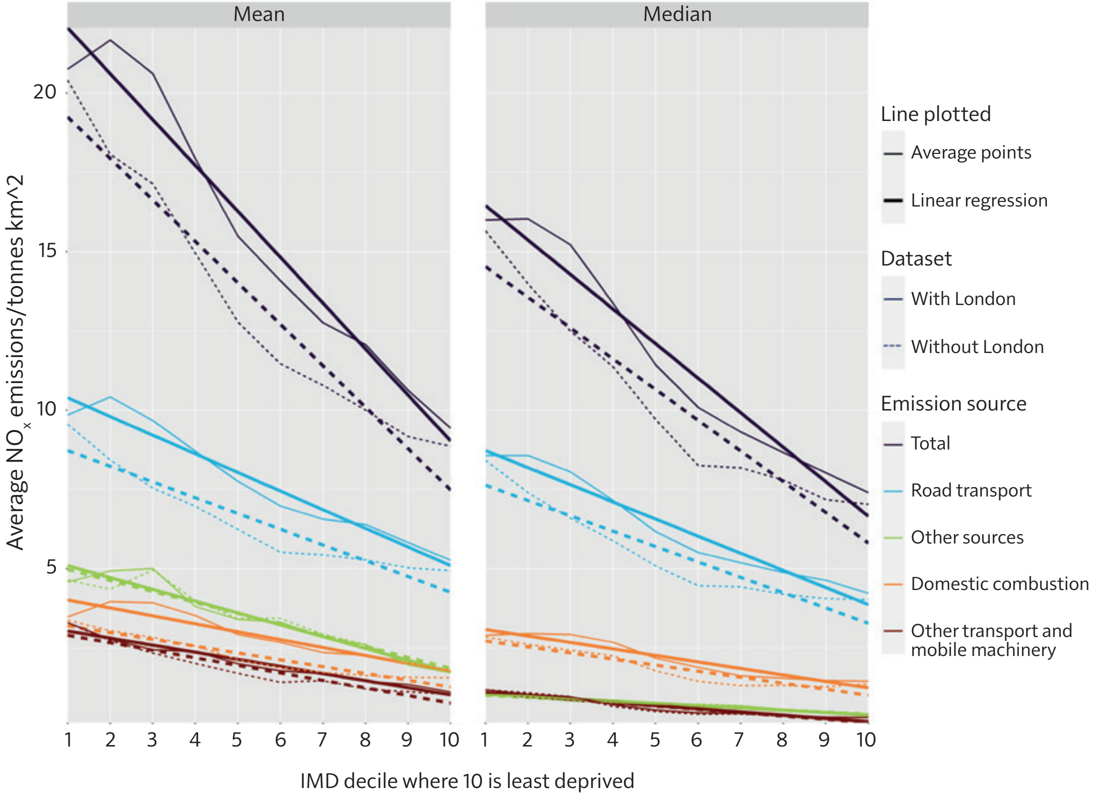
3.4 Future disparities in outdoor air pollution distribution

Air pollution will continue to be unevenly distributed in the UK, and interventions may not result in the same rate or level of change in concentrations at all locations.[34] By far the largest disparity that will exist in the coming decades relates to geography. This can be seen clearly in the future projection of annual average $PM_{2.5}$ concentration in 2030 in Figure 3. The substantial contrast in outdoor concentrations between the southern and eastern parts of the UK and northern and western areas are caused by a combination of differences in population density and differing weather conditions. It is appropriate to view $PM_{2.5}$ as a pollutant at this national scale since it is longer-lived and the effects of local sources, such as individual roads, are less pronounced than for shorter-lived pollutants such as NO_2. Although localised hotspots of $PM_{2.5}$ concentrations exist in northern and western regions, national maps provide a good guide to the prevailing concentrations, which localised sources of pollution may further add to.

In plausible 2030 scenarios such as Figure 3, the vast majority of Scotland would expect to experience very good air quality, in most places meeting the lower 2021 WHO guidelines for $PM_{2.5.}$ By contrast in the Southeast of England, even in the countryside there are likely to be widespread areas with outdoor concentrations of $PM_{2.5}$ in the range 6–8 µg/m^3. Central London stands out as being one remaining region that may continue to exceed 10 µg/m^3 in 2030 and possibly beyond. Geography, proximity to density of sources (UK and transboundary) and weather all play a role in creating this differential.

For short-lived pollutants such as NO_2 and SO_2 the controlling factor that drives distributional trends and exposure is proximity to nearby emission sources. Since the lifetime of NO_2 is only a few hours, concentrations are dependent on very local emissions. This can cause additional inequality with those who live closest to local sources experiencing the highest concentrations. At present there is a disparity in exposure to NO_2 that is affected by an individuals' time spent near to major roads and living in higher-density urban settings. It is inappropriate to generalise for all towns and cities, but currently those in groups experiencing the highest levels of deprivation live frequently in locations that are affected by the highest NO_x emissions, and often highest NO_2 concentrations. An analysis by the Office for National Statistics (ONS) found a positive association between increased long-term $PM_{2.5}$ concentrations and communities with higher Black and ethnic minority populations.[46] Although it affects fewer people overall in the UK, coastal communities near areas of shipping activity such as docks similarly experience higher local concentrations of SO_2.

This is illustrated in Figure 5, which combines information on NO_x emissions (at 1 km x 1 km) resolution) from the National Atmospheric Emissions Inventory with Indices of Multiple Deprivation for England taken from the ONS Lower Super Output Area (LSOA). Decile 1 is the most deprived and 10 is the least deprived (Lower Super Output Area, 2019 data matched to inventory grid). The relationship between NO_x emissions is shown for the whole of the England and Wales (solid lines) and with London excluded (dashed lines). Those in the most deprived areas are living in areas with higher emissions of NO_x, from road transport, and also from other sources such as domestic combustion. The thick dashed/solid lines represent linear fit to data.



Source: Nathan Gray, University of York – provision of analysis and image

Figure 5: Relationship between NO_x emissions in England and Wales

While large-scale geographic gradients in air pollution will inevitably persist into the future, some policies and technology trends may work to reduce local-scale inequalities. The inequitable distribution of NO_2 arising from the passenger diesel transport fleet will diminish over the coming decades as electrification becomes more widespread. The transition of larger vehicles to either battery electric or fuel cell powertrains will occur later than for passenger cars, and so it seems likely that NO_x and its associated community effects will continue to be significant into the 2030s where these vehicles are widely used, such as near ports and stations. The trajectory for other urban sources of NO_x, such as from gas boilers, is less clear since decarbonisation is only in its early phases, and the balance between electrification vs biogas/hydrogen combustion is yet to be established. Adopting the latter would result in NO_2 being elevated, possibly in areas of highest population density, albeit with ambient concentrations lower than today. Since NO_2 has a short lifetime, and hence restricted spatial footprint, individual measures to reduce emissions can disproportionately affect changing population exposure. For example, a strategy to reduce road transport in certain urban centres might only have a small effect on total national NO_x emissions, but that reduction may beneficially impact on large numbers of people. Conversely, adding small-scale biomass power generation in cities could have disproportionately large and negative effects on health.

The effects of current and future policy measures on inequalities in the distribution of $PM_{2.5}$ are less clear, although some reduction in demographic inequality has been modelled.[19] However, since much of the $PM_{2.5}$ in the UK is derived from regional and transboundary sources, the uneven geographic distribution of $PM_{2.5}$ is likely to persist. While the amount of $PM_{2.5}$ that can be controlled directly from within cities is, in emissions terms, relatively modest, some policy actions can deliver reductions in local hotspots – for example, from excluding older vehicles with poor tailpipe emissions, supporting active travel, electrified public transport, and more generally reducing stop-start congestion. In suburban and some rural locations, actions that limit or discourage solid fuel burning would be expected to have benefits on local $PM_{2.5}$ particularly on days with low wind speed when pollution can accumulate.

New technologies may help reduce non-exhaust emissions of $PM_{2.5}$ from transport, such as low-emission tyres, use of regenerative braking, and smoother driving from autonomous vehicles. Fewer private vehicle journeys and less congestion would reduce emissions, bringing multiple benefits if active travel alternatives are used. Further reducing urban road sources of $PM_{2.5}$ would likely have a similar positive effect on reducing inequalities, achieving most improvement in high traffic areas that often have communities with higher levels of deprivation.

3.5 Current and future indoor air pollution

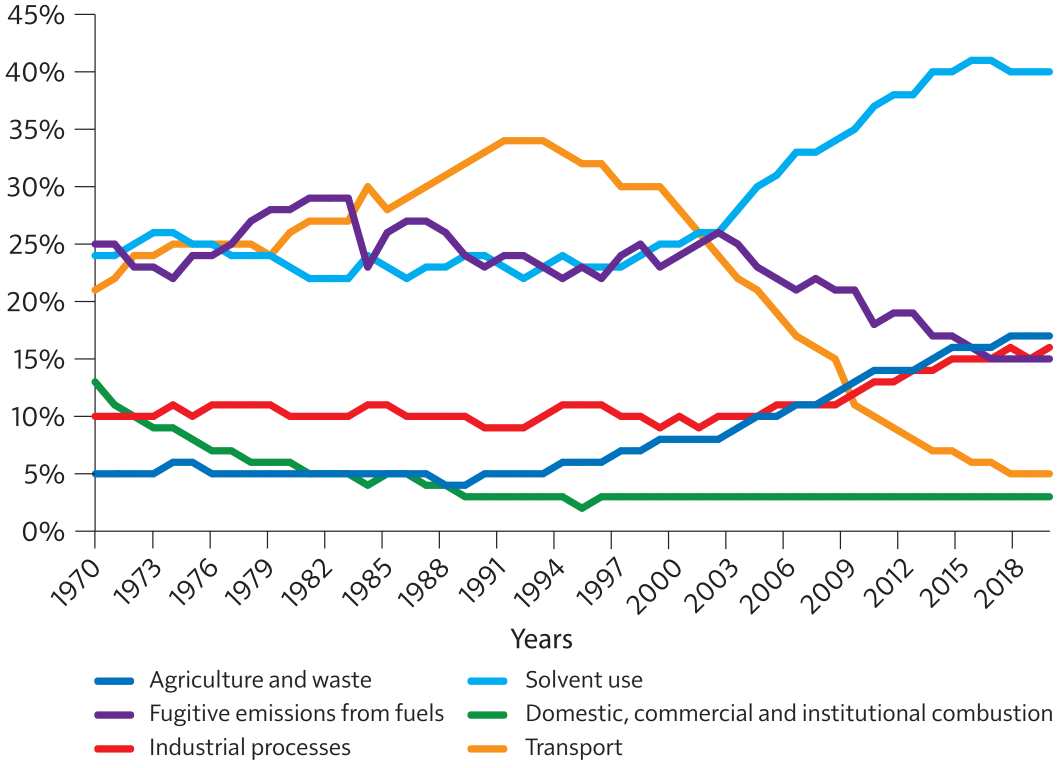
The management and regulation of air quality for public health focuses predominantly on outdoor air. When outdoor concentrations of air pollution are high this becomes a critical factor in determining an individual's overall exposure. Not only is pollution inhaled when people are physically outdoors, but when outdoor air penetrates indoors, so it also sets the baseline for indoor air quality. As outdoor air quality has improved in the UK, the relative contributions from breathing outdoor and indoor exposure have shifted. In many UK locations, outdoor air quality can, (for some pollutants), be better than the air found in indoor spaces, so increasing ventilation and allowing the ingress of outdoor air brings net benefits, not harms. Many of the most important pollutants outdoors are also found indoors, notably $PM_{2.5}$ and NO_2. However, indoor areas can experience higher concentrations of certain classes of pollutant that accumulate due to indoor sources. Significant examples include air pollutants such VOCs and semi-volatile organic compounds (SVOCs), radon and carbon monoxide (CO), and – if encountered at high concentrations – CO_2.[35]

It is very difficult, however, to generalise about past trends or future trajectories for indoor air quality, since it is highly variable between buildings and is controlled to a significant degree by occupant behaviours. Long-term improvements in UK outdoor air quality have likely led to cleaner air entering buildings. Balanced against that has been increasing building energy efficiency, such as sealing windows, which acts to reduce air exchange, sealing in emissions from indoor sources. There are no systematic long-term monitoring data available on indoor pollution trends in the UK. This is a major evidence gap that limits the formulation of policy, or advice on best practice. Indoor air quality from a physical science perspective has recently been reviewed by the Defra Air Quality Expert Group, who identified that the net zero transition in homes could have variable influences on future indoor air quality.[36]

While improving building insulation can reduce ventilation rates, a reduction in air quality is not inevitable, and many engineering solutions balance energy efficiency with ventilation (for example, heat exchangers, cooker hood filtration). Ventilation is vital to managing classical anthropogenic pollutants such as $PM_{2.5}$, and also in reducing humidity and damp, the growth of moulds and exposure to airborne bioaerosols. It is also crucial in high-occupancy settings to prevent the build-up of CO_2 which may affect cognition and mental performance. While more common in countries such as South Korea and China, active indoor air filtration systems in homes can work to reduce concentrations of indoor particles, and their use has increased to reduce airborne respiratory viruses over the last two years. Removing gas phase pollutants such as NO_2 or VOCs from air through filtration is more challenging than particles. Some techniques such as ozonolysis or UV irradiance can lead to secondary pollutants forming. All such inventions have a cost, create a demand for energy and require continued investment in maintenance and consumable items such as filters and chemical adsorbents. It seems reasonable to speculate that active home indoor air filtration and cleaning may be an intervention disproportionately adopted by, and benefitting, higher-income homes.

Domestic decarbonisation plans to replace natural gas with either full electrification or full hydrogen for heating (in boilers and gas fires) and cooking (hobs, ovens) would remove a major indoor source of CO. This would contribute to substantially reducing the small number of fatal events that occur from CO poisoning (15 to 20 deaths per year)[37] and also reduce long-term exposure harms. Future retention of combustion in home appliances in the form of hydrogen and/or biogas gas for heating or cooking, or solid fuel combustion in stoves, would lead to continued indoor emissions of $PM_{2.5}$ and NO_2. The technological pathways chosen for building decarbonisation are therefore particularly influential in determining the future trajectory of indoor air quality.

While net zero delivery can play a major role in reducing some pollutants indoors, VOCs, SVOCs and other organic chemicals such as phthalates and per/poly-fluorinated substances (PFAS), are unlikely to be directly affected. They are instead controlled by trends in materials used for construction, furnishings and consumer products. VOCs can be outgassed from building materials such as woods, glues and flooring, and some of these products are regulated for their emissions, or have existing guidelines for their use. VOCs are also emitted from the use of cleaning and personal care products and from decorative products such as paints and varnishes. While overall national emissions of VOCs in the UK have fallen dramatically since the mid-1990s, solvent emissions, many of which occur in homes, have increased. Figure 6 shows how estimated emissions from solvent sources have grown as a fraction of national VOC emissions since around 2000, at the same time as the introduction of effective controls on tailpipe and evaporative emissions from gasoline cars.[38]



Source: National Atmospheric Emissions Inventory[11]

Figure 6: Trends in sectoral contributions to national emissions of VOCs as a percentage of the overall annual national total, 1970 to 2020

To place domestic emissions in context, the use of compressed aerosol spray canisters (such as deodorants and room sprays) in the UK now gives rise to more VOC emissions into air than are released from all UK road transport combined.[39] Most VOCs released indoors are not directly harmful to health at low concentrations, but in an enclosed space they can be oxidised and lead to the formation of more harmful secondary pollutants such as formaldehyde, acetaldehyde and secondary organic aerosols, a component of $PM_{2.5}$. Reducing indoor emissions of VOCs can be achieved through changing behaviours, reducing overall consumption, increasing ventilation, the reformulation of products to low VOC content, or a combination of these. The Clean Air Strategy proposed that better product labelling may be one way to encourage change, but there are no commitments to require this, or proposals from industry for voluntary schemes. SVOCs can be found indoors at low concentrations in both gas and particle phase, but can be of health significance because they are chemically-persistent and bioaccumulative, including compounds such as phthalates from plastics, halogenated fire retardants and surface coatings, including as PFAS.[40]

Emissions and ventilation are important physical factors that determine indoor concentrations; however, it is time spent indoors that determines overall exposure, and the relative contributions made from indoor vs outdoor spaces. Changes in working practices since COVID-19 may lead to a shift in long-term working patterns that, in turn, may affect an individual's exposure to air pollution. A complex range of possibly competing factors could come into play. More working from home may lead to more time spent in essentially unregulated indoor spaces, balanced against reduced commuting time, less time spent in cars and on public transport, and in city centres more generally. However, other outcomes may result – less commuting at the population level may lead to lower city centre air pollution but increased suburban and rural emissions as homes are heated all through the day.

3.6 Considerations for future air pollution policies

There is considerable action that can be taken to further improve air quality in the UK. For NO_2 and SO_2, a pathway towards almost zero emissions is technically plausible if electrification (using battery or fuel cells) is prioritised over combustion in the delivery of a net zero greenhouse gas budget. For particle pollution, however, there are limits to what can be achieved since particles are sometimes generated as an unavoidable by-product of human activity, including friction. There has been significant media and policy attention placed on reducing road transport pollution in recent years, an entirely appropriate focus to deal with issues of excessive tailpipe NO_x emissions. Longer-term however, it will be ineffective to attempt to manage air quality and engage with the public on this issue by framing it as being solely a road transport problem. It will likely be impossible to ever achieve the WHO recommendation of 5 $\mu g/m^3$ annual mean $PM_{2.5}$ in central London, since the combination of $PM_{2.5}$ deriving from transboundary and natural sources can exceed this value in South East England. A debate is therefore needed about wider options, costs and the benefits of actions that might further improve air quality in the long term.

For decades, regulation and policy has been constructed around achieving air quality objectives for harmful particles using the definitions of $PM_{2.5}$ and PM_{10}. In the longer term, this may not necessarily be the best route for achieving optimal health outcomes from clean air investments. For many years, the medical evidence for the differential toxicity of particles has not been sufficiently compelling nor consistent to recommend a wholesale change towards regulation and control by particle type, size or chemistry (although, it should be noted that a small number of sub-components of PM such as polycyclic aromatic hydrocarbons and metals are already treated as individually harmful pollutants). However, evidence has been hardening around a disproportionate impact on health arising from particles deriving from combustion and transport-related friction. There is also some evidence that other metrics such as total particle number (PN) or particle number concentration of Ultrafine Particles (UFP) are potentially better predictors of health harms than $PM_{2.5}$ (particle mass concentration). PN and UFP are, however, currently measured in only a handful of UK locations. The implications being that it may be sub-micron diameter particles that have most significant effects on health. This could prove a challenge for air pollution management systems; existing legislation and control measures are geared towards regulating the total mass of particles emitted, and these tiny particles contribute very little to that metric. While recommendations for maximum population exposure to UFP, and other possible particle metrics such as black carbon (BC), are not in place, guidance on measurement and definitions are emerging.[18]

Prioritising policy actions to reduce emissions or people's exposure to particle numbers or specific chemicals might have only small and possibly unmeasurable effects on the overall mass of $PM_{2.5}$ in air, but they may remove components that cause most harm. Continuing to measure success in air quality only by the trends and attainment of standards for $PM_{2.5}$ over time may lead to inappropriate prioritising of interventions predicted to lead to the largest change in mass concentration, but not necessarily greatest benefit to health.

The challenge of a move away from $PM_{2.5}$ in the medium to long term is significant, requiring rethinking of how pollution is modelled, measured and regulated, and how the costs and benefits of interventions are determined. It is possible that such a change is forced on regulators if the measurement of $PM_{2.5}$ itself proves unsustainable or too inaccurate in the coming decades. Trying to classify particles by size alone is unsatisfactory since they are not all spherical or of uniform shape, and some change size depending on humidity. Most current measurement methods become subject to large uncertainties when $PM_{2.5}$ concentrations falls below 7 $\mu g/m^3$. Equally challenging is the modelling of $PM_{2.5}$: at low concentrations, it is likely to be as uncertain as measurements, if not more so. Current modelling of $PM_{2.5}$ is often reliant on calibration against measurements, creating a dependency between the two approaches. It may be that a shift to chemical- or number-specific metrics becomes a necessity to provide a way of accurately tracking air quality effects and change over time.

Policies and public guidance on sustaining good air quality in indoor spaces, including public spaces, workplaces and private households, remains incomplete. There are some UK Health Security Agency (UKHSA) guidelines[41] on suggested limits for indoor air quality concentrations, but much of this advice approaches the issue from the perspective of occupational health for healthy working age individuals. While indoor air quality standards can never be applied exactly in the same way as outdoors, better account needs to be taken of indoor air quality guidelines for vulnerable groups and young children, particularly when they are exposed to pollution in indoor public places. The emergence of lower-cost sensors for indoor air quality provides a means to support individuals and building owners in better understanding indoor air quality, seen recently with the use of CO_2 sensors to highlight spaces with poor ventilation.

Emerging and novel pollutants

The group of air pollutants considered in regulation has been largely static over the past 50 years. Technologies and activities that lead to emissions are not static, and there are legitimate concerns over the extent to which atmospheric emissions of novel materials will be managed in the future. While directly harmful chemicals are often identified through product safety testing as they are developed, there is no systematic approach applied to evaluating air quality impacts once released to the air. Novel materials may have low toxicity in their native form but may become more harmful once in the air and subjected to atmospheric oxidation, a process that may add nitrogen and oxygen functionalities to a molecule. This has been observed most recently for flame retardants,[42] but the atmospheric degradation of many other synthetic materials remains poorly described. While the impacts of air pollution on health are rightly a key focus, damage can also arise through chemical accumulation in plants and animals, with effects on ecosystems and the food chain that only emerge after years of exposure. PFAS are the toxic 'forever chemicals' that have been found in the air, rain water, food, and in human blood. PFAS have recently gained media attention due to new techniques that could break them down.[43] Atmospheric emissions and atmospheric transport have undoubtedly contributed to the now widespread distribution and accumulation of these harmful chemicals in the environment, and inhalation may be an important route for ingestion.

There may be future large-scale use of novel chemicals in energy production and for CCS, new chemical emissions associated with industrial manufacturing, emissions from waste disposal or recycling, from future agricultural treatments, or domestic cleaning and personal care products. Mechanical abrasion may lead to new solid materials ultimately becoming airborne and inhaled, something that has received limited policy attention to date. The airborne transport and inhalation of microplastics is an example showing how unintended air quality consequences might possibly arise far downstream from the public use of an originally safe synthetic product. Too great a focus on only meeting existing air quality standards and regulations, without considering how atmospheric composition may change with society and technology more broadly, may lead to problems that could have been intercepted earlier with greater non-targeted surveillance and horizon-scanning. A clear evidence gap exists between the extensive regulatory efforts placed on monitoring existing regulated air pollutants and research studies of emerging atmospheric composition, the latter being rarely systematic or long-term in nature.

Changing behaviour

While there are many reasons to be optimistic about the likely trajectory for air pollution in the UK, the evidence for a broad range of effects on health is ever increasing. Therefore, pressure to continually reduce people's exposure to air pollution is likely to persist well into the future. There are many areas where factors such as policy implementation, desire to meet other environmental targets, behavioural response to policy and use of novel technologies or processes could lead to more or less beneficial outcomes for air quality, depending on the specific pathway chosen. While technological innovation has always had, and will likely continue to have, a strong influence over what can be achieved, the role played by societal behaviours and values should not be neglected. Behavioural change will be important in delivering greater progress on air pollution, and the values which government and businesses are held to will influence decisions, actions and how environmental performance is considered in their success measures. Ultimately these societal factors may be the most important driver for change and determining how much progress can be delivered.

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4 Outdoor and indoor air pollution solutions

4.1 Transport

4.1.1 Road vehicles

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Introduction

Health effects of road vehicle air pollution emissions

Air pollution emissions from road traffic are from the engine exhaust and non-exhaust sources from brakes, tyres and resuspended road dust. The pollution emissions comprise a complex mixture of gaseous and particulate pollutants, many of which can affect health at exposure levels that exist in the UK. The toxic gases from engine exhausts include nitrogen dioxide (NO_2), carbon monoxide (CO) and hydrocarbons (HCs) such as benzene. The particulate matter (PM) emissions arise from engine exhaust and non-exhaust sources, covering a very wide range of particle sizes, from a few nanometres to tens of micrometres in diameter. They have a highly varied chemical composition, from diesel exhaust (mostly elemental carbon) to non-exhaust emissions such as brake wear (rich in trace metals) and tyre and road wear particles (mainly rubber polymer and mineral material). There are also semi-volatile hydrocarbons including carcinogenic polycyclic aromatic hydrocarbons (PAHs) which partition between particle and gaseous phase.

This complex mixture can affect lung and cardiovascular function and cause an increased incidence of lung cancer. Since the mixture arises from a single source, the airborne concentrations are determined mainly by traffic volumes and meteorological conditions, and hence the constituents tend to be very highly correlated with one another. This makes it difficult to differentiate the effects of separate components of the mixture. Many studies have investigated the health effects of traffic-related air pollution (TRAP) as a whole, exploiting the typically strong gradients in concentrations of TRAP in the vicinity of major highways.

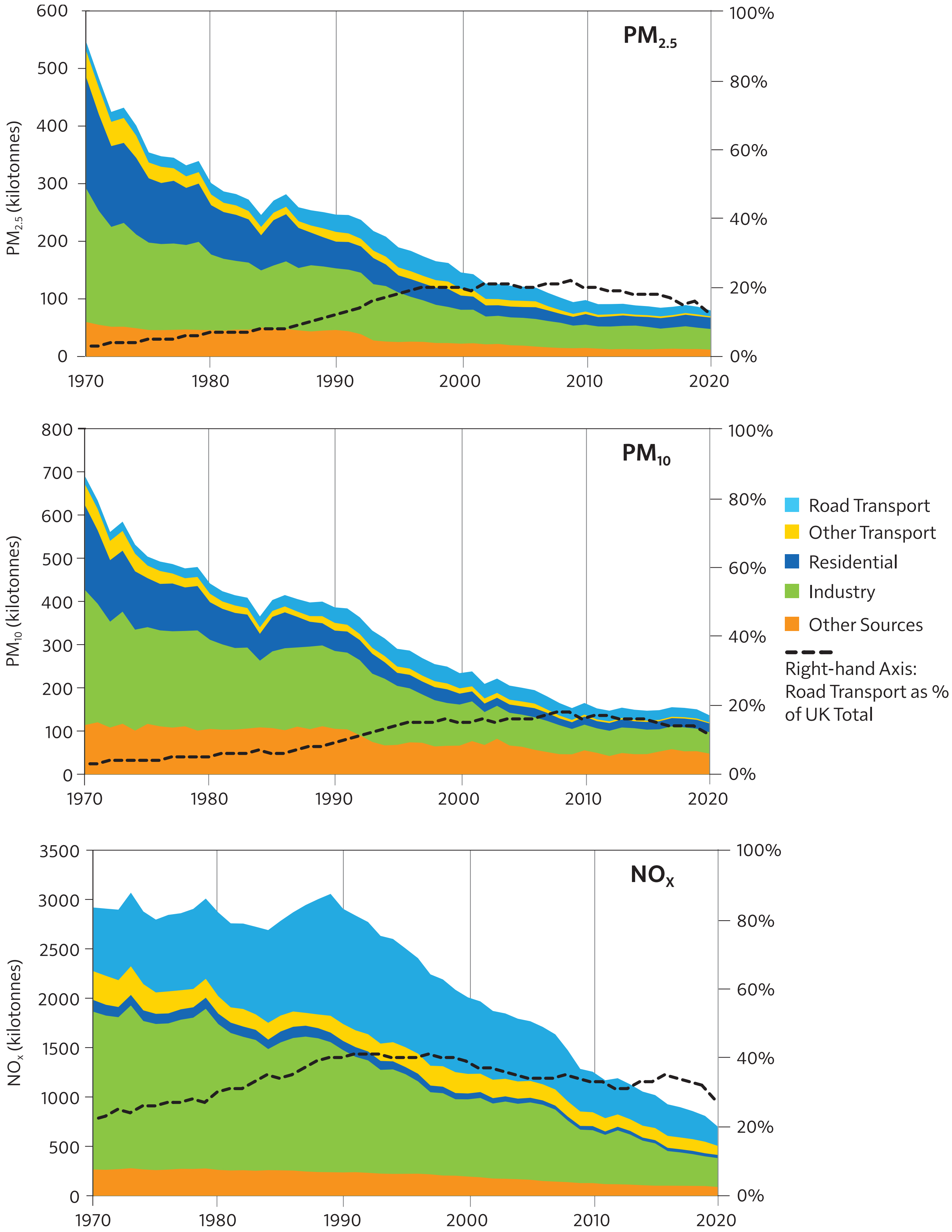
A large systematic review of the effects of long-term exposure to TRAP was conducted by the Health Effects Institute.[1] The study reported an overall high or moderate-to-high level of confidence in an association between long-term exposure to TRAP and all-cause mortality, circulatory, ischaemic heart disease and lung cancer mortality, asthma onset in children and adults, and acute lower respiratory infections in children. Further details of the health effects of air pollution are discussed in Section 1.1.

There are no firm estimates of the contribution of road traffic emissions to morbidity and mortality in the UK. However, a global analysis in 2015 reviewed how air pollution affects mortality,[2] and was broken down according to type of air pollution emission source. The methodology for quantification was different from that used in the UK but gave an estimate of around 20% of total premature mortality due to fine particulate matter ($PM_{2.5}$) and ozone in 2010 arising from land transport (mainly road traffic) emissions.

Trends in road vehicle air pollution emissions and concentrations

Figure 1 shows the trends in estimated emissions of the pollutants particulate matter ($PM_{2.5}$ and PM_{10}) and nitrogen oxides (NO_x) from different sectors over time. Figure 1 also shows an overall percentage contribution from road transport at a national level.[3] Road transport is estimated to currently contribute around 12% of particulate emissions and approximately 28% of NO_x emissions.

While most sectors are reducing their emissions, the percentage contribution from road transport is also reducing, indicating that the pace of change has been faster from this sector. In particular, the downward trend in road transport's contribution to estimated NO_x emissions corresponds with the introduction of increasingly stringent emissions regulations from 1992/93. The changes in regulation are discussed in further detail later in this section.

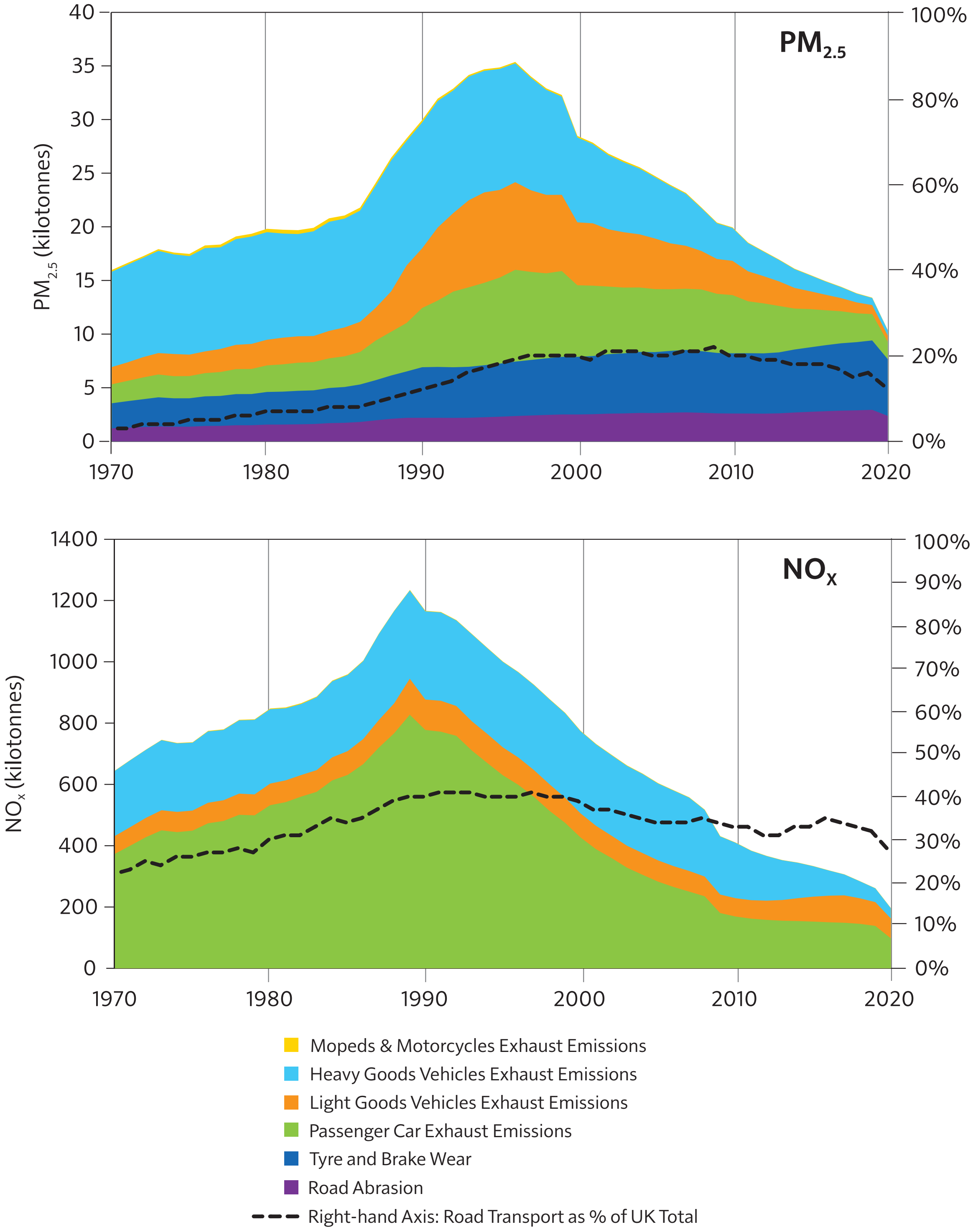


Note: The dashed black line indicates the contribution of road transport to the overall emissions on the right-hand axis .

Source: National Atmospheric Emissions Inventory[3] analysed by Air Quality Consultants Ltd

Figure 1: Trends in PM$_{2.5}$, PM$_{10}$ and NO$_x$ emissions from various sectors over time

Figure 2 shows the trends in estimated $PM_{2.5}$ and NO_x emissions from road transport since 1970, sub-divided by different road transport sources.[3] (PM_{10} is not displayed but has very similar results to $PM_{2.5}$). The substantial decline in overall estimated emissions since the early-to-mid 1990s corresponds with the introduction and subsequent increasingly stringent emissions regulation applied to road vehicles.



Note: The dashed black line indicates the contribution of road transport to the overall emissions on the right-hand axis .

Source: National Atmospheric Emissions Inventory[3] analysed by Air Quality Consultants Ltd

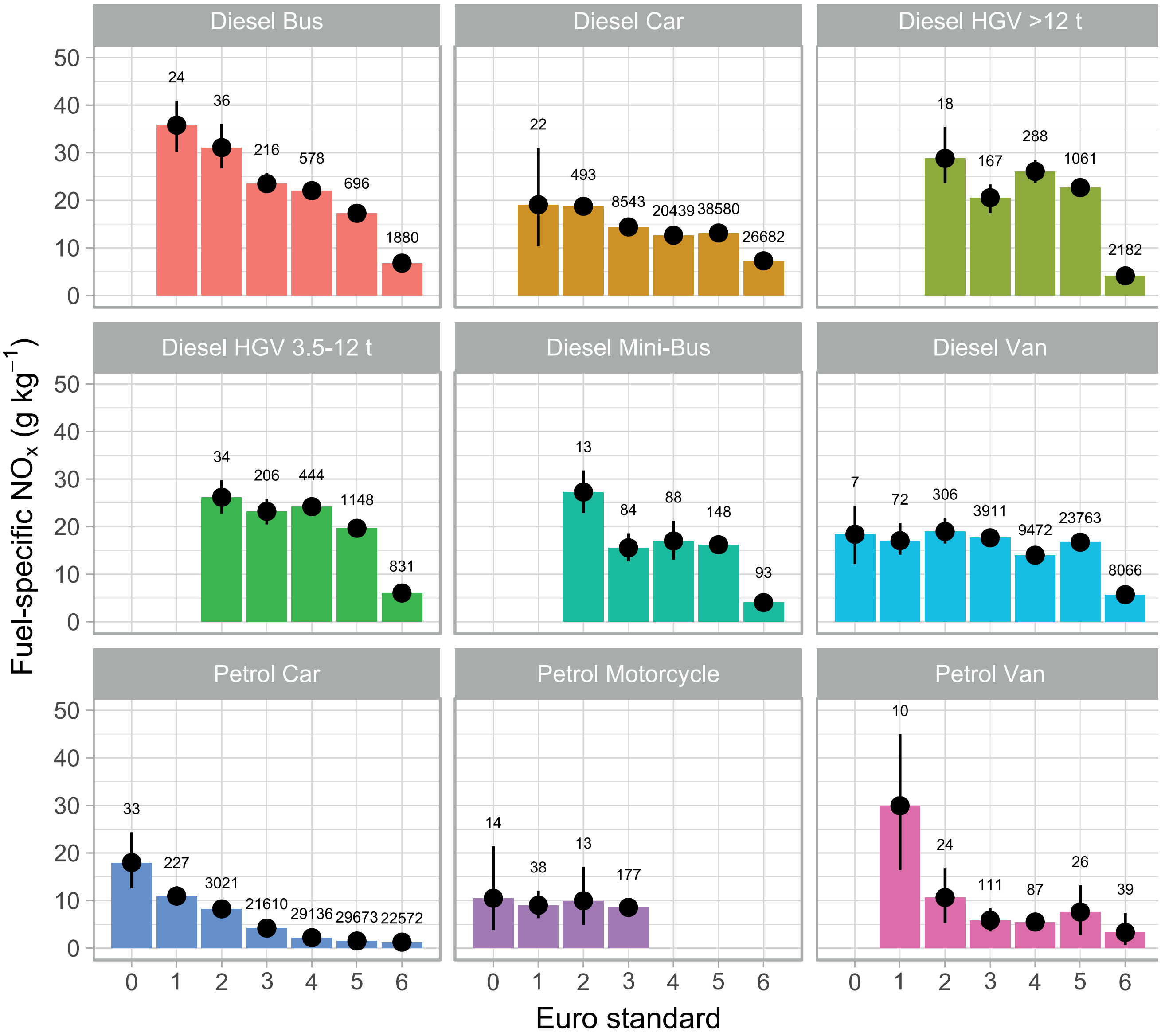
Figure 2: $PM_{2.5}$ and NO_x emissions from road vehicle sources since 1970

The relative contribution of road transport to national total emissions does not reflect its contribution to the UK population's air pollution exposure. This is because proximity to an emission source is important and emissions from road traffic are often associated with populous urban settings in ways that emissions from, for example, heavy industry are not (see Section 4.5.1). The build form of urban environments also often restricts dispersion and dilution of pollutants alongside roads (see Section 4.3). Many of the highest concentrations of $PM_{2.5}$ and NO_2 are at roadside locations, and a large number of people live in close proximity to main roads. The roadside increment is far more prominent for NO_2 than $PM_{2.5}$ because of the large background of mainly secondary particles. NO_x emissions from traffic contribute to secondary particles, but they do so regionally, rather than locally.

The estimated emissions depicted in Figures 1 and 2 were derived by combining estimates of the rates at which different types of vehicles emit, with estimates of the distance travelled on different roads. However, measurements have not always shown the same strong reductions in NO_x concentrations as is suggested by emissions models.[4] While NO_x and NO_2 concentrations measured at UK roadsides typically reduced appreciably between about 1996 and 2002, this was followed by a prolonged period of relatively stable concentrations. As a whole, NO_x concentrations measured at urban roadside sites declined only weakly between 2002 and 2016 and, at many sites, concentrations increased for large parts of this period. Reductions in roadside NO_2 concentrations were often even smaller, and increases even more common; this relates to changes in the proportion of NO_2 in vehicle exhausts.[5]

Analysis of the chemical composition of exhaust plumes has helped to reveal the cause of the discrepancy between emissions forecasts and measurements.[6] While estimated emissions assumed that newer vehicles conforming to more recent Euro standards would deliver improvements over earlier models, this was often not the case when these vehicles were driven on real roads. In particular, average NO_x emissions from diesel vehicles did not fall appreciably between the Euro 3/III and Euro 5/V standards, and in some cases emissions increased, as shown in Figure 3.

Later parts of this section explain why real-world emissions did not decline as expected, and the engineering solutions that were put in place to address the issue. As a result of these efforts, equivalent analyses of NO_x emissions from more recent vehicles have shown significant improvements, (see Figure 3). NO_x emissions from Euro VI heavy duty vehicles have tended to be only a fraction of those from earlier models, and NO_x emissions from Euro 6 diesel cars and vans have also shown appreciable improvements, particularly for the later stages of this emission standard, (see below for more detail).

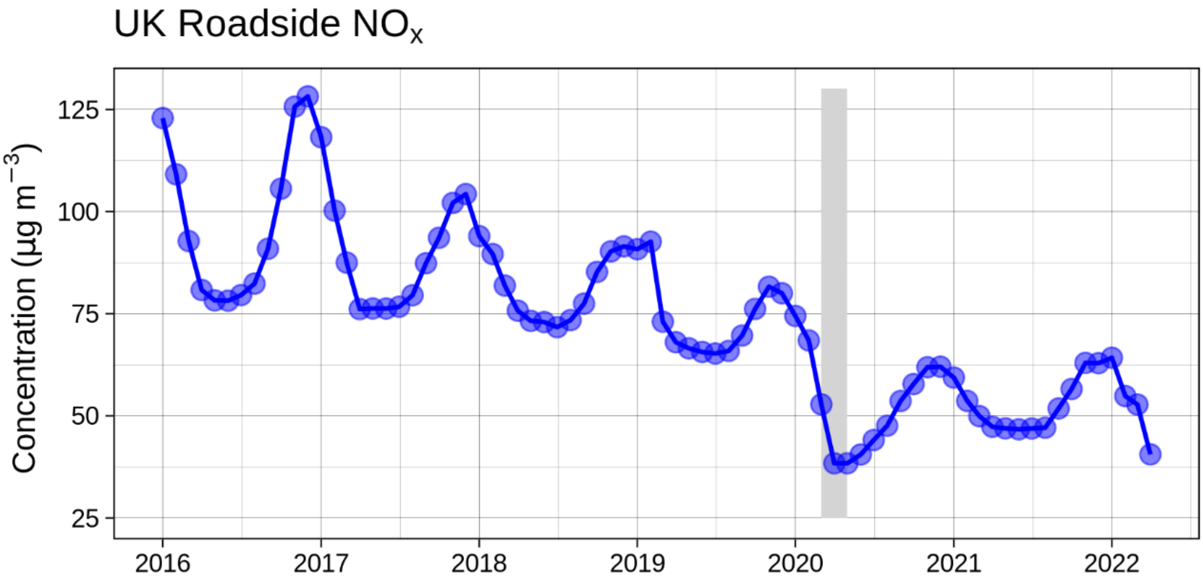


Note: This data represents summaries of remote sensing data collected between 2017 and 2018 by Ricardo Energy & Environment. The uncertainty intervals relate to the 95% confidence interval in the mean, and the numbers at the top of each bar show the number of valid measurements.

Source: Defra (2021)[7]

Figure 3: Summary overview of emissions of NO_x from different classes of vehicle, split by Euro classification

The improvements shown in Figure 3 are also seen in measured concentrations. An analysis of roadside NO_x concentrations between 2016 and 2022[8] shows a decline of more than 40% occurring since 2016, as displayed in Figure 4. This is likely to be associated, at least in part, with the introduction of Euro 6 light duty diesels and Euro VI heavy duty vehicles.



Note: The grey shading indicates the period March to May 2020 when the first UK-wide COVID-19 lockdown was enforced.

Source: Data from UK Automatic Urban and Rural Network (AURN), Scottish Air Quality Network (SAQN), Welsh Air Quality Network (WAQN) and Air Quality England network, analysed by Air Quality Consultants (data adjusted using boosted regression trees)

Figure 4: Average monthly deweathered mean NO_x concentrations from 129 roadside monitoring sites from across the UK

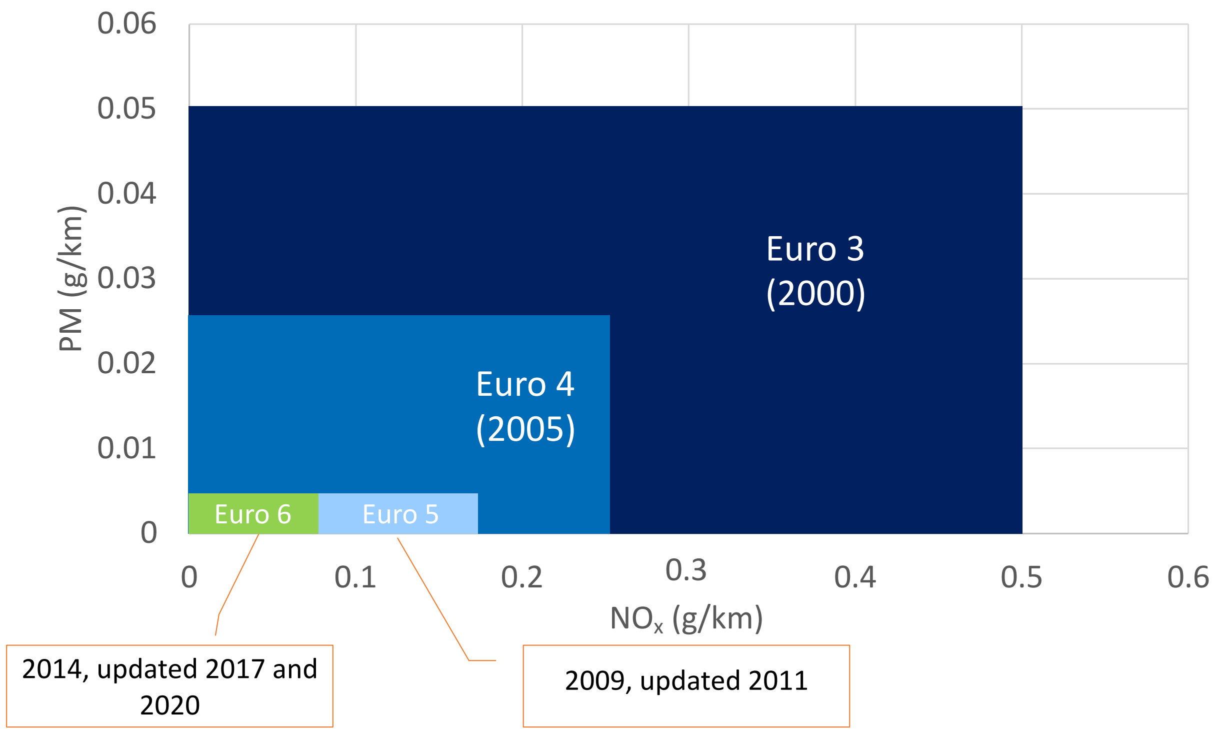
Regulation to reduce road vehicle air pollution emissions

The first European-wide regulations were introduced from 1992, with the first named Euro 1. Tighter restrictions were applied typically every 4 to 5 years, with the most recent Euro 6 standards applying from 2014 for heavy duty vehicles and 2015 for light duty vehicles (for new registrations).

Regulations require each type of vehicle to be tested in a laboratory on a rolling road, following a defined test cycle, intended to simulate on-road driving. For light-duty vehicles these tests also measure fuel economy and carbon dioxide (CO_2) emissions. The exhaust emissions are captured and measured by complex and accurate analysers, and must be below the permitted levels to allow the vehicle to be certified to be sold.

For light vehicles, the emissions are controlled in grams (g) or milligrams (mg) per kilometre (km), whereas for heavy vehicles, recognising the huge variation in vehicle types, they are related to the engine output power, and measured in g or mg per kilowatt-hour (kWh).

Figures 5 to 7 show the most recently regulated Euro levels for total PM and NO_x.

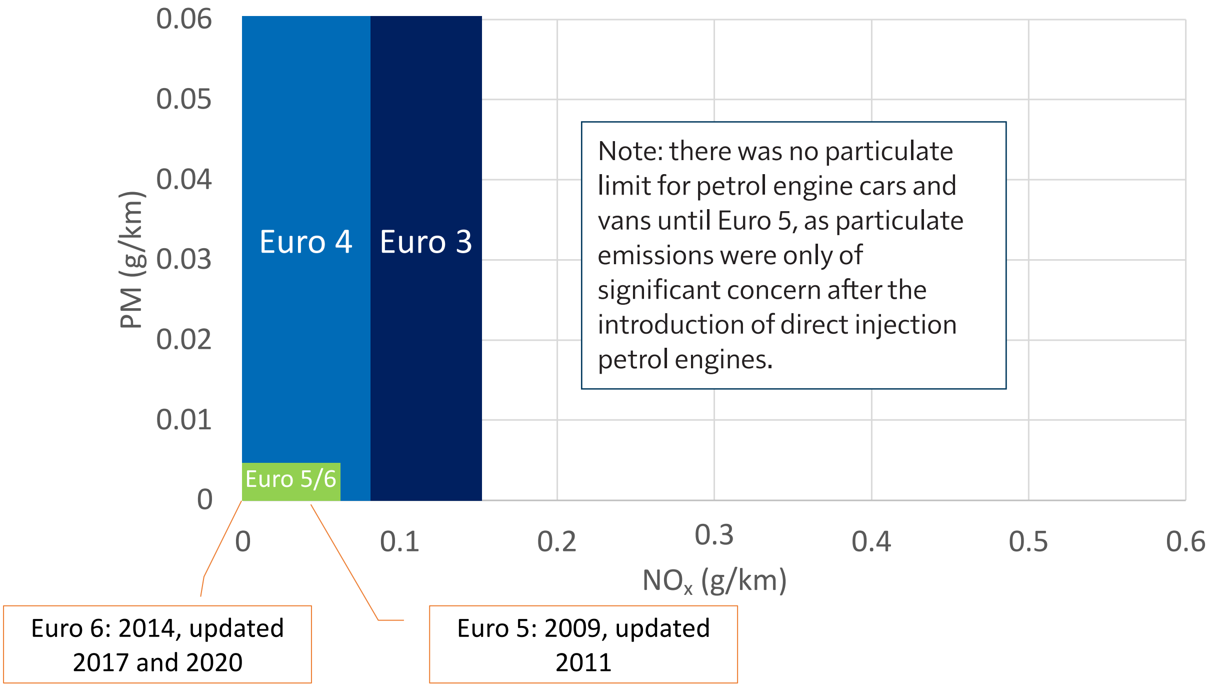


2014, updated 2017 and 2020

2009, updated 2011

Source: Chart created using data from Worldwide Emissions Standards and Delphi Technologies, 2020/21[9]

Figure 5: Evolution of NO_x and PM standards for diesel cars and vans



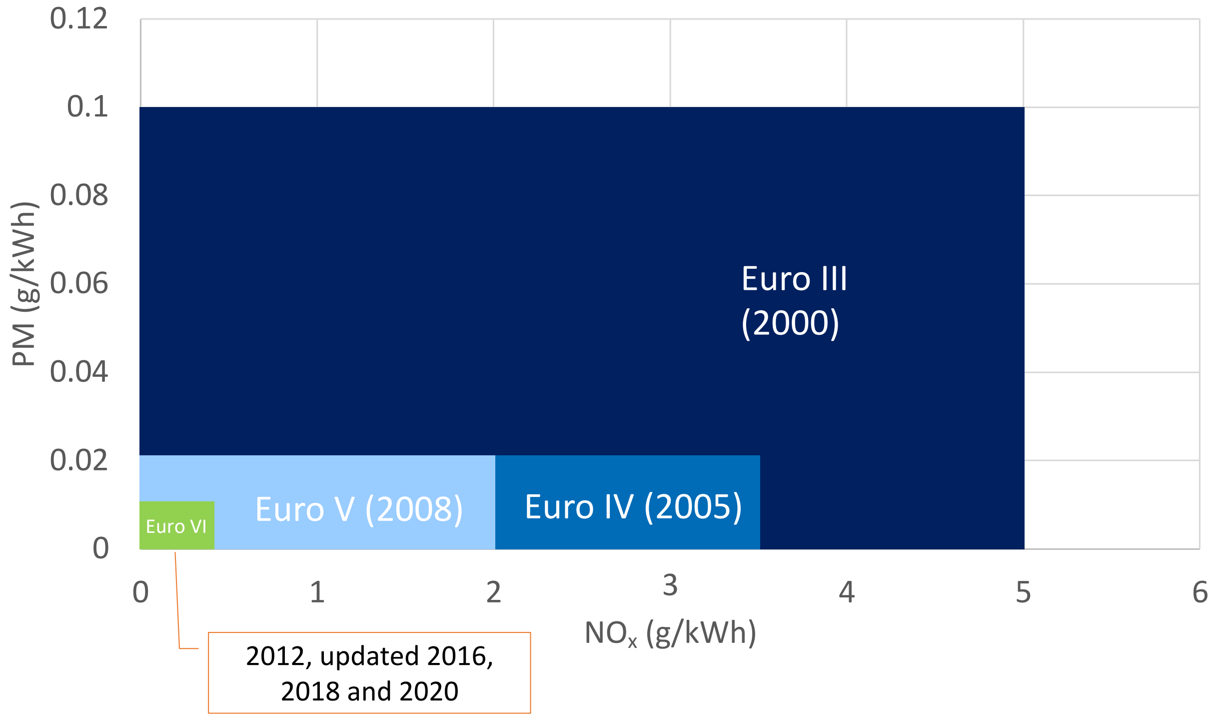
Note: there was no particulate limit for petrol engine cars and vans until Euro 5, as particulate emissions were only of significant concern after the introduction of direct injection petrol engines.

Euro 6: 2014, updated 2017 and 2020

Euro 5: 2009, updated 2011

Source: Chart created with data from Worldwide Emissions Standards and Delphi Technologies, 2020/21[9]

Figure 6: Evolution of NO_x and PM standards for petrol cars and vans



Note: Absolute NO_x amounts 10x scale of light duty vehicles, and per kWh rather than per km.
Source: Chart created with data from Worldwide Emissions Standards and Delphi Technologies, 2018/19[10]

Figure 7: Evolution of NO_x and PM standards for buses and trucks

It can be seen from the size of the coloured areas of the figures that successive Euro regulations have required significant reductions in exhaust emissions, especially from diesel vehicles, where reductions in both NO_x and PM are in the range of 84–90%.

As the health effects of $PM_{2.5}$ have become better understood, additional regulations have been brought in to restrict the specific number of particles emitted, known as PN limits. These tiny particles have little effect on the total mass of PM but can have harmful health effects. PN limits for light and heavy vehicles are typically more stringent than the associated PM requirement, driving further technology development to meet the targets.

Regulation and test conditions

As a result of the diesel emission test 'defeat device' scandal that first emerged in September 2015, combined with atmospheric measurements showing that local levels of NO_x were not falling as rapidly as suggested by the Euro standard limits, many organisations across Europe started undertaking measurements of NO_x emissions from diesel vehicles while driven on the road, rather than in the laboratory. This testing was enabled by the developments of portable emissions measurement systems (PEMS), which were small enough to mount inside a driven vehicle to sample the exhaust gases in real time.

A study conducted by the Kraftfahrt-Bundesamt (KBA) in Germany, reported by the International Council on Clean Technology in 2016,[11] included on-road testing of 30 light-duty diesel vehicles from a range of manufacturers. The KBA results showed that, although a small number of vehicles did match the laboratory test NO_x emissions, the majority exceeded the limit, with an average of around 5 to 6 times the legal New European Driving Cycle (NEDC) test level of 80mg/km, and 8 vehicles exceeded it by a factor of 10 or more. From this and similar testing, it became apparent that the Euro standards based on the NEDC test process did not provide an accurate representation of 'real driving emissions' (RDE).

The main criticisms of the cycle were that it was too short, with too low an average speed, and the acceleration phases were too gentle, not placing the engines under sufficient load compared to real-world driving. The limited scope of the test process had led most vehicle manufacturers to specify NO_x emission control systems which relied on NO_x traps, which stored NO_x under normal conditions and then converted it to nitrogen and water during special 'purge' events. These systems were effective on the slow and gentle NEDC cycle, but much less so in more aggressive real-world conditions, leading to an almost universal switch to more effective (but more expensive) selective catalytic reduction (SCR) systems (see later in this section for further details of this technology).

Since the introduction of Euro 6 standards, the requirements for both light and heavy vehicles have been tightened further with a series of additional test requirements, including the switch from the outdated NEDC for light vehicles, to the more representative Worldwide Light-duty Test Cycle (WLTC), plus additional cycles representing more extreme RDE. For all types of vehicle, the regulations now require actual on-road validation of the emission results, using PEMS in addition to a more extensive suite of laboratory tests.

The combined effects of the lower NO_x and PM limits, more extensive and representative laboratory test cycles, plus on-road testing, have resulted in on-road emissions of these pollutants from diesel vehicles being reduced by up to 95% compared to levels required less than 20 years ago. For petrol engines, the changes have been less dramatic, with the Euro 4 level being broadly equivalent to the Euro 6 diesel standard, which is why these respective levels are required for clean air zones and low emissions zones in England. The London case study in Section 6.3 describes changes to road user charging in the city from 2008, with requirements for Euro standards for different vehicles. It also presents air pollution maps, showing considerable reductions in air pollution concentrations in the city (some of which is from vehicle sources).

Of note, Euro 7/VII is expected to be announced later in 2022 with the inclusion of some additional, currently unregulated emissions, with implementation likely in 2025/26.

So far, this section has looked at road vehicles. Separate requirements are set for off-road machinery (known as non-road mobile machinery) such as agricultural tractors and construction equipment. Further standards apply to diesel engines used in railway locomotives and shipping, which can dominate in specific areas, such as enclosed stations and seaports. Reducing air pollution emissions from the railway, aviation and maritime sectors are discussed further in Sections 4.1.3 and 4.1.4.

Engineering interventions to reduce road vehicle air pollution emissions

Engineering solutions have been developed to achieve the low air pollution emissions required by regulatory standards.

Internal combustion engine technology

Most road transport – from small mopeds through to heavy trucks, as well as off-road machinery – are powered by internal combustion engines. Internal combustion engines operate by combining a mixture of air from the atmosphere with a hydrocarbon fuel – most commonly petrol or diesel, but also including gaseous fuels such as natural gas (methane) or LPG (butane and propane).

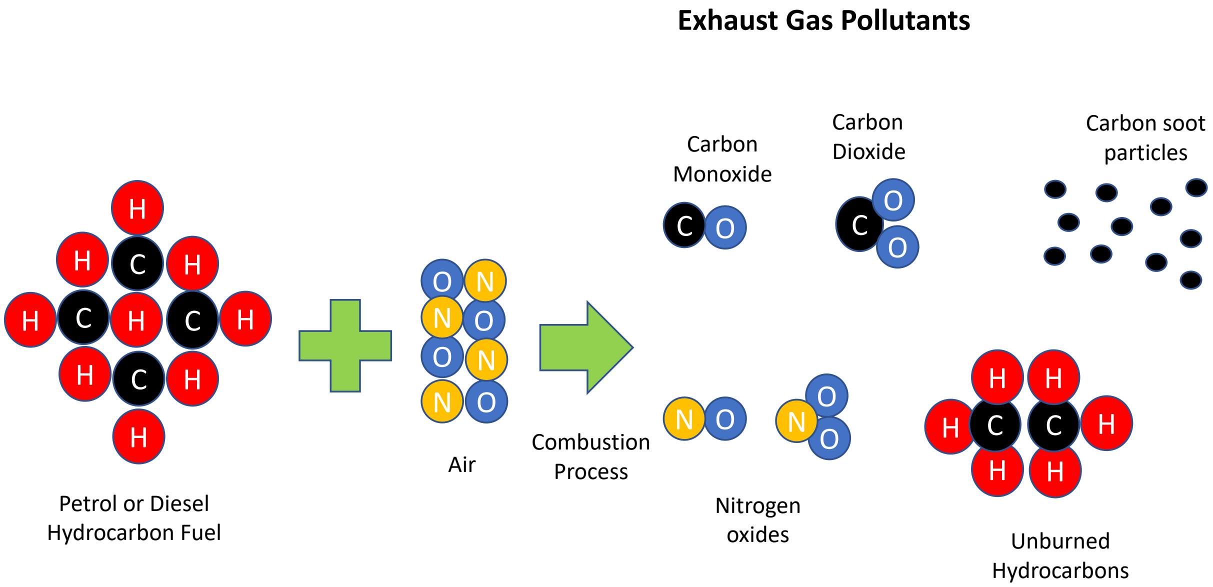
Independently of the size and complexity of the engine, the basic principle of combining and burning a fuel and air mixture inside a cylinder to produce power remains the same. However, there are two core types of engine, depending on how the fuel and air mixture is ignited within the cylinder. In a spark ignition engine – a petrol engine – an electrical spark is supplied via a spark plug within each cylinder, to ignite the mixture at the correct time in each engine cycle. In a compression ignition engine – a diesel engine – the fuel is ignited solely by the heat generated by the air being highly compressed by the piston rising up the cylinder and squeezing the trapped air until it becomes extremely hot, and is able to directly cause combustion of the fuel.

Diesel engines are typically more expensive to manufacture than petrol engines, due to the higher cylinder pressures involved and the very high-pressure fuel injection systems used to deliver fuel directly into the combustion engine. However, they usually offer significantly better fuel economy due to the way the combustion process operates. For this reason, diesel engines have been almost universally favoured in all commercial and heavy duty vehicles, as well as rail and marine applications, for the past 50 years or longer. Due to lower costs and lighter weight (among other characteristics) petrol engines tend to dominate in lighter vehicles. However, with the fuel economy benefits, combined with lower CO_2 emissions, the diesel car market grew steadily until 2016 and sales peaked at nearly 40% of the car market, before there was a rapid decline.

Reducing vehicle engine air pollution emissions

For the engineers designing and developing internal combustion engines, the aim is for the fuel and air to be mixed and burned as close to perfectly as possible to achieve maximum efficiency from the engine and minimum pollution from the exhaust. With perfect combustion, the hydrocarbon (HC) fuel will combine with oxygen (O_2) from the air, to produce only carbon dioxide (CO_2) and water (H_2O).

Despite major advances in the mechanical design of the engines, the fuel injectors and other components, and sophisticated electronic control units (ECUs), it is not possible to guarantee that the fuel and air combine perfectly and burn under all operating conditions. As a result, small quantities of three products of incomplete combustion are emitted from the exhaust: unburned fuel (HC), carbon monoxide (CO) and black soot particles (mainly carbon). In addition, the very high temperatures and pressures that occur during the combustion process can also cause normally unreactive nitrogen (N_2) to combine with oxygen to form nitrogen oxides (NO_x). This is illustrated in Figure 8.



Source: Adapted from Salih AM and Ahmed A-R M[12]

Figure 8: Typical pollution formation in an internal combustion engine

All the above pollutants are formed within both petrol and diesel engines, but both the absolute and relative quantities vary markedly with the engine type as well as the operating condition, especially the load upon the engine. Petrol engines generally emit higher levels of most pollutants, but these are more readily removed by highly efficient catalysts fitted to the exhaust (see later in this section), provided the engine operates at the chemically correct or stoichiometric air fuel ratio. Diesel engines operate with excess air and usually employ exhaust gas recirculation which substantially lowers engine NO_x emissions, but imperfect mixing of air and fuel produces soot particles.

The subject of reducing pollution from internal combustion engines is a complex and far-reaching topic, which has occupied hundreds of thousands of engineers globally over the past 50 years or more, with both vehicle manufacturers and their suppliers having spent hundreds of billions of pounds to achieve the improvements. Within the confines of this report it is only possible to give a very short overview of some key areas.

Engine design

Petrol engines

Since the first Euro regulations in 1992, petrol engines have largely followed the US practice of applying increasingly sophisticated fuel injection and electronic engine control systems (ECUs). Progress in maximising combustion efficiency while minimising pollution has been achieved through combined optimisation of the combustion, aftertreatment and control systems. Fuel injection and ECUs have generally been applied to ensure that the exhaust catalyst can operate at optimum efficiency, particularly during transient conditions such as when varying throttle positions.

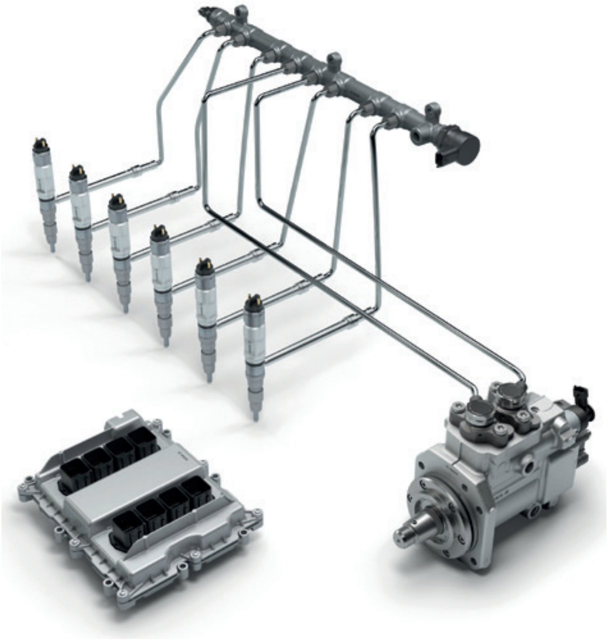
In the closed-loop fuel control, an oxygen sensor in the exhaust sends a signal to the ECU, allows it to continuously adjust and correctly match the fuel injected to the air flowing through the engine, thus greatly improving combustion accuracy, reducing pollutants. Over the subsequent 30 years, ECU control has become more complex and capable, allowing more precise engine combustion and pollutant reduction, as well as CO_2 improvements. From Euro 3 in 2000, ECUs also incorporate very sophisticated on-board diagnostic software, which continuously monitors all operations relating to emission control, and warns the driver if a repair is required, helping keep the vehicle operating in its original condition.

Another major source of HC emissions can be evaporation from the petrol tanks, which is particularly an issue in warm weather. To prevent this, all petrol cars are now fitted with canisters filled with activated charcoal, as used in gas masks. Vapour emitted from the fuel is trapped in this charcoal, and then returned to the engine and burned when the engine is running.

Diesel engines

As with petrol engines, diesels have benefitted from the adoption of advanced engine management, (although 5 to 10 years later, as diesels did not benefit from early development in the US). Alongside turbocharging, the single greatest advance in diesel engine design took place in the late 1990s with the advent of the first common-rail (CR) injection systems.

The CR approach uses one common reservoir of high-pressure fuel from a pump, feeding all the injectors in the engine, each of which is then controlled independently by the ECU, as shown in Figure 9. This allows more accurate control of the timing and quantity of fuel injected on each engine stroke. CR injection was a revolution in diesel technology, with very accurate injection timing and quantity, and the use of multiple injections per engine stroke, which was not possible previously. This reduced formation of NO_x and PM, as well as greatly reducing the noise of combustion, and improving fuel economy and CO_2 emissions. The flexibility of CR also allowed much more efficient aftertreatment systems, (discussed below).



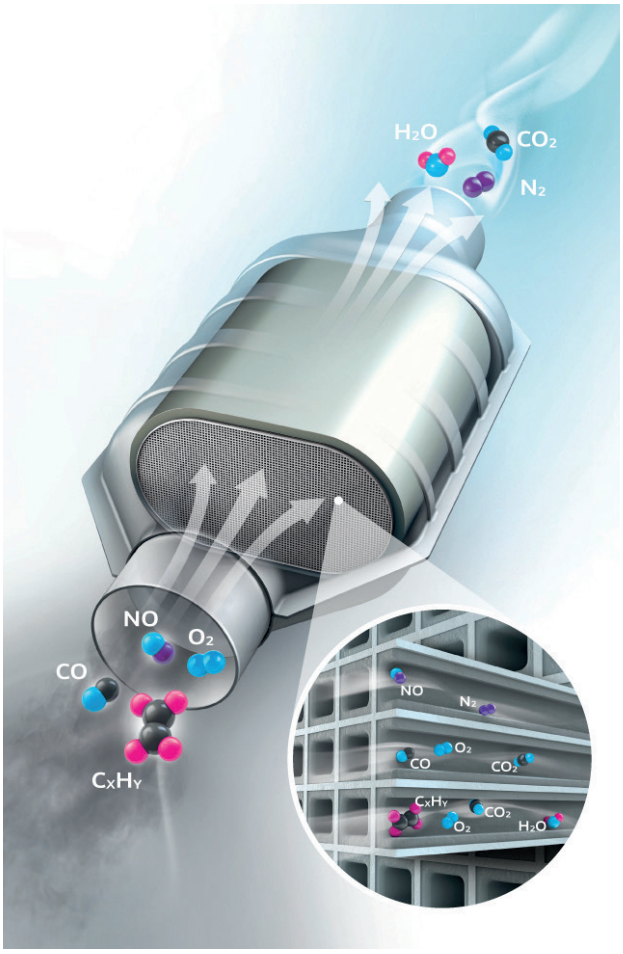
Note: Figure shows high-pressure pump, fuel rail, injectors and ECU.
Source: Courtesy of Robert Bosch, Bosch Media[13]

Figure 9: Typical common-rail system

Aftertreatment systems

Aftertreatment systems are the collective name for all processes used to treat the pollutant exhaust gases after they have left the engine combustion chamber, and before being exhausted to the atmosphere. There are two broad types: catalytic converters, often known as catalysts, which encourage chemical reaction of the gases (HC, CO and NO_x) to form less harmful products; and particle filters, which remove and then burn PM. Alongside the engine design improvements previously described, these aftertreatment systems have contributed greatly to pollution control.

Catalysts are ceramic honeycomb structures mounted in the vehicle exhaust, through which the exhaust gases pass (see Figure 10). The hundreds of small channels in the honeycomb provide a large surface area in contact with the gases, and this surface is treated with a chemical washcoat, containing catalytic precious metals, usually a combination of platinum, palladium and rhodium, which encourage chemical reactions.

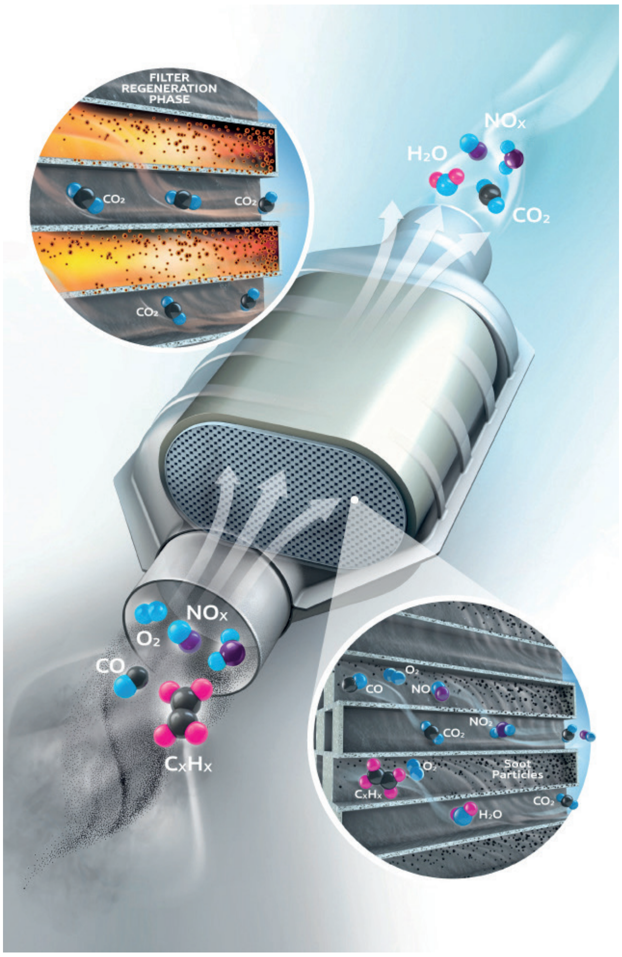


Notes: The figure shows the honeycomb catalyst structure mounted in the exhaust. Pollutant gases enter and are converted via chemical reactions into water, nitrogen and carbon dioxide.

Source: Courtesy of Johnson Matthey

Figure 10: A typical automotive catalyst for a petrol engine

Particle filters use a similar ceramic honeycomb design, but with opposing ends of every small channel closed off. This forces the gas to flow through the ceramic walls, which contain tiny pores that trap the particles, as shown in Figure 11. Advanced manufacturing methods can tune these pores to match the particles generated by different engine types, providing effective PM reduction.



Note: Soot particles from the engine enter the front of the honeycomb structure, and are trapped by the closed ends of alternating channels. When the exhaust reaches a high temperature, these carbon soot particles are burned off to produce carbon dioxide, which flows through the porous channel walls into the tailpipe. In some applications, catalytic metals are also added to the filter walls to provide further treatment of pollutant gases.

Source: Courtesy of Johnson Matthey

Figure 11: A typical automotive particle filter for a diesel engine

Catalysts – petrol engines

Catalysts on petrol engines are specifically designed to simultaneously remove CO, HC and NO_x, and are known as three-way catalysts. To achieve conversion, the catalyst must be hot, and petrol engines inherently produce hot exhaust gases. Mounting the catalyst as close as possible to the engine means that, on modern engines, the catalyst will get hot enough to operate within about 30 seconds of starting from cold, giving effective pollution control, even on short journeys.

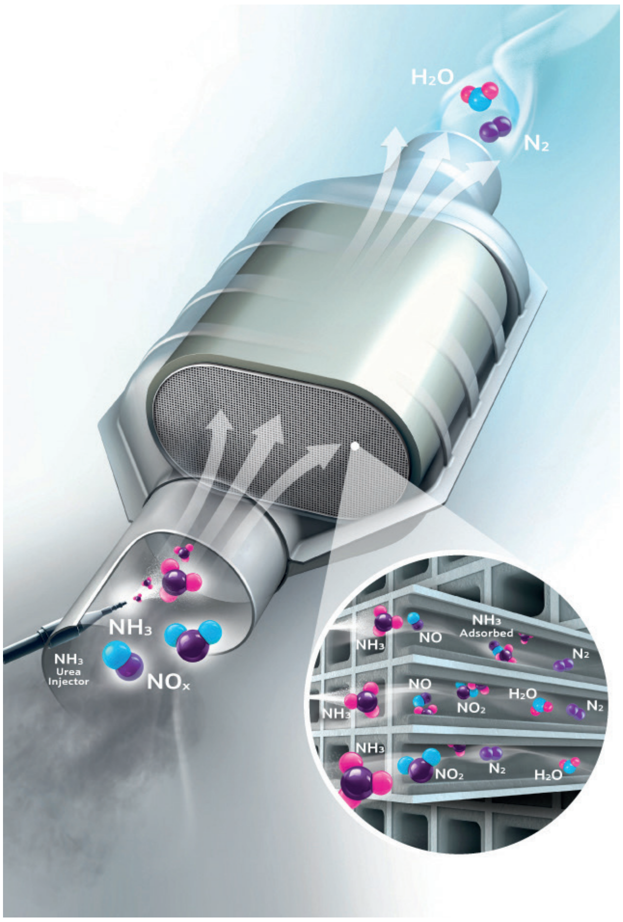
For petrol engines using port-injection, filters are not normally required, as the fuel is vaporised before combustion, which produces negligible PM. On direct injection, petrol engines (as now used by many manufacturers) tend to produce PM: the fuel is injected directly into the combustion chamber and some droplets do not fully evaporate before combustion, causing PM to form. The levels of PM are far lower than on diesel engines, however, the EU 6 strict limits on the number of particles (PN limits), especially the rigorous RDE tests, have required filters on many of these engines.

Catalysts – diesel engines

Unlike petrol engines, where fuel and air are almost perfectly matched to the chemically correct level for complete combustion, diesel engines almost always run with excess air. This excess of oxygen means that it is not possible to use a three-way catalyst to simultaneously treat HC, CO and NO_x. All diesels therefore first use a diesel oxidation catalyst, which very effectively oxidises any HC and CO to CO_2 and H_2O.

The stringent Euro 6/VI regulation for air pollution emissions led most vehicles – especially larger cars, vans and heavy vehicles – to introduce a second catalyst system to control NO_x. This is selective catalytic reduction (SCR), which uses a liquid reagent, commonly known by the trade name of AdBlue, to react with the NO_x in a catalyst, as shown in Figure 12. The ECU measures the NO_x via a sensor in the exhaust prior to the SCR catalyst, and accurately injects the correct quantity of AdBlue to react in the catalyst and convert NO_x into water and nitrogen (H_2O and N_2).

As long as the vehicle is kept topped up with AdBlue, these SCR systems achieve extremely high NO_x conversion rates, often 97–98%. SCR catalysts also need to be hot to function – typically 200°C – which, on modern cars and vans, can be achieved within 2 to 3 minutes of starting (the timing is somewhat longer for the larger systems fitted to heavy duty vehicles such as buses).



Note: Aqueous urea (AdBlue) is injected into the exhaust gas upstream, and the specialised catalysts convert this and the NO_x into water and nitrogen at the tailpipe.

Source: Courtesy of Johnson Matthey

Figure 12: Typical automotive selective catalytic reduction (SCR) system

PM will travel through the catalysts largely unconverted. To address this, all modern diesels for on-road use will add a diesel particle filter (DPF). DPFs are efficient at trapping PM, and when the exhaust gases get hot enough, the trapped carbon PM will oxidise with the excess oxygen in the exhaust to form CO_2.

Fuel quality improvements

Alongside the major improvements made in vehicle pollution control systems, oil companies have worked in partnership with vehicle manufacturers to improve the quality of petrol and diesel fuels substantially, further contributing to air quality improvements. Most visible among these was the move to unleaded petrol in the early 1990s which was mandated by the adoption of catalysts, which can be harmed by lead. Elimination of atmospheric lead was a major step for air quality.

There has also been the dramatic reduction in sulphur content in diesel fuel, which dropped by 99.5% between 1993 and 2011, effectively eliminating the formation of the pollutant sulphur dioxide.

Zero exhaust emissions – light vehicles

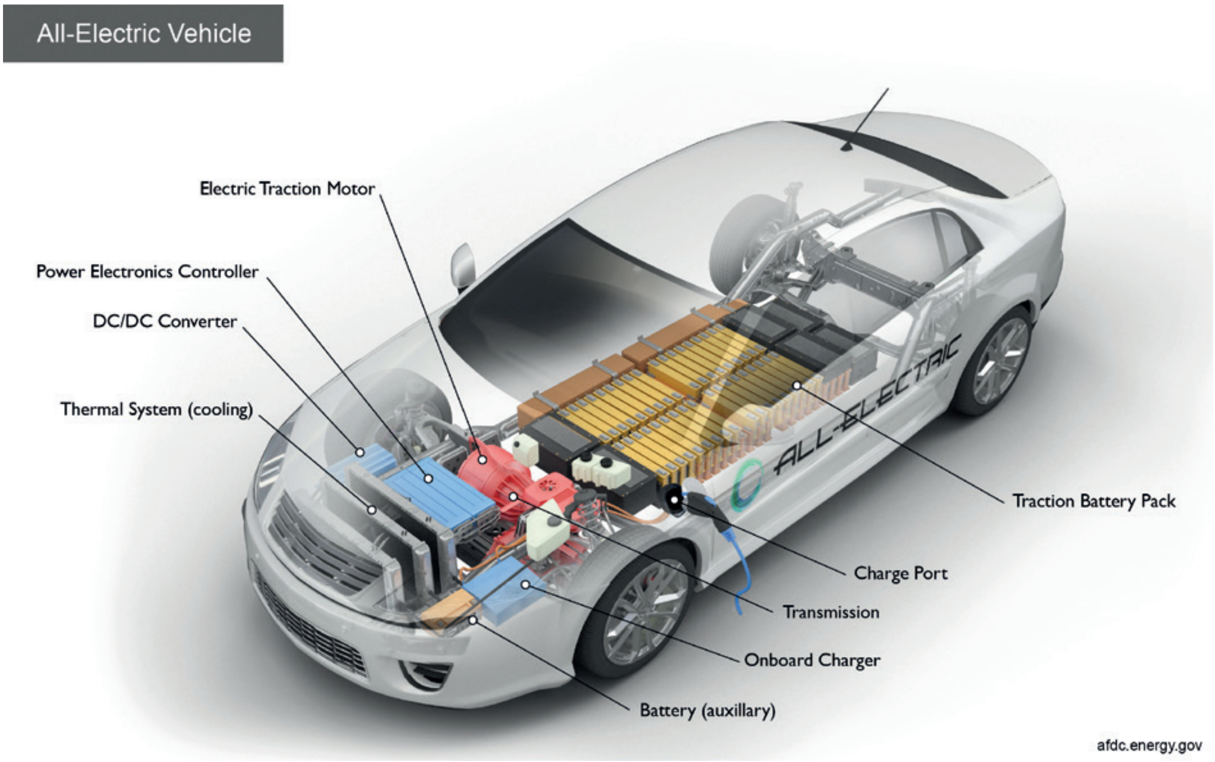
As discussed, for new internal combustion engine vehicles, the engine and aftertreatment technologies create reductions in key pollutants. However, vehicles with near-zero tailpipe emissions, (at least when operating in urban environments), can further reduce people’s exposure to exhaust air pollution emissions. Possible zero tail pipe emissions solutions for different vehicle types are discussed below. There are also non-exhaust vehicle emissions, such as from brake and tyre wear, which are discussed later in this section. Ways to reduce vehicle air pollution emissions through active travel are discussed in Sections 4.3 and 4.4.

For passenger cars and light commercial vehicles in the near term, it is highly likely that the favoured zero tailpipe emission solution will be battery electric vehicles (BEVs), using Lithium-ion (Li-ion) batteries and electric motors. Alternative technologies such as hydrogen fuel cells have been developed and put into production, but their sales remain small, mainly due to relatively high costs and a lack of a hydrogen refuelling infrastructure.

Battery electric vehicles

The primary component of a battery electric vehicle (BEV) is a large, rechargeable, traction battery pack, usually mounted in the floor between the wheels, as shown in Figure 13. The battery is charged periodically by plugging into the mains supply via a cable and charging port on the vehicle. The onboard charger converts the alternating current (AC) of the mains supply into direct current (DC) required for the battery. Once charged, the battery supplies power to one or two traction motors, between either one or both pairs of wheels.Some BEVs have one motor, but many BEVs have two motors, mounted front and rear, giving all-wheel drive. A power electronic controller regulates the power to the motors in response to driver demand. Both batteries and motors require cooling, so BEVs still require a (smaller, but more complex) cooling system, and a DC-to-DC converter changes the very high voltage of the battery (typically around 400 volts) to 12V for all the other vehicle systems.

The main advantage for battery and fuel cell vehicles (which both use electric motors for propulsion) is that, when the driver lifts off the throttle or presses the brake pedal, the motors operate in reverse as generators, converting the kinetic energy of the moving vehicle back into electrical energy, which is stored in the battery for re-use. This process is known as regenerative braking and enables large quantities of electrical energy to be re-captured and effectively recycled, rather than simply lost as heat, as happens with the friction brakes of conventional cars. This re-use of the battery energy is a key factor in enabling BEVs to achieve greater ranges, especially in city driving, when speeds vary greatly and brakes would be used more often. Many BEVs are now designed so that they can be driven in 'one pedal' mode, where the regenerative braking effect when the driver lifts off the throttle is sufficient to bring the vehicle to rest in many driving conditions, without the need to use the brakes at all. The regenerative braking reduces air pollution emissions, as it removes the emissions from friction brakes. An example of a BEV is shown in Figure 13.



Source: US Department of Energy (DOE)[14]

Figure 13: Cutaway view of typical electric vehicle

BEVs are now a mainstream technology, with millions sold globally, and nearly every major Original Equipment Manufacturer having stated publicly, that (at least in Europe) they will produce only electric or plug-in hybrid vehicles (PHEVs) in the sub-3.5 tonne categories from no later than 2030. Batteries have advanced to the point where sufficient energy can be stored to provide ranges up to around 300 miles in cars (depending on the battery size fitted), and typically 150–200 miles in vans. However, these ranges are based on the formal Worldwide Harmonised Light Vehicle test cycle and can be considered optimum. Motorway driving will reduce range considerably, due to the increased power required, and cold weather can have a similar effect due to the energy needed to heat the occupants, and keep the batteries at operating temperature. Nevertheless, the effective range is sufficient for the daily needs of many drivers, and the significantly lower cost of electricity compared with petrol and diesel, plus other benefits such as no road tax, are significant financial incentives. In 2021, data from the Society of Motor Manufacturers and Traders (SMMT) showed that, despite typically higher prices compared to combustion-engine vehicles, fully electric vehicles took a 12% market share in the UK, with plug-in hybrid vehicles a further 7%. BEV sales in 2021 exceeded the previous 5 years combined.[15]

Delivery vans have been the area of greatest sales growth and annual mileage over the past 5 years, driven by internet sales and home deliveries. Electrification of this fleet is therefore important for both air pollution and CO_2 reduction. Development of BEV vans have lagged behind cars by several years, but many manufacturers now offer models, and large manufacturers have committed to major increases in sales from 2022 onwards – for example, Ford, with the launch of the all-electric E-Transit™. The purchase price remains significantly higher than diesel vans, and fleet operators also have significant upfront capital costs with connection charges and charging equipment for depot-based systems. Some operators are willing to absorb the extra costs, and will switch to BEV due to the environmental, social and governance benefits. However, further incentives, subsidies or technological breakthroughs may be required to achieve the necessary take-up rates to meet CO_2 emissions reduction targets and reduce air pollution emissions from van fleets. Many operators may look towards plug-in hybrids as a more affordable alternative. In addition to engineering of EVs and hybrid vehicles, the infrastructure for battery charging locations and capacity are important considerations.

Hybrid vehicles

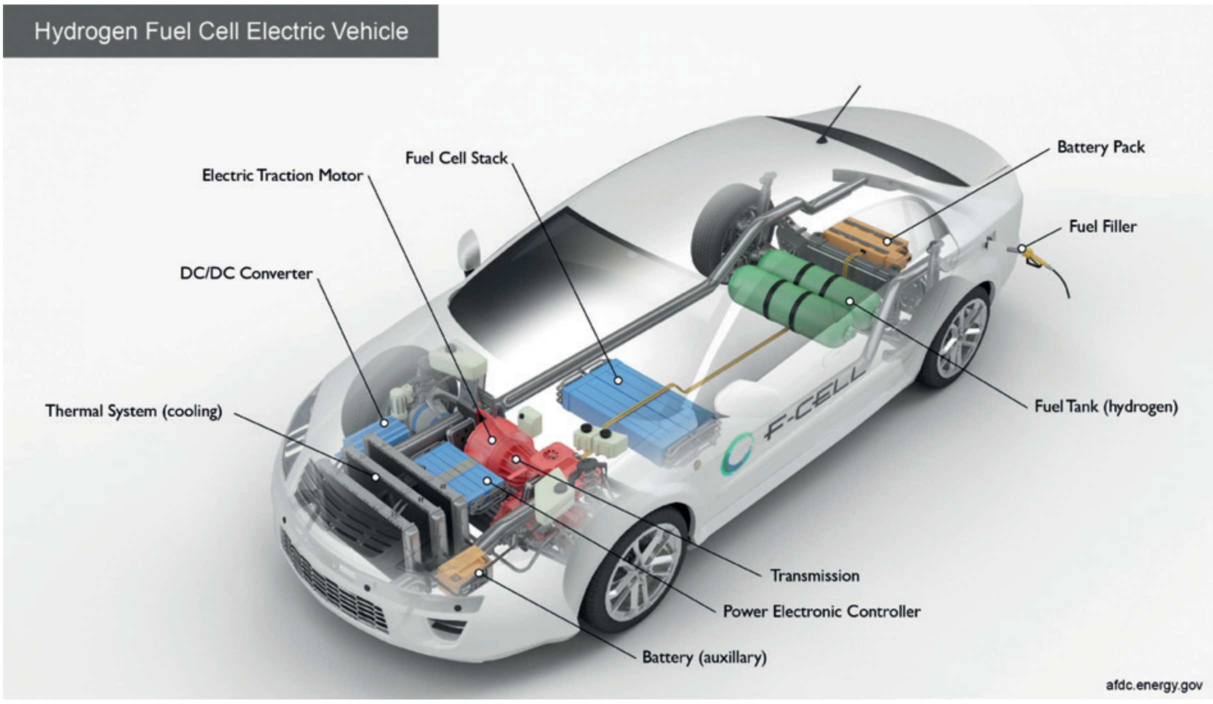
Hybrid powertrains include both a combustion engine and a battery-electric drivetrain. Self-charging hybrids contain a relatively small capacity (2–3 kWh) battery but this can still enable zero tailpipe emissions at low speeds and on short trips. Plug-in hybrids include a larger battery that can be re-charged from the grid and provide longer (typically 30 to 40 miles electric only range) and more frequent trips producing zero tailpipe emissions. Hybrid vehicles use regenerative braking that can significantly reduce friction brake wear and thus reduce particulate emissions produced from friction braking. Future hybrid vehicles will also be compatible with 'geo-fencing', where zero tailpipe emissions operation is enabled for locations where people congregate such as near schools, hospitals and dedicated shopping and pedestrian areas. Most hybrid vehicles contain a petrol engine rather than a diesel engine.

Hydrogen fuel cell vehicles

An alternative zero-emission exhaust solution proposed by several vehicle manufacturers is the hydrogen fuel cell (HFC) vehicle. HFCs share many key components with a BEV, with propulsion from an electric motor, control electronics, and a battery all being very similar. The main difference with an HFC is that, rather than the battery being large enough to provide enough energy for possibly hundreds of miles of driving, the battery in an HFC is substantially smaller and lighter, and is only designed to provide a 'buffer' of energy and power, both for accelerating the vehicle when higher power is required, and to allow energy to be recovered by regenerative braking, when the motors feed it back to the battery. The primary energy source in an HFC is hydrogen gas, usually stored at very high pressure of up to 700 bar (10,000psi) in specially designed cylinders. An example of a hydrogen fuel cell vehicle is shown in Figure 14.

To generate electricity, hydrogen is allowed to flow from the storage tanks to the fuel cell stack, where special chemical units combine the hydrogen with oxygen drawn from the atmosphere. In simple terms, the reaction in the fuel cell is a reverse of the familiar electrolysis reaction, where an electric current applied to water causes it to split into its constituents of hydrogen and oxygen. In the fuel cell, the hydrogen and oxygen are allowed to recombine, and force an electric current to flow around an external circuit, providing energy for the battery and motors. Therefore, the only emissions from the vehicle are small quantities of water.

The main advantages of HFCs include the ability to refuel in around 5 minutes, very similar to a conventional petrol or diesel car. They have significantly greater range than comparable BEVs. The overall weight is usually slightly lower than a comparable BEV, even one with shorter range, but this depends on the exact specification. Also, as the battery is far smaller than in a BEV, there is much less demand on the minerals such as lithium used in batteries.



Source: US Department of Energy (DOE)[16]

Figure 14: Cutaway view of typical hydrogen fuel cell electric vehicle

From a purely technical standpoint, there is much to commend the HFC approach, however, two main issues are currently inhibiting widespread adoption. Firstly, as BEVs have entered the mainstream, with relatively high volumes being produced, costs have fallen, such that HFC vehicles are now considerably more expensive, and the HFC stack is made from expensive materials. Secondly, no hydrogen fuelling infrastructure yet exists, beyond a few specific sites often installed and operated by a local authority or company. The inability to refuel either at home, as with a BEV, or at a widespread network of public fuelling stations, is currently a major issue.

Considering these issues, most industry experts predict that BEVs will be the dominant technology for the foreseeable future in the passenger car and light commercial market. In heavier commercial segments, including heavy goods vehicles (HGVs) and buses, the situation is less certain.

Zero exhaust emissions – other road vehicles

Buses

Due to extensive operation in urban areas, buses are one of the major road vehicles to move to zero tailpipe emissions, with very quiet operation being a further attraction in urban areas. As with light vehicles, the two primary technologies are battery-electric and hydrogen, but the far higher energy consumption of urban buses, especially double-deckers, leads to very large, heavy and expensive batteries being required to achieve daily operating ranges. There is considerable interest in the hydrogen fuel cell option for buses, although to date the BEV derivatives have dominated the zero exhaust emissions market.

Most buses offer opportunities to package sufficient battery capacity, usually 300–400kWh, which will typically give range of 130–150 miles on a double-decker, and 160–200 on a single-decker. This is enough to cover many (but not all) daily services, especially in relatively flat cities, in moderate climates. As with cars, operating in cities with significant gradients, or in cold climates where heating a large bus cabin consumes significant energy, will considerably reduce the range. Such large batteries, often weighing two tons or more, can also reduce the passenger-carrying capacity of the bus to stay under the weight limit. It is the greater range typically available from hydrogen storage, significantly reduced weight, plus refuelling in minutes rather than hours, which is the main attraction of hydrogen fuel cell technology, and may lead to deployment where that capability is required.

Buses typically return to depots overnight for at least 6–7 hours, which gives sufficient time for electric bus charging, even with a relatively modest 50kW. However, the charging infrastructure is expensive and can occupy significant space in constrained depots. Another constraint is often having to supply sufficient grid power to the depot – 50 buses all charging at 50kW requires a large 2.5MW supply, equivalent to around 3,000 houses, and some depots service as many as 200 buses. Most technical barriers are gradually being overcome, and electric bus sales are accelerating globally, including in Britain.

The main barrier for adoption is financial, with the large battery packs making EV buses around 2 to 2.5 times the cost of diesel. High annual mileages also mean that a battery replacement is likely to be required at least once in the vehicle life, adding further cost. Electric bus sales are therefore currently heavily dependent on government grants to achieve a degree of cost-effectiveness for the provider.

Heavy goods vehicles

For heavy goods vehicles (HGVs) with a rigid chassis, in the 7.5-26T weight range, electrification via batteries presents a technically feasible option, especially for vehicles doing relatively short daily mileages such as urban or local deliveries, and returning to base overnight to charge. As with buses, battery packs in the range of 300–400kWh are typically required, and the cost of these currently makes electric HGVs significantly more expensive than diesel – typically up to three times. It is expected that battery costs will decrease with time as global volumes increase, although in 2021 they rose around 10% with increased global demand. Government subsidies for electric HGVs via the plug-in truck grant are capped at £25,000, which falls well short of the current cost differential. As a result, although many major truck Original Equipment Manufacturers offer electric variants, take-up has been extremely low to date.

One area that has seen a significant shift to electric variants is refuse collection vehicles (RCVs). RCVs used in urban areas typically cover very short daily distances, but the intense stop-go operation, heavy weight, and use of compaction equipment, make energy demands very high. Diesel variants can have fuel economy as poor as 1–2 miles per gallon.

Source: Dennis Eagle UK

Figure 15: Dennis e-Collect refuse vehicle used by Islington Council

British manufacturer, Dennis Eagle UK, has had considerable success with their e-Collect electric RCV, see Figure 15, which has been on the market since 2020. Several local authorities have ordered them, accepting the higher cost in exchange for air pollution and CO_2 reductions, and quieter operation, which is popular with residents and operators.

The most challenging area for developing zero exhaust emissions solutions for HGVs is for articulated lorries from 30–44T, as these vehicles play a dominant role in modern logistics. They have very high energy demands due to high vehicle weight and long daily distances. Due to their design, articulated tractor units have very little additional space for packaging batteries or hydrogen tanks, and many operate two or three shift patterns, restricting charging opportunities.

Although some manufacturers have electric variants available, the future of the HGV sector is unclear. Technologies that are under development for HGVs include battery-electric, hydrogen fuel cell, hydrogen combustion engines and other solutions such as pantograph systems (as with electric trains, discussed in Section 4.1.3).

Almost all of the heavy duty engine manufacturers are working to develop hydrogen combustion systems. This is initially using port injection and spark ignition, but future systems will feature direct injection and reactivity controlled compression ignition or spark assisted combustion. Hydrogen's characteristics provide an opportunity to significantly improve air quality. Minor engine particulate emissions (resulting from a very small contribution from lubricating oil consumption in the combustion chamber) can be limited to near zero through the use of conventional gasoline type particulate filters. The primary challenges for widespread use of hydrogen as a transport fuel are likely to be availability and an adequate supply and distribution infrastructure. As such, its early adoption is more likely to be based around depot-based vehicles or in the construction industry.

As an interim technology for the next 15–20 years, many HGV fleets are switching to biomethane as a fuel, stored in either compressed gas or cryogenic liquid form. These offer sufficient range and rapid refuelling to maintain most operating patterns. In pollutant terms, a spark-ignition engine running on methane will offer equal or slightly better emissions than an Euro VI diesel engine, plus it will have considerably quieter operation.

Due to the technical obstacles, and the associated economic challenges, the government has currently set a target of 2040 for trucks more than 26T to have zero tailpipe emissions, and the European Automobile Manufacturers' Association (ACEA) have set a date of 2040 as a requirement for all heavy trucks to be 'fossil free'. This permits ongoing use of renewable combustion fuels, such as biomethane or synthetic diesel, if other solutions prove to be technically, economically or operationally infeasible.

Non-exhaust emissions

Reductions in PM and PN emissions from exhausts has led to increased consideration of the non-exhaust emissions from road vehicles, from brake and tyre wear, resuspension and road wear. In 2000, non-exhaust emissions (NEE) from brake wear, tyre wear, and road surface wear were estimated to be 5.8% of total UK PM_{10} emissions and 4.9% of total $PM_{2.5}$ emissions. In 2016, this increased to 8.5% of total UK PM_{10} emissions and 7.4% of total $PM_{2.5}$ emissions. By 2030, it is predicted to rise to 9.5% of total UK $PM_{2.5}$ emissions if no abatement measures on NEE are introduced.[17] These are relative increases in NEE and engineering solutions to reduce emissions from brake and tyre and road resuspension are discussed later in this section.

Unlike exhaust emissions, which have had nearly 50 years of detailed measurement and analysis process development and global alignment, there are not equivalent measurement methods and standards for non-exhaust emissions.

Brake emissions

Emissions of brake dust are created by the action of the brake friction pads or shoes pressing against the discs/drums while slowing the vehicle. As with many aspects of automotive engineering, brake pad materials are chosen for a complex balance of factors, including stopping ability, resistance to heat build-up in repeated braking events, relative rates of pad vs disc wear, and other factors such as noise. The same car model may have different brake pads specified for different markets, depending on local requirements and preferences. Europe generally has the most demanding braking requirements due to high motorway speeds, especially German Autobahns, plus a significant occurrence of towing, which requires additional stopping capability.

In considering the possibility of reducing the particulate emissions from brakes, it must be recognised that they are a vital safety feature, and any changes to potentially reduce particles must not adversely affect stopping distance.

With around 40–50% of brake particles becoming airborne, an increase of brake use due to increased vehicle mass would have a significantly greater effect on airborne PM. However, a key characteristic of both battery-electric and PHEVs is that they use regenerative braking via the electric motors to slow the vehicle, rather than the friction brakes. Estimates of the reduction in friction brake use on EVs vary, but are in the range 50–95%.[18] A study in 2021 found that regenerative braking can reduce $PM_{2.5}$ emissions by 1.9% to 24%, compared with their combustion-engine counterparts, the largest reductions being on urban roads.[19] There are certainly reports of EV drivers having issues with corrosion and glazing of traditional disc brakes through lack of use. Recognising these changes, some manufacturers are returning to traditional drum brakes on the rear of some models. These are more resistant to only being used occasionally, and more effective at capturing any brake dust created, as well as slightly reducing the rolling friction of the car, with benefits for energy consumption. It remains to be seen if this initiative will become widespread in the industry. The impact on PM emissions is likely to be small, as the front brakes undertake the vast majority of the braking action.

Tyre emissions

As with brakes, tyre wear is a fundamental aspect of their operation, due to generating friction with the road surface to propel, brake and steer the vehicle. As with brake materials, extensive research has gone into developing tyres that provide grip for emergency braking, especially in wet conditions, long life to minimise costs and disposal requirements, low noise levels, and, especially in the last decade, the lowest possible rolling-resistance to minimise energy consumed.

Tyre wear (often aggregated with road wear) broadly correlates to the mass of the vehicle, therefore it is predicted that this is likely to increase on BEVs which are usually heavier than their combustion-engine equivalents.[19] However, on commercial vehicles, where the battery mass is usually a lower fraction of the total vehicle mass, the impact will be lower. Also, many of the predictions around tyres are based on an assumption of 'like for like' replacement of internal combustion engine vehicles with potentially heavier zero exhaust emissions equivalents, which may not be the case in the future. Of significance in this arena are numerous studies looking at lighter-weight electric vehicles for urban use such as 'last mile' deliveries. These studies are mainly focussed on reducing energy consumption and hence carbon emissions, but conducting deliveries with light 'quadricycle' type (L-class) vehicles could offer a useful reversal to any trend to mass increase and hence tyre wear in urban areas.

Reducing air pollution emissions from tyres is an area for research and innovation, and Section 4.1.2 presents examples of two different technological solutions that are being developed with the aim of reducing tyre air pollution emissions.

Another component of non-exhaust emissions is resuspended road dust, which also increases with the weight of the vehicle.[19] It can be reduced by road surface cleaning or the spraying of dust suppressant chemicals, but the benefits are limited and typically short term (only a few hours).[20]

Other emissions sources

There is not sufficient scope in this report to examine the many other sources of non-road particulate and NO_x emissions, but one other road-based source is worthy of discussion.

Most deliveries of food products to shops are conducted by refrigerated vehicles, usually containing chilled and frozen sections. They are an essential part of the food supply chain. On larger vehicles, and especially articulated units, the refrigeration is usually provided by a Transport Refrigeration Unit (TRU) which makes use of a passenger-car sized diesel engine, typically 1.5–2 litres, to drive the refrigeration. On articulated trailers especially, this is done so that the trailer can remain cold even when disconnected from the tractor unit.

A study carried out by Zemo Partnership in 2021[21] compared the emissions from the TRU diesel engines and found that they were many times higher than the Euro-VI parent vehicle. The absence of a diesel particle filter on the TRU meant that PN emissions could be up to 500 times higher than the main propulsion engine; PM levels were around 5 times higher; and NO_x levels were about double. These high levels of air pollution emissions mean that diesel TRUs, although not that many in number, make a significant contribution to total HGV emissions. Also, in the case of a very localised area such as the loading bay of shops, where TRUs may operate for extended periods, the local impact may be very high. The refrigeration industry, and Cold Chain Federation, are conducting studies and trials on alternative solutions, especially all-electric systems. Cryogenic and other options are also being considered.

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4.1.2 Tyres

Tyre wear is a major contributor to particulate matter (PM) air pollution, as discussed in Section 4.1.1. This section summaries the work of two companies which, along with others, are developing technology to reduce air pollution emissions from tyres. These are examples of early stages of work to illustrate different potential approaches.

The Tyre Collective

Siobhan Anderson, Hanson Cheng and Hugo Richardson – Founders of The Tyre Collective

Trapping particles

Source: The Tyre Collective

The Tyre Collective is a clean-tech start-up, developing technology to capture and monitor tyre wear, enabling zero-emission mobility. They are building the first on-vehicle device to capture tyre wear at source. As tyres wear down, the material is charged from friction with the road. Their patent-pending technology uses electrostatics and airflow to attract tyre particles. Positioned near the wheel arch, the device creates an electric field to pull tyre wear out of the air stream. Capturing at source limits its dispersal in the environment and reduces the chance for the material to oxidise and leach toxins. Captured particles can be upcycled into a variety of applications, creating a closed-loop system.

The company is focused on inner-city transport, targeting commercial logistic fleets as a beachhead market and intend to scale their devices across all vehicle segments across Europe and North America. Long term, their vision is to integrate their technology into all electric vehicles (EVs). Their approach to technology development is through on-vehicle and in-lab testing alongside analytical modelling. The aim for on-vehicle testing is to match their in-lab efficiency, where 60% of the mass of airborne particles was captured. If 60% of tyre wear from all vehicles the UK was captured, this is equivalent to 38,000 tonnes of carbon-based PM pollution annually.[1] Their impact on air pollution is determined by assessing the number of tyre particles captured in the coarse to fine particulate matter ($PM_{10}/PM_{2.5}$) range. This is supplemented with chemical testing, toxicology, and measured against existing datasets to model impact at scale.

ENSO Ltd

G Erlendsson – CEO of ENSO Ltd

Source: ENSO Ltd

ENSO is a UK company that makes tyres for electric vehicles (EVs), to extend EV range and reduce tyre pollution, and is a Certified B-Corporation.[2] ENSO is working with leading EV carmakers, as well as large EV fleets, including a partnership with the Mayor of London and Transport for London.

Lower emission tyres

ENSO plans to extend its EV range with low-emission tyres, delivered via a direct-to-customer business model. ENSO's low-emission tyre technology is based on enhancing elastomer formulations at the tyre tread level, to improve tyre durability and lifespan, targeting an overall reduction in tyre particulate matter (PM) pollution by 30–50% per mile. This is partly delivered by stronger and more flexible networks as well as the inclusion of self-healing tyre tread compounds, to reduce and rapidly heal breaks in polymer chains, suppressing and reversing microcrack formation.

ENSO is working in partnership with the Mayor of London, Transport for London, DPD (delivery group) and Royal Mail to highlight and address the problem of tyre pollution. ENSO is conducting fleet trials of ENSO's energy-efficient and low-emission EV tyres, measured against premium tyres from leading competitors. ENSO's business model innovation, selling tyres directly to customers and charging tyres per mile, also creates a strong financial incentive to continuously innovate ever more durable and low-emission tyres. In the longer term, measuring tyre pollution accurately is also needed to assess the full impact of tyres on air and microplastic pollution, and reduce toxicity.

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4.1.3 Rail

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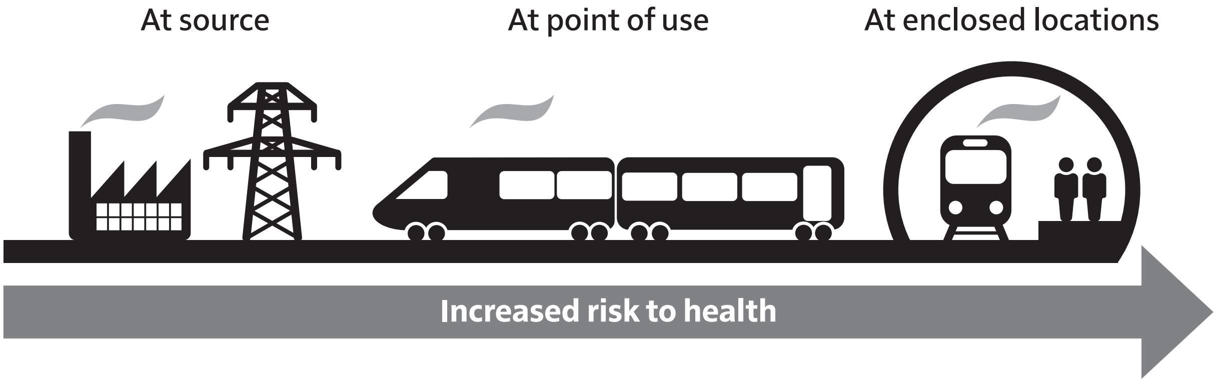
Introduction

For railway operations, air pollution can be emitted through generating power for the train and through friction from railway processes. This friction can occur from interfaces between the wheel and rail, the brake discs and pads, from the collection shoes and infrastructure, and from pantograph carbon wear.

Figure 1 illustrates where air pollution is emitted from railway operations. For trains powered by electricity, the emissions associated with electricity generation have the least impact on health 'at source' as power stations are generally located outside of urban centres. For diesel trains with onboard combustion, the highest pollutant concentrations are where diesel trains enter enclosed spaces, typically at stations, with diesel engines left running for extended periods of time.



Source: Parry B

Figure 1: Relationship between air pollution emission site and exposure risk

Overall, there have been declines in rail air pollution emissions over the last decade. In 2020, in the UK, it is estimated that trains emitted 10.08kt of nitrogen oxides (NO_x), which represents 1% of the total NO_x emissions for that year. This has decreased since 2010 when an estimated 16.35kt of NO_x was emitted by trains. To compare with road transport, in 2020, an estimated 196.48kt of NO_x was emitted by road transport.

There have also been declines in fine particulate matter ($PM_{2.5}$) emissions from railways over the last decade. In 2020, an estimated 0.29kt of $PM_{2.5}$ emissions was attributed to railways (falling from 0.4kt in 2010); this is equal to 0.4% of total UK $PM_{2.5}$ emissions. In 2020, this can be compared to 10.39kt of $PM_{2.5}$ emissions attributed to road transport.[1]

Although total air pollution emissions from trains is lower than from road vehicles, people may be exposed to considerable air pollution concentrations at the local scale in built-up areas, and especially in enclosed train stations. The Clean Air Strategy 2019[2] outlines the need to reduce air pollution emissions from rail and reduce passenger and rail worker exposure to air pollution.

Air pollution emissions from powering trains

Diesel

A significant quantity of diesel traffic exists on the British railway network, as 62% of the National Rail network remains unelectrified.[3] Furthermore, many trains over electrified sections of the network remain diesel hauled because electrification does not cover their entire routing. This is particularly the case for freight trains. Diesel combustion results in air pollution emissions of NO_x, carbon monoxide, unburned hydrocarbons, and particulate matter (PM). There are different approaches to moving away from diesel combustion, as described below.

Electricity

Electrification takes many forms, but the most common for mainline applications is either 25kV alternating current (AC) overhead line or 750V direct current (DC) 'third rail' at track level. Of the 38% of the British railway that is electrified, about two-thirds of this is from 25kV AC overhead line equipment.[3] Although trains powered by electricity do not emit air pollution from this power at the point of use, there are emissions from friction between interfaces, described later in the section.

Bi-mode

To reduce emissions without wide-scale network electrification, there has been significant investment in bi-mode trains over the last decade. A bi-mode train can run on either diesel or electricity and swap between the two modes. Notable procurements include the Intercity Express Programme signed in July 2012, to replace trains on the East Coast and Great Western routes[4] and the replacement of regional services by Greater Anglia with Stadler Fast Light Intercity and Regional Train (FLIRT) units.[5] While these trains represent a reduction in emissions over the incumbent fleets, the diesel engine emits air pollution for a portion of each journey. Bi-modes are generally seen in the industry as a stop-gap, with the intention that they will eventually be remanufactured to be fully electric. This is relatively inexpensive to undertake, but the corresponding infrastructure works are also required.

In some cases, the diesel engines can be swapped for batteries in whole or in part to create a hybrid or 'tri-mode' approach. Overall, these self-powered systems add weight and complexity to the train. The end goal is expected to be mid-life removal of such on-board power components, but this is reliant on the successful continuation of network electrification.

Future opportunities for powering trains

Two emerging technologies that enable self-powered operation of new passenger trains are large traction batteries and hydrogen fuel cells. These are deployable technologies that do not require complete electrification of the remainder of the UK network, and do not rely on a fossil-derived fuel.

Battery electric multiple units

Trains with integrated traction batteries are typically referred to as battery electric multiple units (BEMUs), which is analogous to the term battery electric vehicle (BEV) as described in Section 4.1.1. These trains can travel distances of up to 100 miles on battery power alone. As in the automotive sector, trains can use their electric motors in reverse to generate electrical power under braking termed 'regenerative' or 'dynamic' braking.

A BEMU can be recharged while stationary – for example, by using a deployable piece of infrastructure as used in the Very Light Rail Project.[6] This infrastructure would be built alongside the introduction of a new fleet of trains and is derived from systems already used for electric buses. A train can also recharge while moving if equipped with conventional electric propulsion in addition to the traction batteries. This allows for existing overhead lines or third-rail power to be used to move and charge at the same time.

In England the only significant operation of battery-powered rail vehicles is on the Birmingham tram network, with an order for a minimum of 21 vehicles in 2019.[7]

Hydrogen fuel cells

A hydrogen train makes use of a hydrogen fuel cell as the primary energy source. Fuel cells are best suited to producing power at a steady rate, as they take time to react to increases in energy demand. This is a challenge in the context of any vehicle, as the power requirements are very dynamic. Large amounts of energy are required to accelerate, potentially at short notice, combined with periods of low demand while coasting. To solve this, hydrogen-fuelled trains also make use of integrated traction batteries, though these are smaller than in a BEMU. These traction batteries store energy at periods of low demand and then provide a boost during acceleration.

A common misconception is that a hydrogen-fuelled service can exceed the maximum range allowable under battery power, with ranges of up to 600 miles between fuelling being theoretically possible. While it is true that a single charge of a BEMU can only provide up to 15% of that range, it is possible to charge while moving and within standard turnaround times at termini if the appropriate infrastructure exists. This is no different to a hydrogen train, where the manufacture, logistical supply and refuelling of hydrogen is dependent on the infrastructure available.

The drawback of hydrogen is the relative immaturity of the technical design and demonstration of compliance to the appropriate standards. While hydrogen is very energy dense by weight, it is relatively poor by volume. Integration of sufficient hydrogen fuel may result in the reduction of passenger-carrying capacity and it is expected that significant redesign to the bodyshell is needed to meet all the necessary requirements.

There have been noteworthy hydrogen demonstrators in the UK, notably 'HydroFLEX' by Porterbrook and 'Breeze' by Eversholt Rail Group in collaboration with Alstom. This research and development has materialised in a memorandum of understanding between Alstom and Eversholt to commence development on a new-build hydrogen train for the UK.[8]

Air pollution emissions from other rail sources

PM air pollution is emitted at the interface of several railway processes that are fundamental to the way that trains move around the network, as described below.

Wheel and rail interface

In the UK, all trains have steel wheels that sit on steel running rails. The rotation of the wheel combined with the mass and motion of the train body leads to wear of the wheel and track. This lost material is partially emitted into the atmosphere.

The significant benefits of a 'steel-on-steel' approach include achieving a very small contact patch between the wheel and the rail, which leads to a low rolling resistance and minimises the energy required to keep the train at speed. While innovative technologies where there is no physical contact between the train and the track, such as 'magnetic levitation', would reduce the air pollution emissions of a 'steel-on-steel' design, the increased infrastructure requirements and energy consumption to achieve this may not lead to a net improvement in air quality.

Brake disc and pad interface

A friction braking system physically applies something against the wheel or axle, slowing the train down. This process generates friction, heat and PM. Higher-speed trains typically use brake callipers fitted with brake pads that clamp a brake disc fitted to either the wheel or axle, a system used in a very similar fashion in the automotive sector. Some trains use a brake block that presses against the rolling surface of the wheel, similar to where the tread would be on a road tyre. In either case, this process wears the metallic disc and/or wheel as well as the chosen brake pad or block material and emits PM.

At speed, electric trains use the traction motors in reverse (as a generator) to slow the trains down while regenerating electricity. Some diesel-electric trains also do this, albeit by burning the regenerated electricity away as heat. In both these cases the use of a conventional friction-based braking system is avoided. At lower speeds, the effectiveness of this approach reduces and the friction braking system must take over. For conventional diesel trains, friction-braking is used at all speeds.

Heavier trains will create more wear and more PM. This is important when comparing the air pollution health impact of a relatively light pure electric train, to a train fitted with a battery, bi-mode or hydrogen system, which will be significantly heavier.

Collection shoes and infrastructure interface

Trains that use either a third-rail or fourth-rail system to supply electricity, also emit air pollution due to the friction from this process. The train has multiple metallic collector 'shoes' that sit on the top of the electrified rails. As the train moves, friction and arcing occur between the two surfaces, which causes wear, emitting predominantly metallic PM air pollution.

The only National Rail services that use a third-rail system are south of the river Thames in London, with main operators Southern, Southeastern and South Western Railway. Energy is supplied at ground level in a metal rail at 750V DC. A small metallic pad or 'shoe' is affixed to the train bogie and physically touches the top of this rail to receive the supplied power. The friction between the surfaces as the unit moves along, coupled with a small amount of arcing, degrades these surfaces and causes a loss of material to the atmosphere.

In recent years, using a third-rail system has fallen out of favour, with 25kV AC becoming the primary form of energy distribution. However, in both cases there remains a need to have a physical interface between train and infrastructure, which will lead to PM emissions.

Pantograph carbon wear

Two-thirds of the electrified British railway is powered by 25kV AC overhead line equipment.[3] To access this electricity, trains are fitted with an articulated arm called a pantograph that lifts up to touch the overhead wire.

National rail applications

Mainline trains typically operate with one pantograph deployed, but many are fitted with a second which can be deployed if necessary. The pantograph head is fitted with a carbon strip, which provides a conductive wear plate for the overhead line to physically touch. The overhead line is installed with a stagger pattern that weaves from left to right. This has the effect of moving the contact point on the carbon strip as the train moves down the track to ensure even wear.

The carbon strip is designed to be softer than the wire above it, so it wears sacrificially. The wear rate is therefore typically higher than some of the other interactions. As such, there is a relatively high amount of carbon PM emitted to the atmosphere during electric train operation. Despite this, the benefits are clear that an electric train operating on 25kV AC overhead line equipment is the lightest and most efficient design of train. Any attempt to remove this emission source would add weight or energy-efficiency loss somewhere else within the wider system.

Air pollution in enclosed railway stations

Diesel trains that are required to operate in enclosed spaces represent some of the greatest risk to public health on the railway. Prominent examples from England are London Paddington, London King's Cross and Birmingham New Street stations.[9,10] The emissions of air pollution into a space with little ventilation, can result in people being exposed to high levels of air pollution when present.

A study at Birmingham New Street station in 2016/17[11] measured oxides of nitrogen and PM, finding a long-term NO_2 concentration of 383µg/m^3 and a maximum hourly concentration of 2020µg/m^3. The average concentration of $PM_{2.5}$ was 42µg/m^3.[11] At the time, the station was equipped with carbon dioxide sensors which triggered fans to increase ventilation at higher concentrations. Replacement of the sensors with NO/NO_2 sensors gave reductions of 42% and 81% respectively in NO_2 and $PM_{2.5}$ due to the enhanced ventilation, but pollutant concentrations of NO_2 still far exceeded health-based air quality guidelines.[12]

The alternative solution to increased ventilation is a reduction in emissions. Increasingly, pure diesel trains are being replaced with bi-modes that can run on electricity where the infrastructure exists. Even if overhead lines are only provided at the stations, this allows for diesel engines to be totally turned off in high-risk areas. This is also known as 'discontinuous electrification'. Providing power at main stations would also help with deployments of BEMUs, where the batteries can be recharged after each trip using the natural down-time timetabled at the ends of each leg of a journey.

An innovative approach could be to provide a larger-than-normal auxiliary battery, that enables crucial systems such as air-conditioning to run for longer with the engines turned off. Engine start-stop could be deployed to force units to switch all (or at the very least all but one) engine off after a set period of time – functionality that is still rare on the railway, despite being prevalent in the automotive sector.

Air pollutant concentrations in trains

There is a growing concern that diesel emissions might be entering into the train carriages, exposing passengers and also train drivers and guards to pollutants related to diesel exhaust (such as ultrafine particles) and this has been demonstrated in several international studies. In England, passenger exposure was assessed by the Rail Safety and Standards Board in a study covering 100 journeys using 13 different diesel trains.[13] PM_{10} and $PM_{2.5}$ concentrations were influenced by different sources, including engine exhaust, brake and wheel/rail wear and passenger movements as well as the ingress of ambient air. Elevated PM_{10} and $PM_{2.5}$ concentrations were affected by the measurement position on the train relative to both the exhaust and the distance along the train, with the rear most carriages appearing to be the most highly polluted. The heating, ventilation and air conditioning (HVAC) system also had a significant effect in filtering diesel exhaust in the newest trains. Elevated NO_2 concentrations were also experienced on carriages when bi-mode trains were used, resulting from a combination of non-ideal locations for carriage air intake (relative to exhaust systems) coupled to underperformance of exhaust gas aftertreatment.

Underground and metro applications

Since 1971, all underground and metro services in England have been electric. The electrification systems in use on metro applications in England today are:

- London Underground: 630–750V DC fourth-rail system
- Merseyrail: 750V DC third-rail system
- Island Line: 660V DC third-rail system
- Tyne & Wear Metro: 1500V DC overhead line equipment

As trains running on networks such as the London Underground are already fully electric, this reduces the total PM emissions from the braking system, due to regenerative braking. The operational profile for this type of train usually features sharp deceleration rates and frequent stops – so it is not unreasonable to conclude that overall wear is more extreme.

Third- and fourth-rail electrification systems are common to underground and metro applications. The contact between these rails and the 'shoes' fitted to the train are an inevitable source of emissions for trains used on such operational profiles.

Metro trains in England all have metallic wheels that run on steel running rails and so there is not a significant point of distinction when compared to a typical National Rail service. While the rolling stock itself is often lighter, the passenger payloads can be considerably heavier, which does not lead to an easy conclusion on what type of train experiences more overall wear. Older networks such as the London Underground have much sharper curves than the National Rail, and this also contributes to increased wear.

Air pollution in subway systems is characterised by high concentrations of PM – often several times higher than that above ground. The concentration is influenced by the air drawn into the system, principally from the above-ground areas of the network, via tunnel entrances, and through station entrances by the train movements as well as via active ventilation shafts. The elevated concentrations are caused by additional sources within the network, principally the wear of train consumables (e.g. wheels, collector shoes, brake blocks, motor brushes and lubrication systems), non-train sources (e.g. rail wear, rail grinding, ballast), station sources (e.g. escalators), and refurbishment work (which is episodic and localised) and are common to subway systems around the world. All of the resulting emissions are then resuspended by the train movements.[14]

London has the highest $PM_{2.5}$ concentrations measured in European subway systems. Concentrations remain poorly characterised geographically and temporally but are primarily dependent on the degree of ventilation available to disperse emissions. For instance, the London Underground Circle and Victoria Lines have similar rolling stock with regenerative braking systems but markedly different levels of pollution. A study of exposure in London Underground carriages found that the Victoria Line, which runs deep under the capital and has no open sections, had a mean $PM_{2.5}$ concentration of 381 $\mu g/m^3$. Whereas the Circle Line, which runs above and below ground, allowing cleaner air to be bought into the trains and tunnels had a lower mean $PM_{2.5}$ concentration of 27 $\mu g/m^3$.[15] Despite the growing literature detailing the concentrations found in subway systems, monitoring of air quality in these environments is very rare. Any measurements tend to be limited to short-term campaigns and personal exposure assessments against workplace exposure standards.

Studies quantifying the emission reduction are limited but do suggest that efforts to reduce the rate of emissions from train consumables can result in improved subway air quality. This can be achieved through reduced braking, either from decreased use, regenerative braking or more durable friction materials.

More work has been undertaken to improve ventilation and reduce in-carriage and on-station concentrations. Tunnel ventilation systems can improve air quality relative to relying solely on piston-driven (when the train moves through a tunnel and pushes the air ahead of it) or natural ventilation. However, its efficacy can depend on station design factors, it can be costly to operate and its application to areas of the London Underground may be limited.

Platform screen doors are installed for safety benefits. They create a physical barrier between the platform and the track areas and have been consistently shown to decrease platform PM concentrations. However, the reduced ventilation from the piston effect increases the concentrations in tunnels and consequently in trains.

Filtration approaches have been tested on the platform, in, and on the train. Most electrostatic and magnetic platform filtration technologies report a 40–50% filtration efficiency.[16,17] $PM_{2.5}$ concentrations were reduced by 41% in one Paris Metro station, however, their widespread application would require a substantial number of units, particularly in larger stations.[18] Several studies have also demonstrated the potential for train HVAC systems to reduce in-train PM concentrations, but no quantitative assessment has been made.[14,19] One study examined the potential for a baffle dust collector mounted under the train, using the movement of the train to collect PM. A collection efficiency of 50% was calculated from wind tunnel tests.[20]

As one example of good practice, Barcelona is one of the most studied subway networks in Europe, having been the subject of the EU Improve Life Project.[21,22,23] This established best practice for assessing the concentrations in subway systems as well as recommendations for station design, ventilation and ways to improve air quality. Further afield, Seoul has a measurement system consisting of air quality sensors measuring ultrafine dust, reporting 1-hour and 24-hour concentrations at every station. This is part of broader regulations from the Seoul Metropolitan Government's aim to tackle indoor air pollution via their 'Indoor air quality control at public use facilities: clean air for all' policy which sets standards for 5 substances and requires public disclosure of air quality data. This has resulted in more advanced cleaning approaches in stations and tunnels and air purification systems in trains and stations.

Future considerations

All transportation modes have a measurable impact on air quality. The challenges faced by the rail industry and the automotive sector feature a high degree of overlap. Primarily the shift away from fossil fuels will have by far the biggest effect on public health, and this should be the priority. The ability to accelerate this transition is linked to infrastructure investment in both sectors: in rail this would mean funding for full route electrification, discontinuous electrification and/or rapid chargers in addition to building a viable hydrogen supply economy.

Battery trains are technologically viable but have seen little opportunity in the UK to date. This approach represents a low-risk solution while hydrogen establishes itself in the medium term and wider-reaching electrification projects can be delivered. There may be other considerations for freight trains.

Other sources of particulate pollution have a lesser impact in comparison to the emissions of combustion and remain relatively low overall due to the number of rail journeys taken. Almost all emission types could be reduced by moving to a lighter-weight pure-electric rolling stock with modern regenerative braking.

The importance of complementary station design is important. Any air pollution produced by trains must be separated from passengers and staff, and removed from the area as quickly as possible.

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4.1.4 Aviation and shipping

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Reducing air pollution from aviation around airports

Introduction

Sources of air pollution emissions associated with aviation are aircraft main engines, auxiliary power units (APUs) within aircraft, fixed equipment at airports, handling and related activities on the airside and landside local traffic. The combustion of jet fuel leads to exhaust gases with a mixture of air pollution, with nitrogen oxides (NO_x), particulate matter (PM) of mostly carbon (soot). The use of some fuels results in the emission of sulphur oxides (SO_x). Emissions of carbon monoxide and unburned hydrocarbons have now been largely eliminated. This air pollution, and pollutants from the other sources associated with aviation, can affect people's air quality near airports. The resulting health effects of air pollution are discussed in Section 1.1.

For many years NO_x has been strictly regulated at aircraft certification, and much of the NO_x detected around major airports has long been suspected to be from sources other than the aircraft.[1,2,3,4,5,6] A study of London's Heathrow Airport, which is heavily affected by the local M4 and M25 motorways, showed an influence of airport operations, including aircraft emissions, on NO_x and PM_{10} concentrations in the vicinity.[7]

Most studies of the health effects of aviation have considered only the primary emissions, although secondary pollutants such as particulate nitrates formed from those emissions are also important.[8] There is also concern that aircraft emissions are a substantial source of ultrafine particles,[9,10] typically smaller than those from other combustion sources, which frequently allows them to be observed in city centres at some distance from the local airport.[11]

This section looks at interventions and technologies to enable an improvement of air quality near airports.

Fuels for aviation

Jet fuel (Jet A/A-1) has a typical concentration of sulphur (550–750 ppm), which is many times higher than road transport fuel (10 ppm). In the short term, there is a need to develop ultra-low sulphur aviation fuel. The process of desulphurisation can be achieved in the same way as for road vehicle fuels.[12] In the near-term, 'drop-in' fuels are required, so that they can be used with or instead of fuels based on standard kerosene.

Synthetic fuels can originate from renewable feedstock, waste or residue and contribute to achieving more sustainable aviation fuels (SAF). In the mid-term, synthetic fuels could reduce air pollution emissions, as they contain almost no sulphur or aromatics (combustion of aromatics is associated with the formation of soot PM). With regards to NO_x emissions, the literature indicates that there is generally little difference from synthetic fuels when compared to Jet A/A-1. Making SAF sustainable, commercially viable when produced, and in the required quantity are huge challenges.[13,14,15]

In the longer term, the use of hydrogen needs to be considered with the arrival of sufficient green hydrogen (carbon-free hydrogen production). Research and development are underway to make engine combustion systems ready for hydrogen, as well as the significant challenge of developing hydrogen tank storage options for aircraft.[16,17] An engine's life cycle from inception to retirement is long, perhaps 40 years. It is worth asking if aircraft engines can be designed to burn hydrogen in the future with minimum modifications.

Aircraft operations and aircraft equipment

Increasingly efficient aircraft and engines systems will lead to reduced fuel burn and therefore reduce air pollution emissions. In the mid-term the implementation of hybrid and electrical propulsion could be an option, particularly for very short-haul aircraft.

On-board auxiliary power units (APUs) are powered by gas turbines. As they are subjected to a lower level of engineering optimisation than main engines, air pollution emissions can be relatively high. Providing fixed electrical ground power for aircraft on stands has started to be common, but they could be universal at airports. Pre-conditioned air supply for the stationary aircraft could be standard equipment at all stands.[18]

For aircraft in airports, some air pollution mitigation would come from using a single engine operation while taxiing. However, there could be further reductions in air pollution emissions through extended use of low-emission or fully electrical tugs and having mobile electrical storage on the tug to supply the aircraft's needs during taxiing.[19]

With regards to aircraft operations, reduced engine taxiing has been trialled with success and this technique can lead to reduced fuel consumption, and consequently lower emissions.[20] Optimising the co-ordination of aircraft movement can reduce delays and improve the passenger experience. The opportunity for adjustment of take-off power in line with local aircraft conditions can also contribute to lower fuel burn; this considers pilot actions in the light of actual weight, weather and runway length. Although these adjustments are already taking place, they could be universal.

In and around airports

Reducing non-aircraft air pollution emissions can be encouraged through ensuring that all diesel engines used for operational vehicles, including buses, comply to the latest emission standards and are currently at least within the limits of the Euro 6d vehicle standards. Training of vehicle operators at airports has already shown an impact on emissions and increased passenger comfort.[13] All stationary internal combustion engines used in the airport need to meet the highest level of emissions standards (for off-road machinery: Stage V; and for stationary engines: Medium Combustion Directive). Also, where no electrification is feasible, all internal combustion engine ground machines (on-road and off-road) should use the cleanest alternative fuels.

In the mid-term, airside ground vehicles could be electrified. Given the fleet nature of these vehicles, the logistics of charging should be possible. The weight of batteries is an advantage in an aircraft towing tug, and it might be possible for tugs to use batteries to provide short-term power to aircraft as they are dragged to the runway, thus delaying main engine operation and removing the need for an APU.

Traffic on the land side of an airport is a major contributor to airport-related air pollution emissions. Engine improvements and transition to electrification in road vehicle technology is expected to contribute significantly to reduce this pollution. For this, there needs to be sufficient charging points for the public and for employees, as well as a sustained effort to improve public transport for airport access.[4,18]

Replacing old infrastructure equipment includes the use of better boilers and, where possible, a transition to combined heat and power systems, which could also reduce emissions. The implementation of renewable energy sources is part of the transition towards net zero operation, and directly contributes to better local air quality.[20] To minimise people's harm from aviation-related air pollution, the location of future airports and land use near airports are considerations for long-term planning.

Reducing air pollution from shipping around ports

Introduction

Ports and their activities are significant sources of air pollution in coastal areas and inland vicinities, depending on the local wind patterns. This can affect the health of people living and working nearby. The major sources of emissions are ships that manoeuvre through the port, those that are docked in the port, diesel engine machinery for port activities, and vehicles that feed the port to and from inland. There are more than 120 ports in the UK, ranging from all-purpose ports such as London and Liverpool, as well as ferry ports such as Dover. These ports handle 95% of the UK import and export volume.[1]

Air pollution emissions associated with ports are from fossil fuel combustion and include nitrogen oxides (NO_x), particulate matter ($PM_{2.5}$ and PM_{10}) and sulphur oxides (SO_x).[2] Chemical reactions in the atmosphere between NO_x and SO_x and ammonia (NH_3) from land activities, form secondary PM.[3] Modelling in 2017 estimated that about 6% of UK population weighted background primary and secondary $PM_{2.5}$ was attributed to shipping. For primary $PM_{2.5}$, areas close to ports had greater than average contributions from shipping. Modelling also estimated that 2% and 4.6% of UK population background NO_x was derived from local and regional shipping sources. The greatest contributions were in the south and on the south-east coast of England.[3]

The Department for Transport's *Port Air Quality Strategies* (2019)[4] include Port Air Quality Guidelines to give UK ports a framework to use to produce a Port Air Quality Strategy (PAQS). The framework aims to establish a minimum level of understanding of air quality in ports and to reflect actions that the port is taking to address emissions that are under their control. Currently, the PAQS request only applies to ports with annual cargo volume of at least 1 million tonnes.

Ship fuel

As shipping air pollution emissions are from the burning of shipping fuel, the first step in improving the port air quality would be to aim for a change of fuel. The International Maritime Organization (IMO) regulation addresses air pollution emissions from ships through MARPOL, the International Convention for the Prevention of Pollution from Ships, Annex VI. This includes limits on the maximum permitted sulphur content in shipping fuel in different areas and limits on NO_x emissions. There are also IMO Emission Control Areas, including in the North Sea.[5,6]

While long-term strategies are rolled out, to improve air quality in ports in the short term, the quickest approach could be to incentivise ships to operate on low-emission mode while entering a harbour. An example is the Port of Long Beach offering generous sustainable vessel financial incentives for those ocean carriers bringing their 'greenest' ship into the port.[7] This approach, together with other efforts, including the introduction of regulations during this time period, has enabled San Pedro Bay Ports (Long Beach and Los Angeles) to reduce port-related air pollution emissions by 90% for diesel PM, 63% for NO_x, and 97% for SO_x, from the 2005 level.[8]

In the short to medium term time-frame, a solution is required for the electricity needed for the docking ships, as they usually operate generator engines continuously to supply electricity. Providing the option to plug into the shore power during docking could prevent this, and the shore electricity should be from renewable sources coupled with battery storage. While this could be a solution for ships at berth, it does not help large ships mooring away from the port. For mooring ships, operating on low-emission fuels via dual fuel engines (such as diesel and natural gas), could be supported through incentives or port regulations. Major marine engine manufacturers have already trialled dual fuel engines, with some available now, and it is expected to come into operation from 2030 and onwards.

Passenger ferries that make short and multiple oscillating trips between ports are a source of local emissions. Diesel engines in ferries which operate transiently, will produce more emissions than their steady state operating bigger ships.[9,10] Interventions to reduce air pollution emissions could be similar. Electrification may be the most promising approach to reduce emissions from ferries: since they make short and frequent trips between ports, their charging schedules can be regulated, and electrical operation optimised for a given duty cycle.

Harbour craft

For harbour craft, including tugboats and ferries, electrification or the use of low-emission fuels such as biofuel and liquefied natural gas rather than diesel, could reduce local air pollution emissions. Ports such as in Singapore are moving in this direction.[11] Also, in the port of San Diego, the first electric tugboat deployment is planned for 2023 and it is estimated that, in the first 10 years of use, this will reduce emissions of 178 tons of NO_x and 2.5 tons of PM compared with a conventional tug.[12]

Port machinery

Port machinery and operations powered by diesel are an opportunity for intervention to improve air quality. These include technological solutions, operational improvements and legislation. Port-level machinery, such as harbour cranes and transporters (non-road mobile machines), could be electrified either through batteries or hydrogen fuel cells. There are also other sources of air pollution emissions that are not directly within the control of port authorities – for example, from road vehicles moving in and out of the port for its operations, as discussed in Section 4.1.1.

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4.2 Reducing roadside NO_2 – an example of central and local government action

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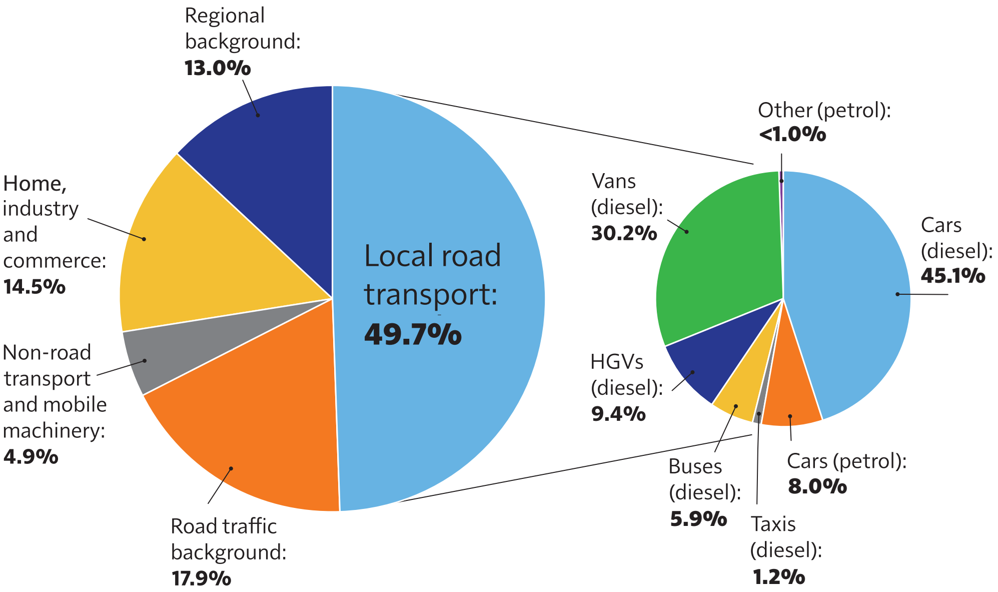
Introduction

Poor air quality is a major environmental risk to human health, and there is clear evidence of a link between exposure to air pollution and mortality and morbidity, (as discussed in Section 1.1). Air pollution predominantly affects those living in major towns and cities due to the concentration of vehicles and other sources of pollution. Although it is inappropriate to generalise for all towns and cities, current population groups who experience the highest levels of deprivation frequently live in locations that have the highest nitrogen oxides (NO_x) emissions and often the highest nitrogen dioxide (NO_2) concentrations.

The government's Joint Air Quality Unit (JAQU) – a joint venture between the Department for Environment, Food & Rural Affairs (Defra) and the Department for Transport (DfT) – is working specifically to reduce roadside NO_2 air pollution across England. This section describes the work of JAQU with local governments to address the complexity of roadside NO_2 pollution, through multi-modal interventions, and discusses the challenges of attributing the impact of interventions on air pollution.

On average, road transport created 68% of roadside NO_x in 2020, as well as contributing to roadside particulate matter. Around 90% of local road transport emissions of NO_x come from diesel vehicles. Figure 1 shows the UK average NO_x roadside concentrations apportioned by source of NO_x emissions in 2020 in the UK.

As described in Section 4.1.1, there has been considerable reduction in vehicle air pollution emissions, with the adoption and uptake of vehicles with more stringent Euro standards. Despite making progress in reducing NO_2 concentrations over recent years, it continues to be the only statutory air quality limit value that the UK is currently failing to meet.[1] The legal limits for NO_2 are: hourly mean value to not exceed 200 μg/m^3 more than 18 times in a year; and the annual mean value may not exceed 40 μg/m^3.



Note: NO_x is the sum of nitrogen dioxide (NO_2) and nitric oxide (NO).
Source: Defra (2021)[2]

Figure 1: UK national average NO_x roadside concentration apportioned by source of NO_x emissions, 2020

The most recent compliance assessment for 2021 showed that 10 out of 43 air quality reporting zones were not compliant with the annual average NO_2 limit value. (A zone is considered non-compliant if one or more locations within that zone exceed the limit value.) This is a substantial reduction from the number in exceedance in the years before 2020, but is an increase from 2020 when traffic flows were reduced due to COVID-19 lockdown restrictions. Some restrictions remained in place at the start of 2021 which, along with the introduction of local measures to reduce NO_2 and the improvement in the UK traffic fleet led to lower roadside NO_2 concentrations on average compared to 2019. All reporting zones were compliant with the hourly NO_2 limit value.

Work to reduce roadside NO_2

With the aim of promoting a cleaner and healthier environment that benefits people and the economy, JAQU published its Air Quality Plan, in July 2017, which was supplemented in 2018, to address high levels of roadside NO_2 concentrations in the UK.[3]

JAQU has been working with more than 60 local authorities with the most persistent NO_2 problems. JAQU is supported by a fund of £880 million to develop and implement local NO_2 plans to achieve compliance with statutory NO_2 limits in the shortest possible time. The funding also mitigates some of the costs associated with reducing air pollution incurred by specific groups. In addition to the JAQU work, local authorities may also implement interventions to reduce roadside NO_2 and address local air pollution 'hotspots' through the Local Air Quality Management (LAQM) process. Examples of different interventions in cities across the country are described in Chapter 6.

How are Local Plans developed?

Local Plans are developed by local authorities, following HM Treasury's Green Book approach. They produce a full business case that sets out the case for change, examines different potential air quality measures, and assesses what would achieve compliance in the shortest possible time. The Local Plan identifies and justifies the preferred option that is best suited and bespoke to the local area.[4] An extensive evidence base is used in the business case development process. This covers transport modelling, emission modelling, air quality modelling, economic impacts of measures, options appraisal and monitoring, and evaluation plans.

What measures might a local authority introduce to address roadside NO_2 concentrations?

Proposals to reduce NO_2 levels involve interventions to reduce transport emissions – for example, a Clean Air Zone (CAZ), bus retrofits or traffic flow improvements. They can include measures to reduce exposure (such as road layout changes), and combinations of solutions can be adopted.

Given the potential impacts on individuals and businesses, when considering equally effective alternatives to achieve compliance, the UK government believes that, if a local authority can identify measures other than charging zones that are at least as effective at reducing NO_2, those measures should be preferred.[5]

Operating a CAZ involves discouraging certain types of the most polluting vehicles from entering the zone by charging them a fee. CAZ areas are classified according to which vehicle types are potentially eligible for a charge: a Class A CAZ covers the fewest vehicle types, and a Class D CAZ covers the most, including private cars.[6]

Types of Clean Air Zones

There are 4 CAZ types: Class A to D.

Class	Non-compliant vehicle types charged
A	Buses, coaches, taxis, private hire vehicles
B	Buses, coaches, taxis, private hire vehicles, heavy goods vehicles
C	Buses, coaches, taxis, private hire vehicles, heavy goods vehicles, vans, minibuses
D	Buses, coaches, taxis, private hire vehicles, heavy goods vehicles, vans, minibuses, cars, and the local authority has the option to include motorcycles

The first CAZ areas to charge a fee were implemented in 2021 in Bath and North East Somerset, Class C (March), Birmingham, Class D (June), (discussed in Section 6.1), and Portsmouth Class B (November).

To mitigate the negative effects of a CAZ, and to help support the most vulnerable groups, the Clean Air Fund (CAF) provides funding to local authorities to offer support packages, such as grants or loans, to certain operators of non-compliant vehicles, including businesses, taxi drivers, and residents.

Other measures to reduce roadside NO_2

Other areas have shown that compliance with legal limits of NO_2 can be achieved as quickly as possible using non-fee measures, rather than adopting a CAZ, including: speed limit restrictions, public transport improvements, traffic management measures and incentives to active travel. Areas implementing these measures are Leeds, Southampton, Nottingham, Derby, Coventry, Fareham, Blackwater Valley, and Basildon and Essex.

Understanding the impact of Local NO_2 Plans

Understanding the impact of Local NO_2 Plans is complex because NO_2 concentrations are influenced by a range of different factors with effects that are difficult to separate. There is inherent variability in air quality data,[7] and it is heavily influenced by meteorology.[8,9] Also, there are challenges with attributing influence to individual interventions that rarely occur in isolation, and the analytical methods themselves bear inherent limitations. It is also important to note that air quality is improving (albeit slowly) in many countries.[10] When combined with other confounding factors such as the COVID-19 pandemic, and most recently fluctuations in fuel prices, it has made attributing the effects to an individual intervention challenging. However, monitoring and evaluating the impact of Local NO_2 Plans is crucial to determine whether NO_2 concentrations have reduced to legal limits, and to assess the wider effects of the measures on the population. Evaluation data will also assist with the development of future plans by providing evidence of what has worked well, and what could be improved in the future.

JAQU and local authorities in Local Plan areas have developed a multi-source monitoring and evaluation programme. At JAQU, this has involved commissioning a programme of analysis being led by Ipsos UK, supported by the Institute for Transport Studies at the University of Leeds. This work aims to assess the impact of Local NO_2 Plans on NO_2 concentrations, alongside the wider effects on the behaviours of key population groups, and the impact of external factors on measuring effectiveness. A broad range of methods are used, including before-and-after analysis of air quality and traffic trends, and case study research that incorporates population group and business surveys, evidence reviews, secondary analysis of data, and in-depth interviews.

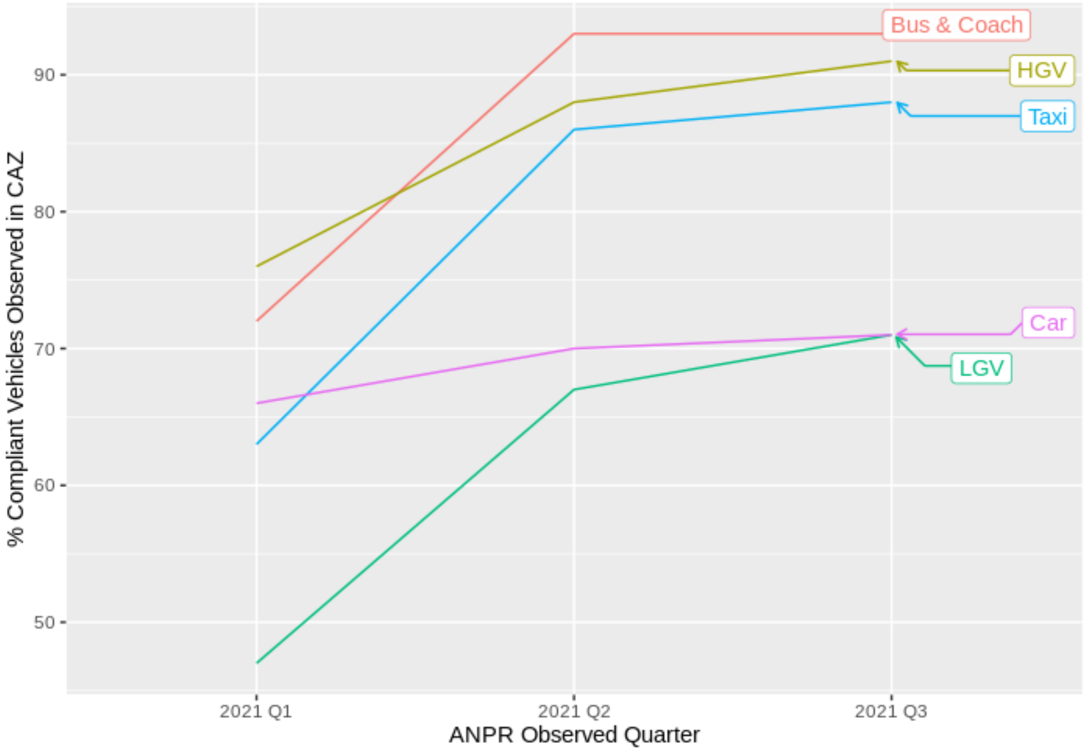
What do we know so far? Early findings on the impact of CAZ areas

While the Institute for Transport Studies have developed a sophisticated package for analysing air quality and traffic data,[11] its use is limited by the short period of data currently available. Data over a longer period is needed for more confident causal claims to be made. However, by drawing on multiple sources of data, some of the early impacts of CAZ areas can be identified.

Air quality and traffic flow

The CAZ areas in Bath and North East Somerset, and Birmingham are expected to lead to behaviour changes among 80–90% of those who use the most polluting vehicles. This includes rerouting or cancelling journeys, or replacing older vehicles with cleaner ones,[12,13] leading to a reduction in the movements of polluting vehicles within the CAZ area. The reduced use of more polluting vehicles is expected to lead to lower emissions of NO_x, resulting in lower NO_2 concentrations.

As the first local authority to implement a CAZ, our early analysis has focused on Bath and North East Somerset, where we have the longest trend of data, and the air quality is showing signs of improvement. While these trends have been affected by COVID-19 lockdowns in the UK over the period analysed (October 2020 to October 2021), along with a local bridge closure in Bath, closer analysis of traffic flow and composition highlights a clear move toward compliant vehicles across all vehicle types, and suggests that the CAZ has been successful in encouraging the enhancement of vehicle compliance.[14] Modelled emissions, alongside an analysis of air quality in comparable locations, suggests that the improved air quality observed may be partially attributed to the introduction of a CAZ.



Note: the CAZ went live in March 2021. ANPR is the Automatic Number Plate Recognition, a tool for for vehicle fleet characteristic observation

Source: Institute for Transport Studies, University of Leeds on behalf of the JAQU Central Evaluation Programme

Figure 2: Vehicle compliance rates observed in Bath and North East Somerset CAZ over time

Knowledge, views, and behaviours

Across all areas where businesses and residents were surveyed in the immediate months following the CAZ launch, awareness of the CAZ was high. Broadly, more residents and businesses supported than opposed CAZ areas, and they could generally see the advantages of cleaner air.

Opposition to CAZ areas tended to focus on the administrative burden in tracking vehicle compliance, with a small share reporting negative effects on business activity so far. Despite high levels of awareness, survey data from businesses (conducted between March and May 2021) suggest that there has been limited behaviour change in the immediate months following CAZ launch. Among those that did claim to alter their travel plans, the most common change was the re-routing of trips. However, these are early findings and more recent data from Bath and North East Somerset shows that more than 700 polluting vehicles have been replaced.[15]

In Birmingham, where the residents are directly affected by the CAZ, the changes in behaviour were balanced across cancelling trips, re-routing and using alternative forms of transport. In Bath and North East Somerset, where residents are not directly affected by the CAZ, some have changed their behaviour, mostly stating that they would cancel or re-mode their trips. Further in-depth analysis of the findings presented here can be found in the Local NO_2 Plans: 2021 Annual Report.[15]

Next steps

The evaluation of the impact of Local NO_2 Plans is ongoing and, over the coming months, will be incorporating more air quality and traffic data from a broader range of local authorities, as they continue to implement their plans. This will be complemented by further case study work in areas implementing CAZ areas, which will involve understanding how the impact of Local Plans has varied for different local groups, including more vulnerable residents or transport users and small and medium-sized enterprises (SMEs). In Bath and North East Somerset, and Birmingham there will be a focus to identify longer-term behaviour change, as well as analyse non-charging measures in other local authorities, including an in-depth study of the results of the introduction of speed limits.

A priority for the next stage of the evaluation will be understanding how Local NO_2 Plans impact health, as one of the key drivers for requiring local areas with persisting NO_2 exceedances to develop Local Plans. Measuring and attributing health impacts is challenging. Health is affected by a wide range of factors, and the timescale over which we might expect to see improvements arising from Local Plans goes beyond the timeframe of the evaluation. However, the evaluation will seek to identify early results by: 1) collecting primary data on resident's health, through surveys and interviews; 2) triangulating this with local air quality and health data from comparable areas; 3) considering sources of secondary data that might be available to this research. The aim is a qualitative assessment of how Local Plans affect health. This approach is still under development, with early findings expected to be reported in the next Local NO_2 Plans Evaluation Annual Report, due for publication in Spring 2023.

As discussed in further detail in Chapter 3, it expected that NO_x emissions from vehicles will continue to reduce through policy implementation and engineering solutions, including more widespread electrification of the vehicle fleet. The trajectory for other sources of urban NO_x is less clear – for example, from gas boilers in commercial and domestic properties – so these are future considerations for NO_2 air pollution.

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4.3 Urban planning

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Introduction

The shape and structure of our towns and cities is intertwined with environmental and health impacts: fresh air, sunlight, sound and temperature contribute to our experience of our surroundings. If we can harness how to design and manage our buildings, streets and spaces positively, we can help to reduce our impact on the environment. However, if we get this wrong, the consequences can seriously affect our health. Urban planning can work to reduce air pollution emissions, and protect people who are living, working and playing in urban environments from exposure to harmful air pollution.

The planning system and health outcomes are intricately and historically linked. The first planning legislation in 1909[1] addressed concerns over basic living standards, as well as a wider campaign for more public open space and better designed streets to allow more sunlight and fresh air into homes. In 1938, Manchester City Councillor Shena Simon reflected on why smoke remained an unaddressed issue in 'A Century of City Government': "The reason is partly because, although smoke kills, it does not kill quickly. Public opinion is not yet alarmed by the smoke evil."[2]

Today, the urban planning system has the overarching purpose of contributing to the achievement of sustainable development and three objectives: social, economic, and environmental. The social objective includes to support strong, vibrant, and healthy communities, fostering well-designed places that reflect current and future needs and support communities' health, social and cultural wellbeing.[3]

There are many sources of air pollution emissions in towns and cities, and the planning system can play an important role in improving local air quality by reducing the level of harmful pollutants and reducing peoples' exposure to them. One important source the planning system can influence is road traffic, and it can also influence urban developments to reduce people's exposure to air pollution.

Urban developments and transport infrastructure

Urban planning can help ensure that new neighbourhoods are designed in a way that reduces vehicle dependency, through the creation of compact, mixed-use neighbourhoods where people can access local services. It can also encourage active travel through the provision of infrastructure for cycling and walking and the design of streets and public spaces that people feel confident and comfortable using.

20-minute neighbourhood

The Town and Country Planning Association's work on the concept of the 20-minute Neighbourhood embodies this approach where 'a resident's daily and weekly needs should be met within a 10-minute walk, in each direction, of their home.'[4,5] In Scotland, the 20-minute neighbourhood concept is within the draft National Planning Framework.[4,5] It has been adopted in Melbourne as an important principle in the city's 30-year Plan and has been piloted locally through community partnerships. While the experience of the COVID-19 pandemic has heightened interest in these approaches, it also harks back to the core purpose of planning: delivering high-quality and sustainable homes and places of work, complemented by access to services and amenities such as parks, green spaces, healthcare facilities, retail and leisure opportunities at the neighbourhood level.[4,5]

Building developments

While compact places may reduce car use, air pollution concentrations may also be affected by building density and form, which can either reduce or increase the dispersion of pollutants. Urban planning can help by avoiding siting homes and active travel routes directly next to traffic routes.

Air pollution concentrations may be higher in urban areas where building densities and the form and scale of buildings can block and weaken winds and thus reduce the dispersion of pollutants.[6,7] There is a balance that planners must get right: designing new developments to be compact to encourage active travel, while ensuring that building forms allow adequate air pollution dispersal to reduce peoples' exposure to poor air quality.

Considering the access and layout of schools, play areas and healthcare facilities can help to reduce pollutant exposure risks for vulnerable people such as children, older people, and others with long-term health conditions.

Urban planning can also work to reduce people's exposure to other sources of air pollution. For example, design of new-build homes can consider where air pollution will be emitted from heating sources in the home and adjacent buildings, whether future residents will be exposed, and optimising the design to minimise residents' exposure to pollution.

Active travel

Turning the hierarchy of road and pavement users upside down, and enabling the health benefits of walking and cycling to be a first choice when making a journey is a huge prize for health and wellbeing, as well as air quality. This is about designing for everyone in a community, irrespective of mobility. This is emphasised in the National Model Design Code, which outlines policies that are material to planning decisions being made across England.[8] The Code highlights that new development should contribute to the creation of well-lit, direct, and overlooked pedestrian and cycle routes and that local councils should consider promoting active travel through the production of local design codes, facilitating easy movement, primarily for those who are walking and cycling. Active travel, the health co-benefits and interventions to increase uptake are discussed further in Section 4.4.

Although the design of new urban environments presents opportunities to reduce air pollution emissions from the start, there are examples of initiatives to support active travel in existing areas. In cities, an important issue for planners is logistics distribution. There are opportunities to move to greener and smaller vehicles in residential environments, for example, electric and cycle rickshaws now being used by the Royal Mail. In London, the Mayor's Transport Strategy aims to reduce traffic volumes by encouraging a shift to walking, cycling and using public transport so that 80% of all trips in London are made on foot, by cycle or using public transport by 2041.[9]

Alongside promoting active travel and the use of public transport, promoting and enabling the use of electric vehicles will also reduce emissions of exhaust pollutants. Improved charging infrastructure for these new electric vehicles will be required, and the scale of demand for these facilities will undoubtedly increase with phasing out of the sale of new petrol and diesel vehicles from 2030 to 2035.[10]

Urban greening

Careful use of green infrastructure, such as trees, hedgerows and green spaces has a role to play in reducing people's exposure to air pollution. Increasing greening can also introduce wider benefits to the visual appearance, natural environment and shading of streets and neighbourhoods. A review by the Air Quality Expert Group (AQEG) concluded that 'overall, vegetation and trees in particular are regarded as beneficial for air quality, but they are not a solution to the air quality problems at a city scale'.[11]

Planting trees can enhance or reduce air pollution dispersion, depending on how the trees affect airflow and turbulence. Vegetation can also act as a barrier to sources of air pollution, reducing pollution concentration on one side, but increasing it on the other side of the barrier. An area of green space, such as a park, can offer people a travel route that is away from the kerbside. Pollution can be removed from the air by deposition in vegetation, although the reduction in air pollution concentrations by urban planting schemes is small. When planning greening, careful consideration of the species and location of plants is needed, as some can release biogenic VOCs.[11] Of note, urban greening may have limited effectiveness seasonally if deciduous species are used.

Planning guidance

When developing new places, it is crucial that the design and layout aims to consider the inter-connections between the various features of the neighbourhood and how they will be used. There is a wealth of policy and guidance that emphasises important considerations for creating well-designed places.

National planning policies for England are set out in the National Planning Policy Framework[3] and this is supplemented by a range of guidance including on design and place-making – for example, the National Design Guide,[12] National Model Design Code,[8] government air quality guidance[13] – and industry guidance such as the Building for a Healthy Life design tool[14] and the Institute of Air Quality Management guidance.[15] The national policy documents provide strong ideas for when and how local policy and decisions on planning applications should consider public health in planning.

Many local authorities have also compiled guidance that can assist in thinking about air quality issues and outcomes. Important considerations include possible changes in vehicle use and levels of traffic congestion, construction sites and associated air quality, large heavy goods vehicle flows over an extended period of time, or new point sources of air pollution. At a detailed level, planning in infrastructure to support electric vehicles is also important, but this should not reduce the emphasis on a modal shift away from private cars to public transport, walking and cycling. The proportion of private vehicles on the roads that are delivery vehicles has steadily increased and planning for distribution and logistics facilities, including 'last mile' delivery and adapting for electric vehicle fleets presents new challenges and demands on land in central locations and new building typologies.

An example of planning guidance is the West Yorkshire Low Emissions Strategy Group guidance for integrating air quality considerations into land-use planning and development.[15] London has also set out an 'Air Quality Positive' strategy. It requires planners, designers, architects, and air quality experts to show what measures have been taken during the design stages to achieve the best possible outcomes for air quality and the creation of healthy places.[16] Further detail on preventative measures in place in London, such as the Ultra-Low Emission Zone, can be found in Section 6.3.

Evidence shows that vulnerable groups, such as young children, the elderly and those with long-term health conditions are at a disproportionately high risk from poor air quality. Careful engagement with vulnerable groups, through the planning and design process, as well as careful consideration of the access to and layout of schools, play areas and healthcare facilities can help to improve these environments. As discussed in Section 1.2, people living in areas of high deprivation and ethnically diverse communities tend to have increased exposure to air pollution. Urban planning has a role in reducing these disparities.

Co-benefits of urban planning to improve air quality and public health

While evidence continues to evolve about air quality and the associated public health impacts of each individual action above, many of the actions will have a range of benefits, especially when implemented together.

To illustrate, while green infrastructure may help to improve air quality, it has other health benefits, such as encouraging greater levels of physical activity through walks in parks, and supporting mental health through connecting with nature in a peaceful environment. Green infrastructure can also support resilience to climate change, by mitigating the urban heat island effect or reducing the impact of flood events, and improving social cohesion, by encouraging safe and accessible places for community interaction.[17]

Similarly, while safe cycling and walking infrastructure can help reduce air pollution, it also encourages greater levels of physical activity, with associated health benefits, as discussed in Section 4.4. It can also reduce carbon emissions and bring economic benefits through reducing road congestion and increasing footfall around commercial and retail areas.

A holistic approach to good urban planning and neighbourhood design can have a positive effect on encouraging healthy behaviours, improving public health overall, as well as achieving a range of wider social, economic and environmental benefits.

There are excellent examples of interventions and strategies across the country that are helping to create better places. However, while we are making significant progress in reducing vehicle emissions and improving air quality in areas such as London, there is still a way to go. Close and collaborative working between health, urban planning and design professionals will be crucial in helping to create new homes and neighbourhoods of the future that support increasingly healthy ways of living and reduce air pollution emissions and people's exposure to it.

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4.4 Active travel

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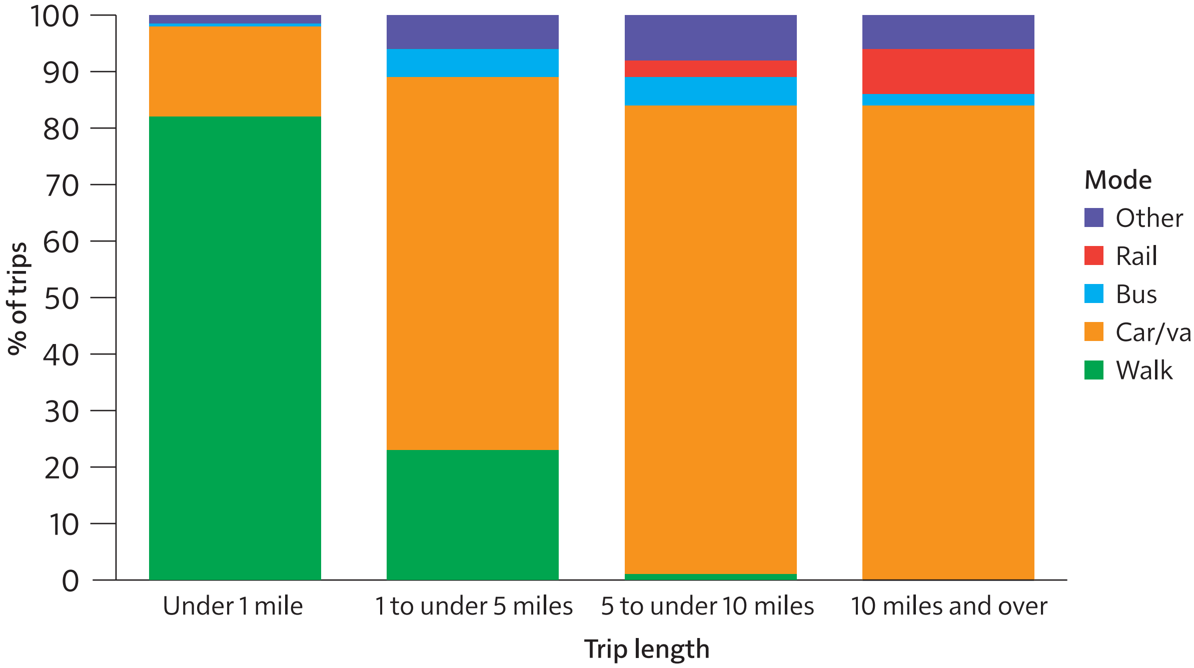
Introduction

Active travel means making everyday journeys by walking, wheeling and cycling, and can include trips made by wheelchair, mobility scooters, adapted cycles, e-cycles and scooters, rather than by motorised transport.[1] Increasing the number of journeys through active travel reduces air pollution emissions from motorised transport and has significant health co-benefits through promoting physical activity.[2] Active travel can also help to address health disparities in inner city areas and on busy main roads, where air quality is often worse and residents tend to have lower incomes and increased risk of long-term health conditions.[3] This section looks at active travel, its health co-benefits, interventions to increase uptake, and how this affects air pollution.

Walking, wheeling and cycling in England

Many people walk for very short trips but use motorised transport for slightly longer journeys. The National Travel Survey[4] found that, in 2020, most journeys under 1 mile were walked, whereas most journeys between 1 and 5 miles were taken by car or van, as shown in Figure 1. Of all trips in 2020, 25% were under 1 mile and 71% were under 5 miles.

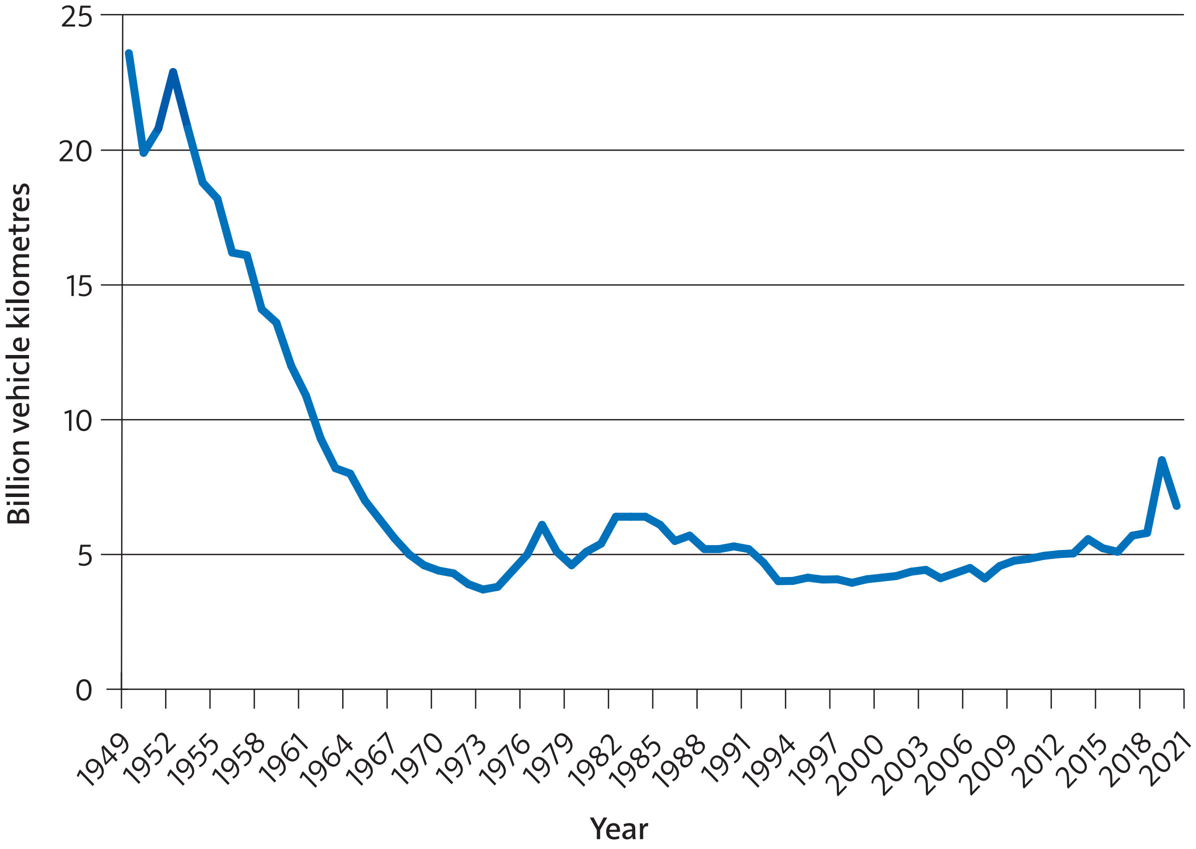


Source: Department for Transport, National Travel Survey 2020[4]

Figure 1: Main modes of transport taken for different lengths of trip

Walking, including with mobility aids, is the most common form of active travel, and is a particularly important contributor to physical activity for women, disabled people, older people, people on lower incomes, and people from South Asian, Black and other ethnic minority backgrounds.[5,6]

Cycling is currently a less common mode of travel, compared with walking, and in 2020 it made up 3% of trips by all transport modes.[7] This has not always been the case and, in the mid-20th century, cycling was much more popular. Figure 2 shows the decline in kilometres travelled by bicycle in Great Britain from 1949. Factors that contributed to this decline include increasing availability and affordability of motorised vehicles, with planning and development policies that also favoured motorised travel. However, since 2011, data shows that there has been an overall upward trend for cycling, with a greater increase from 2016 onwards. During the COVID-19 pandemic, cycling (for leisure) increased considerably. This demonstrates that there is potential to increase cycling rates in the future.



Source: Department for Transport (2022)[8]

Figure 2: Kilometres travelled by bicycle in Great Britain from 1949 to 2021

Cycling rates in England are low when compared to countries such as Germany, the Netherlands, or Denmark, with only 3% of English adults cycling 5 or more times a week, compared to 26% in the Netherlands.[9] In countries with low overall levels of cycling, including the UK, cyclists are disproportionately likely to be male.[10] In England in 2020, 47% of people aged 5 years and over owned or had access to a bicycle, which is a modest increase from the 3-year average of 42% for 2017 to 2019.[7]

There is also a potential appetite from different demographic groups to start cycling, but 85% of people aged over 65, 78% of disabled people, 76% of women, 75% of people at risk of deprivation, and 74% of people from ethnic minority groups never cycle.[11]

There are geographical disparities in England. In 2018/19, the share of adults cycling 5 times per week was highest in Cambridge (29%) and Oxford (19%), and lowest in Burnley (0.1%). This is partly reflected by age variation in the populations and urban density, but there are other environmental and social factors that influence cycling rates, including policies introduced to increase cycling in some areas of the country.[12]

There is clearly scope for increasing active travel rates, and the Government's Cycling and Walking plan, Gear Change, sets out the ambition to increase active travel and change how people move around, particularly in towns and cities.[13,14]

DfT has committed £2 billion for active travel over 5 years, with the aim that 50% of all journeys in towns and cities should be walked or cycled by 2030.[14] The new executive agency Active Travel England was established in 2022 to help deliver this commitment to active travel.

Active travel, physical activity and health

Active travel is being promoted by local authorities and national government to reduce air pollution emissions and gain health benefits from the physical activity of active travel, reduce road congestion and productivity losses.

For children and young people, regular physical activity is associated with better mental health and cardiovascular fitness, contributing to healthy weight status and improved learning and attainment.[15] In adults, there is strong evidence that physical activity has a protective effect on coronary heart disease, type 2 diabetes, mental health problems, obesity and social isolation.[16,17] Many people do not achieve the recommended amounts of physical activity[16] and active travel has the potential to increase this through commuting, visiting local shops and travelling to school.

Clearly, a large-scale change from using vehicles to active travel would reduce the number of vehicles on the road and their associated air pollution emissions. However, when people travel on the roads today (by vehicle or active travel), they are exposed to air pollution emissions from traffic, including nitrogen dioxide and particulate matter from vehicle exhausts, tyres, and brake wear. There is some public concern about exposure to air pollution during active travel, and in a recent survey by Transport for London, air pollution was noted as a barrier to cycling.[18] Reducing road vehicles could increase the desirability of active travel, and increased active travel would further reduce road vehicles (and the associated air pollution emissions).

Through the estimated changes in all-cause mortality, Tainio and others[19] investigated the long-term health effects of active travel and air pollution exposure, and found that the long-term health benefits of active travel outweighed harm caused by air pollution in all but the most extreme air pollution concentrations (and these are very rare in the UK currently).

Active travel interventions

To increase walking, wheeling and/or cycling in a place, interventions tend to be most effective when there are several actions together that reinforce each other and amplify the effect.[20,21]

Interventions are most likely to be successful when they:

- make active travel safer and easier ('making the healthy choice the easy choice')
- place some limits on motorised vehicles ('making the unhealthy choice harder')
- recognise and address cultural and social factors

Changing people's behaviour is easier when the environment changes to support it.[22] When more people travel actively, this encourages others and makes it safer for everyone.[23] For the interventions described below, the impacts on active travel are discussed and, where possible, the effects on air pollution.

Low Traffic Neighbourhoods

Low Traffic Neighbourhoods (LTNs) restrict motorised through-traffic from residential streets, but maintain access for people walking, wheeling and cycling, using modal filters such as bollards or planters, or an automatic number plate recognition camera.[24] This prevents drivers from cutting through and, although it is still possible to drive to and from any point in an LTN, it may require a longer route.[25]

LTNs simultaneously improve conditions for active travel and reduce the convenience of driving short journeys.[26] They have been widely implemented in London, and have been introduced in other places including Birmingham and Greater Manchester,[27] and internationally in New York and Barcelona. Regarding road changes, there are a broad range of attitudes and opinions, but good local engagement, including piloting interventions, has been demonstrated to be effective in delivering change.[24]

A study of LTNs in Outer London found increased levels of active travel in LTN areas compared to non-LTN areas. In the London Borough of Waltham Forest, three years after the introduction of LTNs, a longitudinal survey found that residents' walking levels increased by 115 minutes, and 20 minutes for cycling in the past week.[28] People living in LTNs were also less likely to own a car, with the statistical significance of this trend increasing the longer that the LTN has been in place.[27]

A concern with the implementation of LTNs is the displacement of motor traffic onto the surrounding boundary roads.[29] For LTNs that have been in place for longer, there tends to also be reduced traffic around the LTNs, but evidence is mixed and they are heavily debated. Shortly after LTNs were put in place, traffic on the boundary roads on 12 LTNs were surveyed and, of the 50 boundary roads, traffic had risen on 15 and reduced on 35.[24] Long-term follow-up is needed for the evaluation of LTNs, with high-quality data for baseline traffic volumes, and adjustment for other influencing factors.

A study of LTNs in London started in early 2022, funded by a £1.5 million research grant from the National Institute for Health and Care Research (NIHR). This work builds on previous research and explores the experiences of living in or near new LTNs in London boroughs, and assesses the impact on air pollution concentrations.[30]

School Streets Initiative

School Streets are roads outside schools that have restrictions on motorised traffic at school drop-off and pick-up times, to create pedestrian and cycle zones.[31] These restrictions apply to school traffic and through traffic, with access retained for residents, blue badge holders and emergency services. There is growing evidence that School Streets increase levels of active travel to and from school,[32] and improve air quality around schools.[33] Evaluation of how School Streets influences air quality during pick-up and drop-off at 18 schools across three London Boroughs (Brent, Enfield, and Lambeth) demonstrates that closing roads around schools to traffic can reduce NO_2 levels by up to 23%.[34]

Walking, wheeling and cycling infrastructure

The recent National Travel Attitudes survey explored barriers to walking, wheeling and cycling.[35] It found that road safety and the design and maintenance of footpaths and cycle paths play important roles in encouraging people to walk and cycle more.

Well maintained pavements and no obstacles (such as pavement parking), make walking easier and safer, especially for disabled people and older adults.[28] Conversely, obstructed pavements can be a barrier to walking, including for those walking to school. In one 2021 UK survey, 80% of parents said they would feel safer to let their children walk to school if there were not vehicles parked on the pavement.[36] Other elements to support active travel include benches, enabling those with reduced mobility to rest while walking[37] and better street lighting, which can reduce personal security concerns, especially for women.[38]

Cycle lanes that are protected from traffic by kerbs, or segregated using 'wands' or planters, are necessary on busy and fast roads where cyclists tend to feel unsafe.[13] On such roads, unprotected painted lanes or shared bus lanes, can increase the risk of injury to cyclists.[39] The specific design of high-quality and accessible cycle infrastructure, appropriate for people using a range of standard and non-standard cycles, is available in Local Transport Note 1/20.[40] There is growing evidence that protected cycle infrastructure increases the levels of cycling in towns and cities across the UK.[41] Data from the Wilmslow Road/Oxford Road segregated cycle superhighway in Greater Manchester showed a 70% increase in cycling volumes on the route between 2015 and 2020, compared to no change on control sites during this period.[40]

There is some evidence that barriers between cyclists and vehicles, such as dense foliage, can protect cyclists from vehicle air pollution emissions. However, the pattern of air pollution emissions and dispersion needs to be taken into account,[42] in addition to wider personal safety and practical design considerations.

Reducing the speed limit on roads to 20mph in urban areas reduces accidents[43] and can encourage people to take journeys by walking, wheeling and cycling, and also improve community cohesion. For the remaining vehicles, congestion can increase air pollution emissions. A driving style with fewer accelerations and decelerations emits fewer air pollution particles.[44] The relationship between vehicle speed and air pollution emissions is complex, and depends on many factors, including the road layout, road surface, driver behaviour and weather conditions.

Schools

For primary school children, 'bicycle trains' and 'walking buses', where children living along a set route travel with an adult can encourage active travel.[45] Educational initiatives, such as story reading and knowledge lessons, can also be included.[46] Cycle training can encourage this mode of travel, but there must be safe spaces for children to learn to ride and practise their skills.[47] Living Streets, the UK charity for everyday walking, has implemented a pupil-led initiative where children report how they travelled to school, using an interactive travel tracker. If they travel actively to school by walking, wheeling, or cycling once a week for a month, children are rewarded with a badge. On average, these schools see a 30% reduction in car journeys to the school gate and a 23% increase in walking rates.[48]

Workplaces

There is evidence for workplace promotion of active travel and personalised travel planning,[49] especially when coupled with parking restrictions and/or charges.[50] Providing secure bike parking, drying rooms and showers can remove practical barriers.[51] The Cycle to Work scheme, which allows some of the cost of a new bicycle to be set against tax, has also been shown to increase cycling.[52] Restricting and charging for parking at workplaces encourages cycling and decreases car use. A study of residents in Cambridge, a city with very high cycling rates, found that provision of free workplace car parking was a strong predictor of choosing to drive rather than cycle.[10]

Summary

Active travel can achieve significant health benefits for children and adults, and there is evidence that implementing several interventions together can work to increase the uptake of active travel. Active travel can be encouraged through initiatives to reduce vehicle air pollution emissions on the roads, creating a virtuous cycle – changing from motorised transport to active travel will result in fewer road vehicles, thereby reducing the associated air pollution emissions.

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4.5 Industry

4.5.1 Industry interventions

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Introduction

Industrial air pollution emitters include many processes across a wide range of industry sizes, from large power stations to small backstreet workshops. This means there are also a wide range of air pollutants that might be emitted. Some industrial air pollutants are common to those found in other activity sectors, but others are specific to certain industrial processes. This section's approach is to illustrate how measures taken to control the effects of industrial air pollution have achieved air quality improvements. It does not seek to list all industrial air pollutants of potential concern. Evidence of the health effects of the main pollutants can be found in Section 1.1.

Mitigating the impact of industrial emissions

Over the last 3 decades, concerted effort has been made to reduce air pollution emissions from the industrial sector. A wide range of techniques are used in the industrial sector to minimise emissions, including both primary and secondary techniques.

Primary techniques aim to prevent or reduce the formation of pollutants during the industrial process itself. These measures include product or raw material substitution, switching to less polluting fuels, controlling and optimising processes with automated systems and improving the energy efficiency of a process.

Secondary techniques aim to reduce emissions after the pollutant has been formed but before it is emitted. These are often known as 'end-of-pipe' techniques. Typical methods for controlling common pollutants are described in Table 1 below.

Pollutant/ pollutant group	Typical point source control techniques
Nitrogen oxides (NO_x)	Automated control and optimisation of combustion conditions is the principal primary technique for reducing NO_x formation during combustion. Selective non-catalytic, or selective catalytic, reduction can be used to reduce emissions of residual NO_x formed after application of primary measures. These techniques use ammonia or urea, with or without a catalyst (depending on the temperature and location in the process), to react with the NO_x, forming molecular nitrogen and water vapour.
Acid gases (for example, sulphur dioxide (SO_2), hydrochloric acid (HCl), hydrofluoric acid (HF))	Emissions of these pollutants are derived principally from their presence in raw materials, or the presence of precursors in fuels (for example reduced sulphur species in fuels, such as hydrogen sulphide or mercaptans, will oxidise to SO_2 during combustion). Raw material substitution or switching to fuels with a lower quantity of precursors (for example switching from coal or oil to gas) are effective primary techniques. Scrubbing systems which use an alkaline-based reagent in solid or aqueous form are commonly applied secondary techniques. These reagents react with the acid gases to form solid precipitates of calcium, sodium or magnesium salts, depending on the reagent used.
Particulate matter (PM) and metals	Fuel switching from solid or liquid fuels to gaseous fuels and optimisation of combustion processes are the main primary measures. The use of cyclones, wet scrubbers, electrostatic precipitators or filters are commonly applied secondary techniques. For mercury, which is typically found in vapour form, rather than either a solid or adsorbed to solid PM like other metals, injecting activated carbon into the flue gases is an effective control technique.
Persistent organic pollutants, including dioxins and furans, and dioxin-like polychlorinated biphenyls (PCBs)	Substitution of raw materials where these species or their pre-cursors are present. For combustion processes where these pollutants can (re)form, for example waste incineration, optimised design of the combustion technology and automated control systems are effective primary measures. Activated carbon injection is a secondary control technique.

Table 1 – Controlling industrial air pollution from point source emissions

The above techniques target emissions from chimneys, or so-called 'point source' emissions. However, diffuse or 'fugitive' emissions can be equally important; fugitive is the term used for unintentional releases such as leaks or transient dust sources, including those which escape control via a chimney, flue or other technique. This is particularly the case for solvent-consuming processes and those involving the production, storage and transportation of fuels, which can emit a range of different non-methane volatile organic compounds (NMVOCs), as well as those relating to the processing or transport of solid materials which may give rise to dust. Depending on the type of solvent or fuel, many different types of NMVOCs can be emitted from these processes through evaporation and spillages. Some of these can be toxic, while others play a different role in the formation of secondary air pollutants such as ozone and particulate matter through chemical processes occurring in the atmosphere. For these applications, typical control techniques include solvent management plans, leak detection and repair surveys, the use of vapour recovery systems and applying dust control methods such as enclosing activities and good site management.

In addition to these techniques to reduce total emissions, local air quality is managed through spatial planning (see Section 4.3). For many air pollutants, emissions released close to where people spend time have a disproportionately large effect on their exposure. The immediate effects of industrial emissions are thus often mitigated by separating industrial and residential areas, or other areas where vulnerable people may be exposed.

The local impacts of large emissions sources are also controlled by chimney design. Elevating air pollution emissions with chimney height, while ensuring sufficient momentum and heat, increases air pollution dilution and dispersion. It also reduces contributing to pollution events associated with temperature inversions. Temperature inversions form when air close to the ground becomes cooler than the air above it. This acts like a cap and can 'trap' emissions close to the ground and increase people's exposure to them. Well-designed chimneys often break through, or emit above, the more problematic inversions (Figure 1). While spatial planning and chimney design can reduce local-scale effects, they do not prevent effects further afield, such as ozone and secondary particle formation.

Source: Wesley Kristopher Photography

Figure 1: Hot emissions from Hope Cement Works rise above temperature inversion in the Hope Valley

National total emissions

The National Atmospheric Emissions Inventory (NAEI)[1] estimates the UK total emissions of selected pollutants from man-made sources. This covers all pollutants required for international reporting and other purposes, but not all pollutants of relevance to every industrial process. The NAEI derives its estimates from a variety of sectors and sources, so the reliability of these estimates varies. A unique feature of the industrial sector is that a large proportion of reported emissions come from relatively few, tightly controlled sources. This makes these reported emissions particularly reliable. Conversely, quantifying fugitive emissions is extremely challenging because of their diffuse nature, and these elements of the inventory are less certain.

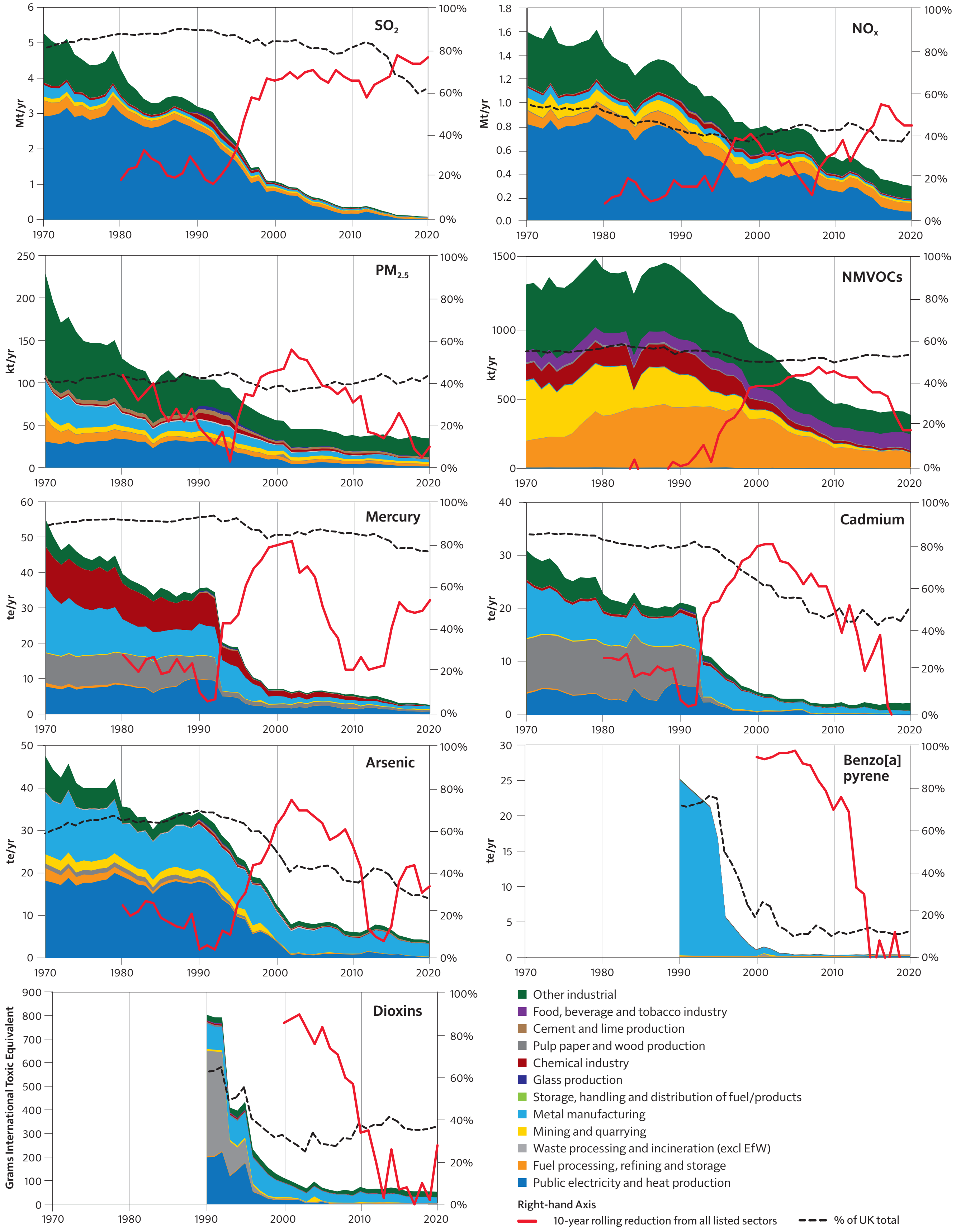
To illustrate trends in some important industrial emissions, Figure 2 summarises recent and historical reported UK total emissions of selected pollutants from industrial processes. This represents a small subset of pollutants in the NAEI, and is an indicative classification of industrial processes. The reliability of the NAEI varies over time and by pollutant, but the trends in Figure 2 nevertheless illustrate patterns seen across many pollutant groups. The stacked colours in Figure 2 show the total mass of emissions from each sector. The red lines show, using the right-hand axes, the relative reductions in total emissions from these sectors in each successive (rolling) 10-year period. This is important because large relative reductions are masked when presenting absolute numbers. For example, the largest absolute reductions in SO_2 emissions occurred between 1990 and 2000, with a reduction in annual emissions from these sectors of >2Mt. The absolute improvements have necessarily reduced since then, but the relative rate of improvement has accelerated. The black dashed lines on each graph indicate the proportion of the UK total emissions (all sectors of anthropogenic origin) made by the listed industries. For example, these industries dominate total UK mercury emissions (>75%) but make a much smaller contribution to total UK NO_x emissions (<50%).

Over the period shown in Figure 2, there have been significant socio-economic changes, including the closure of domestic heavy industry in favour of importing certain products, and shifts in the ways the UK fulfils its energy needs. Since 1990, there have also been various changes to how industrial emissions are regulated, including:

- **1990** – Environmental Protection Act[2] which introduced the system of Integrated Pollution Control (IPC) and Local Air Pollution Control (LAPC). Processes are categorised as either being subject to central control by the Environment Agency (EA) in England (Part A) or authorised by the local authority (Part B). Processes were authorised with sufficient conditions to require the use of Best Available Techniques Not Entailing Excessive Costs (BATNEEC) to control and manage emissions.
- **1996** – Integrated Pollution Prevention and Control (IPPC) Directive.[3] As transposed by the Pollution Prevention and Control Act 1999,[4] this consolidated the permitting requirements for Part A processes and provided a framework for emissions limit values based on Best Available Techniques (BAT).

- **1999** – Solvent Emissions Directive (SED)[5] and Sulphur Content of Liquid Fuels (SCoLF) Directive.[6] The SED targeted the reduction of volatile organic compounds (VOCs) in industry. It required installations to either meet prescribed emission limits, or to achieve equivalent reductions through other means. The SCoLF Directive controls the sulphur content of fuel, which relates directly to the SO_2 emitted from its combustion.
- **2000** – Waste Incineration Directive (WID),[7] which placed limit values on the emissions of specified pollutants from waste incineration.
- **2001** – Large Combustion Plant Directive (LCPD),[8] which placed emissions limit values on SO_2, NO_x and total airborne PM emissions from combustion plant with a thermal input greater than or equal to 50MW.
- **2010** – Industrial Emissions Directive (IED),[9] which combined the IPPC, SED, WID and LCPD directives and introduced new requirements on the development of formal Best Available Technique (BAT) conclusions.
- **2015** – Medium Combustion Plant Directive (MCPD),[10] which regulates emissions of SO_2 and NO_x and total airborne PM emissions from combustion plant with a thermal input greater than or equal to 1MW and less than 50MW, thus supplementing the 2010 IED.

There was advance warning before the regulations were introduced, and they were not designed to take immediate effect on all existing processes. They would not, therefore, be expected to cause an immediate step-change in national emissions. The role of current industry regulation is discussed in further detail in Section 4.5.2.



Notes: Also showing the contribution of these sectors to the total reported UK emissions (black dashed line). Red line shows the % change over the preceding 10 years – where this drops below zero, total emissions increased. Benzo[a]pyrene and dioxins data not available before 1990.

Source: National Atmospheric Emissions Inventory[11]

Figure 2: Total UK emissions of selected pollutants from industrial sectors reported in the NAEI

Public electricity and heat production (for simplicity, 'power stations') dominated emissions of SO_2, NO_x and arsenic prior to 1990. Since then, reductions in coal use have resulted in significant improvements. Implementation of flue gas desulphurisation and limits on fuel sulphur contents have also helped drive the large reductions seen in SO_2 emissions. Emissions of NO_x from power stations increased between 1999 and 2006, and again in 2012, reflecting temporary increases in coal usage, which was not mitigated as effectively by the introduction of NO_x reduction technology as was the case for SO_2. As with SO_2, the largest relative reductions in NO_x emissions have occurred in the most recent part of the time series, driven by continued reductions in power station emissions, as coal use has diminished and generation through renewable sources has increased.

The category 'Other industrial' includes a range of miscellaneous processes, including stationary combustion plant used within unspecified industries. These kinds of plant dominate the $PM_{2.5}$ (fine particulate matter) emissions shown in Figure 2. There were significant improvements up to 2000, but since then, reported emissions have risen. Power stations have also played an important role in the overall trend in $PM_{2.5}$ emissions. Reductions in coal use, and the use of more sophisticated abatement equipment, delivered a 95% reduction in $PM_{2.5}$ emissions from power stations between 1990 and 2020. Relative reductions in other sectors have been smaller, possibly reflecting the difficulty in controlling fugitive sources.

There have been significant reductions in NMVOC emissions since 1990. Legislation to reduce the solvent content of products such as paint has been important, as has the requirement for industries using solvents to implement better control or recovery of emissions. There have also been more stringent controls applied to fossil fuel extraction and refining operations, as well as broader structural changes such as the closure of coal mines. Estimated NMVOC emissions from mining and quarrying have thus reduced from 430kt in 1970 to less than 2kt in 2020.

Three heavy metals – mercury, arsenic and cadmium – are included in Figure 2 because heavy metals are often seen as solely industrial pollutants. However, the black dashed lines show that this is no longer an accurate characterisation. Emissions of mercury and cadmium have shown broadly similar patterns to each other, with emissions reducing rapidly in the 1990s following the introduction of improved controls on the incineration of waste. Waste incineration comprised 40% of the total reported cadmium emissions in 1987 across all sectors, and only 0.4% in 2020. While this comparison is slightly misleading, since modern incineration of waste to generate electricity is reported as electricity production (and thus is shown under 'Public electricity and heat production' in Figure 2), these emissions also remain low when compared with historical values. Emissions of mercury and cadmium have also been driven by a general decline in UK-based metal production, and by the reduction in coal power stations. The pattern for arsenic is different, with large reductions from 1990 linked to the reduction in coal use in power stations. The largest industrial source of arsenic is currently furnaces used in steel production, but most arsenic now comes from non-industrial sources.

The largest source of dioxin and furan emissions in the early 1990s was waste incineration, followed by electricity generation. Emissions from these sources fell by 99% between 1990 and 2020, largely reflecting the closure of older incineration plant, and the imposition of more stringent emissions limits on existing and new facilities. Currently, the largest industrial source of dioxins and furans is the production of sinter in iron manufacturing, although domestic combustion is more significant in a national context.

Emissions of the carcinogenic polyaromatic hydrocarbon (PAH) benzo(a)pyrene from the industrial sources listed in Figure 2 have fallen by 98% since 1990. Almost all of this was caused by improved emissions controls from aluminium production. These sectors have gone from contributing 73% of total UK emissions in 1990 to just 17% in 2020, which also reflects a concurrent increase in emissions from domestic woodburning.[1,11]

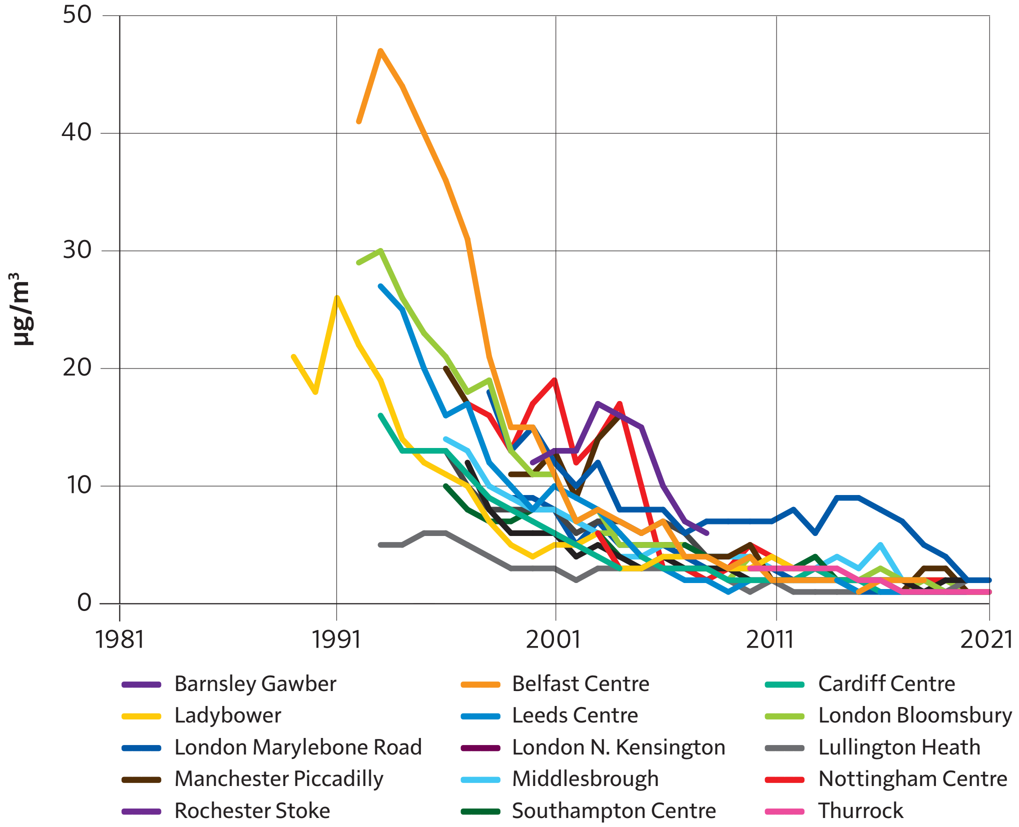
The pattern of changes in industrial emissions is thus complex, with socio-economic factors and energy policy being just as important to national emissions as the imposition of industrial regulation. Nevertheless, for all relevant pollutants there have been significant reductions over the last few decades, meaning that total emissions in 2020 are only a small fraction of those emitted in previous decades.

There is a disconnect between changes to total emissions, and changes to the concentrations to which people are exposed. While the environmental permitting regime may result in more stringent emissions limits for industrial operations close to population groups, overall spatial planning, as well as effective chimney design, means that reductions in total industrial emissions will often have smaller benefits for population-weighted exposure than reductions to non-industrial emissions released in urban areas. The UK-average trends in Figure 2 will also not reflect emissions from individual areas. By way of example, the London Atmospheric Emissions Inventory[12] estimates that industrial facilities regulated by the EA or local authorities contributed just 0.01% of $PM_{2.5}$ emissions in central London in 2019, while commercial cooking contributed 60%; in outer London, industrial facilities contributed 6% $PM_{2.5}$ emissions and commercial cooking contributed 8%.[13]

Concentrations

Demonstrating the effects of these emissions reductions on pollutant concentrations is not straightforward. Changes to the ambient pollution monitoring networks over time mean that compiling consistent measured time series for many pollutants, particularly those which are not strongly linked with urban emissions sources, can be challenging. In many cases, monitoring of particular pollutants did not start until after the large reductions in emissions in the 1990s. Interannual variability in meteorology also affects concentrations measured from one year to the next.

Figure 3 summarises the annual mean SO_2 concentrations measured at Automated Urban and Rural Network (AURN)[13] sites which achieved >75% data for 21 years or more. This is not restricted to industrial areas but shows the same general pattern as the SO_2 emissions, with large reductions in the 1990s and smaller (absolute) reductions thereafter.



Source: Defra (2022)[14]

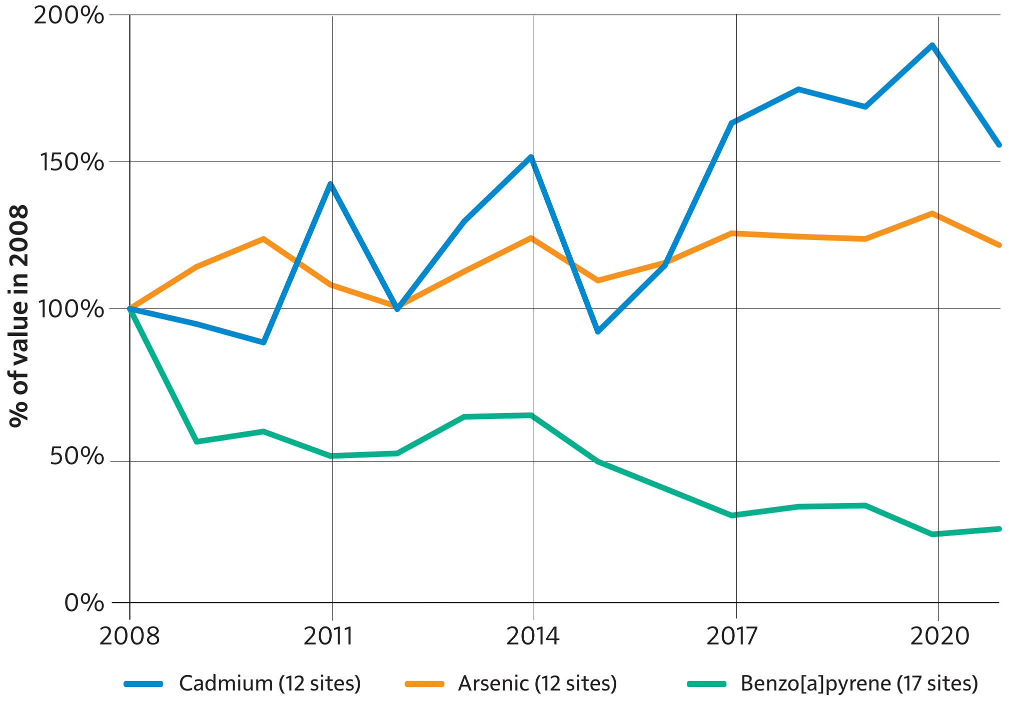
Figure 3: Annual mean SO_2 concentrations at AURN sites which achieved >75% data capture for 21 years or more

Source: Defra (2022)[15]and Defra (2022)[14]

Figure 4: Annual mean total dioxins and furans measured in the UK toxic organic micro pollutants network at sites which achieved >75% data capture for 13 years (2004 to 2016)

Figure 4 summarises annual mean measured concentrations of dioxins measured at the 3 national network sites that achieved >75% data capture for 13 years (the approximate duration of good data availability from this network). The trend is qualitatively downward, and broadly aligns with that of estimated emissions. The red line for dioxins in Figure 2 suggests a reduction in industrial emissions of around 30% over 10 years to 2016, while the concentrations at these 3 sites reduced by between 60% and 80% over the same period.

Consistent data for many pollutants from the national networks has only been available since 2008. Figure 5 summarises the average trend in annual mean concentrations at relevant UK network monitoring sites with good data capture each year. Averaged across the 17 relevant solid-phase benzo(a)pyrene monitors, concentrations have reduced by about 70% since 2008, with the largest reductions occurring at monitors close to industrial areas. Averaged across the 12 relevant heavy metals sites, concentrations of cadmium and arsenic have risen over this period; increases in specific industrial areas (Scunthorpe and Port Talbot) drove a large part of this trend.



Source: Cadmium and arsenic data from Defra (2022);[16] benzo(a)pyrene Digitel (solid phase) from Defra (2022)[14] and Defra (2022)[17]

Figure 5: Relative change in multi-site mean cadmium, arsenic and benzo(a)pyrene concentrations 2008 to 2021 at sites which achieved >75% data capture each year

In practice, changes to concentrations at individual sites often relate to local events and processes, and this is particularly the case with industrial pollutants. Closure, or improvements to, a single factory might have a minimal effect on national total emissions or network-average concentrations, but have a significant effect on the concentrations to which the local population is exposed. Conversely, significant reductions in emissions at a national level may not necessarily result in corresponding reductions in ambient concentrations at a local level if a single industrial emission source dominates the observed concentrations but that source has made only minor improvements to its emissions. Because of this, reducing local exposure often requires cooperation between local authorities, regulators and site operators.

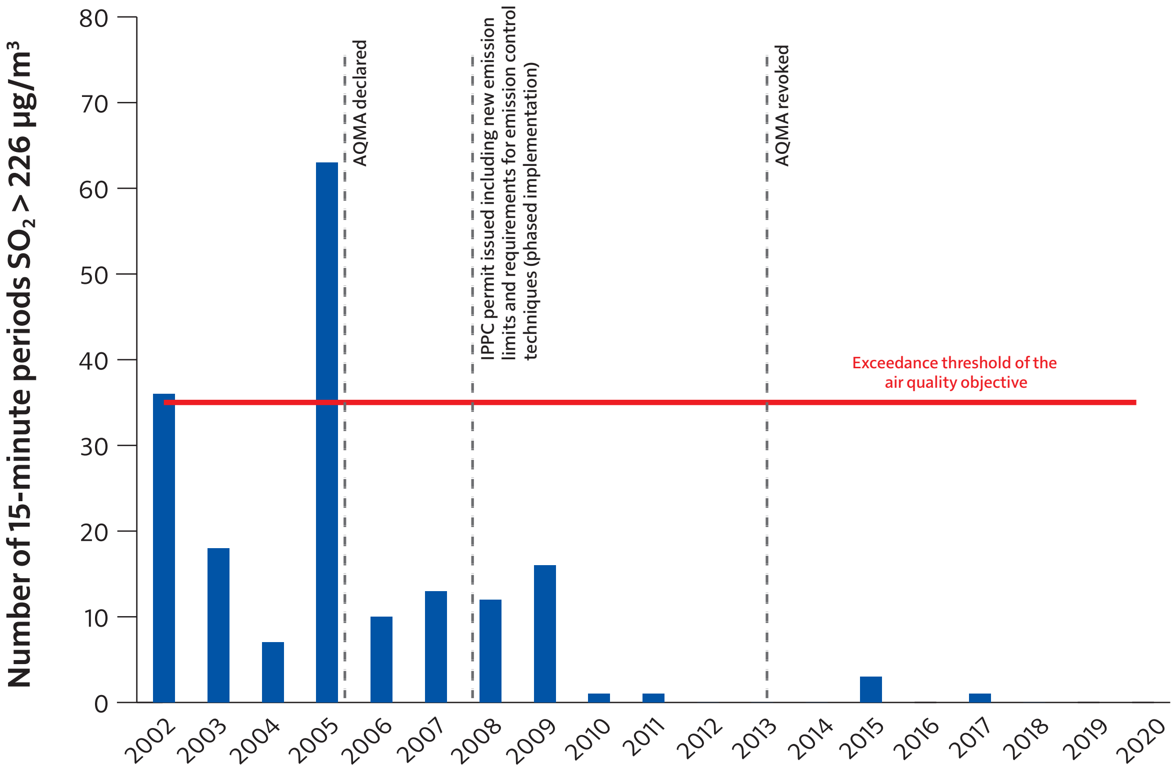
Case study – Fawley

In December 2005, an Air Quality Management Area (AQMA) covering Fawley village, near Southampton, was declared by New Forest District Council (NFDC) following measured exceedances of the national objectives for SO_2. Further investigation identified that the exceedances generally occurred when the village was downwind of 4 main emission sources at the nearby Fawley oil refinery.

NFDC, the refinery operator and the Environment Agency (EA) worked together to reduce emissions from the refinery and improve air quality in Fawley. This included short-term voluntary measures by the operator to implement an emissions management procedure. Under this procedure, the main emission sources at the refinery would temporarily reduce load or switch to using gaseous fuels in preference to oil when Fawley was downwind of the refinery and monitoring systems in the village detected increased levels of SO_2.

Longer-term improvements were introduced through measures available to the EA under the industrial emissions permitting regime. These included a combination of reducing emission limits and requiring technological improvements to key emission sources, such as the permanent conversion of the main steam-raising boiler plant to use lower sulphur fuels and the introduction of more efficient secondary pollution control techniques.

Following the introduction of these measures, no further objective exceedances were observed (Figure 6). Consequently, the AQMA was revoked in 2013.[18]



Source: Air Quality in England (2022)[19]

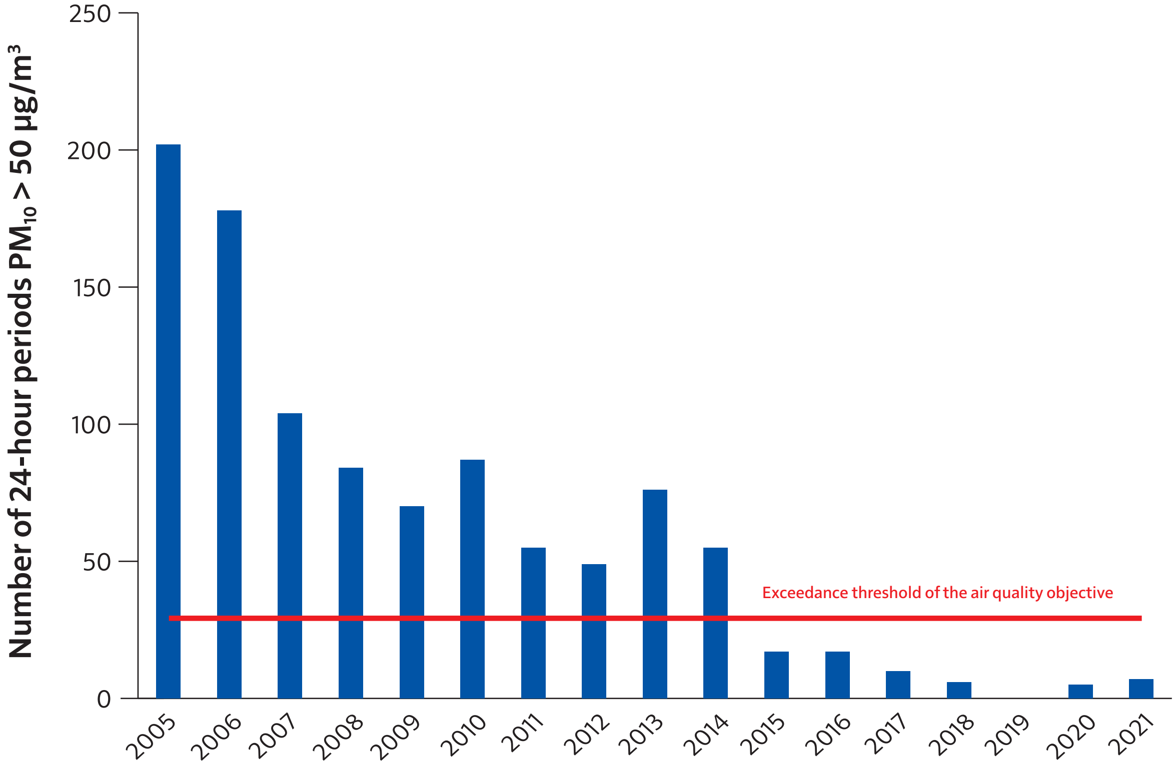
Figure 6: Annual number of 15-minute periods with SO_2 greater than 266µg/m^3 at Fawley monitoring station operated by NFDC

Case study – Horn Lane

In 2005, the air quality monitoring site at Horn Lane in Ealing, London, measured PM_{10} concentrations >50µg/m^3 on more than 200 days. This is well above the 35 days allowed by the national objective, and made it one of the worst-polluted monitoring locations in the UK by this metric. Ealing Council had responsibilities to investigate under the local air quality management regime and under the Environmental Protection Act regarding complaints of statutory nuisance.

The council's investigation suggested that the principal local source was fugitive emissions from the nearby Acton Goods Yard. This is a complex site, comprising 2 separate concrete batching operations, a waste transfer station and several other small industrial premises. Some of these processes are regulated by the council, and some by the EA. It was established that no single operation was ultimately responsible for the high concentrations observed, which were due to multiple issues within the Yard.

The council prepared a Low Emissions Strategy in 2014/15 which provided a framework for voluntary agreement between all site operators and the council. This resulted in a combined effort to implement good site management practices and consequently to improve air quality for nearby residents.[20] Measured concentrations fell below the objective in 2015 and have remained comfortably below this level since (Figure 7).



Note: Graph shows tapered element oscillating microbalances (TEOM) Volatile Correction Model (VCM)

Source: London Air (2022)[21]

Figure 7: Annual number of 24-hour periods with PM_{10} greater than 50µg/m^3 at Ealing Horn Lane

Conclusions

The industrial sector is diverse, and the air pollutants of potential health concern are numerous. Regulation, combined with changes to how electricity is generated and changes to UK industrial activity, has delivered large reductions to national total emissions over the last 30 to 50 years. The concentrations to which individuals are exposed will often depend on which activities take place close to where they live and work. Irrespective of the substantial improvements which have been made nationally, there often remains a need for local action to ensure that populations are not exposed to elevated levels of pollutants emitted by industry.

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4.5.2 Recent industry regulation

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Introduction

There are many sources of industrial air pollution emissions, ranging from large industrial sites (such as chemical plants, oil refineries or power stations) to smaller, more numerous industrial sites (such as petrol stations, light industrial facilities, combustion plants and quarries). Measures taken to control industrial air pollution have improved air quality over recent decades, as presented in Section 4.5.1. This section focuses on the regulatory framework for controlling industrial emissions. A coherent and predictable regulatory framework for setting, updating, and enforcing standards supports investment and innovation to reduce emissions over time. The UK has been at the forefront of reducing industrial pollution, using proportionate regulation, signalled in advance to allow time for preparation, to reduce the emissions that harm health and the environment.

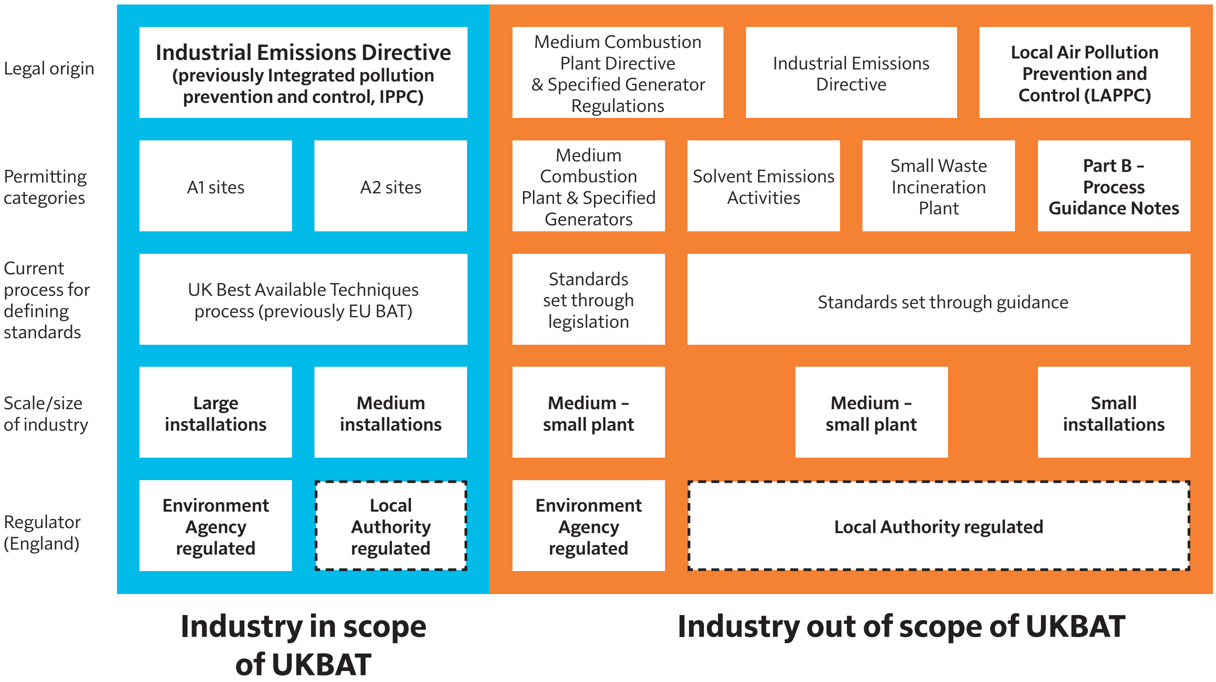
Industry regulatory requirements

The current regulatory framework for industrial air pollution emissions includes both permitting and non-permitting requirements, which set standards on industry and eventually lead to a reduction in emissions. The regulatory framework has developed over time, as outlined in Section 4.5.1.

Environmental permitting

Under the Environmental Permitting (England and Wales) Regulations (2016), certain industrial installations must apply for and comply with an environmental permit to operate. These permits set out mandatory conditions – for example, limits on the levels of pollutant emissions, and requirements to prevent dust during operation. In England, the regulation of industrial sites is split between the Environment Agency and local authorities depending on the size and environmental impact of sites. The Environment Agency predominantly regulates larger sites, and local authorities predominantly regulate smaller and medium industry.

Figure 1 presents the current regulatory framework for environmental permitting, which is all contained in the Environmental Permitting Regulations (2016). The left box presents the environmental permitting framework for large and medium industry installations that are in scope of the UK Best Available Techniques (UKBAT) regime (see Industry activities below). The right box presents the framework for environmental permitting for medium and smaller industrial installations that sit outside of the UKBAT regime. The size and industrial activity of a site will determine where a site fits within the regulatory framework. The standards are part of the regulatory process that informs the permit conditions which operators need to comply with.



	Industry in scope of UKBAT		Industry out of scope of UKBAT			
Legal origin	**Industrial Emissions Directive (previously Integrated pollution prevention and control, IPPC)**		Medium Combustion Plant Directive & Specified Generator Regulations	Industrial Emissions Directive		**Local Air Pollution Prevention and Control (LAPPC)**
Permitting categories	A1 sites	A2 sites	Medium Combustion Plant & Specified Generators	Solvent Emissions Activities	Small Waste Incineration Plant	**Part B – Process Guidance Notes**
Current process for defining standards	UK Best Available Techniques process (previously EU BAT)		Standards set through legislation	Standards set through guidance		
Scale/size of industry	**Large installations**	**Medium installations**	**Medium – small plant**		**Medium – small plant**	**Small installations**
Regulator (England)	**Environment Agency regulated**	**Local Authority regulated**	**Environment Agency regulated**	**Local Authority regulated**		

Figure 1: Industrial emissions regulatory framework – environmental permitting

As an example of the environmental permitting process, the Environment Agency assesses the air pollution emissions from new large 'energy from waste' plants and consults the UK Health Security Agency on applications. The Environment Agency will only issue an environmental permit if the proposed plant does not cause significant pollution or harm to human health.

Other regulatory requirements

There are also regulatory requirements that sit outside the environmental permitting framework in Figure 1. These are requirements for particular products or fuels to have specific standards, or for particular processes to be followed to limit air pollution emissions, including:

- The Sulphur Content of Liquid Fuels (England and Wales) Regulations 2007 & 2014
- Volatile Organic Compounds in Paints, Varnishes and Vehicle Refinishing Products Regulations 2012

Industry activities

Large industry

Large industrial facilities undertaking specified activities must use Best Available Techniques (BAT) to reduce pollution emissions to air, water, and land. These are the techniques that are most effective for preventing or minimising emissions and their environmental impacts. BAT determines the types of abatement, manufacturing, and production technology methods that operators put in place. Since leaving the European Union, a UKBAT regime has been established to develop and set future BAT across the UK for some industries. This is based on a transparent, collaborative data and evidence-led process where regulators and industry work together to set standards that safeguard and build on the high levels of environmental protection already in place.

Medium and small industry

The process for updating standards differs depending on the size of industry. Although larger industrial sources have improved emissions controls through UKBAT, some smaller sources that are not part of the UKBAT process, have been left with lagging emissions standards. Currently, for industries that sit outside the BAT process, there is no transparent and evidence-based mechanism for regulators and industry to determine and regularly update emissions standards collaboratively.

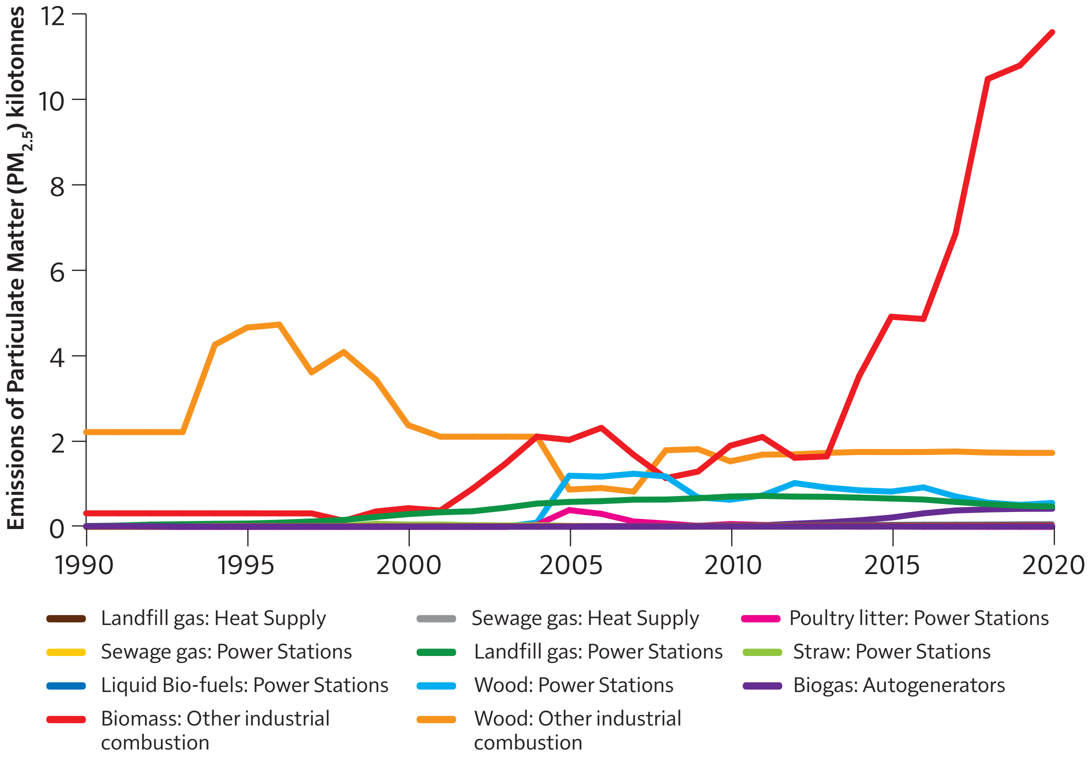
These smaller sites tend to be more numerous, widely distributed and located closer to urban or residential areas. This is either for historical reasons or owing to the location requirements of the businesses. They tend to have lower chimney or exhaust heights, which means pollution is less dispersed away from the local area. While benefitting local areas through jobs and services, the emissions from such sites can contribute to poorer local air quality, and more people may be exposed due to the higher population density. By modernising regulatory standards, there is an opportunity for smaller industrial settings to further reduce the health effects of air pollution emissions.

Future developments in the regulatory framework

The regulatory framework needs to have proportionate and expert-led approaches to identify the right standards. Regulators need the capacity and capability to ensure that air quality is effectively protected.

The way that citizens and stakeholders engage with environmental information is evolving as people expect more accessible information. Currently there is a fragmented landscape of industrial pollution reporting requirements. Therefore, Defra is considering how to improve the communication of industrial emissions information, with the goal of the public and stakeholders being able to easily access relevant information about their exposure to air pollution.

A key consideration for the future regulatory framework will be the dramatic scale and pace of change in UK industry that is required to deliver net zero. This will lead to new industrial processes which require different chemicals to operate and could potentially result in the emission of different pollutants, or the emission of familiar pollutants at a greater scale or in different locations. We have already seen increased industrial combustion of biomass fuels cause an increase in emissions of fine particulate matter ($PM_{2.5}$) as shown in Figure 2. The use of biomass is expected to increase with the emergence of new technologies, such as bioenergy with carbon capture utilisation and storage (BECCS), which can remove carbon from the atmosphere and support low-carbon electricity and hydrogen generation. The government has said that any future BECCS projects will need to meet stringent sustainability and air quality requirements for the production and use of biomass.[1]



Notes: The graph represents annual National Atmospheric Emissions Inventory (NAEI) estimates of fine particulate matter ($PM_{2.5}$) emissions from industrial combustion of biomass. Industrial use of biomass is typically to raise heat that may be used for power generation, to directly heat process vessels, driers and so on.

The category 'Biomass: Other Industrial Combustion' comprises emission estimates from the use of: plant biomass; animal biomass and anaerobic digestion; straw; short rotation coppice; other plant-based biomass; poultry litter; meat; and bone meal. The data represented in the graph comprises solid fuels (biomass), liquid fuels (biofuels) and gaseous fuels (biogases). It only presents emissions data from the use of fuels that are entirely biogenic in origin; it does not include the emissions from fuels that are part-bio and part-fossil in origin, such as smokeless solid fuels or municipal solid waste.

The scope excludes small-scale sources of combustion, such as small-scale waste burning, domestic sources and the burning of straw on agricultural sites. It also does not include any emission estimates from the use of biofuels by industrial operators where the fuels are used in their transport fleet; the emissions presented are from stationary combustion sources only.

Source: NAEI (2022)[2]

Figure 2: $PM_{2.5}$ emissions (kt) from industrial combustion of biomass in the UK (historical data from 1990 to 2020)

Another trend for consideration in the transition to net zero is the increasing interaction between the industrial and agriculture sectors. For instance, the co-location of anaerobic digestion and industrial facilities is starting to take place. The regulatory framework needs to support developments in these new industries and respond to the potential health effects of these changes.

Overall, regulators and industry experts need to respond to new challenges and rapid changes in technologies, and positively engage local communities and civil society, so that the industrial emissions regulatory system helps us to continue reducing air pollution and protecting people's health.

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4.5.3 The construction industry

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Air pollution emissions from construction

Construction sites contribute significantly to air pollution, particularly in urban areas, where poor air quality can harm health and disproportionately affect some of the most vulnerable people in communities, as discussed in Section 1.2.

Of the many different types of pollution emitted from construction sites, the pollutants that are the biggest concern for health are particulate matter (PM), and nitrogen oxides (NO_x). NO_x is emitted by engines that power non-road mobile machinery (NRMM), while PM is emitted from demolition and earthworks. PM often leaves sites on the wheels of vehicles and is then re-suspended back into the air we breathe.

People who work on construction sites, and those living near sites, are most at risk from being exposed to the highest concentrations of emissions from on-site works. As construction sites vary in size and the length of time they are in place, the scale of polluting emissions varies between sites. However, in densely packed urban areas where construction sites are a common occurrence, they can contribute significantly to overall levels of air pollution.

The construction industry has adopted several approaches and regulations to help minimise the construction sector's polluting emissions – for example, hybrid or electric NRMM, emissions standards for NRMM, and low-emission zones for construction plant and planning.

Improving air quality in and around construction sites

Impact on Urban Health,[1] which is part of Guy's & St Thomas' Foundation, are running a 10-year programme that tests equitable interventions to address air pollution in inner city areas. The programme aims to improve health, particularly for those who are disproportionately affected by poor air quality. One of the programme's key areas of focus is working with the construction industry to reduce the sector's pollution emissions.

In partnership with Arup, Impact on Urban Health are developing up to 4 low-emission construction sites in the London boroughs of Lambeth and Southwark. These sites will demonstrate best practice for mitigating air pollution. One of the sites is a social housing estate comprising over 600 homes, with the programme spanning over 6 years. While results will not be available until the developments are completed, their aim is to limit NO_x and PM to levels significantly lower than the standards set by the Greater London Authority's NRMM Low Emission Zone (LEZ).[2] Based on research undertaken by the project, as well as consultations with stakeholders, approaches that are expected to reduce air pollution from construction sites include:

- avoiding the need for diesel generators by planning for on-site provision of grid electricity
- using battery and hybrid powered equipment (often availability, cost and performance are comparable with more polluting alternatives)
- assembling materials in a factory rather than on site
- reducing dust at source by removing 'dusty' material off site or managing dust by using suppression techniques
- ensuring that all vehicles comply with standards described in London's LEZ, and that they are not left idling
- using less polluting transportation methods, such as river, rail and cargo bikes

Impact on Urban Health also partnered with the Centre for Low Emission Construction, based at Imperial College London, to undertake research across the UK and better understand the construction sector's views on how it can reduce air pollution and the wider changes that are needed to scale up low-emission construction. The project involved engaging with people who work in the construction industry, such as equipment manufacturers, regulatory bodies and policymakers, including via a survey, online workshop, and interviews. The full results of the project are published in Impact on Urban Health's Air Quality and Emissions in Construction report.[3]

One of the key findings of the research shows agreement that interventions to improve air quality around construction sites should align with net zero efforts. The research also found that 97% of the 63 people surveyed within the industry agree 'air quality is a very important environmental health concern.'

The research recommended that:

- the most effective way to quickly reduce emissions locally is to ensure compliance with existing regulations
- encouraging adoption of low-emission approaches would reduce emissions regionally
- there is agreement across the construction industry from the research, that better regulation would be the most effective long-term solution for reducing emissions nationally – for example, clearly defined timeframes for the next stage of the European NRMM emission standards would incentivise the development of cleaner machinery

Research has shown that there is rapid turnover for some types of machines, but other machines have longer life expectancies. For example, generators last for roughly 12 years while tower cranes last closer to 20 years. As machine re-sale markets are shrinking, it is expected that, without regulation, there will be slow change in the emission standards of machines.

Reducing polluting emissions from construction sites is important for people's health, particularly in urban areas. Effective action can be taken now to mitigate the sector's air pollution emissions, but underpinning these efforts with regulation, on a level playing field and signalled in advance, is likely to encourage long-term change.

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4.6 Agriculture

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Introduction

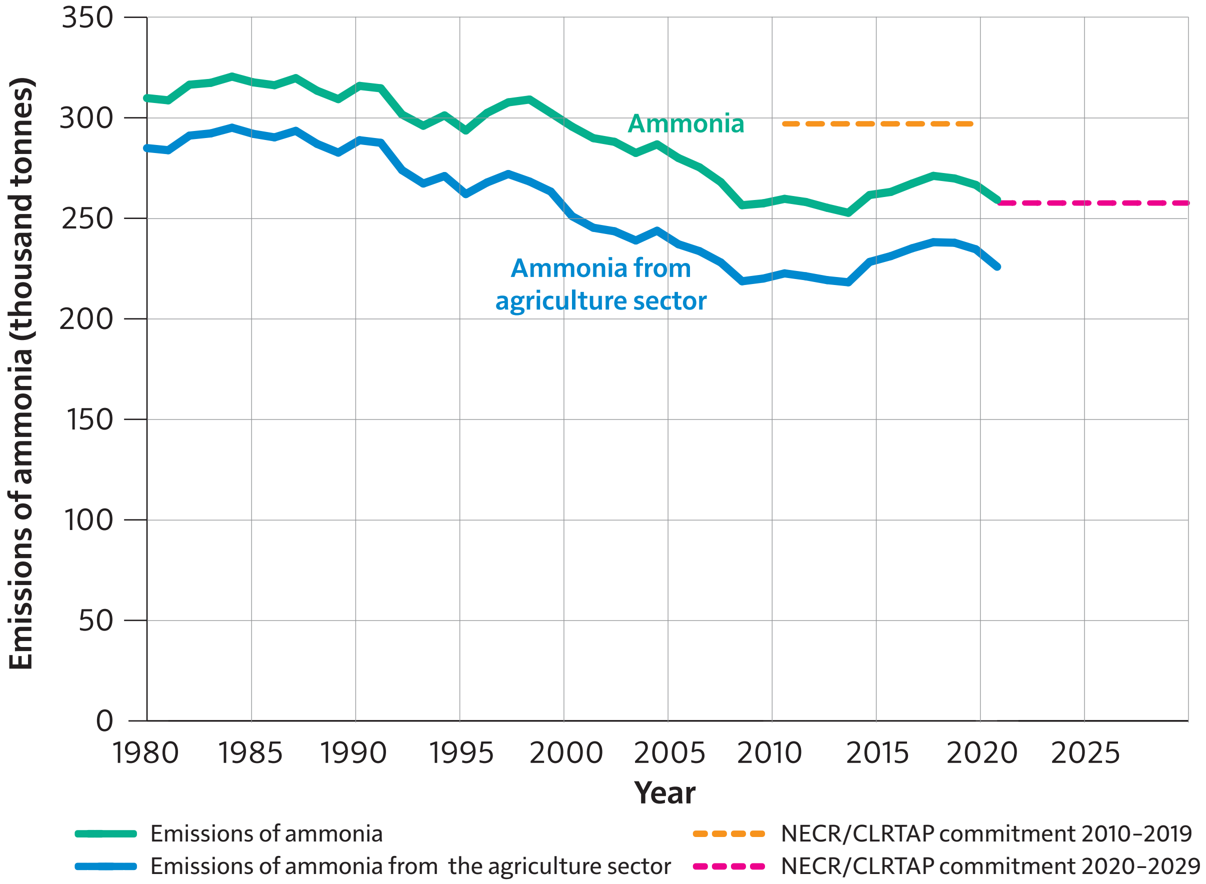
Emissions of air pollutants from agriculture

A range of air pollutants which are harmful to human health are emitted by agricultural activity in the UK, including nitric oxide (NO) and nitrogen dioxide (NO_2) (together known as nitrogen oxides, or NO_x) and particulate matter (PM) from combustion, NO from soil and ammonia (NH_3) from livestock manures, fertilisers, soils and crops. Animal housing is also a source of PM. Combustion within agriculture is a minor contributor to UK emissions (estimated to have contributed to about 4% of total NO_2 emissions in 2019[1]), and the main agricultural contributor to the UK burden of air pollutants is ammonia, often from slurry or fertilisers. The proportions of agricultural ammonia emissions by livestock and fertiliser are presented later in this section.

Ammonia emissions are a significant contributor to fine particulate matter ($PM_{2.5}$) air pollution as gaseous ammonia is transformed to $PM_{2.5}$ following reactions with atmospheric acids (HNO_3, H_2SO_4), as illustrated in Figure 3 – and this $PM_{2.5}$ is transported in the air over significant distances, affecting the health of both rural and urban populations. The health effects of air pollutants are described in Section 1.1. Technological solutions to reduce ammonia air pollution emissions have been implemented in other countries, and the evidence for these is discussed later in this section.

Estimated ammonia emissions in the UK amounted to 259 kt in 2020, of which 87% was from agricultural activities. Until recently, independent assessment of such estimates has been based on comparison of concentrations predicted by models using these emissions with atmospheric monitoring data.[2] More recently, satellite-based remote sensing has been used to independently assess UK ammonia emissions, suggesting that these may be underestimated by 27–49%.[3]

Trends in estimated UK ammonia emissions over the last 40 years, presented in Figure 1, show a decline from the peak in the 1980s to a minimum in 2013, since when emissions are estimated to have increased to 2017, subsequently decreasing in the last 3 years. The estimated reductions in emissions of NO_x, $PM_{2.5}$, PM_{10} and non-methane volatile organic compounds (NMVOCs) over recent decades, have decreased more significantly than NH_3, and this is shown in Figure 7 in Chapter 2.



Note: Independent evidence indicates that UK ammonia emissions increased by 48% between 1970 and 1980 (not shown).[4]
Source: National statistics. Emissions of air pollutants in the UK – Ammonia (NH_3)[5]

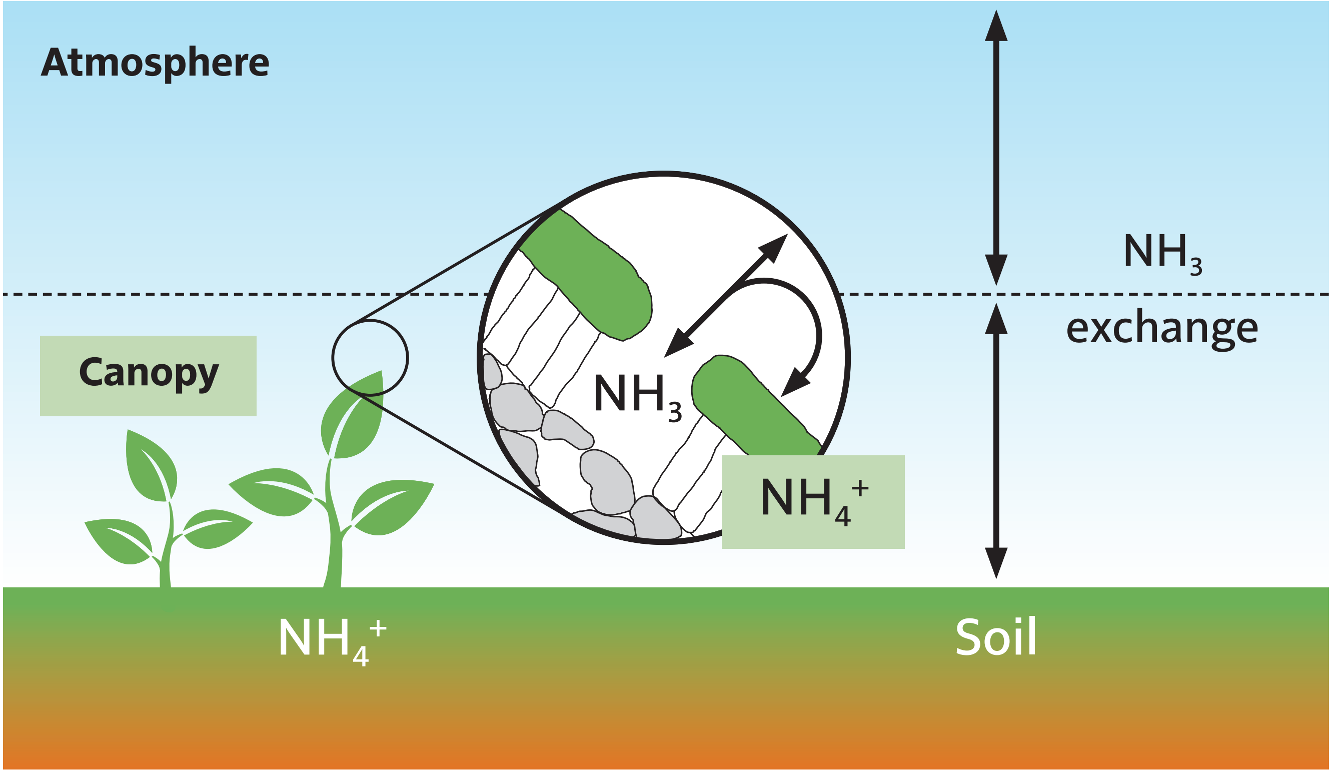
Figure 1: Annual emissions of ammonia in the UK: 1980 to 2020

Emissions of a range of pollutants are addressed by the United Nations Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air Pollution (CLRTAP), often referred to as the UNECE Air Convention, within which National Emission Reduction Commitments (NEC) have been agreed. In 2020, UK estimated emissions of ammonia exceeded the NEC by 1.6kt.

Overall, comparison of national inventory estimates of ammonia emissions with ambient monitoring for the UK suggests that gaseous NH_3 concentrations in the atmosphere have not decreased as quickly as the official inventory predicted over the period 1998 to 2014.[2] This can be at least partly explained by reductions in sulphur dioxide (SO_2) and NO_x over this period, which is reflected by a substantial reduction in ammonium (NH_4^+) in PM and a significant increase in the ratio of NH_3 to NH_4^+.

Sources and sinks of ammonia from agriculture

In biological systems, ammonia exists both as molecular NH_3 and in the ionic form of NH_4^+ and is a key metabolic component of living tissues, notably within amino acids and proteins, as r-NH_2. The partitioning between the two forms (NH_3, NH_4^+) is determined by pH, with most under physiological conditions present as NH_4^+ (only about 1.6% of total ammonia is present as NH_3 at pH 7.4). The equilibrium between the dissolved forms of ammonia is sensitive to losses to the gas phase wherever the liquid surface containing ammonia is in contact with the atmosphere. For example, this can be through stomata in vegetation and air–water interfaces in soil, and on the surfaces of vegetation, as illustrated in Figure 2. The direction of the exchange depends on the relative concentrations in the atmosphere and within vegetation or soil.



Source: Fowler D

Figure 2: The bi-directional exchange of NH_3 between the atmosphere, vegetation and soil

The illustration of ammonia exchange in Figure 2 shows how fertilised crops and soil release gaseous ammonia to the atmosphere. Similarly, when ammonia-rich solid manure or liquid manure ('slurry') is spread on the land, gaseous ammonia is released into the air as atmospheric concentrations are much smaller than those at the surface. The processes of ammonia exchange have been widely studied in relation to crops, and semi-natural vegetation[6] and on land recently spread with manure or slurry.[7]

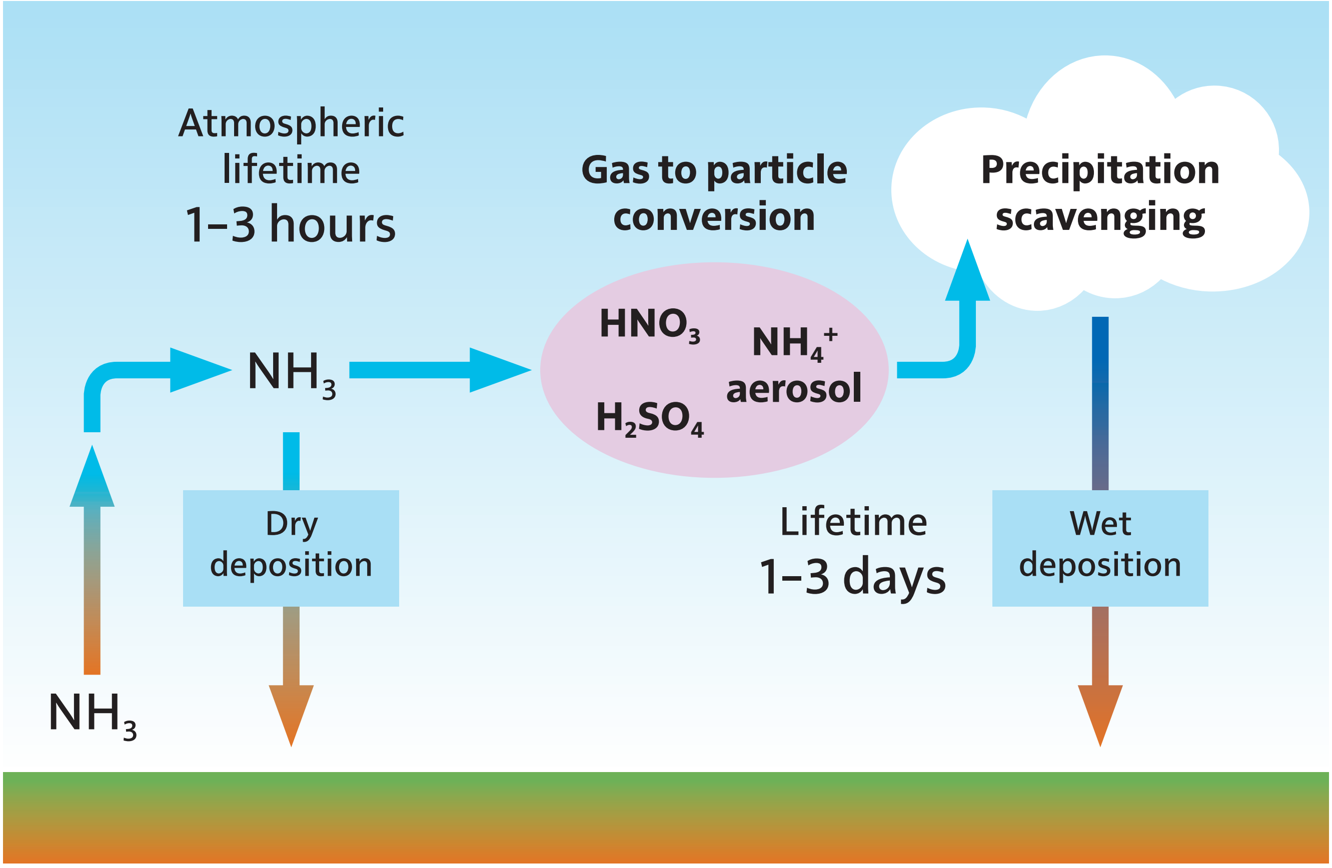
The form of fertiliser used (for example ammonium nitrate or urea) and atmospheric conditions during application are important in determining the fraction of the NH_3 contained within the fertiliser that is released to the atmosphere, as these all affect the surface concentrations of NH_3 in equilibrium with the surface and the subsequent dispersal.[8,9] Knowledge of the exchange processes and field experiments to quantify the net exchange has been assimilated to develop emission inventories for ammonia from the range of agricultural activities and fertiliser practices.

Following its emission to the atmosphere, NH_3 is either deposited back onto terrestrial surfaces by 'dry deposition' (direct uptake) or converted to NH_4^+ in PM through reaction with atmospheric acids, mostly these days with nitric acid (HNO_3) resulting from atmospheric oxidation of NO_2. NH_3 and HNO_3 combine to form ammonium nitrate (NH_4NO_3) containing aerosol with a reversible equilibrium that is dependent on temperature and relative humidity:

$NH_3 + HNO_3 \longleftrightarrow NH_4NO_3$

In practice, this process typically occurs on the surface of pre-existing PM which accumulates following an initial 'nucleation phase'. The PM has a longer lifetime in the atmosphere (of a few days on average) as compared with gas phase NH_3 (which is typically present for just a few hours). The particulate phase NH_4^+ is removed from the atmosphere primarily by rain and snow as 'wet deposition' (that is, via precipitation).

In the UK and Europe, particulate NH_4NO_3 is the main form by which NH_3 is exchanged across international boundaries by air.[10] Modelling long-range transport of air pollutants within Europe as part of CLRTAP routinely provide estimates of the net exchange between individual countries in Europe.[11] Over recent years, with the decline in emissions of SO_2, the contribution of NH_4NO_3 to $PM_{2.5}$ in the UK and more widely in Europe has been a major contributor to ambient concentrations, especially during the spring, when fertilisers and manures are spread on soils and crops. Episodes of elevated $PM_{2.5}$ and NH_4NO_3 in the UK have been observed in several recent years.[12]



Source: Adapted from image © UK Centre for Ecology & Hydrology (UKCEH)

Figure 3: NH_3 release to the atmosphere, transformation to particulate matter and removal by dry and wet deposition

The nitrogen cascade

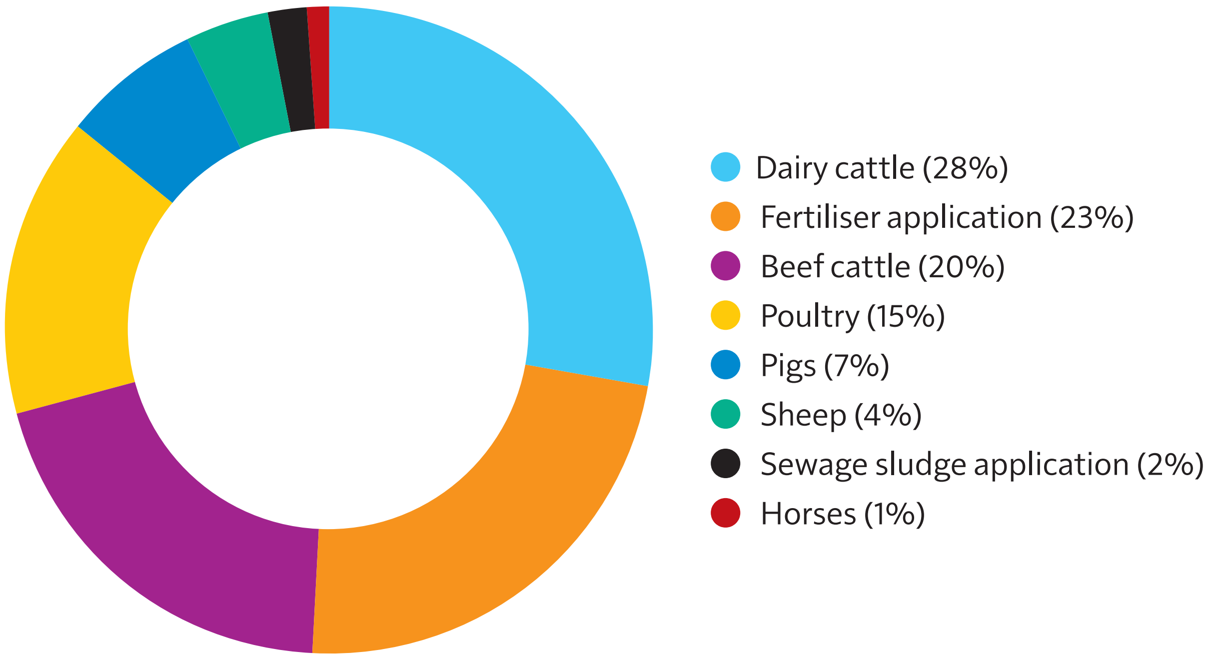
NH_3 enters the farming system as fertiliser either in liquid or solid form, mostly having been produced by high temperature reduction of molecular nitrogen (N_2) in the Haber–Bosch process, or by biological nitrogen (N) fixation by microorganisms in soils. The losses of reactive nitrogen (N_r) to the atmosphere can occur at many stages in the pathway, from the input to the farm to the eventual 'denitrification' of the NH_4^+ or nitrate in soils or freshwaters back to N_2 in the atmosphere. The global nitrogen cycle has been profoundly modified by human activity, both through combustion, which transforms around 40Tg-N of N_2 into NO and NO_2, and the Haber–Bosch process, which produces 70Tg-N as NH_3 annually by direct combination of N_2 and H_2 under high temperature and pressure. The global fixation of atmospheric N by human activity is now comparable in magnitude to that by natural processes, and is a major contributor to poor air quality.[13]

The release of NH_3 to the atmosphere from agriculture represents loss of a valuable resource, especially given the cost of fertiliser-N. Until recently typical prices have been around £700 to £850 per tonne of NH_4NO_3-N, the main fertiliser form used in the UK (from 2017 to May 2021), but recent international instability has greatly increased prices, which are currently at £2500 (September 2022).[14] It is therefore highly desirable to reduce losses, in addition to reducing air pollution. Based on a nominal estimate of US$1 per kg N, it has been estimated that N_r losses to the environment have a global estimated market value of US$200 billion annually.[15] However, the recent political instability will have increased this value, adding to current international concerns related to global food commodity prices. The framing of the recent Resolution on Sustainable Nitrogen Management adopted by the United Nations Environment Assembly[15] 'encourages Member States to accelerate actions to significantly reduce nitrogen waste globally by 2030 and beyond through the improvement of sustainable nitrogen management', recognising that actions to reduce wasted N resources 'offer the potential to save billions of US$ annually', in addition to the air quality and other environmental benefits.

Interventions to reduce ammonia air pollution emissions

Agricultural livestock dominates UK NH_3 emissions (from manure, the application of slurry on the soil and urine), followed by N-containing fertilisers. Almost half of estimated UK ammonia emissions in 2019 were from the beef and dairy sectors, providing respectively 55.9 kt-NH_3 and 57.4 kt-NH_3 in 2020. The other main livestock sector is poultry (33 kt-NH_3), while pigs at 18 kt-NH_3 and sheep at 12 kt-NH_3 are estimated to be smaller sources. See Figure 4 for the estimated NH_3 emissions by livestock and fertiliser.

In addition to livestock, the application of N-containing chemical fertiliser provides an estimated 40 kt NH_3, where urea makes up only around 10% of the usage but contributes around half of the fertiliser emissions, with proportionately much smaller emissions from the main UK nitrogen fertiliser, NH_4NO_3.



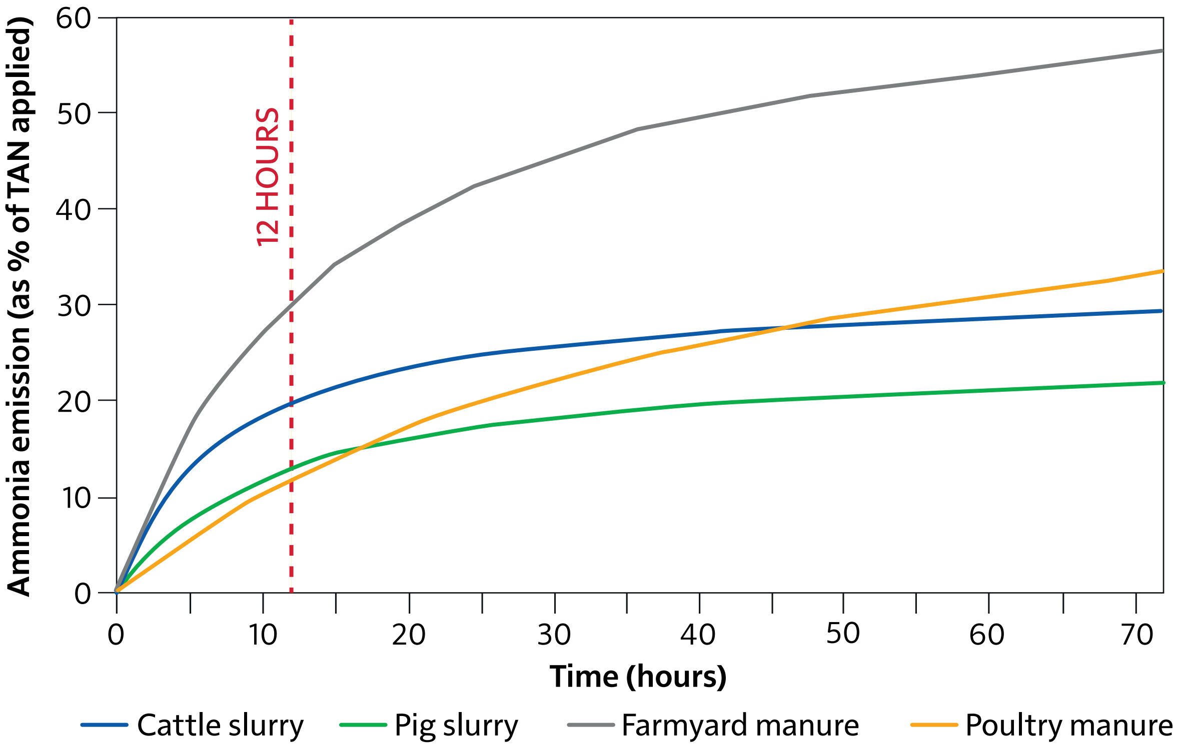
Source: Defra. Code of Good Agricultural Practice for Reducing Ammonia Emissions, 27 July 2018[16]

Figure 4: Agricultural ammonia emissions in the UK in 2016, by livestock and fertiliser

The loss of NH_3 to the atmosphere during the application of manure, including slurry to land, is one of the main sources, estimated to be about a third of agricultural NH_3 emissions in 2019.[17] This is an area in which a range of technical measures can substantially reduce emissions.

Incorporation of manures into bare soil

NH_3 losses from manure and slurry are at their peak in the first hours and days after spreading and continue at high rates unless the manure is mixed into the soil, reducing contact with air. The decline in emissions with time is rapid, with typically 50% of the total ammoniacal nitrogen (NH_3-N) content of farmyard manure lost within 40 hours of spreading.[18] Immediate ploughing to incorporate manure into soil (for example, by a second tractor immediately following) can reduce ammonia emissions from the application of manures by more than 95%. However, if this is not feasible, then ploughing within 12 hours may reduce emissions by around 30% for cattle slurry, 50% for farmyard manure and 60% for poultry manure (see Figure 5).



Note: The figure shows ammonia loss as a percentage of Total Ammoniacal Nitrogen (%TAN) applied (nitrogen in the form of ammonia) with time following application if the manures are not incorporated. The 12-hour recommended target for incorporating the material is shown as the red dashed line.

Source: Code of good agricultural practice, Defra, with data courtesy of Rothamsted Research[16]

Figure 5: Ammonia loss over time

These techniques to reduce ammonia emissions are explained in some detail in the UK Code of Good Agricultural Practice (COGAP).[16] There are many tried-and-tested techniques for reducing NH_3 emissions available to farmers. However, the incentives, regulations and communication have, so far not been sufficient to be effective in reducing UK total emissions substantially.

Techniques to apply liquid manure (slurry)

Four techniques of application are commonly used for liquid manure (slurry):

1. Broadcast (splash plate) spreading, where the slurry is forced from the tank onto a metal plate which spreads the fluid laterally and deposits a wide band on the soil or vegetation. The process provides substantial opportunities for release of NH_3 to the air during and following spreading.
2. Narrow band spreading through a trailing hose. For this, hoses fitted along a horizontal boom from the tank take the slurry close to the vegetation or soil, provide rows of narrow-band application and reduce contact with the atmosphere relative to broadcast spreading.
3. Trailing shoe application. This method also has trailing hoses, which take the slurry from the tank to a device that parts the vegetation close to the soil surface and thereby allows the slurry to be applied onto the soil below the vegetation canopy.

4. Slurry injection into the soil. The slurry is directed from the tank to a row of injectors below the soil surface at depths between 50mm and 150mm.

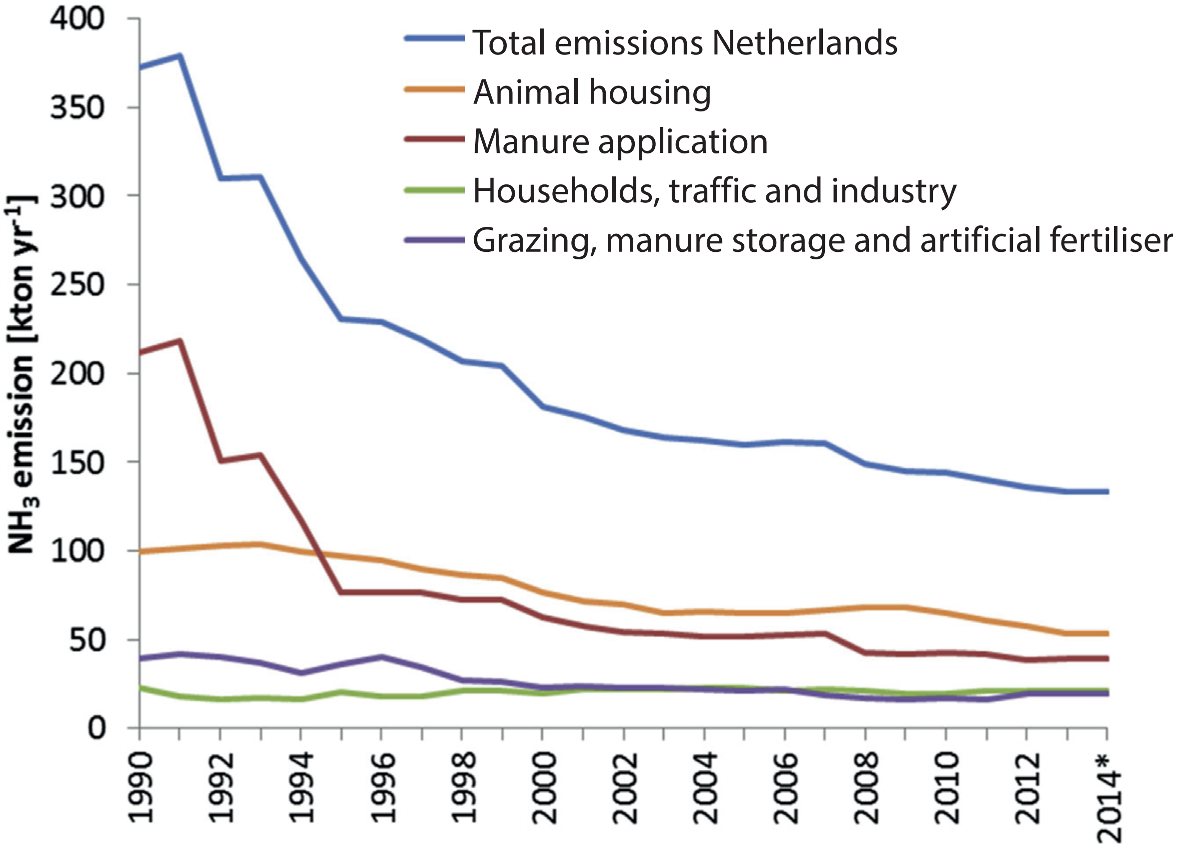
These techniques have been tested experimentally, and methods 2 to 4 from the above list have been shown to reduce NH_3 emissions by between 26% and 73% in UK conditions.[18] There is also wide experience of these approaches across Europe and North America. They can provide a cost-effective means to reduce emissions, where the value of the N saved can exceed the implementation cost when equipment is regularly used.[8,19]

Other techniques to reduce NH_3 emissions include covering slurry stores – in laboratory-scale and on-farm studies using granules and straw as covers, this has been shown to reduce odour emission by about 83–91% and NH_3 emission by between 80% and 90%.[20] Detailed guidance on such methods has been provided by the UNECE Air Convention both for NH_3 specifically[8] and considering wider interactions in the context of integrated sustainable nitrogen management.[9]

Evidence of the success of ammonia control measures elsewhere in Europe

The problem of poor air quality is global, and the contribution of agriculture to PM is widely recognised in Europe, North America and East Asia.[21,22,23] Experience from two European countries shows that it is possible to achieve substantial reductions in NH_3 emissions. The countries with the most ambitious NH_3 policies are the Netherlands and Denmark, both of which are estimated to have reduced their national NH_3 emissions by around 50% since the early 1990s.[23]

In the case of the Netherlands, a reduction of agricultural emissions of at least 60% has been claimed, though an independent review concluded that the available data presented was more consistent with a reduction of around 50% (40–60%).[24] Figure 6 illustrates the estimated trend in agricultural NH_3 emissions reported for the Netherlands, which introduced its ammonia policy shortly after 1990. By far the largest reduction in NH_3 emissions is attributed to measures related to manure application.



Note: *The emissions in 2014 are assumed to be the same as in 2013 in this study as final numbers were not yet available.

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Figure 6: Estimated contributions to the changes in NH_3 emissions from agriculture in the Netherlands, 1990 to 2014

In both the Netherlands and Denmark, with support from government investment the reductions in NH_3 emissions were achieved through strict programmes of national regulation that focused primarily on manure management, including land application of manure, manure storage and animal housing. Technically, all the measures were achievable by farmers and in the Netherlands have now been in routine use for over 20 years. Although farming systems inevitably vary between and within countries, and this needs to be understood, the evidence for these interventions is relevant to the UK context.

Considering the country case studies together, the main measures adopted have been:

Prohibiting the free surface spreading of liquid manure – In both countries a high-ambition approach was taken and use of the 'splash plate spreader' was prohibited. Surface 'band spreading' was also considered insufficient, apart from exceptions, with shallow injection of liquid manure approved instead. One exception is a trailing shoe band-spreading approach, specifically designed and accepted in the Netherlands for use on grass swards over vulnerable peat soils, so as not to break the coherency of the root mat. In Denmark a relaxation to permit the use of band-spreading methods (trailing hose or trailing shoe) has also been approved where the manure is acidified immediately prior to application (a proprietary system is in use on many farms that wanted to avoid manure injection).

Requirement to use covered manure stores – A wide range of covered manure storage approaches have appeared, from tanks to covered lagoons to slurry-bag approaches. The costs of using covered manure stores are to some extent compensated by the higher N content, consistency and lower water content of the stored manure product.

Requirement to use low-emission housing – A wide range of animal housing systems are in place in the Netherlands and Denmark. In particular, pig and poultry buildings with controlled ventilation are used both to optimise indoor climate for the animals and to allow cleaning of the exhaust air, using chemical or biological methods. In the Netherlands, it is reported that smart metering is increasingly being installed to allow central administrative monitoring of the air purification systems.

Overall, it appears that the largest gains in reducing emissions, with the lowest cost to farmers, have been associated firstly with low-emission manure spreading, and secondly with low-emission manure storage.[26] A combination of covered manure stores and improved manure spreading can be particularly cost-effective by maximising the N saved for agricultural benefit.

Further issues relevant to reducing emissions from livestock

In the case of livestock housing on some poultry and pig farms, local emission controls are already in place in the UK as part of the permit process, which also considers proximity to designated conservation areas. Planning permission requirements also take account of NH_3 emissions. In these cases, keeping poultry manure/litter dry until it is incorporated in the soil is the key to reducing emissions.

The largest livestock sector of NH_3 emissions in the UK and Europe is cattle. Here, there are major opportunities for cost-effective NH_3 emission reduction through manure storage and land spreading. Currently, the naturally ventilated nature of most cattle housing in the UK can make it harder to control emissions from this source. However, there are opportunities to reduce emissions by restricting the area of soiled surfaces and cleaning by scraping and washing down. Research is needed to improve housing design for cattle that reduces NH_3 emissions while simultaneously considering opportunities for animal welfare, energy and water savings.

Reducing NH_3 losses following mineral fertiliser application

About 2% of fertiliser-N is lost as NH_3 from solid NH_4NO_3 in UK conditions, but the actual amount varies with weather conditions, with warm dry conditions leading to the largest losses. The losses of NH_3 from urea-based fertilisers are more typically 10–20%, but can be as much as 50% of the fertiliser-N.[8]

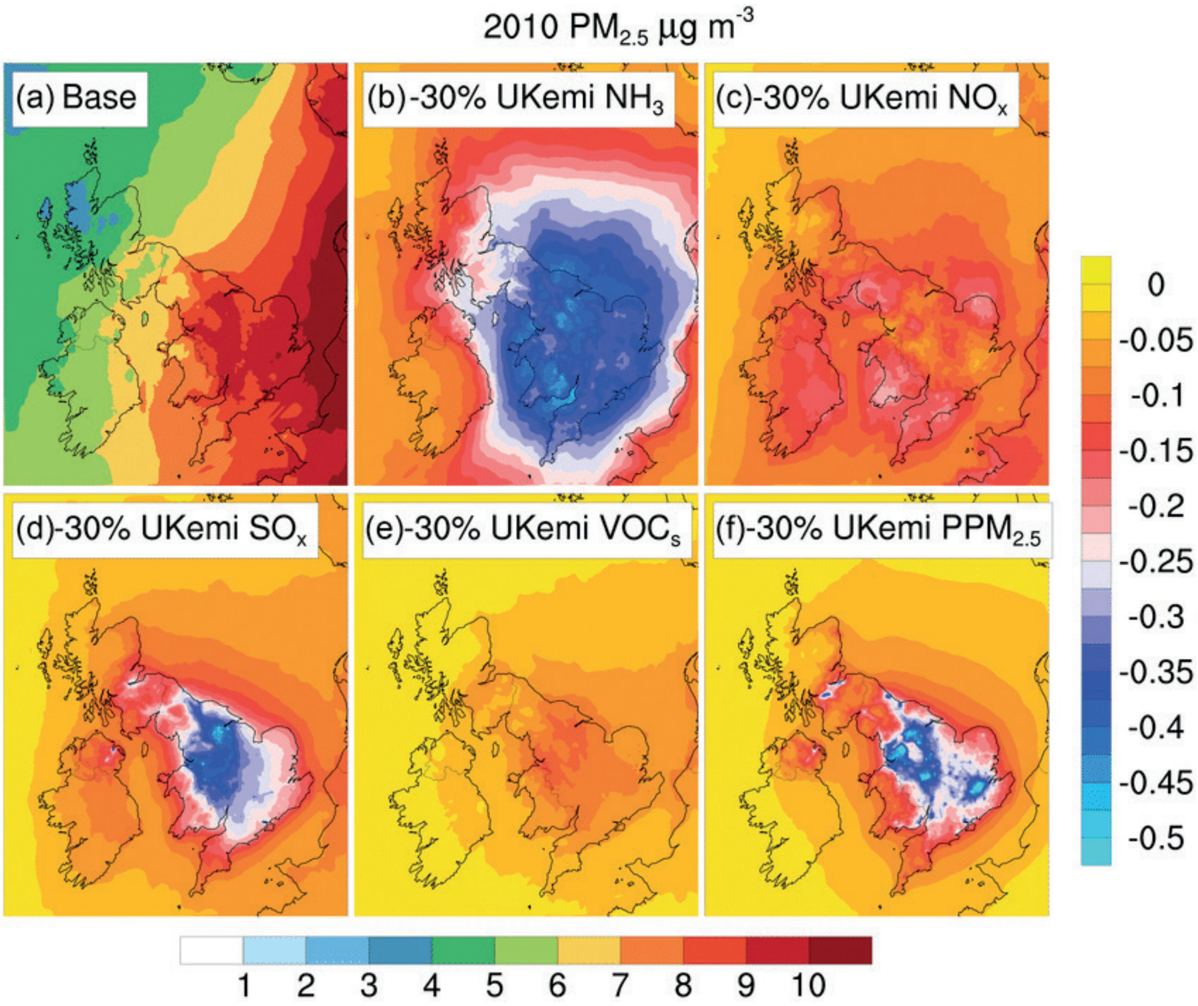
One of the most cost-effective ways to reduce part of the NH_3 emissions is through low-emission mineral fertilisers. In the UK, most N is applied as NH_4NO_3, which is associated with low NH_3 emissions, while emissions from urea are much higher. While urea is typically cheaper to purchase, 10–20% of the N applied may be lost as NH_3 emissions under UK conditions. This loss can be minimised, for example by incorporating urea into the soil (as widely practised in Canada), by using chemicals that slow the breakdown of urea (‘urease inhibitors’) or by using NH_4NO_3 instead.[8]
An application timing management system (ATMS) can also be used to reduce NH_3 emissions from

fertiliser application,[7] for example by applying fertiliser during periods of cold or wet weather. However, caution is needed in applying fertiliser during winter, when crops are not actively growing, since this can increase nitrous oxide emissions and nitrate leaching. To date, it appears that strict regulatory requirements in relation to mineral fertiliser application have not been adopted in either the Netherlands or Denmark. However, under the Revised German Fertiliser Regulations, from 1 February 2020, urea as fertiliser 'may only be applied if it has been given a urease inhibitor or is incorporated immediately, but no later than four hours after application'.[27]

Impact of reducing ammonia emissions of $PM_{2.5}$ air pollution

The benefits of control measures to reduce NH_3 emissions to date include reductions in particulate NH_4^+, which have declined more rapidly than NH_3 concentrations in air. However, from the measurements alone it is unclear how much of the NH_4^+ reduction observed can be attributed to decreases in NH_3 emission and how much to the simultaneous decrease in emissions of NO_x and SO_2. Such attribution is only possible through model scenario runs. Because the formation of NH_4NO_3 involves an equilibrium with the concentration product of NH_3 and HNO_3, there are areas where NH_4NO_3 formation is NH_3-limited (meaning it responds more sensitively to changes in NH_3 concentration) and areas that are HNO_3-limited.

A modelling study, using the same EMEP4UK modelling framework that has successfully reproduced past trends, suggested that a 30% reduction in UK NH_3 emissions would reduce $PM_{2.5}$ concentrations by 0.3 to 0.5µg/m^3 over most of England and Wales for the reference year 2010 (see Figure 7).[12] At the same time, the model suggested that about 50% of the PM related to NH_4^+ in the UK originated from gases emitted elsewhere in Europe. Thus, additional NH_3 emission reduction across Europe would result in a larger reduction in PM.



Note: The figure shows: (a) $PM_{2.5}$ concentrations simulated for 2010 (bottom colour scale) and changes in $PM_{2.5}$ concentrations in response to 30% emission reductions of (b) NH_3, (c) NO_x, (d) SO_x, (e) volatile organic compounds and (f) primary $PM_{2.5}$ (right-hand-side colour scale).

Source: Reproduced from Vieno et al. 2016[12] © 2016 The Authors. Licensed under CC BY 3.0

Figure 7: Particulate matter concentrations in England and Wales, simulated for 2010 and different emissions reductions scenarios

Some of the high-NH_4NO_3 episodes in the UK are dominated by UK emissions, while others are controlled by European emissions outside the UK,[10] and some high-NH_4NO_3 concentration episodes may be particularly insensitive to NH_3 changes because they are HNO_3-limited. In such conditions, it becomes even more important to consider the full suite of acidic compounds which may neutralise NH_3, as well as the role of NH_3 itself in atmosphere-affecting oxidation processes that affect $PM_{2.5}$ formation.

Conclusion

Overall, it has been estimated that the costs of NH_3 mitigation, even for ambitious reduction scenarios, are much smaller than the estimated societal benefits.[28,29] There is an opportunity to combine the most cost-effective approaches to improve N use efficiency and reduce wasted N resources by further upscaling and technological refinement as the circular economy approach emerges more strongly in the next few years. Here, innovative approaches in improving nitrogen management may help to save costs on purchased N inputs and improve productivity on farms.

Potential savings on recurrent practices may help to make this sustainable and could provide motivation for farmers to reduce NH_3 and other nitrogen emissions. Several studies have attempted to compare the cost–benefit in NH_3 controls for $PM_{2.5}$ with those of further control in NO_x and SO_2.[28, 30]

The technology and engineering solutions to reduce agricultural air pollution emissions discussed in this section are practical, but they require capital investment. Government and industry need to work together to develop and implement the solutions, with supportive policy mechanisms, and offering the potential for many co-benefits that align with other agriculture policy areas, including planning, biodiversity and water quality.

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4.7 NHS

4.7.1 Tackling air pollution for better health: the role of the NHS in England

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Introduction

Delivering high-quality healthcare to the 56.5 million people living in England involves the operation of an organisation at a very large scale. The National Health Service (NHS) is the biggest employer in Europe, with one in every 25 working-age adults in England devoted to providing care for others in the NHS workforce. The health service is distributed across 18,000 acute care, mental health, ambulance, and community services buildings, with a further 9,000 buildings in general practice. Up to 18,400 vehicles are owned and leased by the NHS for use in a range of care settings – a fleet second only to that of the Royal Mail, nationally.

As a consequence of providing such a large-scale service, the NHS contributes to local air pollution through its energy consumption, transport and travel, and also emits 5% of the total carbon emissions from the UK and 40% of all public sector carbon emissions. As discussed in Section 1.2, air pollution can also contribute to health inequalities. With its primary responsibility to ensure the health and wellbeing of people in England, it is important that the NHS acts to reduce its own contribution to air pollution from its activities. The NHS has a role as an anchor institution to support local communities to do the same, while reducing health inequalities.

The NHS has two central and closely aligned targets: to halve the NHS contribution to poor air quality within a decade while reducing health inequalities, and to reach net zero for all carbon emissions related to delivering its health service by 2045. Some of the interventions to achieve the air quality target are described below. The trajectories and interventions to achieve net zero are described in detail in 'Delivering a 'Net Zero' National Health Service'.[1]

NHS hospitals and energy use

Air pollution emissions from NHS hospitals

Hospitals and the secondary care estate are the largest source of air pollution emissions from the NHS. On-site electricity and heating were responsible for an estimated 2,400 tonnes of nitrogen oxides (NO_x) and 57 tonnes of fine particulate matter ($PM_{2.5}$) in 2019.[2] This largely comes from gas use, with NHS Trust accounting for about 5% of non-domestic gas consumption in England.

Over recent years, the NHS has almost halved the estate's $PM_{2.5}$ emissions, down from 95 tonnes per annum in 2013. This has been achieved through investments in decarbonising heat sources and energy efficiency.

Reducing air pollution emissions

To reduce air pollution emissions and carbon emissions further, every NHS Trust in the country has developed its own Green Plan and net zero strategy, including a localised approach to decarbonising heating, as well as transitioning the fleet to less polluting vehicles and encouraging active travel, which will also work towards eliminating NO_x emissions. These strategies have been supported with over £670 million investment into more cost effective methods of heating, improved energy efficiency of buildings and renewable energy generation across the health service.

Efforts are also underway to reduce clinical waste incineration, through improved waste segregation, optimising the use of personal protective equipment (PPE) and cannulation, creating reusable masks and surgical gowns, and recycling materials into bins and toolboxes.[3,4,5]

Together, these interventions are ultimately designed to all but eliminate NO_X emissions, transition away from gas heating, and deliver a low air pollution and low carbon healthcare system.

Examples of current action

An example of efforts to reduce air pollution, carbon emissions, and improve health inequalities are the 1,000 roof-mounted solar photovoltaic (PV) panels installed on 7 buildings across the University Hospitals of North Midlands NHS Trust. These solar panels produce around 210MWh per year and, partnering with local charity, Beat the Cold, the funds raised from the government feed-in tariff are assisting local and vulnerable patients suffering from fuel poverty and cold homes. Around £150,000 has been raised so far.[6]

Likewise, Milton Keynes University Hospital refurbished its roof with improved insulation and almost 2,600 solar panels. This produces on-site 8% of the Trust's total electricity requirement (853MWh per year, equivalent to the annual energy requirement of 200 homes) and contributes to a more comfortable environment for staff and patients.[7] The 11,000 solar panels installed across a 7.7 hectare 'Field of Dreams' provides Castle Hill Hospital's total energy supply over the summer months – generating 50MWh per day – enough power to meet the average daily energy needs of up to 6,250 UK households.[8] The power resilience was critical to the provision of care during the July 2022 heatwave.

Vehicles, travel, and care closer to home

Air pollution emissions from NHS-related road travel

The NHS has a large and diverse vehicle fleet, including ambulances, emergency rapid response vehicles, and staff and patient transport vehicles. In 2017, patients, visitors, staff and NHS suppliers accounted for 3.5% (9.5 billion miles) of all road travel in England. Exhaust emissions from the NHS fleet and business travel account for 30% of NHS NO_x emissions (800 tonnes of NO_x in 2019). Travel and transport contribute a larger proportion to NHS $PM_{2.5}$ emissions, with 30% (35 tonnes) of the total attributed to non-exhaust sources (tyre and brake wear) on top of the 10% (11 tonnes) of NHS $PM_{2.5}$ emissions coming from vehicle internal combustion engines.[9] These non-exhaust emissions highlight the need not only to transition to a zero-exhaust emissions fleet, but also change the way we travel and how we deliver care.

Reducing air pollution emissions

Work is underway to reduce vehicle air pollution emissions, and over three-quarters of NHS operated vehicles are low exhaust emission. Manchester University NHS Foundation Trust and others operate an almost entirely electric fleet. A fully zero exhaust emission fleet for the entire health service is considered possible by the mid-2030s.[1]

Increasing access and uptake of active forms of transport to better serve NHS staff and patients requires partnership with other system leaders and across organisational boundaries. This includes the NHS working with local authorities to improve public transport to NHS sites across all 42 Integrated Care Boards, and work to reduce health inequalities through more equitable access to underserved groups while at the same time helping reduce local air pollution. NHS organisations have roles as anchor institutions, generating a positive impact within the local community in ways beyond providing direct healthcare. Great Ormond Street Hospital's work to become a clean air hospital and improve local air quality is described in Section 4.7.2.

Healthcare professionals are well placed to identify carbon-intensive travel in care pathways and can influence uptake of less polluting options. They can also support broader community actions, for instance, when school nurses drive the implementation of interventions to create cleaner air around schools.

The NHS has set a target of providing 40–50 virtual beds per 100,000 people in England by December 2023. Realising this ambition will support suitable patients in their home environment while saving a considerable number of patient and visitor travel miles.

Examples of current action

There are pilot schemes to make progress on fleet electrification, including 21 zero exhaust emissions rapid response vehicles, the world's first fully electric double crewed ambulance and the public sector's first fully electric heavy goods vehicle.

E-bikes are offering cleaner and frequently more rapid delivery of local community health visits and courier services. They have been trialled by Trusts across England, with the delivery time of chemotherapy drugs halved between the Oxford University Hospitals NHS Foundation Trust sites.[10,11,12] Patients on the Isle of Wight have received chemotherapy via drones – delivered 8 times faster and with far less pollution.[12]

Trusts are supporting active travel among staff: 96% of Trusts have cycle to work schemes, and 74% have cycle leads (up from 52% in 2020). Cycling incentives are supported by better cycling infrastructure for staff and patients – Manchester University NHS Foundation Trust has created over 200 additional cycle parking spaces and improved storage and shower facilities.[13]

Local authorities have been awarded funds to pilot active travel social prescribing. This can include training link workers in walking and cycling interventions, developing cycle hire or loan schemes, providing cycling training courses, guided rides and walks and installing infrastructure to support safe cycling.[14]

Virtual wards support patients who would otherwise be in hospital to receive the acute care and treatment they need in their own home. There are 243 virtual wards across the country with occupancy and capacity continuing to grow.

Other roles of the NHS in reducing harm from air pollution

Air quality alerts and patient education – particularly for those at risk of adverse health effects – could help reduce individual air pollution exposure during acute periods of poor air quality.[15,16,17] Advice on taking quieter routes to school and work when feasible may also help reduce long-term exposure. Information for patients and the public is discussed in further detail in Section 5.3, which also highlights the need for medical optimisation of health conditions that are exacerbated by poor air quality. Here, the NHS Core20PLUS5 programme focus on chronic respiratory disease and hypertension among the most deprived populations, and other groups experiencing health inequalities, will help improve these vulnerabilities.[18]

However, the most effective long-term interventions to reduce air pollution exposure are actions that stop air pollution emissions at the source. Therefore, while important efforts are underway to educate health professionals and patients about the health effects of air pollution, the NHS is also directly tackling its own contribution to air pollution, while expanding access to care and improving efficiency. With its target to halve its contribution to poor air quality within a decade, alongside broader government support, the NHS can make a significant contribution to reducing the estimated 26,000–38,000 deaths that occur every year from poor air quality[19] while reducing health inequalities across England.

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4.7.2 The NHS, a hospital example

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The Clean Air Hospital

The NHS acknowledges its role in reducing air pollution emissions, improving the local environment and people's health,[1,2] and this is discussed in Section 4.7.1. As a step to improving air quality, Great Ormond Street Hospital for Children in London and the charity Global Action Plan co-created the Clean Air Hospital Framework (CAHF).[3] The CAHF sets out the vision for what it means to be a Clean Air Hospital, and how to help reduce levels of air pollution to protect people's health. A Clean Air Hospital aims to improve air quality outside and inside the hospital, provide advice to help protect staff, patient and public health from air pollution and works with others to champion the case for clean air locally and nationally. Figure 1 shows example features found in a Clean Air Hospital.
The CAHF enables hospitals to identify their current level of performance on tackling air pollution, and to develop an action plan to improve air quality in and around the hospital.

Source: Global Action Plan

Figure 1: The Clean Air Hospital Framework vision for a Clean Air Hospital

Since the introduction of the CAHF at Great Ormond Street Hospital in 2019, action has been prompted in different areas, including trained patient transport drivers, new electric ambulances, and the incorporation of air quality in some tender criteria. A car-free Play Street Programme has been embedded, air pollution monitoring equipment installed to measure fine particulate matter ($PM_{2.5}$) and nitrogen dioxide (NO_2), and there have been education and creative sessions with Young People's Forum members. Staff-wide engagement sessions have been delivered and there is an organisational commitment to treat both the patient and the broader environment.

Becoming a Clean Air Hospital involves time, innovation and expense. Although it has not been possible to quantify changes to air pollution around the hospital, in two years Great Ormond Street Hospital has moved from 15% to 38% completion of CAHF actions. NHS Trusts in England are encouraged to use the CAHF to improve their own performance in becoming a Clean Air Hospital.

Plans for the public realm improvements

Great Ormond Street Hospital's work with the CAHF highlighted unsuitability of the public space on the hospital doorstep. Analysis of the air quality data on the street found that air pollution levels exceeded those recommended by the World Health Organization in 2021 – for daily levels of both NO_2 and $PM_{2.5}$. In a survey, 87% of respondents felt that the hospital street was dominated by parked and moving vehicles, and 61% complained about noise and disruption coming from deliveries, hospital drop-off and waste collection.

There is an opportunity to transform the existing street, and provide a healthy, sustainable and child-friendly street space that could act as an exemplar as a healthy hospital street. This is at the concept stage and is due to be developed to the design stage later in 2022.

The transformation, illustrated in Figure 2, would enable effective access to the hospital, and provide benefits to air quality and wider issues. There is a safer environment with fewer cars, suggested planting for biodiversity, and sustainable drainage, trees for shade, benches to encourage social interactions, and outdoor furniture for play. Improving the public space and the impact of Great Ormond Street Hospital on the surrounding neighbourhood is an important step towards an approach that considers the environment as an inseparable part of treatment and convalescence, supporting clean air around the hospital.

Source: LDA Design

Figure 2: The public realm outside Great Ormond Street Hospital

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4.8 Indoor environments

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Introduction

People spend a substantial part of their day indoors. The Office for National Statistics (ONS) Time Use Survey[1] indicates that around 40% of people's time is 'sleeping and resting' which is largely at home, while the USA National Human Activity Pattern Survey[2] indicates that up to 87% of a typical adult day is spent in enclosed buildings and 6% in vehicles. Work, study, shopping and leisure activities all occur indoors. Indoor air therefore dominates the air that people breathe in a typical day. While there has been extensive consideration of, and effective plans for, many aspects of outdoor air pollution, the air we breathe indoors has not been considered as widely. As outdoor pollution has decreased, and is set to decrease further, the relative importance of indoor air pollution increases. Historically in England, open fires burning coal or wood were used widely for heating and cooking in homes, resulting in significant indoor air pollution. This source of pollution has reduced greatly, but indoor air quality remains an important public health consideration.

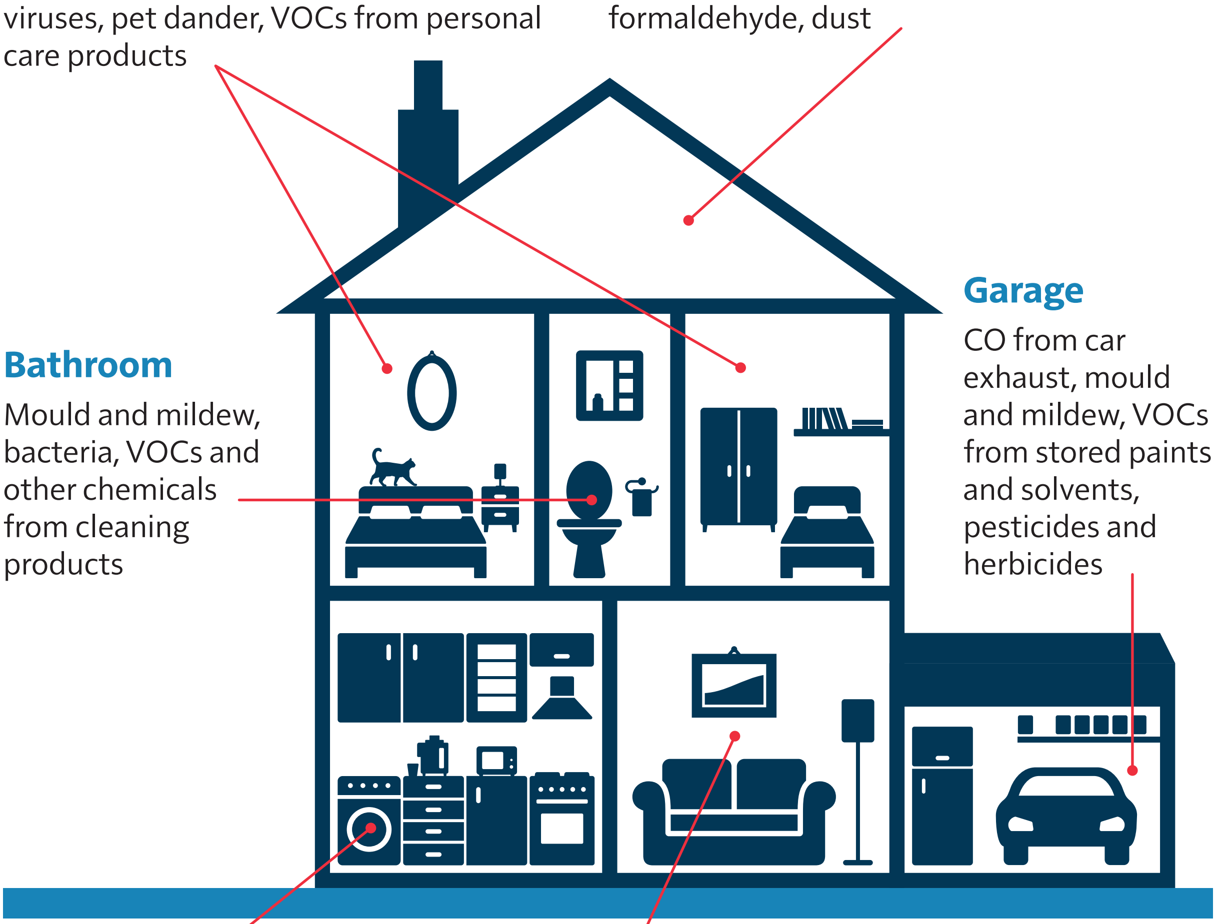
There are some major areas of overlap between outdoor and indoor air pollution, and some important differences. Nitrogen oxides (NO_x) and particulate matter (PM) are important in both spaces. Outdoor air pollution can move into many indoor spaces, so reducing outdoor air pollution is important for indoor air quality. In addition to ingress of outdoor pollution, NO_x is generated from combustion processes, mostly from solid-fuel burning stoves or cooking on gas hobs. Primary PM sources indoors include activities such as cooking and combustion processes.

Some chemicals and other pollutants are much more common indoors than outdoors, including volatile organic compounds (VOCs) due to chemicals used in household objects such as personal care products, cleaning products, paints, glues and aerosols and in the fabric of the building. Some 'natural' pollutants, including moulds, are more common especially in buildings that are not as well designed or maintained.

Other indoor pollutants include carbon monoxide (CO), which is linked to poorly maintained gas boilers and solid fuel appliances. Asbestos can be present in older buildings, radon from the ground, (and cigarette smoke, with well-recognised health harms, although beyond the scope of this report). Carbon dioxide (CO_2) can build up, particularly in densely occupied indoor spaces that have little air exchange with the outdoors, since its dominant source is exhaled breath. While only harmful at high levels, CO_2 is a useful proxy for other pollutants.

In addition to emissions of primary pollutants, transformation processes can lead to the formation of secondary pollutants indoors. An example is the formation of the harmful pollutant formaldehyde, from the VOC limonene. The chemistry of these processes is discussed further in Section 5.1.

Example sources of indoor pollutants in a home are presented in Figure 1.



Bedrooms

Dust and dust mites, bacteria and viruses, pet dander, VOCs from personal care products

Attic

Man-made mineral fibres, asbestos, formaldehyde, dust

Bathroom

Mould and mildew, bacteria, VOCs and other chemicals from cleaning products

Garage

CO from car exhaust, mould and mildew, VOCs from stored paints and solvents, pesticides and herbicides

Kitchen

CO, NO_2 and particulates from gas cookers/stoves, VOCs from household cleaning products

Living areas

Radon from soil/bedrock, CO and NO_2 from fires and wood-burning stoves, VOCs and formaldehyde from carpets, paints, glues, furniture and air fresheners, tobacco smoke, pet dander

Source: Copyright © 2016 Royal College of Physicians (2016).[3] *Adapted with permission*

Figure 1: Indoor pollutants and their sources

There is considerable variation between buildings, the surrounding outdoor air quality and occupant behaviour, and there is also a lack of measurement data for indoor air quality in UK buildings, as discussed later in the section. These factors mean that is it currently challenging to quantify indoor air pollution in different buildings.

However, one study measured weekly average indoor and outdoor nitrogen dioxide (NO_2) concentrations in 60 homes in the UK. During the winter, NO_2 concentrations were higher in homes with gas cookers, compared with electric cookers, but they were significantly lower than outdoor concentrations. During the summer, concentrations were not significantly different between homes with gas and electric cookers, or between indoors and outdoors.[4] A review of studies from Europe and the US evaluated how representative outdoor measures are of personal exposure to fine particulate matter ($PM_{2.5}$) and NO_2, and examined the proportion of people's exposure to air pollution that came from outdoor sources. This review estimated that about 44% of personal exposure to $PM_{2.5}$ came from outdoor sources, and 74% of exposure to NO_2 came from outdoor sources.[5]

In a study of indoor air quality in 60 homes in Kent, England the total concentration of VOCs found indoors was, on average, between 1.5 and 4 times higher than the concentrations measured directly outside the homes, with the greatest difference seen during the winter months. For specific VOCs released from household products, such as butane, indoor concentrations were up to 50 times higher than found outdoors.[6]

When thinking about addressing indoor air pollution, 4 factors should be borne in mind. The first is that there is a spectrum from wholly public shared spaces that everyone has to use, such as schools, supermarkets or public buildings, through to wholly private spaces such as owner-occupied homes. The potential role for regulation to improve air quality differs across this spectrum. The second is that once built, a building could be in use for many decades, and so poor design can literally build in air pollution, and subsequent changes may undermine design intentions. The third factor is that there are some important tensions between maximising air quality through ventilation and maintaining room temperature efficiently, unless this is thought about from the design stage and maintained in use. The fourth is that some very vulnerable people, such as those with severe asthma or cardiovascular disease, or their carers, may need to take particular care to minimise air pollution exposure indoors.

As for outdoor air pollution, there are inequalities in access to good indoor air. People living and working in the most deprived areas are more likely to have poor indoor environments, as discussed in Section 1.2. These homes are also more likely to be overcrowded, with shared spaces, poor ventilation and thermal performance, and limited amenities. These factors can lead to poor indoor air quality, cold, damp and mould, and higher fuel use.[7]

Indoor air quality (IAQ) knowledge and evidence

Currently, there are gaps in knowledge about indoor conditions in buildings, and this was highlighted during the COVID-19 pandemic. Evidence of environmental conditions, in particular ventilation, has been sparse and public awareness of indoor pollution is limited; one of the significant challenges is that air pollution is 'invisible' unless at very high levels. Humans are sensitive to thermal comfort but cannot detect harmful pollutants as readily.

Evidence of the health impacts of outdoor air pollution has been established over many years, through extensive measurement of external air quality across multiple locations worldwide and correlating this to population data on mortality and morbidity. The same data does not exist for buildings, but it is well recognised that exposures to pollutants indoors substantially impact on health. Many of the pollutants indoors are the same chemicals as those found outdoors. However, the causal relationships between indoor air quality (IAQ) and health are difficult to quantify for the following reasons:

- IAQ differs in every building and is influenced by the building itself, its location, season and weather, people and their activities, and the outdoor air quality nearby.
- Indoors, there is a range of pollutants, chemicals, and interactions, and these complex variables are difficult to control in small-scale studies.
- There is a lack of measured data on IAQ and related parameters such as temperature, humidity and ventilation rate in the majority of buildings.
- Data is not routinely collected on the performance of buildings, including ventilation and indoor air quality.
- Pollutants can have variable concentrations – for example, particulates in a home may have a low mean, but short durations of very high peak exposures during certain events such as cooking.

Despite the challenges with providing evidence of causal relationships between indoor air and health, there have been substantial insights derived from a wide range of studies. These include IAQ measurement studies, intervention studies, controlled chamber-based studies, cohort studies, citizen science approaches and modelling studies to demonstrate the importance of good indoor environments for health.

Evidence for the health effects of air pollution is discussed in Section 1.1. Indoors, there is evidence for specific pollutants such as asbestos,[8] carbon monoxide, and a range of industrial exposures. Correlations between ventilation rates and Sick Building Syndrome symptoms, perceived air quality, respiratory infections and allergies.[9,10,11,12] There are correlations between health outcomes and broad exposure to PM and VOCs and evidence for the health effects of building-related problems such as damp and mould.[13,14] In instances where causal relationships between pollutants and health have been identified, strong measures and regulations have been enacted – for example, use of CO detectors, radon barriers and banning of asbestos in building materials.

Lessons can be learned from health-evidence case studies[15,16,17,18] and attempts to characterise the health burden associated with outdoor air quality.[19] Over the past 10 years, awareness of the importance of IAQ has grown and has led to evidence-based reports, guidance and recommendations to improve indoor air. These include: World Health Organization (WHO) evidence and guidance on IAQ,[20,21,22] National Institute for Health and Care Excellence (NICE) guidance on IAQ at home,[23] Public Health England (PHE) IAQ guidelines for selected VOCs,[24] a significant report from the Royal College of Paediatrics and Child Health (RCPCH),[25,26] and recently the Royal Academy of Engineering's work on infection resilient environments.[27,28] All these reports are consistent on the need to adopt a range of behavioural, technical and regulatory measures to improve IAQ.

The recent report on IAQ by the Air Quality Expert Group for the Department for Environment, Food & Rural Affairs (Defra) includes further detail about indoor air pollutants, exposure to indoor air pollution in different settings, and interventions to improve IAQ.[29]

Developing strategies for tackling indoor air pollution

In this section we provide an overview of approaches that can be taken to manage IAQ and consider the complex range of environmental, physical, regulatory, and behavioural factors that impact on the effectiveness of solutions. We discuss how strategies to manage IAQ are dependent on the pollutant source and the setting, and highlight where there are trade-offs and opportunities for win-win situations.

There are differences between public and private buildings, when considering policies and interventions to reduce indoor air pollution. In public buildings, individuals have limited control over the indoor environments, and there is potentially greater state responsibility for IAQ, compared with inside private buildings. For example, in a school, pupils and staff are required to spend a large part of their day inside the buildings, but these individuals do not usually have control over the pollutant levels indoors. Similarly, in workplaces, retail, transport or social venues, individual employees or members of the public usually have limited control over the air quality and rely on the owners or operators of those buildings to implement appropriate actions.

In contrast, inside a home-owner's dwelling, the inhabitants have more control over the indoor air, through their behaviours and choices about products and building ventilation. There is a spectrum of how much influence an individual has over their indoor environment – for example, landlords have significant control over the condition of rented properties. Responsibilities for work environments may rest directly with a business and their staff, or may be managed by third parties who either own the building or are contracted to manage it. Interventions to improve IAQ range from state regulation, through to public information to inform people's choices.

Overall principles for managing IAQ

The basic principle for tackling indoor air pollution can be summed up as a three-stage source-pathway-people process,[30] as shown in Figure 2. See below for further details on specific interventions.

Figure 2: The basic principles for tackling indoor air pollution

Remove or reduce the source

"If there is a pile of manure in a space, do not try to remove the odor by ventilation. Remove the pile of manure." (Max von Pettenkofer, 1858)

It is widely recognised that the most effective way to address poor IAQ is through tackling the source of air pollution.[23] This can be achieved by removing, reducing, or changing the use of polluting sources, or by sealing or enclosing sources. The ease of source control depends on the pollutant, how and where it is generated, and whether there can be an alternative that does not emit air pollution. Indoors, sources may be due to: the fabric of the building; products brought into and used in the environment (such as carpets or cleaning materials); or pollutants that come in from the outside air. For most people, it will be much harder to control building materials if the house has already been constructed, compared to changing the use of various consumer products, or using different materials and finishes when decorating or refurbishing.

Manage the air pollution pathways

"Set wide the window. Let me drink the day." (Edith Wharton, 1909)

Airborne pollutants are transported from the source to people through airflows, therefore solutions to manage pollution pathways focus primarily on ventilation to remove or dilute the pollutant. Ensuring good ventilation can reduce peoples' exposure to indoor pollutants that cannot be fully controlled. Ventilation is also essential for wider health and wellbeing, and for thermal and moisture control in buildings. Ventilation can also reduce people's exposure to airborne infectious diseases including COVID-19 and influenza.

The effectiveness of ventilation will depend on the type of system installed and how it is operated. It will also be affected by external weather conditions, with wind flows and temperature differences influencing ventilation rates, movement of air between spaces within buildings, and the exchange of pollutants with the outdoor air. If using 'natural' ventilation of the building, IAQ will improve most effectively if outdoor air pollution has been minimised.

Where ventilation cannot be achieved, air cleaning can provide barriers between the source and people. This may be most effective in higher-risk environments where the emission of pollutants is higher, or in settings where people are particularly vulnerable to harm from air pollution. Air cleaners may also be effective where outdoor air is highly polluted, and therefore simple ventilation strategies may increase exposure to some pollutants through ingress from outdoors.

Protect people

"Keep the air he breathes as pure as the external air, without chilling him."
(Florence Nightingale, 1860)

Strategies to protect occupants from air pollution harm include:

- reducing use of building materials that may contain pollutants
- raising awareness of possible sources of pollution, such as the use of certain cleaning products

- ensuring that there is adequate provision for ventilation and that it is maintained
- ensuring awareness of the presence of pollutants, the importance of ventilation and how to achieve it – for example, using product labelling and indoor air pollution sensors

There may be other operational strategies where it is not feasible to effectively manage exposure to air pollutants through source or pathway controls – for example: reducing the density of people in a space; moving vulnerable people to different locations; scheduling pollutant-producing activities when buildings are at lower occupancy; locating pollutant-producing facilities in separate areas; or, in the case of significant harmful air pollution, short-duration use of personal protection such as masks.

Selecting appropriate strategies to manage IAQ depends on the pollutants, the location of the source, the frequency and duration of emissions and the vulnerability of the people who are exposed. In all cases, some form of ventilation is required. Longer-term solutions such as improving building ventilation and systems are more critical for long-term exposure to air pollution, while managing very short-lived air pollution spikes (such as a fire outdoors, construction or demolition) may be more suited to temporary behavioural or technology solutions.

Figure 3 shows classifications of strategies to manage IAQ, including preventing indoor air pollution and reducing people's exposure. The most challenging scenarios are those where indoor and outdoor sources are both present for a long duration.

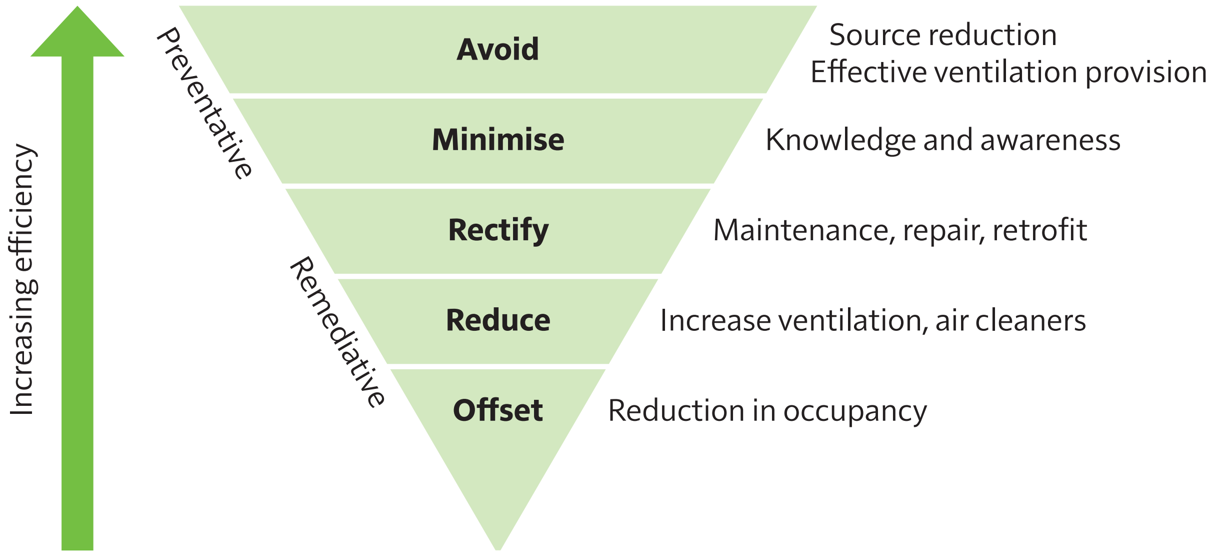


Figure 3: Classifications of IAQ solutions

Influence of building type and activities – public and private buildings

Non-domestic buildings include a wide range of settings that people visit, including for work, education, health, retail, entertainment, travel and hospitality. Occupants include workers and visitors who are exposed to the IAQ in these spaces and are reliant on the ventilation provision and management undertaken by building owners and managers. Buildings may be in private or public ownership, which can influence decisions and funding for IAQ mitigations. The management of public and private buildings varies but is predominately undertaken by third parties, including building owners, landlords, agents and facilities managers. Larger organisations may have in-house expertise, while smaller organisations rely on external providers, or may have no support.

Non-domestic buildings represent many building types, ranging from small high-street premises to large prestige offices, manufacturing facilities and warehousing, and large multi-building campuses such as universities and hospitals. Buildings are dynamic and their use and occupancy change significantly over time. While new buildings are expected to meet building standards at the time of construction, there are very limited mechanisms to maintain compliance as they are adapted over time.

There is currently very poor understanding of the ventilation provision and effectiveness across the non-domestic sector and how this varies by building type and organisation. There tends to be marginally more data from public buildings such as schools, as permission to collect and publish this information tends to be easier than for buildings in private ownership. There is also a huge variability in the understanding of the quality of indoor environments in non-domestic settings and the capabilities to manage them effectively.[31]

Domestic environments where people live and sleep are largely controlled by the residents, but they are dependent on the nature of the construction and the heating and ventilation provision. The majority of dwellings in the UK are owner occupied (65%),[32] with the remainder being various forms of rental and controlled by a landlord. Interventions in rental properties could be mandated through standards and regulation, however, in owner occupied dwellings, changes depend on decision-making by the owners. While it may be easier to address IAQ with new dwellings, addressing IAQ in existing homes would likely achieve greater results for health, as almost 80% of homes in the UK were built before 1990, and almost 20% were built before 1920.[32]

There is evidence that domestic IAQ is related to social inequalities: people living in the most deprived areas and, in particular, in rented properties are more likely to live in homes that are overcrowded with lower energy efficiency, have inadequate heating and ventilation, are poorly maintained, and are more likely to have poor IAQ.[33,34,35,36] Improving domestic IAQ has several specific challenges, including that the responsibility for identifying a problem often lies with the owner who may not have the knowledge, funds or agency to address the problem.

Behavioural factors

With the exception of air pollution associated with odours, accurate human perception of air quality is typically weak, and so an occupant's ventilation behaviours are predominantly driven by thermal comfort and energy consumption. Ventilation use is also limited by other concerns, such as managing noise from outdoors, and security concerns.[37,38] As such, achieving a healthy indoor environment is rarely a pure engineering challenge and complex behaviours need to be accounted for.

Effective strategies to improve IAQ require behavioural change, alongside the intervention to remove or reduce air pollution. There is evidence from interventions, such as smart thermostats, that the people most likely to use such devices effectively are those who already have strong environmental attitudes and technical skills.[39] Studies on energy efficiency also suggest that behaviour change is more effective when feedback allows comparison with other environments or people.[40]

Barriers to improving IAQ may include lack of awareness of issues, lack of understanding about how to use systems and devices properly, concerns over other consequences such as noise, comfort and security, and concerns over energy use. In some settings, building occupants have a lack of agency (real or perceived) to make changes that improve IAQ. However, motivators that can act to enable individuals and organisations to improve IAQ include concern for the health of themselves or others, presence of significant odours, damp or mould, and desire to take actions that are environmentally sustainable and healthy for wider societal benefit.

Evidence for practical interventions to reduce indoor air pollution

In this section we discuss some of the interventions that can be carried out by individuals, organisations, industry, local and national government to improve IAQ. This includes interventions to remove or reduce the air pollution source, manage the air pollution pathways and protect people from exposure, especially those who are most vulnerable to harm.

Removing sources of indoor air pollution

A wide range of actions can be taken to remove or reduce indoor pollution sources.

Limitations on building materials and finishes that contain pollutants can reduce built-in sources that produce emissions for longer periods. This may include reducing the use of some materials or providing effective barriers to transmission indoors. Better labelling of materials will assist designers and specifiers to avoid products containing harmful substances.

Products that release chemicals and particles, such as air fresheners, candles, cleaning products and personal care products can often be removed, replaced with lower-emission sources or their use reduced. Where such products are necessary, exposure can be reduced by ensuring good ventilation when they are used.

Keeping the indoor environment clean through regular dusting and vacuuming can reduce particle sources and washing bedding regularly can mitigate exposures to house dust mites and biological pollutants. While outside the scope of this report, avoiding smoking indoors is well recognised as a significant action to reduce exposure to particles and a range of toxic chemicals, and extending this to vaping is also shown to reduce indoor chemical exposures.[41] A number of studies show that avoiding burning food when cooking and using splatter guards can cut exposure to a range of emissions. Also, simple source control actions, such as using cooker extract hoods (when available), and using the hob's back burners can also reduce exposure.[42,43]

Building materials, paints, fixtures and furnishings have also been recognised as sources of indoor air pollution. This can include emissions of chemicals used in the manufacture of the product that are released over time, or emissions associated with damage to materials such as fibres and particles, or mould spores from damp materials. Some sources are technically straightforward to mitigate by selecting lower-emission furnishings and paints or replacing gas appliances with electric. However, where the emissions result from materials integral to the building, it can be difficult to remove the source without substantial effort or cost. In all cases, information is needed for consumers to enable selection of appropriate materials.

Effective action to remove indoor sources requires public understanding of the health effects of the emissions in public environments, workplaces and homes. This understanding requires reliable and unbiased information on the likely emissions and health impacts of products to help people make better choices, and measures such as standards to reduce the emissions from products. Many products are marketed as 'freshening' the indoor environment or as 'natural' despite them substantially increasing the level of pollutants in the air.[44] Studies suggest that industry action to modify formulations of cleaning products could lead to improvements in IAQ.[45] There are requirements to manage risks from chemicals (REACH regulation),[46] some materials are banned or have restricted use, and there has been a UK government pledge in the Clean Air Strategy to develop voluntary labelling for products containing VOCs.[47] However, there are not currently any mandatory requirements around emissions from products or their labelling.[25]

Managing heating systems

Some heating systems can have direct impacts on IAQ. Open-flame appliances such as gas boilers and solid fuel stoves can produce PM and harmful gases including CO and NO_x. These systems have existing requirements for CO sensors and annual safety checks in rented properties. However, indirect impacts of these systems include pollution emitted to outdoors, which can then affect other properties, particularly in dense urban environments. Of particular concern is the use of solid-fuel stoves and open fires in urban areas. Recent data suggests that domestic combustion accounts for 15% of primary PM_{10} and 25% of primary $PM_{2.5}$ emissions.[48] The burning of solid fuel in nearby homes is regularly cited as a major barrier to opening windows for ventilation. See Section 4.9 for further discussion of domestic solid fuel burning.

Heating systems and building insulation can also have an indirect impact on IAQ. Where buildings are poorly insulated and/or inadequately heated, there is a greater likelihood of IAQ problems due to damp and mould. This may result from ineffective or poorly maintained systems, or due to fuel poverty, resulting in occupants not heating spaces for long periods of time or reducing the amount of ventilation in the home.

Heating and ventilation are inextricably linked. Buildings lose heat through fabric and ventilation losses and the heating system is required to meet these demands. As buildings become better insulated, the importance of ventilation losses become more important. The heating provision should also be linked to ventilation to ensure comfort and fresh air. For example, location of radiators below windows helps to temper incoming ventilation air through trickle vents and assist with mixing and distribution of fresh air.

Ventilation and air cleaning approaches

Ventilation is the provision of outside air to an internal space, essential to remove internally generated pollutants and, in summer, removal of internal heat to maintain comfort. Some air will enter the space through infiltration via tiny gaps in construction, which should be minimised to reduce unwanted heat loss (although providing some outside air, this is not effective ventilation). Ventilation is purpose designed to provide the required amount of air for the activities in the space – either by appropriately sized openings for natural ventilation or mechanical systems.

The provision of ventilation should not be confused with strategies for cooling or heating the air. Thermal comfort (through heating or air conditioning) can be achieved in conjunction with ventilation through a central air-handling system, local de-centralised heating and cooling systems (including with heat recovery). However, it is very common for heating and cooling to be carried out separately with local 'split' systems that only cool existing internal air and provide no fresh air. Caution is needed in these situations to ensure that there is also a supply of ventilation to remove pollutants. Ensuring that building owners and occupiers are clear about the way their space is ventilated and conditioned is essential for providing a thermally comfortable and well-ventilated environment.

There are many methods of ventilating buildings. Domestic and smaller commercial environments most commonly use natural ventilation via windows, passive vents and sometimes doors. Some domestic settings have mechanical ventilation systems, commonly extract systems for bathrooms and kitchens, but sometimes whole-house systems, some with heat recovery. Larger public and commercial buildings' ventilation methods range from natural ventilation, decentralised supply and extract to large building-scale centralised air-handling units. Essential to the correct operation of all ventilation systems is good design and maintenance, and occupant understanding of how to use the systems effectively.

Good ventilation is due to the total volume flow rate through a space and the effectiveness of the ventilation, which is related to how the air moves in space. The required volume flow rate of air depends on the building type and activity. However, for most non-specialised spaces, a value of 10 litres per second per person (l/s/person) is common.[49] The majority of studies have shown that symptoms of Sick Building Syndrome increase substantially with airflow rates below 10 l/s/person.[9] Several studies have demonstrated that building ventilation rates affect self-reported symptoms of Sick Building Syndrome until ventilation rates reached 25 l/s/person.[10] If sources of pollutants are controlled, then 4 l/s/person has been recommended as adequate,[50] although this does not consider human sources such as infectious disease.

Total air flow rate is only one part of the story. How the air is distributed in a room and how it moves between rooms plays an important role in reducing the concentration of pollutants that are breathed by occupants. In some spaces full mixing of the air in the space is ideal, ensuring that clean air is distributed evenly throughout the space. In tall spaces it may be more appropriate to introduce clean air at low level near to occupants, allowing upper unoccupied regions to become stagnant, warm and full of bio-effluents. If this is well above the occupant breathing height, then the quality of the air is less important. Where activities create specific contaminants, such as in laboratories or during cooking, the most appropriate solution is a well-designed local exhaust ventilation that removes pollutants directly from the source before they mix with the air in the room.

Careful design of ventilation systems to ensure successful contaminant removal can result in good IAQ for occupants, with reduced energy cost due to the need to condition less air. Effective ventilation is bespoke to the building's design and the activities of its residents. For this reason, retrofitting a ventilation system should be carried out with appropriate input from a ventilation expert. Table 1 presents different ventilation methods, their uses and the main advantages and disadvantages of each approach.

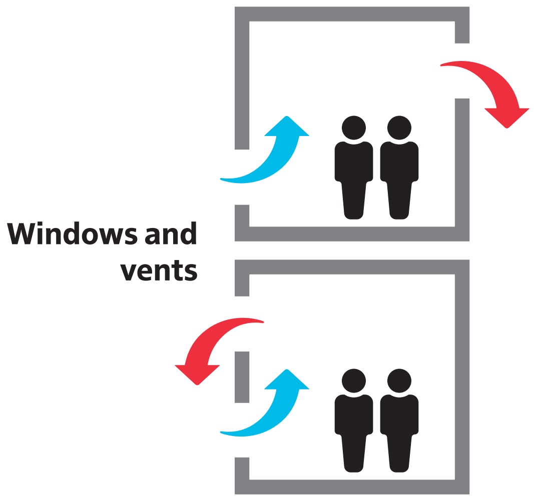
Windows and vents

Useful for: Smaller spaces with low occupancy.

Pros: Users can easily and intuitively increase their ventilation.

Cons: Control tends to be based on thermal comfort. No opportunity to recover heat, resulting in increased energy and cost for heating.

Advice: Where possible, enable cross-ventilation by opening windows on opposite sides of a space. Use upper and lower openings together to increase your ventilation efficiency through stack ventilation in mid-seasons. In winter, using just high openings can reduce drafts and allow the air to warm before it reaches occupants.



Extract fans

Useful for: Spaces where there is known generation of contaminants, particularly over short time periods.

Pros: Useful to provide additional ventilation during retrofit. Known removal route from a space, placing that space under negative pressure and ensuring that contaminants do not circulate to the rest of the building.

Cons: No opportunity to recover heat, resulting in increased energy/cost for heating.

Advice: Ensure extract fans are paired with an appropriate air transfer grille or door undercut to ensure the flow of incoming air. This should be located to prevent short circuiting of air flow in the space. Keep extract fans free of dust, and regularly wash or replace filters in cooker hoods.

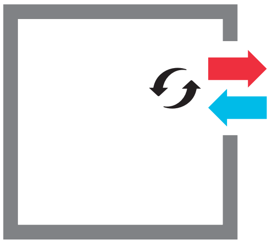
Heat recovery ventilation **Useful for:** Retrofitting ventilation into domestic and smaller public/commercial buildings. Can range from single room units to whole building systems. Appropriate where external noise, or egress of internal noise is an issue. **Pros:** Recovers heat so will reduce the energy required for heating in comparison to extract only. Can also enable filtering of inlet air. **Cons:** More expensive than extract alone, and some buildings lack the space to easily install. **Advice:** Think carefully about how the air will move through the space and ensure that there is clear guidance on using and maintaining the system.	**Heat recovery ventilation** 

Table 1: Different building ventilation methods

Metrics for measuring ventilation rates

Ventilation rates for buildings are commonly given in either litres per second per person (l/s/person) or air changes per hour (ac/hr). Air changes per hour are the number of times the total volume of room air is supplied to the room in 1 hour, whereas litres per second per person has the benefit of varying per occupancy. In some spaces there is a need to remove a particular source from the space continually over time, regardless of the number of people present. In these cases, air changes per hour is a useful metric. An air change rate of 3 ac/hr will remove 95% of contaminant that was in the space over a 1-hour period if it is a single pulse of pollution (not a diffuse, continuous source, such as the building fabric or the occupants).

Measuring ventilation rates accurately in situ is complex and fraught with uncertainty. While not an accurate measure of ventilation rate, monitoring CO_2 values in occupied buildings nevertheless provides a relatively simple method to understand the balance between outdoor air supply (with a relatively constant value of CO_2) and the number of people in a space (all breathing out CO_2).

Air cleaning devices

In some cases, ventilation may need to be coupled with air cleaning technologies to appropriately manage air quality. This is the case where there is high outdoor air pollution which prevents IAQ being effectively managed through ventilation alone. Air cleaning may also be beneficial to manage indoor sources, usually on a short-term basis, if ventilation rates are insufficient.

Many air cleaning technologies are available, but the strongest evidence for effectiveness is for fine grade filters including high-efficiency particulate air (HEPA) filters and, in the cases of pathogens, cleaning by germicidal UVC, ultraviolet disinfection.[51] HEPA filters can be highly effective in removing PM (including microorganisms) and a recent systematic review of studies in homes, schools and offices show that there is effective reduction in $PM_{2.5}$ when portable air cleaners are used.[52] Many gaseous pollutants (for example, from combustion sources) are more challenging to remove, although sorption methods such as activated carbon filters have been shown to be effective. There is evidence that some technologies marketed as air purifiers may produce harmful secondary air pollutants including ozone, formaldehyde and ultra-fine particles.[53]

However, air cleaning does not provide fresh air so, where air cleaning is desired, it is vital to integrate ventilation considerations within the selection and implementation of technology. In mechanically ventilated buildings, filters can be designed into the ventilation system to remove most harmful PM. Where partial recirculation of the indoor air is appropriate, germicidal ultraviolet (UVC) cleaning or high-grade filters can be installed within the ducts to mitigate indoor sources. With appropriate design and regular maintenance, the system should be capable of delivering adequate air quality. This includes mechanical ventilation with heat recovery units for domestic and smaller commercial buildings, where the system can incorporate filters to manage ingress of outdoor pollutants.

When the ventilation relies wholly or partially on naturally driven airflows, typically through windows, then occupants are implicitly controllers of their outdoor air supply rates. In such cases, where there are external challenges, local air cleaning units that are portable or fixed within the room itself have become increasingly popular. Such devices can be very effective,[51,52] however, there are a number of considerations around size of units, space required and noise being an issue of concern in some spaces.[54] In addition, air cleaning devices consume considerable energy in their manufacture, running and maintenance. All of this highlights the need to account for behaviour in design, and to manage ventilation behaviours during operation.

Understanding and adapting IAQ through sensors

The use of sensors to inform and protect occupants is well-established for pollutants that have immediate health risks, for example, CO in residential environments, and sensors to alert occupants to chemical exposures in specialist environments such as laboratories or manufacturing. Sensors are also widely used as part of mechanical ventilation systems in commercial, public and (more recently) domestic buildings to adapt settings in response to temperature and CO_2 concentrations. However, most harmful indoor air pollutants cannot be perceived by humans, and so other forms of detection may be necessary to identify risks.

Improvements in technology have resulted in more readily available sensors that can give indications of IAQ. These relatively low-cost sensors, which measure markers such as temperature, humidity and CO_2, have been available with in-room displays for at least a decade. Sensors offer scope to provide occupants with real-time indications of some elements of their IAQ. This can be valuable in domestic and non-domestic environments.

The most common use of IAQ sensors is to monitor CO_2 emitted by occupants in their exhaled breath as a marker for ventilation rate. There are two approaches to using low-cost CO_2 sensors.[55] First, usage by those responsible for the building to log the environmental conditions in a space as part of assessing ventilation and air quality conditions. Second, real-time use by occupants to manage ventilation, where the reading on the sensor provides a visual indicator when actions need to be taken, such as opening windows.

Most currently available low-cost, reasonable quality sensors can reliably measure temperature, humidity and CO_2. Some sensors also measure PM and/or total volatile organic compounds (TVOCs) but these often display poor selectivity and limited accuracy. Some use data from different sensors in the device to calculate an air quality index. While these sensors can be very effective at identifying poor ventilation or thermal conditions conducive to poor indoor environments, low-cost sensors have limited accuracy and are not able to detect the full range of pollutants in indoor spaces, and particularly pollutants such as NO_2. Also, the monitor itself is not a solution to IAQ problems, but measuring it enables the 'invisible to be visible' and allows appropriate actions to be taken.

Sensors are increasingly being recommended through standards and guidance. For example, Scotland requires that CO_2 sensors are installed in domestic bedrooms,[56] and regulations in England and Wales have been revised to introduce a requirement to monitor IAQ in certain new buildings, including offices and public buildings.[57] There is some evidence from smaller-scale investigations of the effectiveness of CO_2 monitors in schools, which has been shown to be positive for time scales of a few weeks.[58,59,60] Research into the effectiveness when delivered at large scale and over longer time periods suggests that the engagement and take-up in schools and homes is mixed.[61] There is also growing evidence from international studies, including the French IAQ Observatory[62] that longer-term measurement over a large number of buildings is now feasible and provides valuable evidence for long-term changes as well as the impact of short-term events.

Building knowledge and capability

Assessing IAQ

Prior to taking actions to improve IAQ, an assessment is needed to determine the most appropriate strategies. In the case of workplaces, public buildings or other private non-domestic buildings, this may be a formal assessment undertaken by a building services engineer or occupational health professional. In domestic environments, it would be undertaken by the owner and may involve professional advice. For rented properties, it would be the responsibility of the landlord, also possibly with professional advice.

Although the International Society of Indoor Air Quality and Climate database summarises a range of guidelines for different aspects of IAQ in multiple countries,[63] there are no consistent formal IAQ assessment criteria for indoor air that can be applied across a range of environments.[30] There is also little primary legislation in the UK requiring specific IAQ standards to be met in most environments, except for specific pollutants such as radon and CO. Legislation applies in the case of exposure to certain hazardous substances in workplace environments where the Control of Substances Hazardous of Health (COSHH) Regulations 2002 include workplace exposure limits (WELs) defined by the Health and Safety Executive.[64]

New building design and major retrofit are covered by the Building Regulations. These set expectations for ventilation rate, thermal comfort conditions, fabric thermal performance and devices which may result in significant indoor pollution, such as combustion devices. While there is reference to guidelines for indoor air pollutants in the Building Regulations, there is no requirement to demonstrate compliance in use.

Guidelines for IAQ provided by WHO are not legally binding but act as a set of recommendations for policymakers to refer to. These include guidelines on dampness and mould relating to excessive production of bioaerosols,[65] a range of chemical pollutants[66] and household fuel combustion.[67] The global air quality guidelines provide recommendations on biological contaminants of indoor air, selected air pollutants typically measured in indoor settings, and household fuel combustion.[68] Similarly, in the UK, guidelines exist for selected VOCs in indoor air[69] and NICE provides guidelines for IAQ in domestic environments.[23]

Many commonly used energy assessment tools – Standard Assessment Procedure (SAP) and Reduced Data Standard Assessment Procedure (rdSAP) – do not include an assessment of ventilation beyond an assumption of air change rates. Some environmental assessment tools – such as Building Research Establishment Environmental Assessment Method (BREEAM) – and some elective standards (Passivhaus, Energiesprong, Association for Environment Conscious Building (AECB) – cover some of the factors that influence IAQ, but the majority do not. One exception is the WELL Building Standard® which is aimed at commercial buildings and assesses the environment with the primary motivation to evaluate health and wellbeing factors. This includes parameters of thermal comfort, noise, light, air quality as well as mental health and wellbeing. The International Organization for Standardization (ISO) standards for IAQ measurements has a methodological framework, and the Institute of Air Quality Management provides a detailed approach to undertaking more formal IAQ assessments.[30] Emerging standards such as PAS 2035, and related retrofit standards such as Superhomes[70] contain more explicit requirements for IAQ standards. The Housing Health and Safety Rating System is an official evaluation tool for local authorities to evaluate dwellings and includes a number of aspects of IAQ such as mould, asbestos, CO, combustion products and VOCs.[71]

A challenge for IAQ assessment includes the lack of ability to measure and assess all pollutants and their possible interactions. For many well-recognised pollutants, there is not clear agreement on appropriate levels in indoor environments, and there are emerging pollutants and secondary pollutants from chemical interactions, where the health risks are less certain.

Education and training

To enable effective IAQ assessments and provide healthier buildings, there is a need to build skills and knowledge over the longer term for designers and specifiers, facilities managers and building owners and consultants. The current awareness of ventilation and actions such as providing CO_2 monitors to schools provides opportunities to bring education on healthy environments into the national curriculum alongside other health and environmental measures including energy, sustainability, healthy eating and physical activity. There are already excellent examples of educational resources aimed at primary schools aligned to the RCPCH report[24] including quizzes, worksheets and experiments. For older children, there are opportunities relating to use of sensors in science experiments as well as potential to build IAQ sensors in design and technology, electronics and computer science classes.

Supporting training for professionals is critical to upskilling capabilities in the built environment sector. The recent Royal Academy of Engineering report on Infection Resilient Environments[31] identified skills gaps in knowing what good ventilation looks like, how to manage it and what to do about poorly ventilated spaces. The report highlighted an urgent need to identify skills gaps and to put training and re-skilling in place. Experiences with the introduction of new technologies (e.g. mechanical ventilation with heat recovery systems) suggests that training and education for professionals needs to understand user behaviours alongside the technical solution. It is particularly important that education and training on IAQ is developed alongside the focus on net zero to enable both aspects to be addressed together.

Raising public awareness

Improving IAQ starts with raising awareness of the health impacts of indoor air and how to create healthy environments at home, in workplaces, social settings and public spaces. There is relatively little data to evaluate public understanding of IAQ, although Global Action Plan carry out a UK-wide Clean Air Public Insight Tracker (CAPIT) survey[72] which, in 2020, reported that 72% of respondents felt that IAQ impacted on their health.[73] Studies of ventilation have shown that people generally consider IAQ to be good, even when measurements indicate that it is not.[74]

Public health campaigns have previously focused on pollutants with known major health effects. However, general public health messaging about the indoor environment is limited and is often overshadowed by concerns about outdoor pollution.

Alongside awareness of indoor air pollution, there is a need for simple guidance for different population groups. This includes members of the public and those who own or manage buildings but do not have specialist knowledge or training relating to IAQ. Some advice about how to reduce indoor air pollution is common sense. The NICE IAQ guidance[23] and RCPCH report[25] both recommend raising awareness of IAQ and have summary messages that are public-facing. Charities that support people who are particularly vulnerable to the effects of indoor air pollution provide good public channels. There is also a body of material developed by the built environment industry bodies – for example, 'My Health, My Home' led by the BEAMA ventilation group, Building Engineering Services Association (BESA) beginners guide to IAQ, and the joint Scottish Ecological Design Association (SEDA)/Health Effects of Modern Airtight Construction (HEMAC Network) guides – as well as highly technical guidance with engineering and scientific professionals as their main target audience.[30,50,75] Although this material exists, there are not clear routes to access it, and therefore information is unlikely to get through to those groups who are not already aware of the importance of good IAQ.

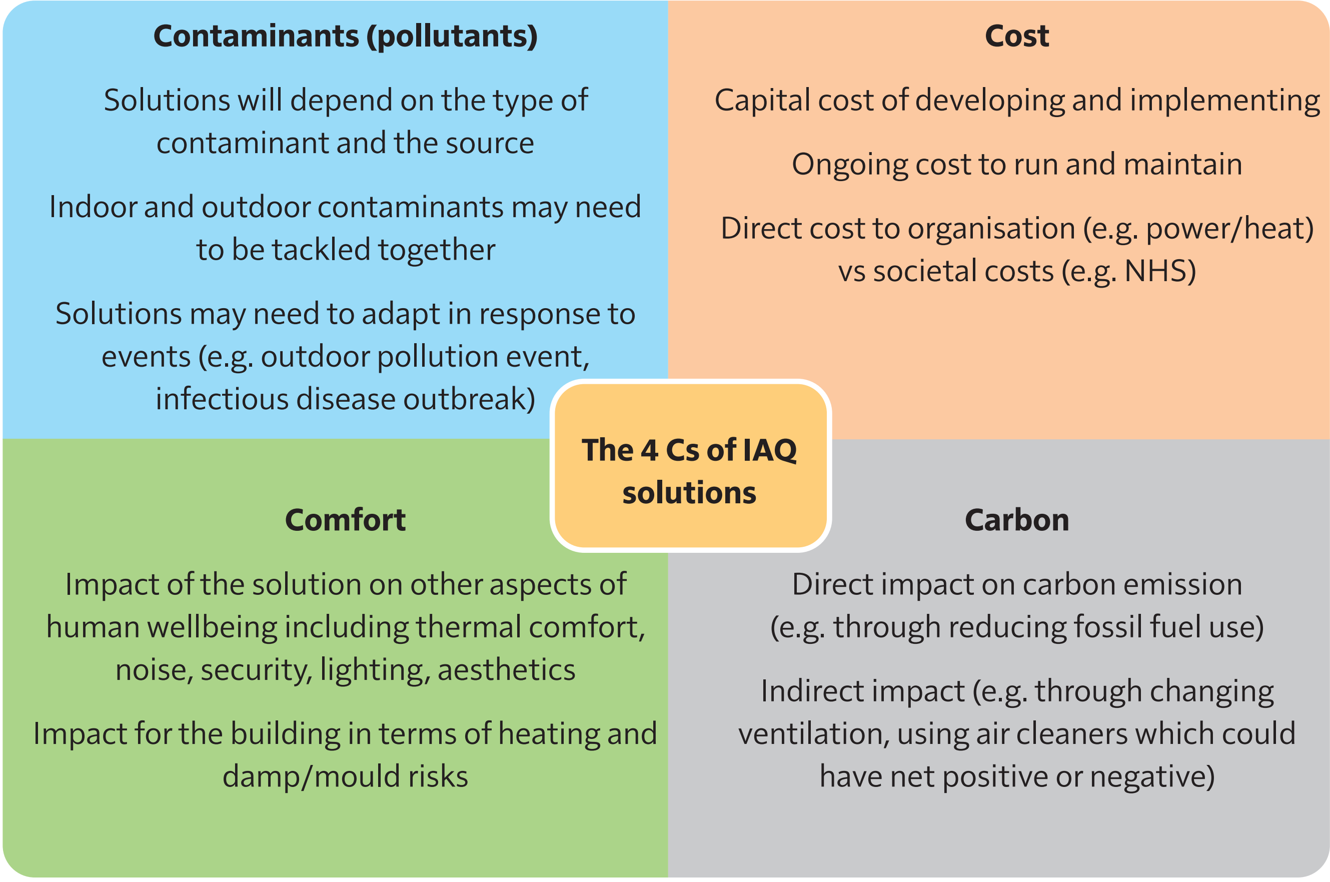
Public advice may raise awareness, but one of its challenges is that, while there are general principles for IAQ and how to optimise it, the differences in season, locations, building use and ventilation provision mean that some advice may not be relevant to all indoor environments. For example, advice to open windows is less viable in winter.

The COVID-19 pandemic has raised awareness of ventilation and the 2020 CORSAIR survey indicated that 75% of people recognised the importance of ventilation.[76] This increased public awareness led to schemes to identify parameters for ventilation provision and IAQ. Worldwide publicly available information includes ventilation assessments of school classrooms in New York,[77] live CO_2 measurements in schools in Boston[78] and an app to view ventilation in restaurants in parts of Tokyo. In Scotland there is a requirement for domestic properties to be provided with simple, but bespoke 'quick-start guides'.[79]

Considerations and trade-offs when selecting solutions

Solutions for managing IAQ will likely have other health, economic and environmental impacts, which may have net positive effects or may have unintended negative consequences, particularly where design is not considered in a holistic way.[30] For example, improving the energy efficiency of buildings by reducing ventilation losses may lead to worsened IAQ if solutions for effective ventilation are not included. Conversely the effects of liberal use of ventilation include energy consumption (where warmed or chilled air is lost), thermal comfort (cold and draughts), external pollution, noise from outdoors and from ventilation equipment, and, in some circumstances, security and safety. The consequences of changes to buildings are connected in complex relationships and an integrated approach to decision-making is needed.[80]

Figure 4 shows some of the main areas where IAQ solutions may have an effect in terms of the '4 Cs' – contaminants (pollutants), cost, carbon and comfort.



The 4 Cs of IAQ solutions

Contaminants (pollutants)

Solutions will depend on the type of contaminant and the source

Indoor and outdoor contaminants may need to be tackled together

Solutions may need to adapt in response to events (e.g. outdoor pollution event, infectious disease outbreak)

Cost

Capital cost of developing and implementing

Ongoing cost to run and maintain

Direct cost to organisation (e.g. power/heat) vs societal costs (e.g. NHS)

Comfort

Impact of the solution on other aspects of human wellbeing including thermal comfort, noise, security, lighting, aesthetics

Impact for the building in terms of heating and damp/mould risks

Carbon

Direct impact on carbon emission (e.g. through reducing fossil fuel use)

Indirect impact (e.g. through changing ventilation, using air cleaners which could have net positive or negative)

Figure 4: Impact of air quality solutions in terms of the 4 Cs

In buildings, energy use and thermal comfort are important, and to a significant degree 'non-negotiable'. Improvements to these reduce fuel poverty, cold-related mortality and damp and mould, and so have important health benefits.[81] However, care is needed to ensure that there are not unintended negative consequences – for instance, there is evidence of increased radon in retrofitted properties[82,83] and modelling studies have demonstrated the health risks of not improving ventilation in domestic retrofit.[84,85]

Developing and applying standards and regulations

Strategic oversight

Policy relating to IAQ crosses the interfaces of multiple government departments and agencies[73] including:

- UK Health Security Agency, Office for Health Improvement and Disparities, and Department of Health and Social Care are responsible from a public health perspective.
- Department for Levelling Up, Housing and Communities is responsible for the building regulations and planning policies.
- The Building Safety Regulator and Health and Safety Executive are responsible for ensuring safety of those who occupy buildings.
- Department for Business, Energy & Industrial Strategy, via the Office for Product Safety and Standards, is responsible for product standards.
- Department for Environment, Food & Rural Affairs has oversight of outdoor air quality and atmospheric emissions, including from buildings.
- Other departments such as Department for Education and Department for Transport have responsibility in schools and transport respectively.
- Local authorities and environmental and public health teams who have responsibility for providing local guidance, support, advice and assessment.

Standards and guidance also cross multiple organisations with some areas, such as schools[86] and hospitals,[87] applying additional guidance compared to other public buildings, workplaces and homes.

The need for a strategic approach to IAQ has also been recommended in previous reports and guidelines. The RCPCH[25] guidance recommends developing a national strategy and policy for IAQ including reporting to the Cabinet Office. The RCPCH[25] and NICE[23] guidelines recommend increasing local authority responsibilities to specifically include IAQ in air quality plans, encourage joint working across local authorities, health and care providers and local organisations, support for environmental health officers to assess air quality in homes and schools, and addressing inequalities through local and national government strategies. This may include providing air quality testing and mechanisms for residents to report IAQ problems and funding to support low-income households to make IAQ improvements.

Improving standards

While new buildings are subject to building standards these are quite limited in scope and often poorly applied. There is good evidence that many buildings constructed to recent building standards fail to meet the minimum requirements for a number of aspects including ventilation.[88] At present, significant aspects of compliance are achieved at design stages and requirements for post-completion and in-use compliance are limited.

Most critically these standards are not relevant or applicable to most older buildings in the UK, where the only IAQ standards that apply are those relating to workplace exposure limits. Regulations for ventilation are predicated on moisture control, and do not recognise contextual issues, such as number of occupants, building form or location, or external factors such as noise of external pollution sources. Building standards rely heavily on guidance documents, which become the de facto standard, and minimum standards become norms.

Reliance on guidance documents also leads to a loss of skills to design from first principles. Recent changes to regulations have been influenced by 'single issue' elements, including energy reduction and more recently fire, which have affected ventilation and IAQ. For example, increasing requirements for airtightness to reduce energy loss have been effective, but the building is increasingly reliant on the designed and installed ventilation provision.

The challenge is providing evidence of the effects of indoor pollution on chronic illness. The burden of proof required to drive changes in regulation is substantial, even when there is strong evidence – for example, health effects of asbestos were first identified in 1931, but it was only fully banned in 1999. A prerequisite to any change of standards is therefore a requirement to ensure that standards are being achieved, maintained and updated where required to maintain public health.

Alongside building regulations, effective product standards and ensuring compliance could manage emissions and peoples' exposure. As highlighted above, labelling of products that lead to chemical and particulate exposures from building materials, furnishings, paint and products for cleaning and hygiene would be an important step for enabling consumers to choose lower-emission products

In recent years, air cleaning devices and low-cost sensors have become more widely available, however, there are a lack of standards for both. In the case of sensors, quality standards would give reassurance that sensors can be used appropriately and interpreted reliably. Lack of air cleaner standards has been identified as a significant issue,[31,52] as these devices are marketed to protect people from harmful pollutants, including infectious pathogens. Although many devices are good quality, some have been shown to produce harmful by-products, while others are ineffective. Standards for air cleaners are currently limited to electrical safety and general product standards and currently there is no requirement for independent testing or verification of effectiveness.

Knowledge gaps and future research priorities

There is good recognition that IAQ has a significant effect on health and the mitigation strategies to manage IAQ through source control, effective building and ventilation design and managing human exposure are already identified. However, many knowledge gaps remain, relating to: causal links between specific indoor exposures, intervention strategies and health outcomes; implementation of technology and behavioural management strategies in reality; and interactions between indoor air, outdoor air and the changing climate.

IAQ data

A key challenge is significant lack of data on air quality, ventilation rates, occupancy and activities for most indoor settings. As a result, evidence to directly relate IAQ parameters to health effects is missing for many indoor pollutants. A priority would be to start to develop systems to gather large-scale datasets of environmental conditions in buildings and use this to undertake population-level analysis of health effects and trends. There is also limited data on the variability within and outside buildings for many pollutants. Research is needed to understand the effects of urban form, external and building-related pollution sources, and how weather, climate and events, such as fires, affect pollution distribution and exposure.

The proliferation of low-cost sensors highlights opportunities and specific knowledge gaps. There is a need to understand the capabilities of using large-scale sensors, including the accuracy of sensors and strategies to couple sensors with the Internet of Things (IoT) and machine-learning approaches. This could enable more effective analysis of the variability in IAQ across different building systems, understanding of health effects and improving public understanding of IAQ. It could also enable development of tools and apps for buildings or people to respond to temporal variations more effectively in environments.

Design and standards

Work is needed to develop reliable and accurate tools for design and modelling for design teams that can balance energy and IAQ demands, but also account for occupant comfort and interaction. Current design and compliance tools are limited in scope and predicated on energy use, but more holistic tools are needed to accurately predict performance under a range of occupancy, seasonal and climatic scenarios. Underpinning this is a need for better models to understand airflows, both in and around buildings that determine air pollution exposures. This includes accurate digital models of buildings and urban environments and better use of digital twins (virtual models) to incorporate aspects such as IAQ.

The net zero challenge will require significant changes in the performance of buildings, both for new buildings but also retrofitting existing stock. The effects of these changes on IAQ needs further investigation through examination of potential effects but also developing and testing solutions. Work is needed to develop applicable solutions to performance-based standards and compliance. Good standards are only valuable if they can be applied in use. This may involve the development of advanced monitoring and testing solutions but also systems for their delivery.

Behavioural interactions and societal effects

Solving air quality problems is often seen as primarily related to regulation and technology solutions, but there is a substantial behavioural and societal component in determining IAQ exposures and in making decisions around investments to address poor IAQ. There is a need for greater understanding of behaviour on IAQ, including baseline data on public awareness of IAQ and the exposures people experience on a daily basis, and data on how people use and interact with building systems and technologies that are designed to manage IAQ. Research is needed to better understand and quantify the economic and social cost of indoor pollution and develop system approaches to identifying benefits and whole-life performance. At present, the cost impacts of pollution are borne by health services, but mitigation costs are borne by the construction industry and building owners. Longitudinal research is also needed to provide better evidence on how pollution affects chronic disease over the life course. A particular area of research should be disadvantaged groups and communities who can be more affected by poor IAQ through poor housing, polluted urban environments and lack of resources and agency for mitigations. Another area that requires greater understanding is the effect of synergistic co-exposures of multiple air pollutants on people's health.

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4.9 Domestic space heating, including burning of solid fuels

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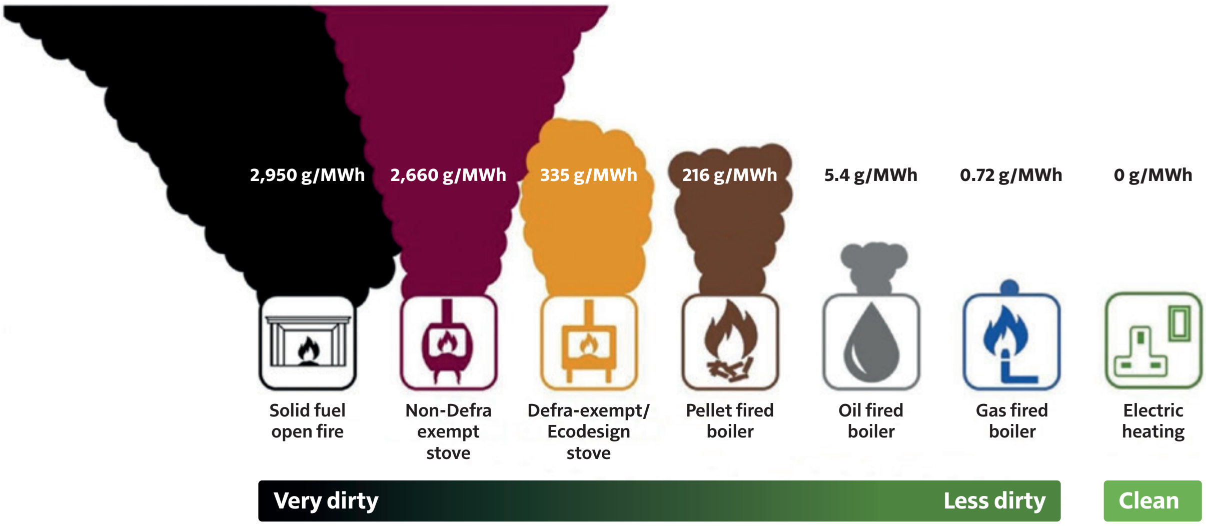
Introduction

Historically, homes were heated by burning coal or wood in an open fire, and this resulted in considerable mortality and morbidity from particulate matter (PM) air pollution, in addition to the health risks of burns and housefires. The Great London Smog in 1952 was caused by the burning of smoky, high-sulphur coal and the presence of weather conditions that did not disperse the pollution. It is estimated to have resulted in the premature mortality of about 12,000 people.[1] After this event, the Clean Air Act of 1956 created 'smoke control areas' where the burning of harmful substances could be banned. This eventually led to widespread reductions in urban emissions of smoke,[2] and in the 10 years from 1956 to 1966, concentrations of PM reduced by 75% in the capital.[3] The Act was consolidated in 1993, so that in smoke control areas in the UK there is now a limit on how much smoke can be emitted from a chimney, and only authorised fuel can be burned unless an 'exempt appliance' is used.[4]

Most domestic spaces in the UK are now heated using natural gas in boilers. Natural gas is a fossil gas consisting mainly of methane. However, around 1.1 million households are not connected to the natural gas grid[5] and instead use fuels such as oil, liquefied petroleum gas (LPG), coal, manufactured solid fuels and wood to generate heat. Other heating methods include electric heaters, and the transition to net zero carbon is stimulating the development of low-carbon heating systems such as heat pumps, heat networks and possibly hydrogen.

In the UK, about 1.5 million households burn wood and just under 400,000 households use coal and other solid fuels.[6] Although some households depend on this solid fuel burning for space heating, many homes burn solid fuels in conjunction with other space heating methods for heating and for aesthetic purposes, especially in urban areas.

Domestic space heating is necessary to maintain people's thermal comfort, health and wellbeing. The different methods of heating emit varying amounts of air pollution. As shown in Figure 1, open fires emit the most fine particulate matter ($PM_{2.5}$) and gas boilers and electric heaters emit the least.



Note: The air pollution emissions will also depend on the age of the appliance, how it is maintained and used and the fuel burned (for example, dry or wet wood).

The following definitions were used: *Solid fuel open fire*: wood burned in an open fire. *Non-Defra-exempt stove*: wood in a conventional stove. *Defra-exempt/Ecodesign* ***stove***: wood in an advanced/ecolabelled stove. *Pellet fired boiler*: wood in pellet stoves and boilers. *Oil fired boiler*: fuel oil in a medium (>50KWth <1MWth) boiler. *Gas fired boiler*: natural gas in a small (≤50kWth) boiler.

Source: Emission factors taken from EMEP 2019 Guidebook[7] (1A4 small combustion tables). Adapted from the Clean Air Strategy[8] with updated data

Figure 1: The relative PM$_{2.5}$ emissions from domestic heating methods

Domestic solid fuel burning

Air pollution emissions

Domestic solid fuels are burned for heating and cooking and for aesthetic purposes, both indoors and outdoors. These solid fuels include wood, wood-based briquettes, smokeless fuels and coal-based briquettes, manufactured solid fuels and coal. They are burned using indoor open fireplaces, closed stoves and boilers, and in outdoor chimeneas, firepits, barbecues, pizza ovens, bonfires and incinerators. The data presented here relates to domestic combustion, but there are also public indoor (and outdoor) spaces, such as pubs and restaurants, which burn solid fuel.

The Department for Environment, Food & Rural Affairs (Defra) estimates that nationally in 2020 domestic combustion from indoor appliances contributed 15% of all primary PM$_{10}$ emissions and 25% of all primary PM$_{2.5}$ emissions. Wood as a fuel contributed 17% of all primary PM$_{2.5}$ emissions. These estimates were calculated using the revised estimates of fuel use in domestic combustion in 2022. From 2010 to 2020, the relative proportion of national PM$_{2.5}$ emissions from domestic wood burning increased by 35%.[9] It is estimated that 10.3 kilotonnes of PM$_{2.5}$ were emitted in 2010 and 13.9 kilotonnes were emitted in 2020 from domestic wood burning.[10]

When wood and other solid fuels are burned indoors, air pollution travels to the outside through the chimney or flue and pollution is also released indoors, particularly when an open fire is used or the stove door is open.[11]

When quantifying air pollution emissions from domestic combustion, there are challenges in determining whether the $PM_{2.5}$ emissions are from indoor or outdoor sources. As discussed in the review by Mitchell et al.,[12] the common measurement methods cannot differentiate definitively between different sources, and there is variation between different kinds of measurement equipment. Also, primary air pollution emissions from stoves, such as volatile organic compounds (VOCs) and nitrogen oxides (NO_x), can form secondary PM in the air, thereby increasing the overall concentration of PM from wood burning.[12]

Air pollution emissions from domestic combustion can be estimated using information about how much wood and other solid fuel is burned and the appliances that are used. However, these estimates are challenging, as the emissions vary according to the age, type and use of appliances, and the type of fuel burned.

An alternative way to estimate the PM from wood and solid fuel burning is to use ambient measurement. There is no standard method to measure wood-burning particles in ambient air. Several methods exist, including reprocessing measurements of black carbon, that are made routinely at a small number of locations in the UK using multiwavelength aethalometer measurements. These reprocessed measurements reveal spatial and temporal variations in PM from wood burning and give estimates about long-term trends. Font et al.[13] analysed data from long-term measurement locations (2 urban sites in London and Glasgow and 3 rural sites in Kent, Hampshire/Oxfordshire and Auchencorth Moss, Midlothian in Scotland). From these locations, the greatest concentrations of PM from wood burning were measured in London, and these were nearly 5 times greater than those in Auchencorth Moss. Across the locations, concentrations were around 3 times greater in winter than in summer, indicating that the impacts from winter heating were greater than those of summer outdoor burning. In contrast to estimates from the air pollution emissions inventory, measurements suggest a slight downward trend since 2009, at between 1 and 5% per year.

Variation within the population

In the UK, there is seasonal variation in domestic combustion, with more indoor burning taking place in the winter and outdoor burning taking place most often as barbecues in the summer and bonfires in the autumn.[14] The study commissioned by Defra and carried out by Kantar in 2018–19 found that in the UK population, the incidence of indoor burning was 8% for all solid fuel, and about 7% for wood. Most people who burned solid fuel indoors lived in urban areas, reflecting the fact that this is where most of the population live. In the study, of the total people who burned indoors in the UK, 5% lived in London and 16% lived in the South-East of England. Also, 13.6% of the population had burned in their garden, and of these outdoor burners, 15% lived in London and 21% lived in the South-East of England.[14]

In the Kantar Core Activity Survey, the reasons people gave for burning solid fuels indoors were the following, with some overlap between groups: 8% burned as their main source of heating (this group tended to be more rural, less affluent and older), 24% burned to save money and for the sense of self-sufficiency, 23% burned to supplement their main heating source, 18% burned as part of tradition and 28% burned for aesthetic reasons. Of the people who burned solid fuel outdoors, 73% was for cooking and barbecuing.[14]

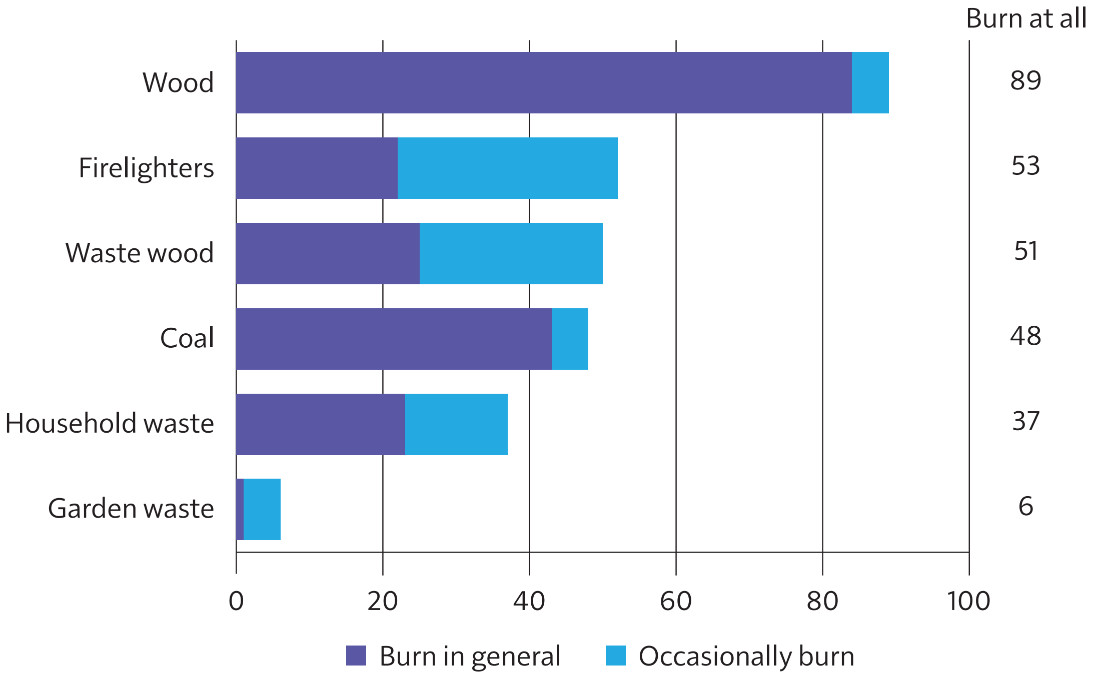
Overall, air pollution from domestic solid fuel burning has the greatest impact on population health in urban areas, where there is the highest population density. However, individuals who burn solid fuels in rural areas may also be exposed to high levels of indoor, as well as outdoor, air pollution.

Solid fuels and appliances

When burning solid fuel to heat domestic spaces, the air pollution emissions vary depending upon the type of fuel and the appliance that is used to burn it.

Types of solid fuels that are burned indoors

Wood is the main fuel that is used for indoor burning in the UK. The Kantar 'Point in Time' survey found that 84% of people reporting that they burned solid fuel indoors said that, in general, they burned wood (this category included logs, briquettes, pellets and wood chips), with 25% burning waste wood and 43% burning coal.[14] Figure 2 shows the percentages of the types of solid fuels used generally and occasionally, by people who burned indoors.



Source: Adapted from Kantar. Burning in UK Homes and Gardens. Research Report. 2020. Prepared for Defra[14]

Figure 2: Types of solid fuels generally and occasionally used by people who burn solid fuels indoors (as a % of people who burn indoors, multi-response allowed)

Air pollution emissions from burning different fuels

Table 1 shows the estimated differences in $PM_{2.5}$ emissions that result from the burning of different fuels. Currently there is research being undertaken, funded by Defra, to further quantify the air pollution emissions from solid fuel combustion.

Fuel	$PM_{2.5}$ emissions when burned
Wet wood	28.87 grams per tonne
Dry (seasoned) wood	7.21 grams per tonne
Manufactured solid fuels	1.6 grams per tonne
Smokeless coal	1.76 grams per tonne

Source: The Air Quality (Domestic Solid Fuels Standards) (England) Regulations 2020[15]

Table 1: $PM_{2.5}$ emissions from burning different types of fuel

Moisture content of wood

When burning wood, there is considerable variation in air pollution emissions, depending on its moisture content. When wet wood is burned, it produces more smoke and harmful particles compared with burning dry wood.

Defra states that dry wood should have a moisture content of 20% or less.[16] The 'Ready to Burn' label indicates that there is 20% moisture content or less, and this certification is now required when selling small volumes of wood. Larger volumes of wood can still be bought wet for people to dry out (season), and Defra advises that the wood is stored in a dry area and allowed to air-dry for at least 2 years before burning.[17]

Despite the air pollution harms of burning wet wood, not all wood is dried sufficiently before it is burned. The Kantar study[14] found that 51% of those who had burned wood in the previous 7 days had used pre-dried or seasoned wood, and 25% had dried or seasoned their own wood (among this group, only 16% had seasoned for over one year). In this survey, 20% of all those who had burned wood in the week leading up to the interview had burned wet wood and 12% were not aware of the level of seasoning of the wood.

As household financial pressures increase over the colder months in winter 2022/23, there is concern that people may burn wood that is not seasoned, waste wood, or other materials to generate heat for their homes and avoid the costs of heating from a gas boiler.

Other types of solid fuel

Manufactured solid fuels include briquettes and fire logs. For these fuels, the 'Ready to Burn' logo indicates that burning them will not exceed the sulphur and smoke limits. Coal smoke is carcinogenic, and in England sales of the most polluting coal, bituminous or traditional house coal are being banned in phases. Instead of using the most polluting coal, Defra recommends using smokeless coal (anthracite) or manufactured solid fuel, where appropriate for the appliance, and using briquettes on open fires.[17]

Open fires and indoor stoves

The choice of appliance used to burn fuel indoors also has a significant impact on air pollution emissions. When compared with an open fire, modern stoves reduce air pollution emissions by up to 9 times: open fires emitting an estimated 2,950g/MWh of $PM_{2.5}$ and Defra-exempt and Ecodesign stoves emitting around 335g/MWh,[7] as shown in Figure 1.

When using a stove, there is transient spillage of pollutants into the room when re-fuelling and de-ashing, but a tight seal on the stove door should minimise spillage of pollution into the room during operation of the stove. Burning techniques that minimise smoke and pollutant production are advised by Defra in 'Burn Better: Making Changes for Cleaner Air'. Other actions that help to minimise pollution emissions include sweeping the chimney and servicing the stove regularly.

When the appliances and fuels are tested, the conditions may be different to those in people's homes, and may not reflect the performance of the appliance after several years of use. For example, Coulson et al.[18] carried out 390 chimney tests on stoves in 51 New Zealand homes and considerable emission variation was found, even on emissions from the same stove. The average emission rate from the most modern stoves tested was 2.6 times greater than the maximum emission rate permitted during regulatory tests. This variation adds complexity to estimating air pollution emissions from domestic combustion.

Regulation for fuels and stoves

Regulations exist for the fuels that can be burned and the appliances that can be installed. Smoke control areas (SCAs) in England only permit the burning of authorised fuels unless using appliances that have been exempted for use in the area. However, local authorities report that there is low awareness of this legislation, and it can be difficult to enforce.[8] The Environment Act 2021 aims to make SCAs easier to enforce by making a breach a civil rather than criminal offence.

Fuels for use in England (including outside SCAs) must meet the requirements of The Air Quality (Domestic Solid Fuels Standards) (England) Regulations 2020.[19] The 'Ready to Burn' scheme ensures that the standards are met – for example, the sale of small volumes of wood is only permitted when it is certified as 'Ready to Burn'.[20]

For appliances, the new Ecodesign regulations, launched in January 2022, mean that all new solid fuel room-heating appliances placed on the market must meet new seasonal efficiency and air pollution emissions requirements for PM, NO_x, carbon monoxide and organic gaseous compounds. These regulations only apply to new installations, and not to appliances that already exist in homes.

International evidence for the impact of fuel and stove interventions

Internationally there are several examples of interventions and policies to reduce PM from wood burning. The evaluations have also demonstrated the health benefits of the interventions.

Stove replacement schemes

Stove replacement schemes can be divided broadly into schemes that fund the replacement of an old stove with a newer low emission stove and those that fund replacement of stoves with non-solid-fuel heating.

A well-known stove replacement scheme took place in the United States, in the small mountain town of Libby, Montana. Here, most people rely on wood to heat their homes, producing 82% of the town's PM air pollution. Between 2005 and 2007, over 1100 stoves were replaced, rebuilt or surrendered, including 98% of the town's oldest appliances. The majority were replaced with wood stoves and pellet boilers that met modern standards, and around 8% of people moved away from wood burning altogether. This led to a decrease in wintertime PM pollution of 27%, allowing the town to meet US legal limits. After the stove swap-out, the town's children experienced less wheezing and fewer respiratory infections and sore throats. The benefits were not only seen in the families that had wood stoves at home; the improvement in air pollution applied throughout the town, providing evidence that wood smoke can affect whole neighbourhoods.[21,22]

In Launceston, Tasmania, rather than focusing on improving stove standards, the intervention involved encouraging people to switch to electric heating. Between 2001 and 2004, grants of A$500 were offered to homeowners to subsidise a change in heating fuel. The number of homes heated with wood reduced from 66% to 30% and particle pollution in the air dropped by 40%. Winter death rates dropped by around 11%, the change being clearest among men. Improvements were seen in cardiac deaths and respiratory problems in both men and woman when compared with the Australian control town of Hobart, where no incentive scheme was offered.[23]

Burn bans

Many areas of the US put in place burn bans to reduce home heating emissions when unfavourable meteorological conditions are expected.[24,25]

The burn ban in San Joaquin Valley in southern California was evaluated by Yap and Garcia.[26] Here, winter is characterised by cold rainy weather and dense low fogs, and the most severe smogs have been attributed to home wood burning. A new scheme for wood-burning bans was introduced in 2003, to be imposed when air pollution was forecast to be poor. PM air pollution concentrations and health metrics in the first three winters of the scheme's operation were compared with the three winters prior to the scheme. Burn bans were called on around 100 times each winter. The winter average $PM_{2.5}$ decreased by around 11–15%. Hospital admissions for cardiovascular and ischaemic heart disease in people aged over 65 decreased by 7–17% (depending on the health end point chosen). Improvements were greatest in those areas that had originally had the highest prevalence of home wood burning.

A wood-burning advice system operates in Flanders, Belgium,[25,27] and asks people not to use wood heating unless it is their primary source of heating. Alerts are sent by press release when the running daily mean concentration of PM_{10} is greater than 50µg/m3 and this is expected to persist for the next 24 hours. Alerts are typically issued 3 or 4 times each winter. An air pollution evaluation has not been undertaken, but a survey of 600 people showed the effectiveness of the scheme in raising awareness, with 70% of people being aware of the alerts (this rose to 80%

among people that burn wood). The scheme was supported by 90% of the population, with 50% of wood burners saying that they had adjusted their behaviour: 20% reported that they had stopped burning and 30% stated that they burned less than before. It is believed that the wood burning alerts have changed the public and political perspective on the impacts of wood burning.

Other domestic space heating methods and air pollution

Although the burning of solid fuel, particularly in open fires, produces the highest levels of $PM_{2.5}$ air pollution, other methods of domestic space heating are also sources of air pollution.

In the UK, over 22 million households are connected to the natural gas grid, and in 2020, 38% of the UK's gas demand was used for domestic heating.[28] The combustion process in gas boilers is a source of NO_x emissions, which is released into the ambient air through domestic boiler flues.[29] In addition, when gas boilers are not working properly and there is incomplete combustion of the gas, they can emit harmful carbon monoxide.

In 2021, the Office for National Statistics analysed dwellings in England with an energy performance certificate (estimated to be more than half of all dwellings in England). Of these dwellings, 79% used mains gas to fuel central heating, and 11% used electricity.[30]

Although gas boilers are very common, 16% of homes in Great Britain are not connected to mains gas. These homes use either electricity or alternative heating methods, such as liquid petroleum gas, heating oil or solid fuel of coal, coke or wood. Households without mains gas are more likely to be in fuel poverty and tend to be in rural areas,[31] and may find changing to an alternative heating method logistically and financially challenging.

Domestic heating systems for net zero carbon

As gas boilers are also a source of carbon emissions, the Department for Business, Energy & Industrial Strategy (BEIS) Heat and Buildings Strategy plans to phase out the installation of new fossil gas boilers from 2035. There is ongoing work to identify the best solutions for heating different buildings, including the use of air or ground source heat pumps or heat networks, and potentially switching the natural gas in the grid to low-carbon hydrogen.[32]

Heating that relies on electricity, through the use of electric heaters or heat pumps, is not a source of air pollution at the point of use – however, it can be an expensive method of heating.[33] Hydrogen combustion causes NO_x, so if hydrogen is used as a means of heating urban dwellings in the future, this could be the last major source of NO_x, since road vehicles will have switched to electric power.[34,35]

In addition to domestic space heating, effective insulation of people's homes reduces the demand for heating and helps to maintain adequate building temperatures for people's thermal comfort and health. Even if there is a shift to hydrogen-based heating, if the demand for heating can be reduced, the amount of NO_x released is likely to be lower. The considerations for balancing building insulation with effective ventilation for indoor air quality are discussed in Section 4.8.

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5 Air pollution chemistry, monitoring, forecasting and information

5.1 Where air pollution comes from and where it goes

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Introduction

This section builds on the information in Chapters 2 and 3 for those who would like more detail about the atmospheric chemistry behind how primary pollutants are transformed to secondary pollutants, transported in the air, deposited onto surfaces and broken down in the environment. These stages ultimately determine the spatial reach of a particular pollutant, and how it affects the air that people breathe. Successful mitigation against air pollution requires a good understanding of the processes that determine local levels of pollutants. Throughout this section, outdoor and indoor spaces will be distinguished, since the make-up of pollution as well as the environmental conditions vary widely.

Primary emissions of air pollutants

To recap, most of the primary pollutants affecting human health in the UK originate from anthropogenic sources. However, highly polluting natural events across the globe include volcano eruptions, dust storms and forest fires.

Outdoor primary pollutants include particulate matter (PM), nitrogen oxides (NO_x – a mixture of the gases NO and NO_2 formed in combustion processes), sulphur dioxide (SO_2), ammonia (NH_3) and volatile organic compounds (VOCs). When the least reactive VOC, methane, is separated out, the remaining compounds are referred to as non-methane VOCs (NMVOCs). The major emission sources of these outdoor pollutants and the recent trends over time are presented in Chapter 2.

Indoor spaces include different sources of primary pollutants, as discussed in Section 4.8, but many classes of pollutants are the same as outdoors. This includes PM from cooking, combustion processes and mould (a bioPM), NO_x from combustion processes and VOCs from, for example, consumer products. Other indoor pollutants include carbon monoxide (CO), asbestos and radon (as well as cigarette smoke, which has well-recognised health harms, but is beyond the scope of this report). Indoor spaces have smaller volumes compared to the outdoors, so surface sources of air pollution, such as carpets, fabrics and furniture, can be significant. Indoor sources of certain long-lived emissions such as persistent organic pollutants (POPs) also affect outdoor levels of these species through leakage and ventilation from indoor to outdoor spaces.[1]

Transformation of primary pollutants

Some primary pollutants are stable in air and simply move through space with air currents. They are diluted when moving away from their sources and when being mixed with cleaner air. However, many pollutants transform over time, and the speed and nature of these transformations depends on the environment the pollutants are emitted into.

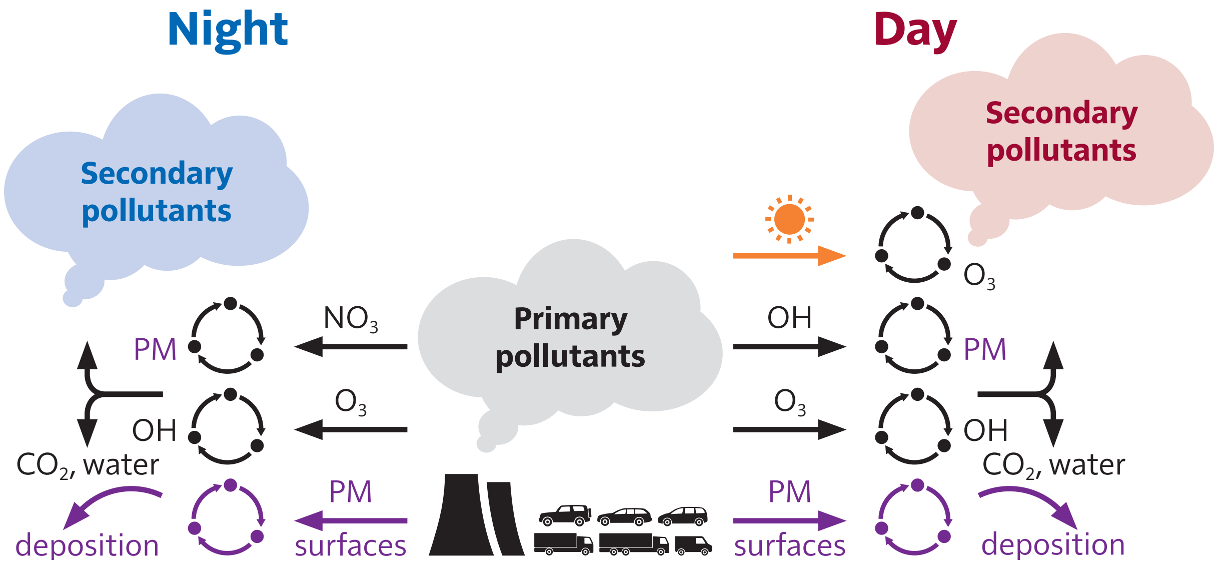
Transformations can break down the primary pollutants, and can also lead to the formation of secondary pollutants. These secondary pollutants can have different properties to the originally emitted compounds. They are often less well understood, and some, like formaldehyde, a secondary pollutant indoors, may be more harmful than the primary pollutants.

This transformation of primary pollutants occurs via three main processes:

- breakdown by sunlight ('photolysis')
- interaction with highly reactive gases
- interaction with liquids or solids ('heterogeneous uptake')

Daytime processes outdoors are dominated by sunlight, which leads to direct photolysis. Sunlight also generates the gas-phase radicals, hydroxyl radicals (OH) – often referred to as the atmospheric detergent – which rapidly break down most pollutants. At night, in the absence of sunlight, other highly reactive gases lead the degradation of pollutants. These include photolabile nitrate radicals (NO_3) and ozone (O_3), which is present throughout day and night, but somewhat less reactive than both OH and NO_3. The relative importance of the pollutants' interactions with liquids or solids depends on the availability of surfaces for the pollutants to collide and interact with, compared to the levels of reactive gases.

These three transformation processes contribute to the breakdown of primary pollutants to different extents depending on the local conditions and are schematically illustrated in Figure 1.



Source: Pfrang C

Figure 1: Schematic display of the most common pollutant transformation processes during night and day

The three processes illustrated in Figure 1 are photolysis (orange), reaction with gas-phase species (black) and heterogeneous uptake (violet). The processes leading to the recycling of OH, O_3 and PM are illustrated by black and violet circular arrows, with the dots indicating reactive intermediates. This scheme does not detail the underlying and often complex radical chemistry. These transformations lead to formation of secondary pollutants, CO_2 and water vapour. The residence times of pollutants are determined by these transformation processes together with removal via dry or wet deposition (rain).

Ozone

O_3 is a secondary pollutant, formed during the transformation of primary emissions when there are high levels of NO_x, VOCs and sunlight. If NO_2 is present in sunlight, O_3 is formed from the photolysis of NO_2. A product of this photolysis reaction is NO, which can in turn react with O_3 to regenerate NO_2 (hence there is no net production of O_3). For effective O_3 formation, the third component of high concentrations of VOCs is required.

The limiting factor for O_3 production depends on the relative levels of VOCs and NO_x (that is, the ratio of VOCs to NO_x). Reactions of O_3 with VOCs cause formation of OH radicals, involving many cyclic reactions[2,3,4] beyond the scope of this chapter. These processes lead to the oxidation of VOCs in reactions that also involve NO_x. OH catalyses some of the reactions, and dozens of other chemicals take part. The main results are the formation of O_3 and NO_2 (available to produce further O_3) and the regeneration of OH (available to catalyse the production of more O_3). The O_3 formation rate depends on the specific VOC and NO_x concentrations. Generally, O_3 is most likely to reach levels harmful to health in polluted regions on hot, sunny days.

Particulate matter

PM components are emitted both as primary particles and as precursor gases that lead to the formation of secondary PM. In the UK, secondary $PM_{2.5}$ frequently makes up a significant proportion of the $PM_{2.5}$ that is experienced.

Secondary inorganic PM is formed as nitrate from oxidation of NO_x, producing nitric acid (HNO_3), which reacts with NH_3 (for example from agricultural sources) to form ammonium nitrate (NH_4NO_3). It is also present as sodium nitrate ($NaNO_3$) when HNO_3 reacts with sea salt particles. Although SO_2 is declining in the UK, inorganic PM is also formed as sulphate from oxidation of SO_2, producing sulphuric acid (H_2SO_4), which again reacts with NH_3 to give ammonium sulphate.

Secondary organic PM (often also referred to as secondary organic aerosols, SOAs) is formed from the oxidation of NMVOCs in complex chemical processes involving thousands of individual components. Some of these organic compounds, such as certain polycyclic aromatic hydrocarbons (PAHs), are highly toxic, and their reaction products, functionalised aromatics, can be even worse. Overall, SOAs have been shown to be a major component of atmospheric organic PM,[5] which represents a significant and sometimes major (20–90%) mass fraction of PM sizes below one micron in diameter. The SOA fraction ranges from 64% to 95% of the total organic PM when moving from urban to remote regions.[6] Generally, the precursors of SOAs include VOCs emitted from both biogenic sources (for example terrestrial vegetation, grassland and forest) and anthropogenic sources (for example biomass burning, coal combustion, transportation, solvent use and industry). In the atmosphere, these VOCs are oxidised by O_3, NO_3 and OH to form less volatile products, which undergo further reactions or partition into the condensed phase, leading to complex chemical profiles within the aerosols.

Outdoors and indoors

Most of the factors that influence pollutant transformation differ substantially when comparing outdoor and indoor spaces. Indoors, there is limited availability of sunlight, so photolysis does not play a significant role except in the immediate vicinity of poorly filtering windows. Also, since the ultraviolet proportion of sunlight that leads to formation of highly reactive OH outdoors is largely filtered out by windows, it is generally assumed that there is much less OH present indoors than outdoors. It is also assumed that O_3 leaking in from outdoors, is the major oxidant of indoor pollutants. However, it has very recently been discovered that high levels of OH radicals can also be generated indoors due to the presence of people and O_3.[7]

Indoor surfaces tend to be larger relative to the volume of air compared with outdoors: compare the size of indoor furniture with that of raindrops. They also change less frequently, so pollutants can build up on surfaces over longer periods of time. For example, long-term build-up of grime on the inside of windows can play an important role in indoor air pollution and the formation of highly reactive gases indoors.[8,9]

There are also different levels of pollutants indoors compared with outdoors, including in general higher levels of VOCs and less NO_x. An important transformation is the production of formaldehyde from the VOC limonene through reaction with O_3 indoors.[10] Also, temperatures and moisture levels differ, which both affect the speed at which pollutants are broken down.

There is much greater uncertainty about the transformation processes that happen indoors compared to outdoors due to variation in individual behaviour, diverse building fabrics and conditions, especially in private homes, and often uncontrolled and variable ventilation rates. Currently, there is limited understanding of how pollutants are transported and how they change in indoor spaces across the UK.

'Reach' of pollutants – time in the air, pollutant mixing and transport distances

The time a pollutant can remain in the air is determined by the speed of transformation processes and deposition of larger PM on the ground or collision with surfaces such as buildings, leaves or raindrops. The pollutant's lifetime determines how far it can travel from its source and its transport distance also depends on the speed and turbulence of the air, which is largely determined by wind speeds outdoors and air exchange rates indoors.

The lifetime and associated transport distance of key air pollutants are illustrated in Figure 2 for outdoor pollutants and Figure 3 for indoor pollutants. The pollutants have a wide range of lifetimes, from less than one second for highly reactive pollutants, to hours, days and even years for the long-lived pollutants outdoors. It is important to note that Figure 3 considers an indoor air exchange rate of 0.5 per hour, which substantially reduces the apparent indoor lifetime of the less reactive pollutants. These lifetimes determine the reach of these pollutants, ranging from minimal transport away from the source location to a global scale.

Outdoors, pollutants have a wide range of lifetimes. For example, NO_2 has a shorter lifetime than $PM_{2.5}$, and therefore has shorter-range effects. Indoors, the indoor–outdoor exchange of pollutants is highly variable with time and location, and it also strongly depends on the building type, building fabric and condition as well as occupant behaviour. Most commonly, outdoor air will be an additional source of indoor pollution,[11] but depending on the relative concentrations, indoor emissions can also become a source of outdoor pollution, for example for POPs such as flame retardants or stain-proofing additives in consumer products.[1]

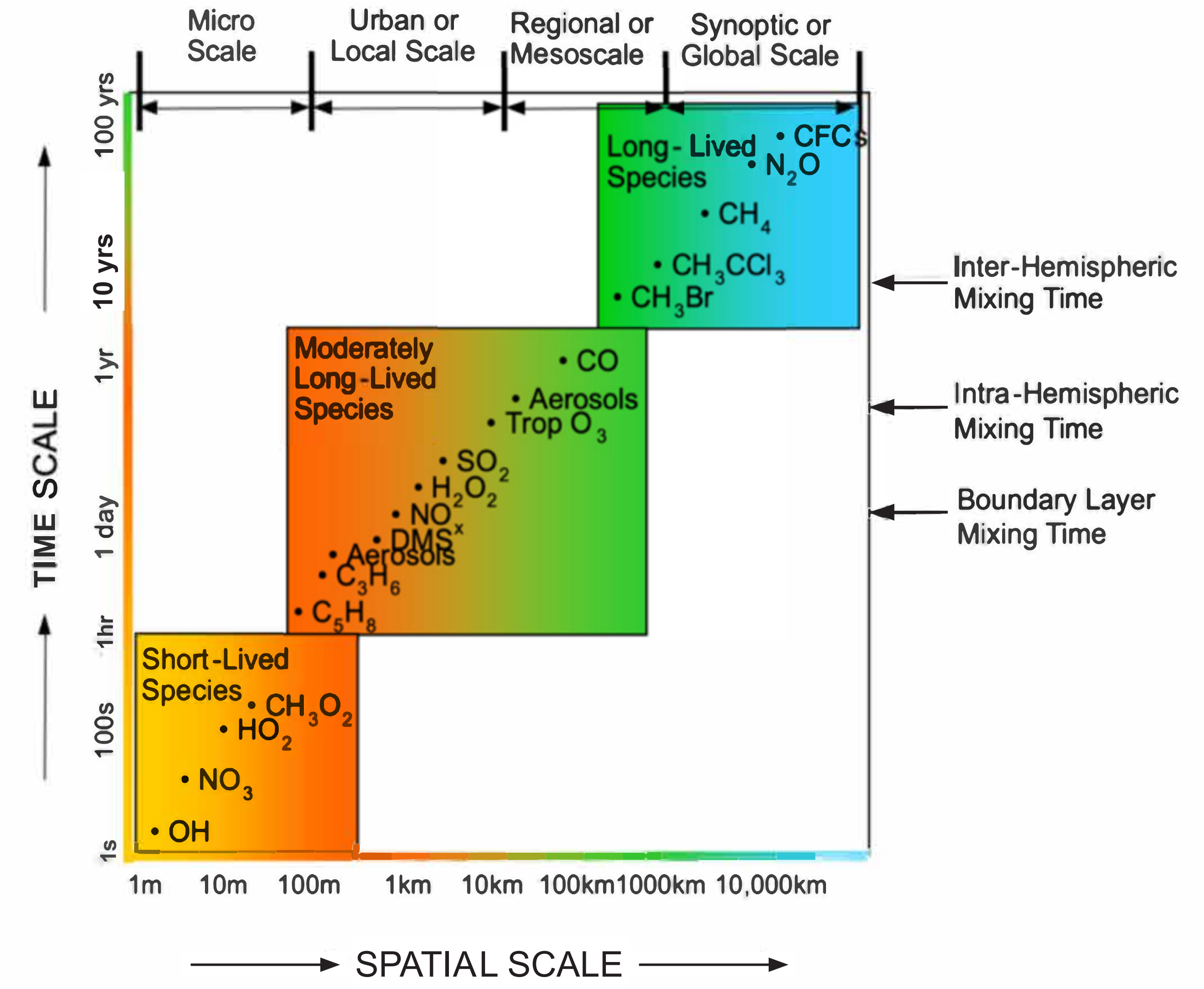


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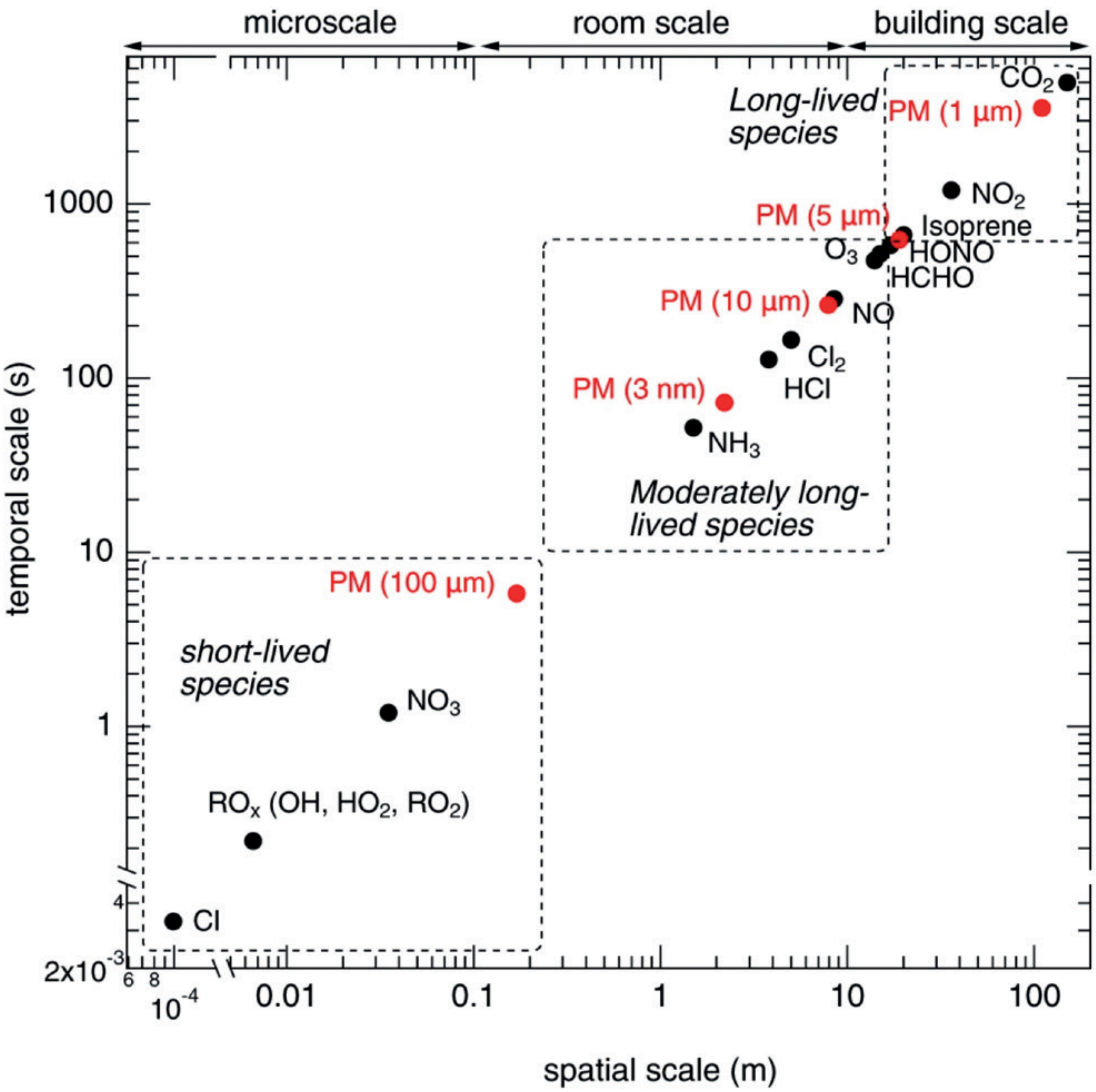
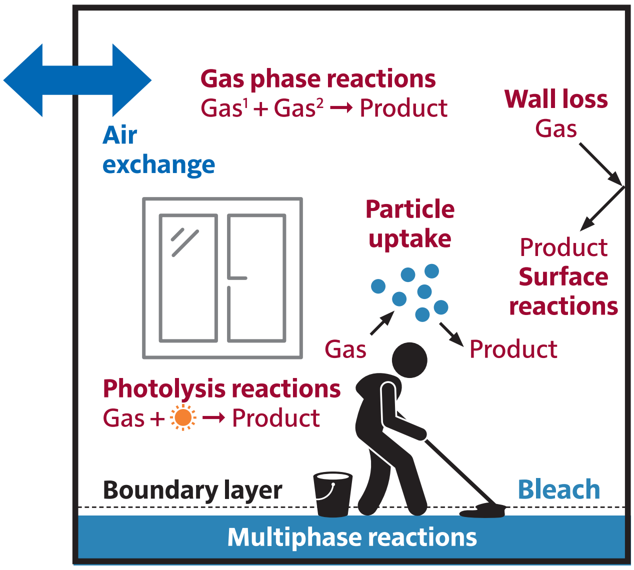
Figure 2: Relating lifetimes and reach of pollutants: temporal vs. spatial scales outdoors



Source: Lakey et al., 2021.[12] Article licensed under a Creative Commons Attribution 4.0 International License

Figure 3: Relating lifetimes and reach of pollutants: temporal vs spatial scales indoors (assuming a typical indoor air exchange rate of 0.5 per hour)

The reach of pollutants can be considered at different scales, for indoor air pollution inside a room or building, and for outdoor air pollution at the local, regional, national and international scales. Different scales of the reach of pollutants are presented in Figures 4 to 7. Figure 4 illustrates how a cleaning event within a single room can lead to microscale concentration gradients, with short-lived OH radicals being confined to sunlit zones near the windows.

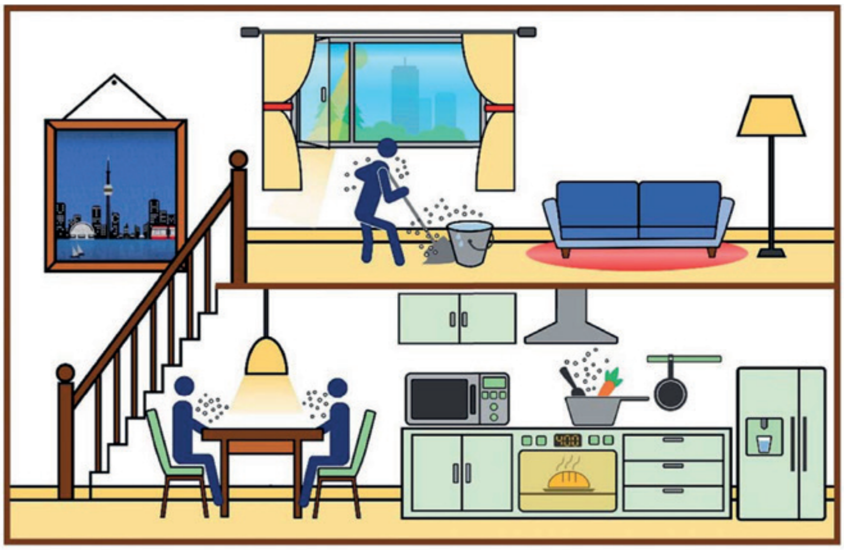


Note: Figure shows a single room indoors and a cleaning event leading to microscale concentration gradients, for example with short-lived OH radicals being confined to sunlit zones near the windows.

Source: Adapted from Lakey et al., 2021.[12] Article licensed under a Creative Commons Attribution 4.0 International License

Figure 4: Scales of air pollution and its transport: cleaning indoors (room-scale)

Air pollution at the building scale is shown in Figure 5. This illustrates examples of peoples' cooking and cleaning practices, which can lead to intermittent emissions of specific pollutants, such as the terpenoid VOCs and chlorinated molecules, which superimpose upon more steady emissions from building materials and furnishings. People affect these pollutant levels by opening and closing windows and doors and stirring up particles from the ground when they move. Overall, the effects of humans on the indoor environment have not been as well documented as those of the buildings themselves, because their transient nature is hard to capture. Human skin[13] and soiled clothing[14] are also important sinks for O_3 and sources of VOCs indoors.[15]

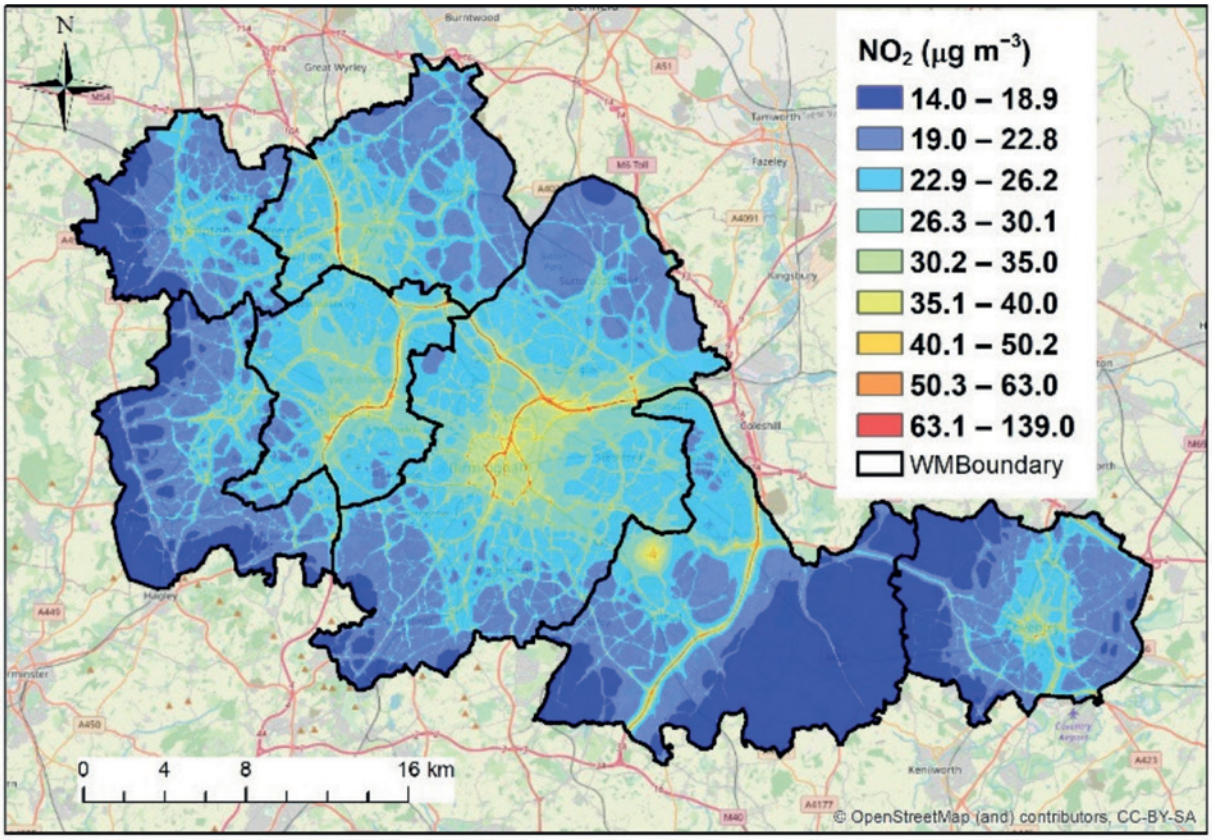


Note: Figure illustrates the interior of a private home at building scale with cooking and cleaning practices leading to intermittent emissions of specific pollutants.

Source: Abbatt and Wang, 2020.[15] Article licensed under a Creative Commons Attribution-NonCommercial 3.0 Unported License

Figure 5: Scales of air pollution and its transport: cooking and cleaning (building scale)

Figure 6 illustrates how pollutants are distributed outdoors on a regional scale, with an annual air quality map of the moderately long-lived pollutant NO_2 in the West Midlands. NO_2 can travel over considerable distances, with lifetimes in the range of minutes to hours. The main factors dictating its spatial distribution are chemical sinks, in particular the reaction with OH to produce HNO_3 during the day and the formation and subsequent reaction of NO_3 at night.

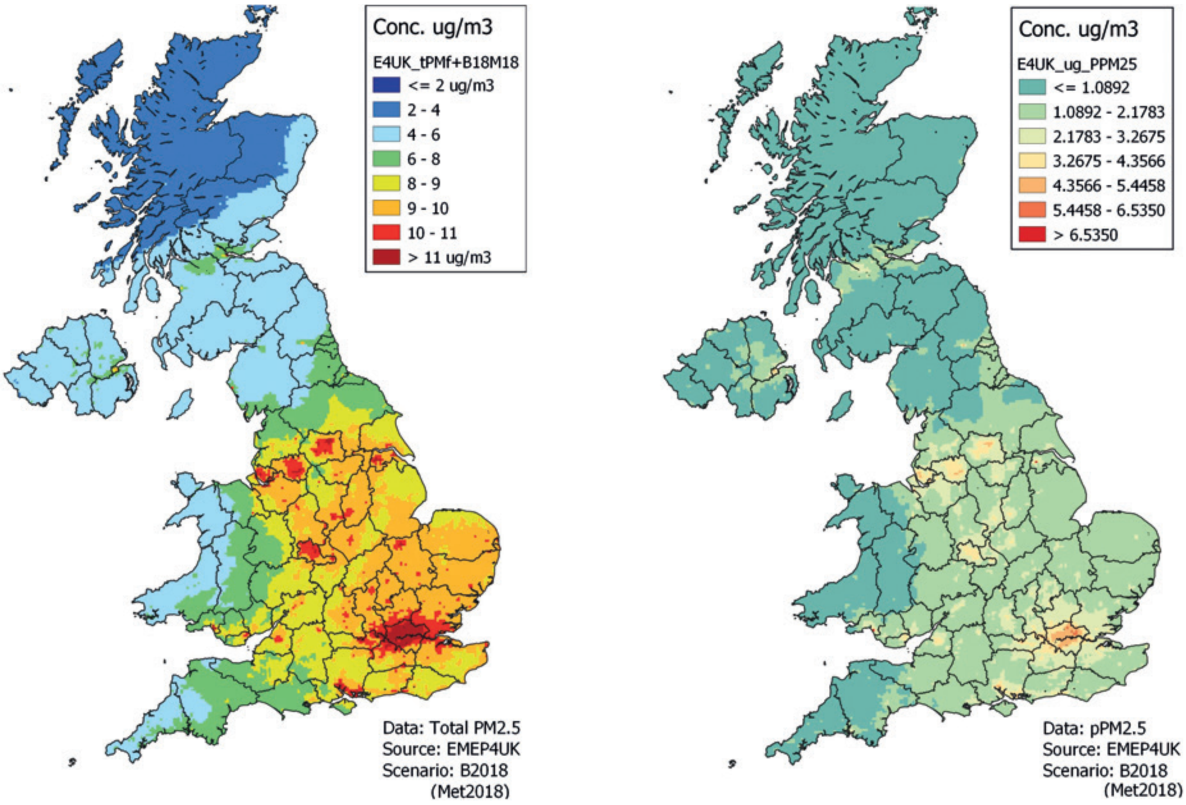


Note: Figure illustrates the outdoors at a regional scale: annual air quality map of the pollutant NO_2 (lifetimes in the range of minutes to hours) in the West Midlands. The map shows strong concentration gradients away from roads, indicating that NO_2 concentrations are strongly source-dependent and not spatially well mixed.

Source: Zhong et al.[16] Article licensed under the open access Creative Common CC BY license

Figure 6: Scales of air pollution and its transport: NO_2 outdoors (regional scale)

The modelled annual average concentrations of the longer-lived pollutant $PM_{2.5}$, with a lifetime of about 3 to 5 days, is shown across the UK in Figure 7. The total mass of $PM_{2.5}$ reflects a complex mixture of secondary aerosols, natural dusts and sea-salt, and primary particles emitted from anthropogenic sources. The comparison of the total $PM_{2.5}$ (left panel) and the primary $PM_{2.5}$ (right panel) illustrates that a significant proportion of $PM_{2.5}$ in the outdoor atmosphere is secondary and regional in nature; primary $PM_{2.5}$ is much more localised near to anthropogenic sources. $PM_{2.5}$ is an important example of a pollutant where looking at emissions alone would miss a major proportion of the pollutant's abundance and impact in the UK.



Note: Left panel – Modelled total $PM_{2.5}$ (including primary, secondary and natural components), Right panel – Primary $PM_{2.5}$.

Source: Oxley T et al.[17]

Figure 7: Scales of air pollution and its transport: outdoors, UK-wide maps of annual average concentrations of $PM_{2.5}$ (lifetimes in the range of 3 to 5 days) in 2018

In summary, air pollution is a complex problem and tackling it requires a detailed understanding of the sources, sinks, properties, lifetimes and thus the reach of the pollutants. Directly emitted, primary pollutants interact with sunlight and highly reactive gases. They degrade at varying speeds, but also transform into harmful secondary pollutants. The concentrations of both primary and secondary pollutants vary depending on location, time and human behaviour. In terms of human exposure, it is particularly important to better establish the indoor air quality that individuals experience in the UK and how it will change in the future.

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5.2 Air pollution monitoring, forecasting and alerting

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Introduction

Air pollution monitoring and modelling allows us to measure and map the pollutant distribution across the UK and understand how these levels change with the weather and emission rates. This data can be used as part of an information system to inform people about their air pollution exposure in different places or on different days, and to prompt public alerts when the levels are high so that action can be taken to reduce the risk of health harm.

Air pollution monitoring and modelling data can also be used to inform policymakers about where, for example, there are areas of consistently high air pollution. This can help to guide policy development and decisions about possible interventions, as well as aiding evaluation of the effectiveness of actions taken to reduce pollution.

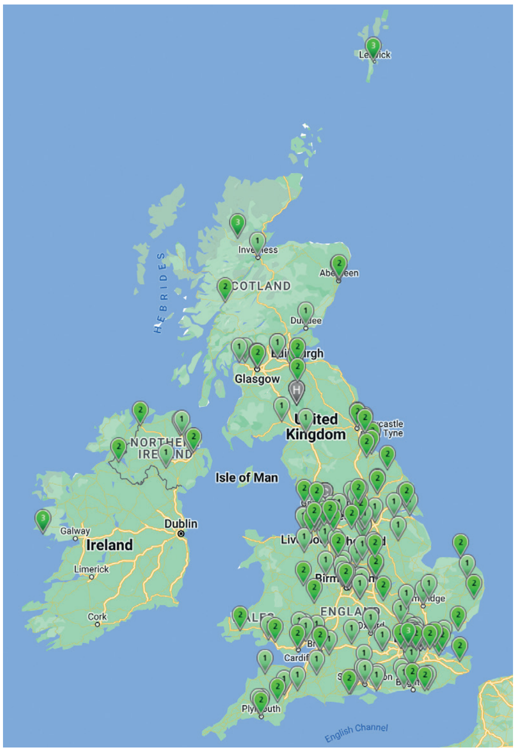
Air pollution variation between places

Distribution of air pollution monitoring sites

There is an extensive range of networks in the UK for monitoring the presence and levels of pollutants in the air. Some networks, such as the Black Carbon Network, cover specific pollutants, while others focus on air pollutants which deposit to the ground and affect plants and pollute soil or groundwater. Some networks make automated measurements which are relayed in near real-time to a central data archive, while others are non-automated and samples must be collected, analysed and reported to the archive on a periodic basis.

The pollutants nitrogen dioxide (NO_2), particulate matter ($PM_{2.5}$ and PM_{10}), ozone (O_3) and sulphur dioxide (SO_2) are in the UK's Daily Air Quality Index (DAQI),[1] discussed later in this section.
The most comprehensive networks for monitoring these pollutants are those automated networks which take hourly measurements of one or more of the 5 pollutants. At a national scale, the most important of these networks is the Automated Urban and Rural Network (AURN). Consisting of around 170 sites, this network provides the most complete and up-to-date picture of pollution levels across the UK, as shown in Figure 1. Locations of the AURN monitoring sites have been dictated largely by where compliance with statutory requirements needs to be assessed.

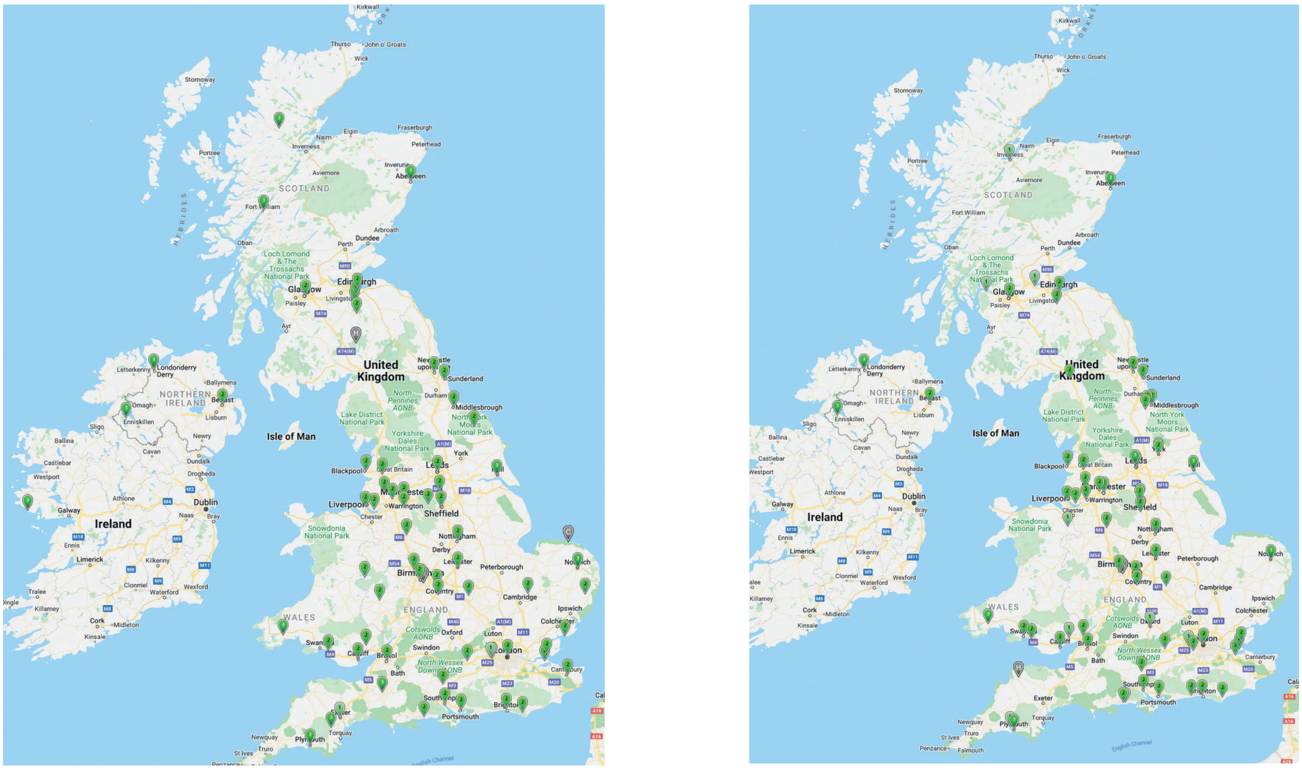
Most AURN measurement sites do not measure all the air quality pollutants, so under some conditions the overall index at a specific individual location can be misleading. There may also be local hot spot areas of high pollution that are not captured by this monitoring network.



Source: Defra UK-Air²

Figure 1: AURN air quality measurement sites

Currently, there are gaps in spatial coverage for the pollutants O_3 and $PM_{2.5}$. The locations of O_3 and $PM_{2.5}$ AURN hourly measurement sites are shown in Figure 2. Although additional local networks complement this, they do not address the larger gaps.



Source: Defra UK-Air³

Figure 2: Locations of O_3 (left) and $PM_{2.5}$ (right) hourly observation sites for mainland UK

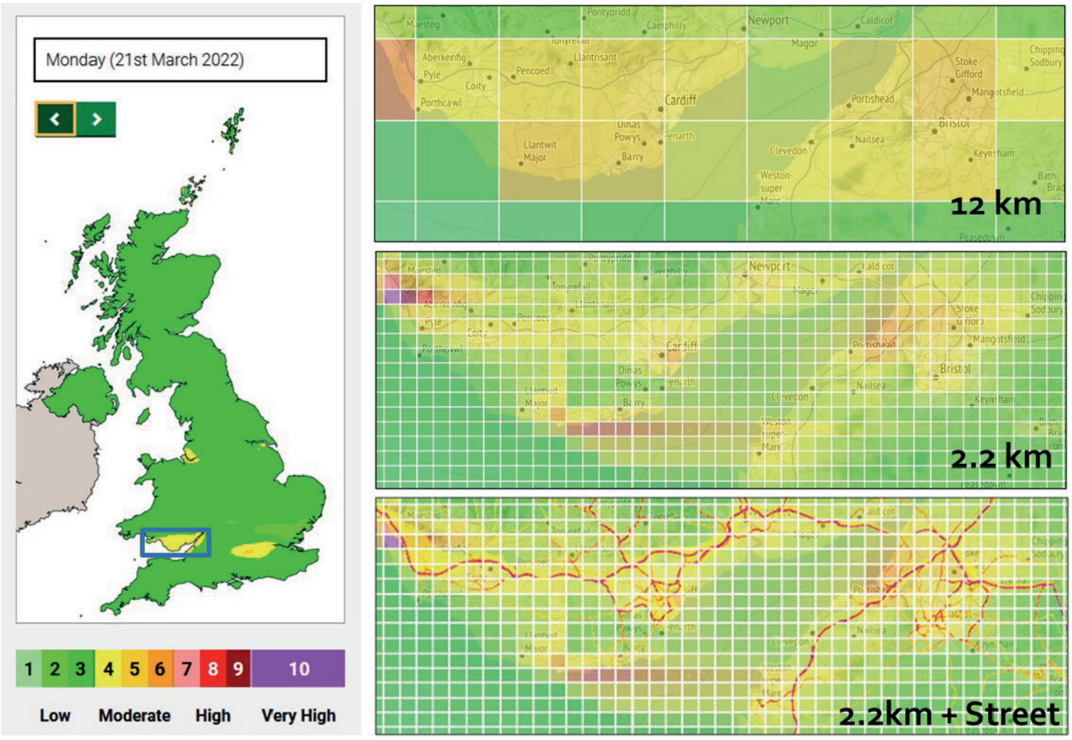
Many local authorities maintain automated monitoring networks in addition to the AURN to support local air quality management. These are usually associated with locations such as industrial sites, roads and junctions, where pollutants may exceed statutory limits. Therefore, the local authority sites usually measure a limited set of the air pollutants, frequently only one or two. A good example is the London Air Quality Network (LAQN), which has around 130 monitoring sites spanning Greater London, with a few extending beyond the M25. Defra has now collated many of these local authority measurements centrally and made them available on the Defra UK-Air website.[2] They are also available via the Air Quality England website.[4]

Future expansion of air pollution monitoring networks could improve the mapping of pollution levels between different locations, and additional sites in rural locations would help to monitor background conditions. Expanding the networks could also enhance forecasting models that combine observations with models through data fusion techniques, such as the Met Office system.[5]

Spatial resolution of air pollution modelling

Air pollution in urban areas can vary significantly over relatively short distances. Spatial and temporal averaging 'smooths out' localised high pollution values which occur close to sources, so dose estimates for people living or working near to these pollution sources can be significantly underestimated and those further away overestimated. This loss of discrimination contributes to a 'blurring' of the dose–response relationship.

Air quality modelling linking regional and street scales together is possible and is used in London.[6] It is being developed for larger geographical areas through the Multi-Model Air Quality System for Health Research (MAQS-Health) project,[7] part of the Strategic Priorities Fund (SPF) Clean Air Programme. The Met Office is exploring this as part of a future UK forecast and modelling capability. The new techniques, as illustrated in Figure 3, provide the possibility of enhancing the resolution of air pollution modelling to street scale across the whole of the UK. Creating such capability nationally would represent an improvement in the data available to the public and local and national government.



Note: This approach, being developed under SPF Clean Air, relies on running multiple linked models and requires considerable computer resource but is now a possibility for the entire UK.

Source: Internal Met Office data

Figure 3: Example of enhancing resolution in regional modelling linked to street-scale air quality

Variation in air pollution over time

Seasonal variation

Levels of pollutants in the air are determined by the rates of emissions, the transformation processes they go through in the air and their subsequent dispersion and loss from the air, as described in Section 5.1. The prevailing weather conditions play a key role in this balance, resulting in seasonal variation in elevated pollution episodes.

In summer in the UK, hot, sunny days favour higher pollution levels, promoting oxidation processes in the atmosphere and leading to increased formation of secondary pollutants, including O_3 and PM.

In spring and autumn, conditions of light south/south-easterly winds over Southern England draw in additional pollution from continental Europe. A particular example is the elevated springtime concentrations of nitrogen compounds arising from agricultural emissions which, together with traffic emissions, contribute to the formation of secondary PM.

In the winter, high air pollution days also occur under conditions of light winds. These events see elevated concentrations of NO_2 and PM. Pollution from road transport often plays a main role[8] and the contribution from domestic woodburning has become increasingly significant in recent years.[9]

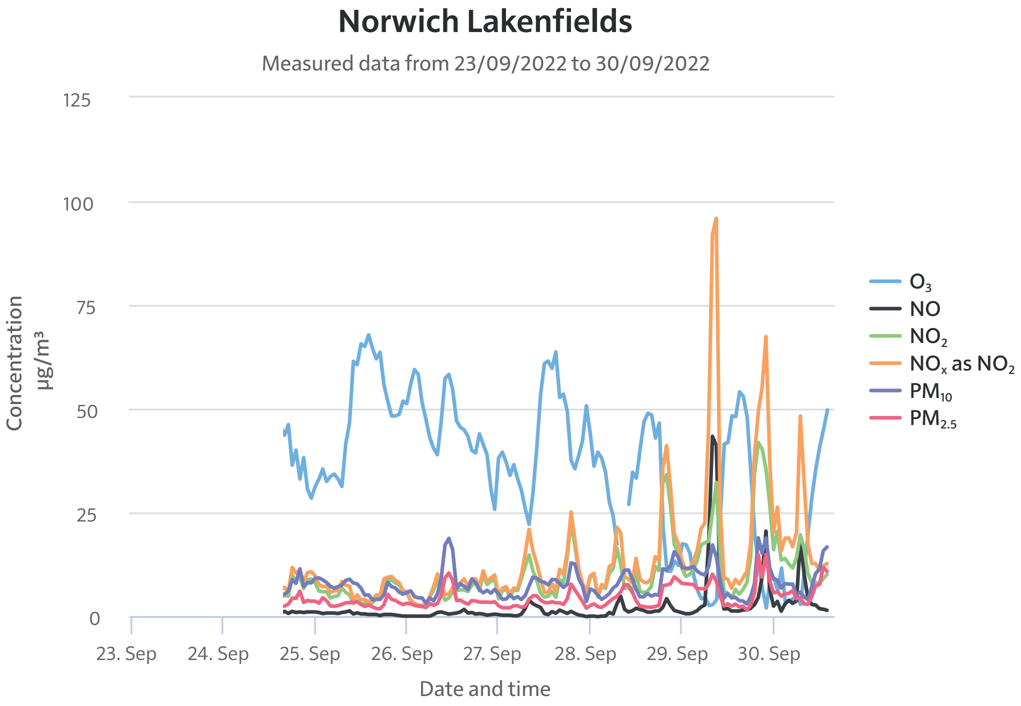
There are other seasonal activities, such as bonfires, which contribute to air pollution at different times of the year.

Over the course of a year, these 'episode' conditions typically occur 10–15 times and result in periods of elevated pollution levels typically lasting from 1 to 5 days.

Variation between days and within each day

Higher pollution levels are often associated with weather patterns which give light winds resulting in poor pollutant dispersion, so UK emissions linger and increase in concentrations in the air.

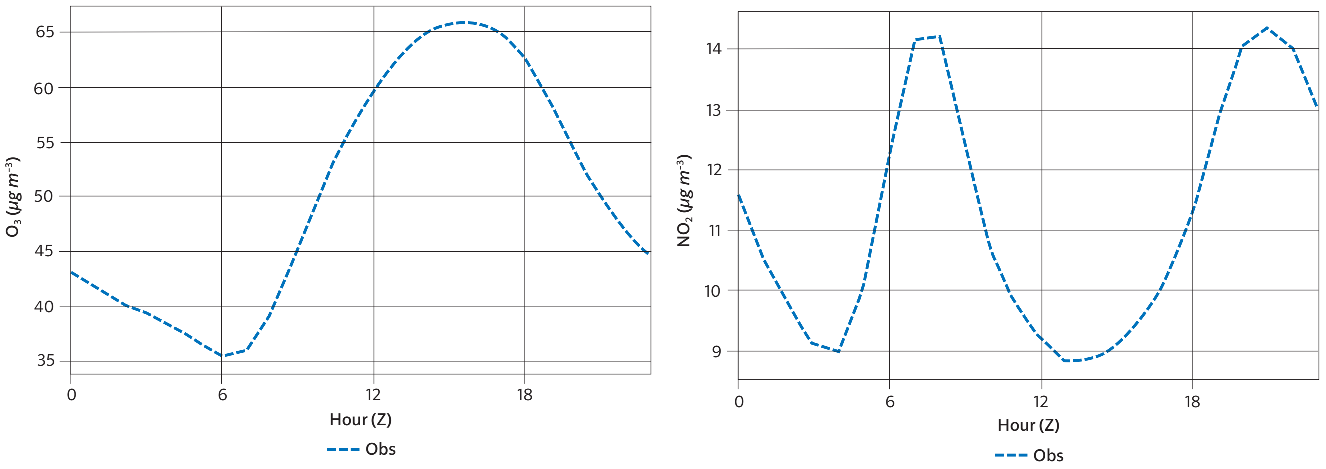
An example of air pollution variation over several days is shown in Figure 4. On the Defra UK-Air website,[1] hourly averaged, measured concentrations of pollutants from AURN sites are available in multiple formats, including the main map showing the DAQI at each site and time-series graphs which show how the levels of pollutants have varied over recent days and hours.



Source: Defra UK-Air[10]

Figure 4: Example hourly pollutant time series at Norwich

Within a day, 2 of the air quality pollutants, O_3 and NO_2, exhibit consistent time variations – see for example Figure 5.



Note: Three-month averaged (July to September 2021) time variation by hour of day for ozone (left) and nitrogen dioxide (right) measured at AURN urban background sites.

Source: Internal Met Office data

Figure 5: Time variations for air quality pollutants O_3 and NO_2

O_3 levels peak in the afternoon or early evening (depending on the time of year) in a process driven by the presence of sunlight. NO_2 levels in urban locations typically peak twice each day, following the pattern of the morning and evening rush hours. For $PM_{2.5}$ and PM_{10} the time variation is not consistent from day to day.

Forecasting

In general, air quality forecasting is carried out via numerical models which account for pollutant emissions, dispersion and the formation and loss processes in the atmosphere, enabling the prediction of pollution concentrations in the air for the coming hours and days. Knowledge of pollutant emissions plays an important role in the forecast model, and the UK's National Atmospheric Emission Inventory (NAEI)[11] provides detailed, annual average emissions at 1km resolution across the UK.

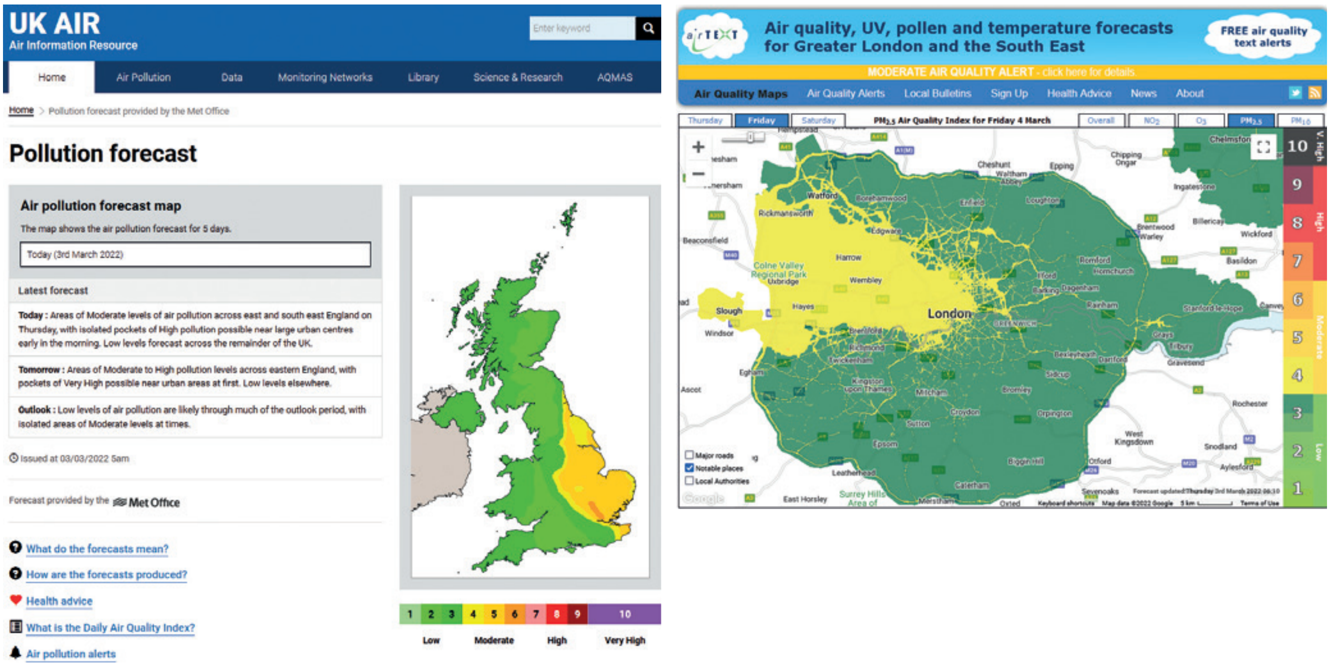
The air pollution forecast is presented on the Defra UK-Air website,[12] and from there it is disseminated onwards by email, freephone and web map services to the public, media and other organisations. For specific locations this information is also accessible through the Met Office website and app. As with all forecasts, air quality predictions are subject to uncertainties and errors, mainly associated with uncertainties in pollutant emissions, atmospheric formation and loss processes, and weather conditions.

The forecast model predicts values of the individual pollutant concentrations at each location, and these are combined to produce the DAQI,[1] the national alert system to provide information to the public about the current and forecast outdoor air pollution levels in local areas. The DAQI is a measure from 1 to 10 where 1 indicates the lowest pollution values and 10 the highest. The DAQI is divided into 4 bands: 'Low' (1–3), 'Moderate' (4–6), 'High' (7–9) and 'Very High' (10).

On the national scale, the Met Office provides a DAQI forecast[5,13] up to 5 days ahead (see the left panel of Figure 6). How the DAQI communicates air pollution information and the associated health advice to the public is discussed in Section 5.3. Of note, the Air Quality Information System

(AQIS), including the DAQI, is currently under review. This review will bring together work on air quality alerts, advice and guidance, and will recommend how to improve the current system for individuals, healthcare professionals, government bodies and others.[14]

More locally, an example is the airTEXT service,[15] which provides a forecast up to 3 days ahead, with finer-scale predictions along major roads within Greater London.



The map shows the air pollution forecast for 5 days.

Today : Areas of Moderate levels of air pollution across east and south east England on Thursday, with isolated pockets of High pollution possible near large urban centres early in the morning. Low levels forecast across the remainder of the UK.

Tomorrow : Areas of Moderate to High pollution levels across eastern England, with pockets of Very High possible near urban areas at first. Low levels elsewhere.

Outlook : Low levels of air pollution are likely through much of the outlook period, with isolated areas of Moderate levels at times.

Issued at 03/03/2022 5am

Source: Left: National air quality forecast on the Defra UK-Air website.[21] Right: AirTEXT forecast for London and the South-East of England from airTEXT website[15]

Figure 6: Examples of air quality forecasts

Forecast models can provide hourly variations for all pollutants. Such data exists from measurements and models, but the DAQI does not provide this information at present. Developing new ways of providing hourly air pollution information to the public and other interested parties has the potential to assist individuals, business and public bodies, in planning decisions and other air pollution interventions.

Air pollution notification and warning

The main purpose of air quality monitoring and forecasts is to provide the public, and in particular people vulnerable to respiratory and cardiovascular health problems, with notification and advance warning of poor air quality conditions. Monitoring is also used for air pollution research, which is discussed later in this section.

Notifications and alerts are issued via the Defra UK-Air website.[12] Statutory requirements specify the conditions under which the public must be informed or alerted as follows:

- measured O_3 levels exceed 180µg/m^3 for one hour: public to be informed
- measured or forecast O_3 levels exceed 240µg/m^3 for 3 consecutive hours: public to be alerted

- measured SO_2 levels exceed 500µg/m^3 for 3 consecutive hours over 100km^2 area: public to be alerted
- measured NO_2 levels exceed 400µg/m^3 for 3 consecutive hours over 100 km^2 area: public to be alerted

Other local alerting services and public announcements are also now increasingly becoming available, and it is important that these complement each other.

Alerts about high levels of air pollution are accompanied by advice about how individuals can reduce their risk of harm, and this advice is discussed in Section 5.3. A more proactive approach to notifying and warning the public and organisations about air quality, supported by appropriate information and advice, could increase awareness and action to reduce polluting activities as well as mitigating exposure and reducing health impacts.

One ongoing review, being carried out on behalf of the UK Public Weather Service,[16] is looking at public use of Met Office air quality forecasts. Initial results highlight that people are generally interested in, but are passive recipients of, air quality information. Users tend to assume that warnings will be actively disseminated through media channels when important. In addition, while users are interested in air quality forecasts, there is minimal understanding of what warnings mean for them and what actions can be taken. Enhanced warnings along with clear explanatory information on relevance and actions, as done for other hazards such as the Met Office Severe Weather Warnings service,[17] could have impact. This work will help to inform the wider review of the AQIS discussed earlier in the section.

Other considerations

Indoor air quality

Air quality modelling science has generally focussed on the outdoors. However, most people spend most of their time in indoors, including at places of work and study, on transport and in homes. As discussed in Section 4.8, outdoor pollution does seep indoors with the normal flow of air exchange. However, there are additional sources of pollution in indoor environments which can exceed the levels of pollution found outdoors. Linking outdoor and indoor monitoring and modelling will be required to develop a holistic vision of the effects of poor air quality. Although research in this area is increasing, further studies need to be undertaken and practical developments are required.

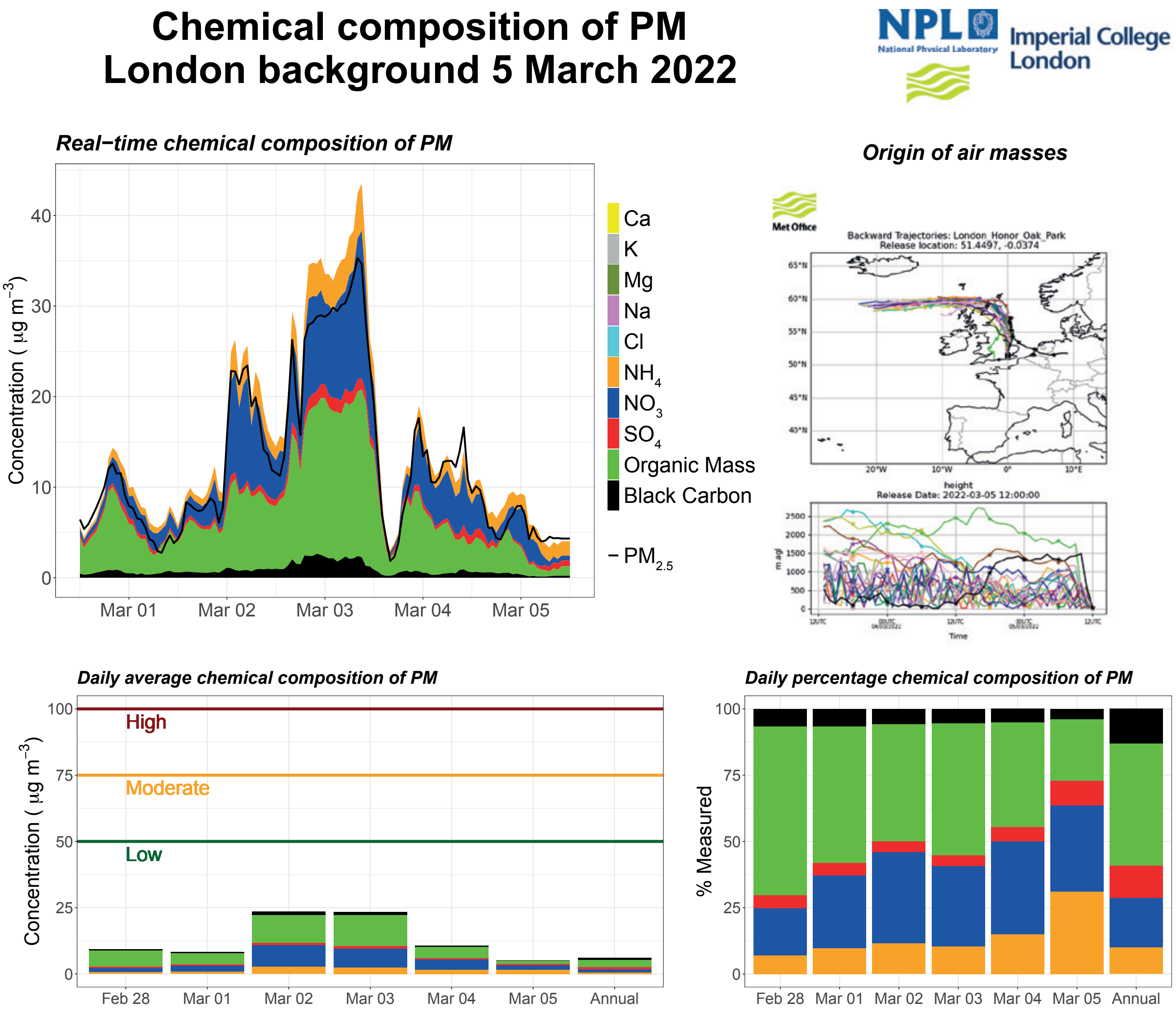
Compound environmental impacts

Treating environmental effects on health holistically could capture different challenges and streamline the response and messaging. The influence that environmental factors such as temperature, UV, pollen and air quality have on health have, to this point, largely been considered in isolation. However, there is potential to link many of these hazards, and the management of the health effects. For example, the compounding impacts of air pollution and pollen are reasonably well established.[18] Although further work to quantify the joint impacts remains to be done, in the future this could form the basis of an integrated alert service for the management of asthma and hay fever. Similarly, the coincident effects of poor air quality during summer heat waves[19,20] and winter cold spells are also well documented, and consideration could be given to air quality levels when giving alerts for forecast temperature extremes.

Air pollution research monitoring networks

Research networks that measure air pollution also exist, such as the Urban Observatories at Newcastle and Manchester.[4] These provide a high density of sensors in the urban environment and can be useful for detailed mapping of pollution across particular cities. They may also include a more extensive suite of measurements which go beyond the species contributing to the DAQI, such as measuring PM_1 and solar radiation. These more extensive data can be used to further develop understanding of the science underpinning atmospheric pollution.

The chemical composition of particle air pollution $PM_{2.5}$ and PM_{10} is often complex, including many different chemical components. To better characterise and understand PM pollution in the UK, measurements of its detailed chemical composition are needed. An example of what is possible is provided by the 'PM Dashboard' produced by Imperial College, as shown in Figure 7.



Note: Shows the breakdown of chemical composition of particulate matter at the Honor Oak Park measurement site in London.

Source: David Green, Imperial College London

Figure 7: Imperial College 'PM Dashboard'

In addition to this speciated measurement site in London, there are also similar sites in Birmingham and Manchester. They are known as 'supersites' and are funded by the Natural Environment Research Council (NERC).[21] More speciated PM sites are being introduced and expansion is being looked at to support the tracking of concentration changes as the new $PM_{2.5}$ target is introduced. Further improvements to spatial coverage and diversity of local environments would aid in the characterisation, quantification and identification of the sources of PM pollution. This would also help to improve modelling and the characterisation of which particulates are most harmful to health, and would in turn enhance the targeting of interventions.

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5.3 Patient and public information about air pollution

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Introduction

People's exposure to poor air quality varies because air pollution concentrations vary between places, times of the day, throughout the year, and with changes in the weather and human activities. Information about variations in outdoor air pollution is underpinned by monitoring and forecasting, as discussed in Section 5.2. Some people are at greater risk of short- or long-term harm from air pollution compared with others, and these inequalities are discussed in Section 1.2.

To reduce the health harms of air pollution, the primary aim is to reduce emissions, which is a societal responsibility. National and local work to further reduce air pollution emissions, and therefore people's exposure, is important and the evidence for interventions in different sectors is discussed in Sections 4.1–4.9. Alongside this work, individuals may also be able to act to further reduce their risk of harm. Therefore, the public should be provided with information about variations in the quality of the air they breathe, the effect of pollutants on health, likely pollution sources, and actions to reduce their own emissions and exposure to air pollution.

This information and advice may lead to changes in individual behaviour when possible, therefore reducing air pollution emissions and mitigating the health risks. Many of the suggestions to reduce an individual's exposure to air pollution are simple and they may appear obvious. Actions to reduce exposure to air pollution can be additive and the suggestions may be of particular interest to those who are most at risk of harm from air pollution. However, it is important to note that people who are exposed to the highest concentrations of air pollution, and those most vulnerable to health harms, may be less able to reduce their individual exposure – for example, by moving away from a highly polluted area, reducing their occupational exposure or changing the air quality within their home. Therefore, air pollution information and advice is part of wider work to reduce and remove emissions from different sources and sectors.

Advice for individuals to reduce their risk of harm from air pollution must be proportionate and balanced with the health benefits of other actions. For example, the health benefits of physical activity are clear, and physical activity outside should not be discouraged unnecessarily.

The effectiveness of communicating air quality information to the public and patients therefore depends on whether individuals receive information that is applicable, reliable, and understandable, as well as the feasibility of relevant actions. Information can be provided to the whole population, to those most at risk of health harms, and to healthcare workers who can then advise individual patients about actions that are specific to them. Information and advice can be offered through public messaging or to those who actively search for information, for example, through websites or apps.

Advice that healthcare professionals can give to patients

For patients who are most susceptible to harm from air pollution, the most important action that can be taken is to optimise the medical management of their health condition, to enable them to lead a life as unrestricted as possible.

In addition, it is important that healthcare professionals have sufficient knowledge to provide evidence-based advice to patients about exposure to air pollution. This may require training about air pollution and the health risks, and actions that can reduce exposure and harm.

Training for healthcare professionals

Professionals can be equipped with toolkits to screen and identify at-risk populations, influence behavioural change, and help prevent and/or control associated disease. For example, the National Capabilities Framework includes nationally agreed standards required of professionals who care for children and young people with asthma. The standards include knowledge of air pollution and there is associated training.[1] Also, the charity Global Action Plan, funded by the Department for Environment, Food & Rural Affairs (Defra) and the Clean Air Fund, provides resources for healthcare worker training and information about air pollution.[2]

Understanding air pollution exposures and offering advice

General practitioners and allied healthcare professionals in the community are well placed to advise patients who are vulnerable to harm from air pollution, in addition to healthcare professionals in other specialties, such as paediatrics, cardiology, respiratory medicine and nursing. However, understanding patients’ exposures to air pollution can be difficult since the sources and types of pollution vary between communities and households.

Alongside questions about diet, physical activity, smoking and alcohol, healthcare professionals could ask vulnerable patients about their air pollution exposure. These questions should focus on the proximity of the patient’s household and workplace to urban or industrial environments, their commuting practices, occupation, and time spent near heavy traffic. Additional enquiries should focus on outdoor physical exertion (for example, active travel during commutes, manual work, exercising), if patients have noticed air pollution events that trigger symptoms, and open-ended questions about air pollution in the local community to identify any other sources of risk.

An understanding of outdoor air pollution exposure also requires healthcare professionals to be equipped with local air pollution data supplied by a reliable source. Some examples of sources of air pollution information are listed at the end of this section. This could enable healthcare professionals to be better placed to design and discuss individual and/or family tailored strategies.

To find out about indoor air pollution at home, healthcare professionals could ask about the type of fuel used for cooking and heating, how the home is ventilated, and what sort of cleaning, personal care and do-it-yourself (DIY) building and repairs products are routinely used. This may provide useful information to help gauge the extent of exposure to sources of indoor air pollution, and enable healthcare professionals to advise on changes to behaviours or products, where possible, that could improve indoor air quality.

Recommendations to reduce exposure should:

- Emphasise the importance of avoiding the pollutant source as this is the most effective intervention to reduce individual risk of harm.
- Guard against negative behavioural patterns, such as individuals avoiding outdoor exercise unnecessarily.
- Be tailored to an individual's susceptibility to harm and the availability of alternative options to reduce exposures.
- Take into account equity and ethical considerations.
- Avoid advocating the use of unvalidated, inaccurate personal pollution-monitoring devices and any interventions designed to reduce air pollution exposure and the risk of adverse health outcomes that are scientifically unproven.

Other healthcare sector roles

The health impacts of air pollution should be included in clinical practice guidelines for healthcare professionals. Medical societies, other specialist societies and patient organisations can contribute their scientific knowledge and expertise to develop evidence-based guidelines. They also have the networks to distribute guidelines, training and implementation through websites, medical curricula, textbooks, professional training programmes and scientific meetings. It is also important to include input from patients and the public in the design and development of these resources.

Healthcare professionals, medical societies and patient organisations can also raise the topic of air pollution and its related health effects at local, national and international levels.

Through education, guidelines and advocacy, healthcare and public health sectors should ensure that it is society's responsibility to provide a healthy public environment, rather than the responsibility of individuals. However, individuals can play a role in reducing risk by staying informed (as outlined below), requesting information on air quality levels and the associated health effects, and supporting decision-makers to take measures to mitigate problems. Individuals can also contribute by lowering their own emissions whenever possible, especially in private indoor spaces.

The National Health Service (NHS) is also working to reduce its own air pollution emissions from NHS hospitals, vehicles and travel, and this work is described in Section 4.7.1.

Practical interventions to consider for different situations

This section presents advice for how people can reduce their exposure to outdoor and indoor air pollution in different circumstances. Some of these suggestions are common sense, and some apply only to certain population groups, especially those who are vulnerable to harm from episodes of high air pollution, or those concerned about the long-term effects of air pollution exposure. In the absence of specific evidence for intervention, some of the following advice is based on reasonable public health principles.

During high outdoor air pollution days (a high pollution episode)

This advice applies to days when air pollution levels are high, due to changes in the weather and/or human activities.

Individuals

- Be aware of the air quality situation through the Daily Air Quality Index (DAQI).[3] This is the national alert system to provide information to the public about the current and forecast outdoor air pollution levels in local areas (see further information at the end of this chapter).
- Patients who are susceptible to harm from high air pollution days should have optimal medical management to ensure the best possible protection from the adverse health effects of air pollution.
- During high outdoor air pollution days, individuals who are sensitive to air pollution (such as the elderly and/or those with lung or heart problems) should potentially limit their exposure by reducing their time outdoors or by adjusting the timing and location of outdoor physical activity.

Shifting outdoor physical exertion away from times and locations where air pollutant concentrations are highest would reduce the inhaled dose of air pollution.[4] This is because the inhaled dose of air pollutants is determined by the pulmonary ventilation rate as well as the air pollutant concentration. However, the risks of reducing the benefits of outdoor physical activity should be considered. For example, in healthy adult populations, the long-term beneficial effects of regular physical activity in reducing mortality outweigh the adverse effects of air pollution[5] when background concentrations of fine particulate matter ($PM_{2.5}$) are < 100 µg/m^3. Concentrations above this level are rare in the UK – for example, during the most recent pollution episode in March 2022, $PM_{2.5}$ concentrations were < 50 µg/m^3.

Local authorities or city administrations

Local authorities and city administrations have roles to play in reducing air pollution emissions through coordinated actions – for example, to reduce emissions from local transport, domestic solid fuel burning, industry and agriculture. Current work to reduce air pollution in Birmingham, Bradford and London is described in Sections 6.1–6.3. During an episode of high air pollution in populated urban areas, strategic action by local authorities – for example, closing or diverting roads to reduce the volume of traffic – requires accurate and accessible air pollution monitoring programmes. There is also an opportunity to research the effectiveness of these and other responses to protect harm from exposure to air pollution episodes.

General advice for people who commute regularly

For many people in urban areas, exposure during the daily commute, despite its relatively short duration, is responsible for a disproportionately large fraction of total exposure to outdoor air pollution.

In transportation micro-environments, such as cabins of passenger vehicles, buses, trains and airplanes, people are often in close proximity to sources of air pollutants such as vehicle tailpipe emissions, products of vehicle and road wear, and resuspended particles. Exposure in vehicles is often the highest, but this will depend on the vehicle type and age and how vehicles are ventilated (filtration and open or closed vents or windows). While the health impacts of short-term, higher-concentration exposures to air pollutants, which often occur in transportation environments, are poorly understood,[6] people who spend a lot of time driving are probably vulnerable to greater health impacts.

Measures that could be taken by regular commuters, to reduce air pollution exposure include:

- When possible and safe, walk or cycle along less polluted roads, since even one street back from a busy road will have much lower pollution concentrations.[7] Maps of air pollution by road may be available (see below for an example for London).
- If commuting by car on a congested road, setting the air supply to recirculation and trying to keep windows closed can help to reduce the ingress of outdoor traffic-related air pollution.
- If travelling by public transport, be aware that some journeys will lead to higher exposure to air pollution than others. Air pollution is likely to be higher during rush hour and, for example, on an underground tube line.
- Avoid the rush hour if possible.

There is limited evidence on the efficacy of face masks for air pollution (that is, masks covering the nose and mouth to filter out $PM_{2.5}$ particles but not gaseous pollutants, unless equipped with an adsorbent) to protect public health in real-world situations within healthy or susceptible individuals. A recent review of air pollution evidence concluded that it has not been possible to measure potential exposure reduction from face mask use. Also, improvements in cardiovascular health indicators were inconsistent and data was insufficient to determine respiratory benefits.[8] Therefore, there is a need for more carefully designed and high-quality studies in healthy and at-risk populations to determine the effectiveness and tolerability of face masks for use to protect against harms of air pollution.

For people who work outdoors regularly

Outdoor workers, particularly those working with or around diesel-powered equipment or vehicles, are likely to have higher exposure to outdoor air pollution than indoor office workers. Emissions from diesel vehicles such as forklifts, lorries, buses, trains and tractors, particularly in enclosed spaces such as garages or workshops, can cause health problems. Inhaling high quantities of diesel exhaust fumes can cause irritation in the respiratory tract within a few minutes of exposure, but prolonged exposure over many years is likely to be more harmful.[9] People working with fixed power sources such as compressors, generators or power plants, and in sectors such as tunnelling, mining or construction could also be at risk.

An example of a past initiative to help outdoor workers reduce exposure to air pollution is the Canairy App, developed by the British Safety Council and the Environmental Research Group (now at Imperial College London).[10] Drawing on LondonAir's Nowcast map of current air pollution, the Canairy app calculated a worker's hourly exposure to nitrogen dioxide, ozone and particulate matter ($PM_{2.5}$ and PM_{10}), and compared this to World Health Organization (WHO) guidance. It provided workers with information to help them avoid the highest levels of pollution during their work and gave employers insights to inform health risk assessments and work scheduling to reduce their exposure to harmful air pollutants.

Indoor air pollution

Although concentrations of ambient air pollutants are generally lower indoors than outdoors, the ratio of indoor to outdoor air pollutant concentrations varies widely, depending on the type of pollutant, the location, design, and state of repair of the building, the climate, season and occupant behaviour, such as window and door opening habits. People may receive most of their total exposure to ambient particulate air pollution while indoors.[11] Indoor air pollution in public and private spaces is discussed further in Section 4.8.

Reducing exposure to air pollution while indoors

The following suggestions are mainly for private indoor spaces, and most are common sense. People who are especially vulnerable to harm from air pollution, and their carers, may wish to consider these suggestions. Some actions can be taken by the building occupier, others are under the remit of the homeowner or landlord, and others apply to building planning, design and construction. For owners and operators of private buildings, there is a need to consider actions to promote good indoor air quality for vulnerable people who may be using the spaces.

- Be aware that the burning of solid fuel at home can cause significant indoor air pollution.
- Minimise the lighting of scented candles and incense that increase indoor pollution.
- When decorating the home and embarking on DIY projects, use products that are low in volatile organic compounds, keep windows open and store products that contain chemicals (such as paints, solvents and glues) safely according to manufacturer instructions.
- Increase ventilation if you are using spray cleaners, paints or other products during use and for a period of at least 30 minutes after to ensure removal from the space.
- Cooking, especially with gas, is a major source of indoor pollution so use an extractor fan if available, and/or open a window while cooking. Try to avoid burning food and if possible, use splatter guards to cut down emissions when frying. When replacing appliances, try to choose electric rather than gas.
- For home cleaning and personal care products, it is possible to use less polluting versions, such as unscented solid or liquid products, rather than those that are dispensed as aerosol sprays.

- Keep the indoor environment clean through regular dusting and vacuuming, and wash bedding regularly.
- Try to ensure good ventilation to reduce exposure to indoor pollution and effective building insulation and/or heating to reduce the risk of damp and mould.
- If possible, install extractor fans and ventilation systems, check that they are working properly, and maintain filters.
- Maintain windows that open and ensure that they are accessible.
- Open trickle vents on windows so there is a constant background air supply.
- Close windows for short periods when there is high outdoor air pollution.
- Look at whether spaces can be rearranged to move vulnerable people further from pollution sources, for example, by sleeping in rooms further away from a main road.

Equity considerations

For people with the highest risk of harm from air pollution, interventions to reduce or remove pollution at source to reduce exposure is particularly important. In most settings, low-income communities are more likely to experience higher exposures to ambient pollutants.[12] These communities have the largest potential need to adopt protective actions to reduce their exposure levels and health impacts from air pollution. However, they may also be the least able to take advantage of interventions because of lack of options and financial resources. It may be more difficult for people to reduce their exposure to air pollution if they have limited influence over the location of their home, residential building quality, the type of cooking and heating fuel, natural ventilation versus air conditioning, buying filtration equipment, and flexibility in mode of transport.

Personal interventions to reduce exposure to air pollution, such as avoiding places with poor air quality, reducing physical activity outdoors on high pollution days, or using indoor air purifiers raise issues of equity. This is because the need for appropriate measures, and access to them, might be unequally distributed across communities. These equity considerations are important in determining people's exposures to air pollutants and their vulnerability to adverse health effects. They also play a role in shaping possible actions, especially for those most at risk of being affected by air pollution.

Caution about unintended consequences

When recommending actions to reduce individual exposure to air pollution, accessibility for all and wider implications must be considered. For example, the following unintended consequences may negate or even reverse the intended benefits of avoiding outdoor air pollution:

- Reduced physical activity (for example, if children are discouraged from playing outside).
- Increased home energy use, due to reluctance to leave the home.
- Increased exposure to air pollutants from indoor sources (for example, cooking fumes, resuspended dust, cleaning products) due to staying indoors and limiting ventilation.

Raising public awareness of air pollution

Public awareness of air pollution could increase through access to engaging and high-quality information in places that people see regularly, such as digital signs on bus stops, rail stations and shopping areas. Information in primary care and hospital settings could also help to inform patients and their carers of the potential health risks. Air pollution monitors sited at healthcare settings and schools could also help to raise general awareness of air pollution.

In an ideal world, people, especially those at risk, would stay abreast of their local air quality by regularly checking an air quality index. They could do this through traditional or social media, or a smartphone app before going to work, school or pursuing leisure activities. This could prompt them to take action when pollution is increased.[13]

The DAQI has been available since 2011 and provides public information about real-time and forecast levels of outdoor air pollution (as discussed in Section 5.2). The DAQI aims to alert the public to pollution episodes (when concentrations may exacerbate symptoms or pose a risk to health), and it is used for communicating risk of acute harm in general and to those who are most vulnerable. The health advice linked to the DAQI air pollution bands is presented in Figure 1. However, the greatest health benefit is likely to be achieved with daily reductions in exposure to air pollution to mitigate the risk of chronic harm. The DAQI can also be useful in raising awareness of the risks associated with long-term pollution exposure.

In light of the need to provide relevant information to all vulnerable groups, and because of advances in understanding of the health effects of air pollution over the last 10 years, the DAQI (and associated health advice), is currently under review. This is part of a wider review of how air pollution information is communicated to the public.[14]

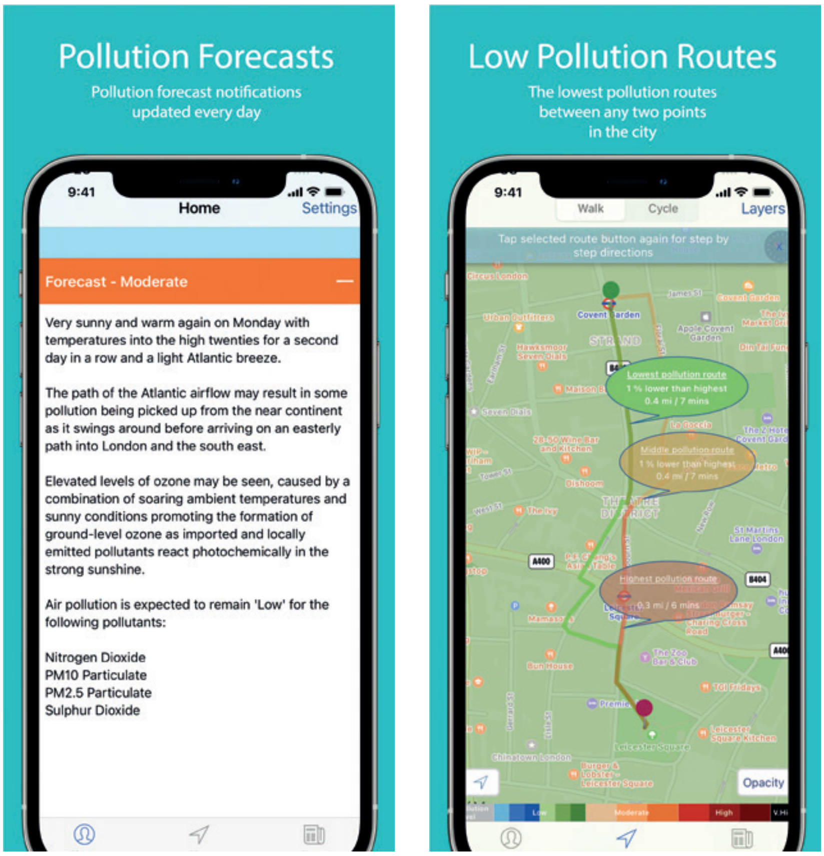
Air pollution banding	Value	Accompanying health messages for at-risk groups and the general population	
		At-risk individuals*	General population
Low	1–3	Enjoy your usual outdoor activities.	Enjoy your usual outdoor activities.
Moderate	4–6	Adults and children with lung problems, and adults with heart problems, who experience symptoms, should consider reducing strenuous physical activity, particularly outdoors.	Enjoy your usual outdoor activities.
High	7–9	Adults and children with lung problems, and adults with heart problems, should reduce strenuous physical exertion, particularly outdoors, and particularly if they experience symptoms. People with asthma may find they need to use their reliever inhaler more often. Older people should also reduce physical exertion.	Anyone experiencing discomfort such as sore eyes, cough or sore throat should consider reducing activity, particularly outdoors.
Very high	10	Adults and children with lung problems, adults with heart problems, and older people, should avoid strenuous physical activity. People with asthma may find they need to use their reliever inhaler more often.	Reduce physical exertion, particularly outdoors, especially if you experience symptoms such as cough or sore throat.

* Adults and children with heart or lung problems are at greater risk of symptoms. Follow your doctor's usual advice about exercising and managing your condition. It is possible that very sensitive individuals may experience health effects even on low air pollution days. Anyone experiencing symptoms should follow the guidance provided.

Source: Defra, UK AIR. Daily Air Quality Index[3]

Figure 1. Public health advice and the UK Daily Air Quality Index (DAQI)

Alert services accessed via apps are becoming increasingly informative and engaging by providing real-time data. These apps also proactively warn registered users of impending pollution events, and a London example is shown in Figure 2.[15,16] These services also offer tailored advice about how specific groups can reduce exposure – for example, by providing low-pollution journey planners.



Pollution Forecasts

Pollution forecast notifications updated every day

Forecast - Moderate

Very sunny and warm again on Monday with temperatures into the high twenties for a second day in a row and a light Atlantic breeze.

The path of the Atlantic airflow may result in some pollution being picked up from the near continent as it swings around before arriving on an easterly path into London and the south east.

Elevated levels of ozone may be seen, caused by a combination of soaring ambient temperatures and sunny conditions promoting the formation of ground-level ozone as imported and locally emitted pollutants react photochemically in the strong sunshine.

Air pollution is expected to remain 'Low' for the following pollutants:

Nitrogen Dioxide
PM10 Particulate
PM2.5 Particulate
Sulphur Dioxide

Low Pollution Routes

The lowest pollution routes between any two points in the city

Tap selected route button again for step by step directions

Source: Environmental Research Group, Imperial College London

Figure 2. CityAir smartphone air pollution information app

Examples of air pollution information resources

UK Air Information Resource (Air) – Pollution forecast/Air pollution map – https://uk-air.defra.gov.uk/forecasting/

UK Air Information Resource (Air) – Latest measurement summary – http://uk-air.defra.gov.uk/latest/

CityAir app – City of London – https://www.cityoflondon.gov.uk/services/environmental-health/air-quality/cityair-app

London Air – Air pollution/Air quality by local authority – https://www.londonair.org.uk/LondonAir/Default.aspx

Examples of air pollution and health resources

Asthma + Lung UK – Air pollution – https://www.blf.org.uk/support-for-you/air-pollution

British Heart Foundation – Air pollution – https://www.bhf.org.uk/informationsupport/risk-factors/air-pollution

Public Health England – Health matters: air pollution – https://www.gov.uk/government/publications/health-matters-air-pollution/health-matters-air-pollution

Committee on the Medical Effects of Air Pollutants – https://www.gov.uk/government/groups/committee-on-the-medical-effects-of-air-pollutants-comeap#publications

Global Action Plan: Our lives. Our planet – https://www.globalactionplan.org.uk

World Health Organization – Air pollution data portal – https://www.who.int/data/gho/data/themes/air-pollution

United States Environmental Protection Agency – Learn about the Particle Pollution and Your Patients' Health Course – https://www.epa.gov/pmcourse/learn-about-particle-pollution-and-your-patients-health-course#overview

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6 City examples – work to reduce air pollution

6.1 Birmingham

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Introduction

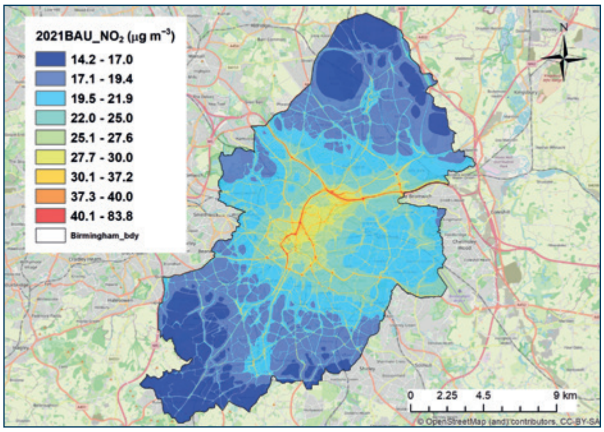
Birmingham is the second largest city in the UK and has an estimated population of 1,144,900, which is expected to rise by 8% (to approximately 1,251,689) by 2043.[1] It is the youngest city in Europe, with 40% of adults aged under 25 years and a median age of 32.7 years. It is also the most culturally and ethnically diverse city in the UK outside of London.[2] In addition, Birmingham boasts a total of 631 parks and green spaces and more than 35 miles of waterways.

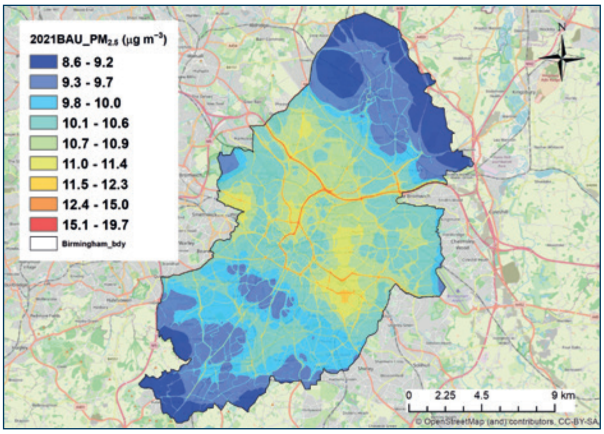
Despite these substantial assets, Birmingham faces significant health and social care challenges. There are 1 in 3 children living in poverty and 1,836 families are being supported by family services. Life expectancy for both males and females in the city (78 and 82 years, respectively) is lower than the national average.[3] There is also a considerable gap in life expectancy between the richest and poorest wards of the city, and many health outcomes vary substantially between ethnic groups.

Air pollution is a major health risk in the city, contributing to up to 900 premature deaths (that is, deaths before the age of 75) each year. It affects health at all stages of life, and those who tend to be most affected are the young, the old and the most deprived communities.[4] Children in highly polluted areas of Birmingham are 4 times more likely to have reduced lung function when they become adults.[4]

Given this challenging context, it is a pivotal moment for Birmingham's actions to reduce air pollution. As discussed in Chapter 2, air pollution is emitted from multiple sources, including transport, industry, agriculture and domestic combustion. To address transport emissions, citizens and partners across the city are challenging the antiquated 'car is king' philosophy, a legacy of Birmingham's historical contribution to the motor industry and its car-centric planning and transport design. Significant work is underway to create spaces for people that encourage exploration of the city via sustainable methods.

Figures 1 and 2 display annual air quality maps of mean NO_2 and fine particulate matter ($PM_{2.5}$) levels over Birmingham for 2021 (data in units of micrograms/m^3) as simulated by Zhong et al.[5] as part of the West Midlands Air Quality Improvement (WM-Air) programme.[16] The models assume 'business as usual' traffic activity, not the reductions in activity due to COVID-19 restrictions. It can be noted from Figures 1 and 2 that there are localised concentrations of NO_2 along the major road network, and wider spatial distribution of $PM_{2.5}$ concentrations.





Source: Zhong et al.[5] as part of the West Midlands Air Quality Improvement (WM-Air) programme[16]

Figure 1: Annual air quality map of mean NO_2 over Birmingham for 2021

Figure 2: Annual air quality map of mean $PM_{2.5}$ over Birmingham for 2021

Strategies, plans and monitoring

Birmingham City Council (BCC) published an Air Quality Action Plan (AQAP) covering the period 2021 to 2026 in April 2021 under the Local Air Quality Management regime.[6] Its focus is to reduce road transport through promoting modal shift from single-occupant transport to public transport and alternative means of travel, as well as incentivising the use of alternative fuelled vehicles.

In January 2022, BCC launched its 'Clean Air Strategy – Blue Sky Thinking for a Greener City'.[7] This strategy links into the AQAP and the 'Brum Breathes' programme (BCC's public-facing air quality work programme). The Clean Air Strategy sets out a clear set of actions, priorities and pledges that will enable all citizens to be a part of the journey towards improved air quality. It also outlines the following 5 priorities, which can be used by decision-makers to improve air quality and reduce their carbon footprint:[7]

- **Improving the fleet of vehicles** – Discouraging the most polluting vehicles (private and public) will lead to an overall reduction in air pollution.
- **Improving the flow of traffic** – Smoother and faster journeys that help reduce congestion will help reduce emissions.
- **Reduce the volume of traffic** – Moving from private car use to walking, cycling, public transport or working from home can reduce the number of vehicles in use.
- **Reduce sources of and exposure to air pollution** – By reducing the sources of air pollution and our exposure to poor air quality, we decrease the likelihood of poor health in people and damage to the environment.

- **Empowering behaviour change** – To encourage and support individual behaviour change to improve air quality by embedding into our culture (businesses, organisations, local communities, the council) the policies, guidance and capability to be less polluting.

BCC is also improving the natural environment, which can absorb pollutants, encourage active transport and extend the distance between air pollution sources (often traffic) and people. In 2021 BCC launched the 'Our Future City Plan: Central Birmingham 2040', kick-starting the conversation on the future development of Central Birmingham.[8] One of the Plan's themes – 'City of Nature' – recognises that although Birmingham has significant amounts of green space, there are gaps in central areas of the city. This has led to the creation of BCC's 25-year Plan for a City of Nature. BCC is also collaborating with local and international partners to prepare an Urban Forest Master Plan covering the period 2021 to 2051 and is seeking to transition to putting nature at the very heart of the city.[9]

Air pollution emissions in Birmingham

Although road transport is the major source of NO_2 in Birmingham, primary PM emissions have a wider range of emissions sources, including commercial and domestic combustion, industrial emissions and road transport. Secondary PM sources include those derived from nitrogen dioxide (NO_2) (for example from transport and power generation), sulphur dioxide (SO_2) (for example from power generation), volatile organic compounds (VOCs) (for example from industrial, commercial and domestic emissions and from the biosphere) and ammonia (NH_3) (for example from agriculture).[10] In addition, air pollution is transported from sources outside of Birmingham, and these also contribute to the air pollution that affects people's health in the city.

The following sections describe interventions being taken by Birmingham to reduce air pollution emissions from transport. Examples of interventions to reduce industrial air pollution emissions are then presented.

Actions to reduce transport air pollution emissions

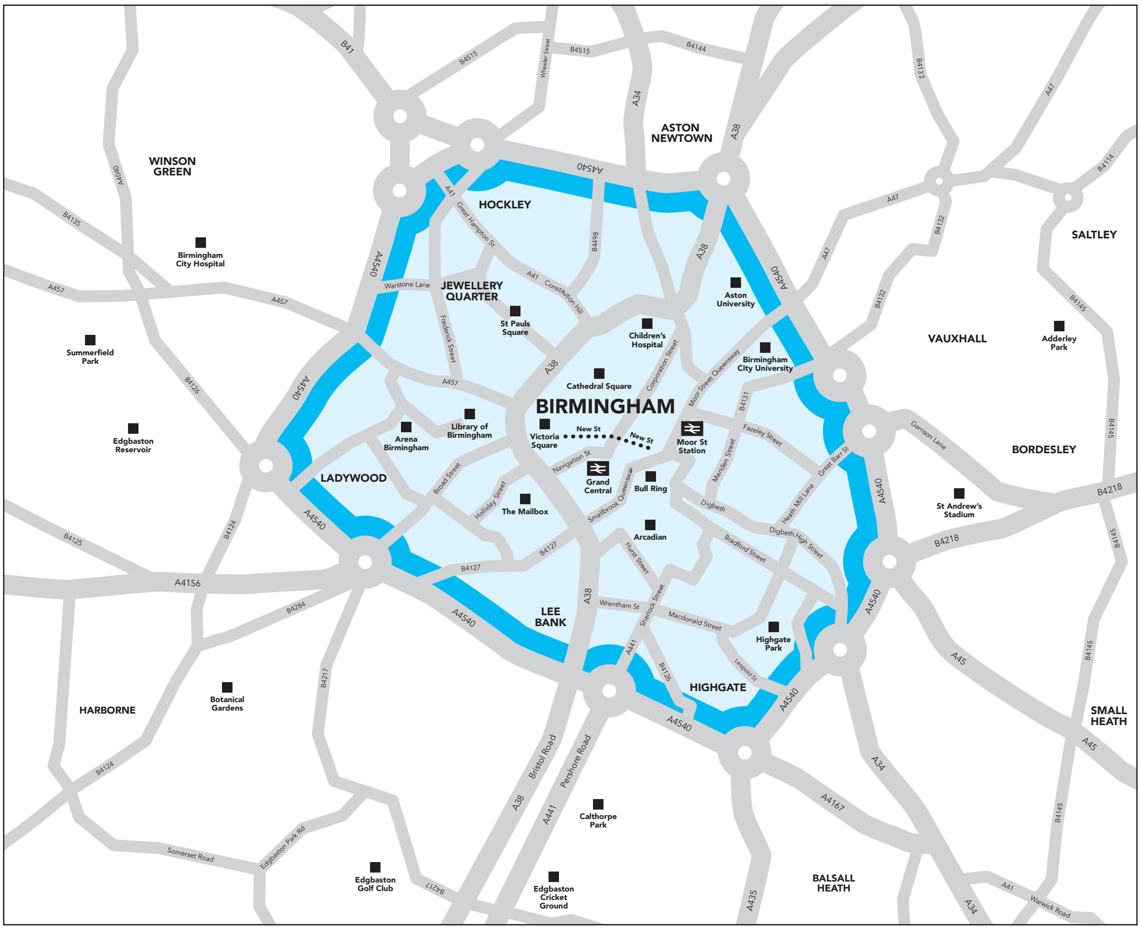
Transport planning

The Clean Air Zone

In recent years, monitoring data has shown that the legal limit for annual average NO_2 has been exceeded at some limited Birmingham city-centre locations. Modelling in 2018 and 2019 showed that a Clean Air Zone (CAZ) with additional measures (known as 'CAZ D') would be an effective intervention to quickly improve air quality in areas of NO_2 exceedance.[11]

A public consultation about the CAZ proposals was conducted between July and August 2018, facilitated by public drop-in events and invitations to key stakeholders, including local businesses and taxi drivers. A total of 10,389 responses were received from individuals and 356 from organisations,[12,13] and these views were responded to and considered as the plans for the CAZ were developed. To help citizens to prepare for the introduction of the CAZ, the planned measures were advertised heavily using media across the city and important information was shared via the BCC and Brum Breathes websites.[11,14]

Birmingham's CAZ became operational on 1 June 2021, and it is the largest single area-based intervention outside London, covering all vehicle types.[13] Figure 3 shows a map of where the CAZ is located in Birmingham.



Source: Brum Breathes

Figure 3: A map outlining (in blue) the location of the CAZ in Birmingham

The monitoring and evaluation programme for the CAZ is mainly focused on real-time NO_2 monitoring. Information can be accessed via the Brum Breathes website.[15]

Researchers in the WM-Air team have also analysed the early data on the NO_2 changes seen over the first 3 months of implementation of the CAZ.[16] This provisional analysis – using data from automatic monitoring stations – applied a machine learning weather normalisation approach to correct for meteorological factors, and an augmented synthetic control methodology to isolate the impact of the CAZ policy. The intention of the CAZ was to reduce NO_2 emissions, and analysis indicates reductions in average NO_2 concentration ranging from 1–6 micrograms/m^3 at sites within the CAZ with no clear evidence of displacement effects, although the monitoring network is limited. Analysis found no significant impact attributable to the CAZ on local $PM_{2.5}$ concentrations within the CAZ.

Electric vehicles and sustainable taxis

In addition to the CAZ, interventions on specific vehicle types are expected to reduce vehicle air pollution emissions, and they include the uptake of electric vehicles in the city and a low-emission taxi fleet.

As part of the BCC's 12-year Electric Vehicle Strategy, 3,000 electric vehicle charge points will be rolled out at strategic locations across Birmingham.[17] Charge points will be placed along major routes for in-trip charging, at destinations and in residential areas. For the 30% of households that do not have off-street parking, technology will be introduced, such as charge points embedded in kerbstones and lampposts.

To reduce air pollution emissions from the Birmingham taxi fleet, in April 2019 BCC announced that 39% of its Clean Air Fund support from central government would be earmarked for taxi drivers.[18] The hackney carriage support package includes funding towards the running costs of ultra-low-emission vehicles (ULEVs) or an approved clean vehicle retrofit. A leasing scheme enables drivers to try a council-owned ULEV vehicle before buying their own. The private hire upgrade package includes funding towards the purchase or lease price of a ULEV, the running costs of a ULEV or the purchase or lease of a CAZ-compliant vehicle (petrol or diesel).

Active travel infrastructure

This section describes interventions that have been designed to support people's ability to travel by walking, wheeling or cycling, rather than using motorised vehicles.

'Places for People' project

Following receipt of funding from central government via the COVID-19 Emergency Active Travel Fund, in 2020 BCC launched the 'Places for People' (PFP) project.[19] This project aims to reduce air pollution by reducing the amount of traffic in residential neighbourhoods, as well as creating outdoor environments that are safer for people to walk, cycle, play and socialise in.

In phase 1 of the programme, BCC delivered 2 PFP pilots in Kings Heath and Lozells, alongside early demonstration projects to address traffic problems on select streets in Bournville, Castle Vale and Moseley. These were introduced as trial measures, but BCC now has funding to develop the schemes and make them permanent. Figure 4 displays a modal filter preventing motorised vehicles from driving through a section of road but still allowing pedestrians and cyclists to pass through.

Source: Birmingham City Council

Figure 4: Image of a modal filter in Moseley, Birmingham

The first phase of the scheme in Kings Heath and Moseley was reviewed through public consultation and through reviewing research from other organisations (including the Department for Transport's Residents' Survey and Transport for All's 'Pave the Way' report).[20] In general, there was agreement that action needed to be taken to reduce pollution, but there were challenges in reaching a consensus on how this should be done. Revisions were made to the scheme that aim to mitigate key concerns and BCC will continue to work together with the local community and project board to shape the project.

The PFP project is being evaluated using air pollution monitoring diffusion tubes at priority sites. Once available, the average annual mean will be published using an online live tool, and there are plans to implement more sophisticated air quality monitoring tools in Bournville in 2022.[21]

Walking and cycling routes

The canal towpaths in Birmingham are being developed to improve access to and from Birmingham's waterways for thousands of cyclists, walkers and wheelchair users.[22] Work started in March 2014 and since then over 50km of towpath has been upgraded with an all-weather surface, along with access improvements such as wheeling ramps, lighting and wayfinding upgrades and widened sections of canal within the city centre.[23]

Green and off-road routes are being developed for pedestrians and cyclists. These are pathways that provide recreational and transportation linkages and serve to connect pedestrians and cyclists to nature. By January 2020, Birmingham had constructed about 24km of new and upgraded green routes.[24]

To support cycling in the city, segregated cycle tracks have been built on 2 main road corridors: the A34 and A38. Both routes are over 3km long and were opened in June 2019 to provide high-quality, two-way segregated cycle tracks with priority crossings at side roads and signalised crossings for pedestrians and cyclists at major junctions.[24] Further work is underway to join the existing A38 segregated cycle track to the National Cycle Network.

In 2020, during the COVID-19 pandemic, temporary cycle routes were created to help people continue to cycle as the lockdown eased.[25] Supported by the COVID-19 Active Travel Fund of the Department for Transport (DfT), many routes involved light segregation from other traffic. This is where the cycle lane is on the road, but motorised vehicles are prevented from entering the lane by physical barriers, such as plastic bollards bolted into the road surface, as shown in Figure 5. Following a review in April 2021, 3 city-centre routes are being taken forward for permanent development.

Source: Birmingham City Council

Figure 5: Image of a pop-up cycle lane in Birmingham

Modal shift to active and sustainable travel

This section describes interventions that have been designed to support a modal shift to active travel and to protect children and young people from air pollution.

Transport for West Midlands cycle and e-scooter hire

In summer 2021, bikes available for hire and docking stations were launched across the West Midlands to encourage people to cycle and explore new places.[26] Electric bicycles were added to the scheme in December 2021.

During its launch month (May to June 2021), almost 500 cycle rides were taken each day in Birmingham, and as of April 2022,[27] the scheme has recorded over 200,000 journeys and 64,000 individual user sign-ups.[28] The Commonwealth Games in summer 2022 presented an opportunity to further increase awareness and usage of these bikes. Evaluation is currently underway, including a survey to gather insights on users and behaviour changes since the scheme launched.

In addition to bicycles, Transport for West Midlands has also begun trialling rental e-scooters within 3 zones, including Birmingham city centre.[29] The trial is being operated by Voi. Riders must be at least 18 years old and have a provisional or full UK driving licence.

Since the launch in Birmingham in September 2020, riders have covered over 1.2 million miles and many have reported making modal shifts, such as leaving the car at home and using a scooter to get to a public transport station.[30] The success of the scheme is expected to continue, facilitated by BCC's plans to divert car traffic from the city and provide more car-free lanes and protected areas for bikes and e-scooters.

Big Birmingham Bikes

The Big Birmingham Bikes (BBB) scheme works at the grassroots level and engages with communities living in areas of higher deprivation. The scheme includes offering free bikes to individuals and it has distributed over 7,000 to date. This has been delivered by The Active Wellbeing Society, in collaboration with numerous community groups. The latest giveaway of 500 bicycles was launched in February 2022 and funded by the DfT's Active Travel Fund via Transport for West Midlands.[31]

The scheme has also made bikes available for short-term loan at several wellbeing centres across the city, and it is supporting volunteers from these local areas to become cycle trainers, bicycle mechanics and ride leaders. The scheme teaches those with little or no cycling experience how to ride confidently around the city, and the free cycle training has given people confidence to cycle safely with their peers.[32] BCC identified that traffic speed was a major barrier to participation, so 20mph zones have been installed across residential and central areas.

Monitoring of BBB usage was done initially through GPS trackers on the bikes, and more recently through a smartphone app.[32] The recipients of bikes permit tracking and can view their cycling journeys using an online dashboard. This data also acts as a deterrent against possible thefts and presents an opportunity for BCC to identify cyclists that are regularly using roads and routes and ask them to take part in relevant focus groups and consultations. This method of monitoring has assisted engagement and provided information that can be used to inform future policy and infrastructure planning and implementation.

Note: Image shows Birmingham City Council Travel Demand Manager Peter Edwards with Birmingham resident Ahmed Jalalabadi and The Active Wellbeing Society Interim Head of Cycling Sue Mellor.

Source: Birmingham City Council

Figure 6: Big Birmingham Bike launch 2022

Modeshift STARS

Modeshift STARS is a scheme for the delivery of effective travel plans in education, business and community settings. It improves air quality by reducing the number of vehicles and congestion around these settings.[33,34] It recognises schools, businesses and other organisations that have displayed excellence in supporting active and sustainable travel. BCC's Travel Demand Management Team supports local schools and workplaces to increase levels of active travel through registering with the Modeshift STARS scheme. BCC has 273 schools registered on the scheme, and many achieve national accreditation awards each term. Over 100 workplaces based in Birmingham are also registered, ranging from large public and private sector employers to small and medium employers.

Schools

Car-Free School Streets

A pilot Car-Free School Streets (CFSS) scheme was set up in Birmingham (following a successful pilot in Solihull) with the following aims:[35]

- to cut down on traffic and parking pressures outside schools
- to discourage car journeys to school and encourage walking and cycling
- to make the streets outside schools safer at the start and end of the day
- to improve air quality and create a more pleasant environment for everyone

Six schools were selected for the pilot, which started in September 2019. Selected streets around the schools were designated as pedestrian and cycle zones for agreed times at the start and end of the school day during term time. Vehicles are not permitted to drive in this zone between these times unless they have a permit, with exceptions for certain groups and situations. This scheme was delivered using an Experimental Traffic Regulation Order and prominent signage at the entrances and exits of the restricted streets and the use of cones, banners and marshals further emphasised closures (as demonstrated in Figure 7).[36]

Source: Birmingham City Council

Figure 7: Image of a street involved in the CFSS scheme in Erdington, Birmingham

A questionnaire completed by about 500 school staff, parents and residents 6 months after the start of the pilot[36] found that feedback on the initiative was largely positive. The majority of respondents felt that the street around the school was safer, that it was a more pleasant environment and that it was healthier. Most felt that it should continue and that other schools in Birmingham would benefit from the scheme. The effects of CFSS are being evaluated to identify opportunities to expand and to decide whether it should be made permanent. BCC hopes to resume monitoring of the impact on air pollution shortly.

School air pollution sensors

The BCC Clean Air Strategy includes the pledge to improve air quality monitoring at schools across the city. Seventy schools across Birmingham will have an air pollution sensor installed from March 2022.[7]

This initiative is being run in partnership with the company Airly, whose sensors will monitor outdoor levels of PM and NO_2 in the immediate vicinity of schools.[37] All children, parents, staff, local citizens and officials will have free access to the air pollution data, and schools will be able to integrate it directly into their websites. This project aims to increase understanding of the air quality around schools, and to engage students, teachers and the wider public about how their behaviour can help or hinder pollution levels.

BCC will provide additional information on air quality, its impacts on health and wellbeing, and active travel, via the Brum Breathes website.[38] A co-production approach is being used to ensure that local schools can influence the project’s design and delivery.

Working with industry to minimise air pollution emissions

For many years Birmingham has been on a journey with local businesses to ensure they are sustainable and contributing to a healthy environment for all. The Greater Birmingham Chambers of Commerce has worked closely with BCC to raise awareness of the CAZ and related business support.

BCC's AQAP recognises the continued importance of reducing emissions locally through the proactive and reactive regulation of industry and nuisance emissions.[6] This is delivered through the Environmental Health (EH) service and involves regulation of over 200 industrial processes and responding to complaints from citizens about smoke, dust, fumes and gas emissions. The EH service assists Planning Management by assessing thousands of planning applications to ensure negative effects on air quality are mitigated. Residents are protected from new emissions from developments through reducing emissions at source via design, layout and other measures such as incentivising updates of low-emission vehicles and providing electric vehicle charging points.

Tyseley Energy Park

Tyseley Energy Park (TEP) is an Energy Innovation Zone in Tyseley, Birmingham, that has a mission to encourage clean energy innovation in Birmingham and across the region by developing new technologies and turning them into commercially viable energy systems.[39] Via its development plan, TEP is committed to delivering low and zero carbon power, transport, heat, waste and recycling solutions for a greener, cleaner and healthier Birmingham.[40] The TEP technologies that have implications for air pollution emissions are described below.

Biomass power plant

Birmingham Bio Power Ltd (BBPL) are the owners of a 10.3MW biomass renewable energy power plant (BPP) based on the TEP in Birmingham. The plant entered commercial operation in 2016 and Gravis Capital has been the sole owner of BBPL since 2021.

The BPP uses waste wood as its feedstock to produce electricity, providing a more sustainable option than sending this to landfill, where it would decompose and produce methane.

Flue gas emitted into the atmosphere from the BPP is continuously monitored for pollutants in accordance with the plant's standards and environmental permit. Birmingham's air quality monitoring focuses on PM and nitrogen oxides (NO_x), and the BPP performs well under statutory limits for both. To reduce particulate emissions, the BPP uses filter bags to capture fine ash particles from the flue gas and these are then removed from site. To reduce NO_x, the BPP injects urea into the hot flue gas path. In 2017, independent modelling of the expected dispersion emissions from the BPP's main stack, assessed against environmental quality standards for the protection of human health, reported a negligible effect across all identified sensitive receptors (including primary schools and a train station).

Through the introduction of new private capital, technologies and techniques, BBPL has provided the local community with employment opportunities and a source of sustainable power generation equivalent to the amount required to power 17,000 local homes.[40]

Energy recovery facility

A state-of-the-art energy recovery facility (ERF) was built in Tyseley, Birmingham, by Veolia in 1996, which takes 350,000 tonnes of Birmingham's rubbish each year and converts it into electricity. To ensure that recycling initiatives are not compromised, the facility was designed to treat waste that cannot be reused, recycled or composted and was built with a lower capacity than the total waste generated in the city.[41]

The ERF operates 24 hours a day throughout the year and operates well within the UK standards for emissions to atmosphere. Operators are monitored by the Environment Agency and performance reports for the facility are publicly available.[40] Incinerator bottom ash (IBA) is the non-hazardous material that is produced from the incineration process, which is reprocessed by extracting metals and by crushing and screening to produce a material that is usable as substitute aggregate in applications such as road building. Of the IBA produced from the ERF in TEP, 95% is recycled in this way.[41] Air pollution control residue (or fly ash) is the only hazardous waste produced from the incineration process and makes up about 2% of the outputs.[41] This strongly alkaline waste is transported in sealed powder tankers and used to neutralise acidic wastes to produce a neutral filter-cake material.

The ERF is preferred over the use of landfill due to the opportunity to recover valuable and sustainable power. The ERF generates up to 25MW of energy, which is enough to power 41,000 Birmingham homes.[42]

Refuelling hub and green hydrogen

TEP is home to the UK's first multi-fuel, open access, low and zero carbon fuel refuelling station, offering hydrogen, compressed natural gas, biodiesel and electrical vehicle charging options.[43] To date, the station has benefited from a £10 million investment from both public and private funding, including £1.5 million from the Greater Birmingham and Solihull Local Enterprise Partnership. The facility is part of the Birmingham Transport Plan, supporting the introduction and supply of cleaner fuels to improve air quality and reduce the levels of air pollution across the city.

The green hydrogen development at TEP is owned by ITM Power, a company that designs and manufactures electrolyser systems that generate green hydrogen.[44] In 2021, a hydrogen refuelling station was commissioned, which is the largest of its kind in the UK. It takes power from a dedicated offshore wind turbine and generates zero carbon, fuel cell grade hydrogen. Hydrogen is produced on site using a 3MW ITM power proton exchange membrane electrolyser, which splits water into hydrogen and oxygen. The site comprises a car refueller, 2 bus refuellers and a tube trailer refueller and can generate over a tonne of hydrogen per day, which is enough to fuel up to 40 buses per day.[43]

Hydrogen buses

BCC and National Express West Midlands (NXWM) have worked together to procure 20 zero-emission hydrogen fuel cell double decker buses as part of BCC's Clean Air Hydrogen Bus pilot, as shown in Figure 8. These buses started carrying passengers in December 2021 and are the only hydrogen buses operating in England outside of London.[45]

Hydrogen fuel cell buses are less polluting compared with diesel buses, as they only emit water from their tailpipe and have reduced brake usage due to regenerative braking. With each bus covering about 65,000 miles per annum, they will save 631kg NO_x emissions per year compared with the equivalent diesel buses. The buses are refuelled at TEP's hydrogen refuelling station, can be fully refuelled in 7 to 10 minutes, and can run for 300km on a single tank. Drivers are specially trained to drive the buses, as these behave differently to combustion-engine-driven buses, and are taught how to preserve the fuel cell charge for as long as possible.

The pilot has been a catalyst for the city to secure further government funding for another 124 hydrogen buses. Monitoring and evaluation for this pilot is at an early stage and all partners involved have pledged to share performance data and knowledge with any interested parties. NXWM is also training engineers and apprentices to maintain hydrogen buses, and this knowledge will be transferable to any hydrogen vehicle.

Source: National Express West Midlands 2021

Figure 8: Hydrogen fuel cell bus in Centenary Square, Birmingham

Working with academic partners

The West Midlands Air Quality Improvement Programme – WM-Air

WM-Air is a programme funded by the Natural Environment Research Council and led by the University of Birmingham.[46] WM-Air seeks to apply environmental science expertise to support the improvement of air quality and associated health, environmental and economic benefits across Birmingham and the West Midlands. It comprises 21 diverse project partners including BCC and facilitates a multidisciplinary and cross-cutting approach to improving health and wellbeing.

To date, WM-Air has provided Birmingham with expert support, evidence and tools to enhance air quality monitoring and to understand related effects across the city. This has included insights into real-world on-road vehicle emissions, health impact assessment and support for engagement with local schools. WM-Air has produced evidence and reports on the CAZ, the effects of COVID-19, World Health Organization Air Quality Guidelines, areas of exceedance, low-traffic neighbourhoods and the Commonwealth Games. The tools that have been produced include a design charter for air quality, a working tool for assessing the benefit of green infrastructure and a working tool for assessing the effects on health of policy decisions around air quality at a ward level.

Opportunities for air pollution interventions

Indoor air quality

Indoor air quality is a growing area of study, and researchers at the University of Birmingham are currently undertaking a scoping review on indoor air quality impacts with 'CleanAir4V' – a network that is working on air pollution solutions for vulnerable groups.[47]

In Birmingham, BCC works with partner agencies to improve indoor air quality in council-owned properties (including reducing damp and mould). Measures include installing extractor fans, anti-backdraught shutters, window vents, mechanical ventilation heat recovery systems, whole house ventilation systems and a 'fabric first' approach to improving insulation. All rooms also include a heat source set to a minimum temperature that is located strategically to prevent cold bridges. Additionally, residents are provided with a home user guide on preventing dampness and mould within their property.

While these measures are helping to improve indoor air quality, there is scope for further action. A review of the Birmingham Development Plan commenced in March 2022 and work is underway to develop a new local plan that runs through to 2042.[48,49] This review provides a significant opportunity to benefit both indoor air quality and sustainability when guiding decisions on planning, development and regeneration.

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6.2 Bradford

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Source: Bradford District Metropolitan Council

Figure 1: Bradford

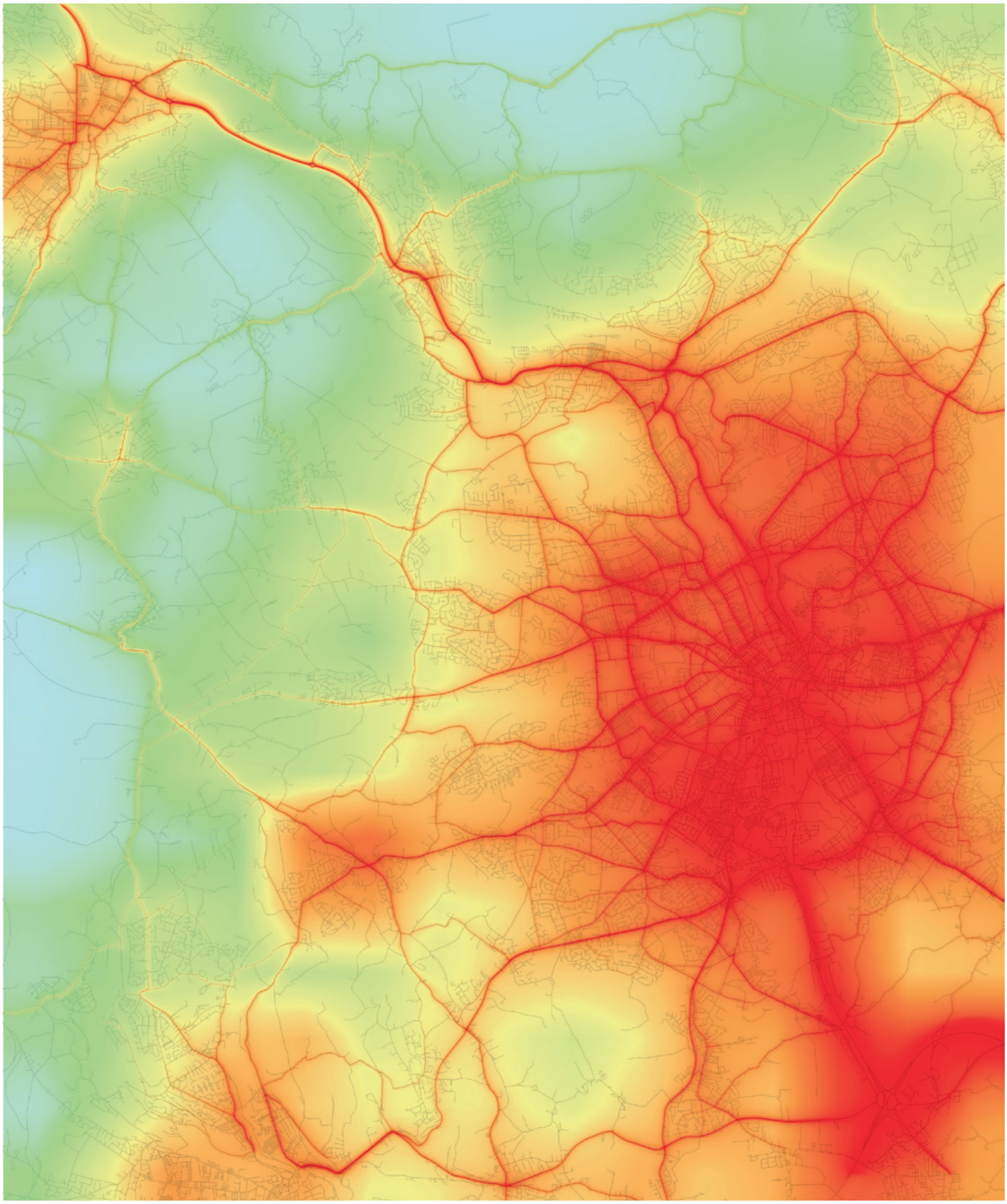
Introduction

Surrounded by the beauty of the Yorkshire Dales in the North of England, the Bradford Metropolitan local authority district, including the City of Bradford, is the seventh largest populated in England, with over 546,000 residents.[1] It is a young district, with more than one quarter of its population aged under 20.[1] A third of citizens are from ethnic minority groups, and around half of the births in the district are to families of South Asian origin.[2] It is a vibrant city in which to live and work. But like many other cities, it does have challenges, including areas of very high deprivation. A third of the population live in the most deprived decile compared with England and Wales averages,[3] and in tandem with high levels of deprivation are high levels of ill health.

Pollution is a key contributor to ill health within the city. Routine monitoring of air shows that both nitrogen dioxide (NO_2) and particulate matter (PM) are above World Health Organization guidelines across large parts of the city, particularly in areas near busy roads (see Figure 3). NO_2 is of particular concern, as exceedances of the Air Quality (England) Regulations 2000 have been identified in the city by both the government and the council. Pollution is linked to a range of health outcomes, as described in Section 1.1 of this report. The most recent figures in Bradford suggest that 500 people die from respiratory-related disease each year. There are over 13,000 diagnosed cases of chronic obstructive pulmonary disease (COPD) and more than 41,000 people diagnosed with asthma.[4] It is estimated that a third of asthma cases in the city are attributable to air pollution.[5] The burden of pollution-related disease falls disproportionately on more vulnerable groups. Poorer communities are subject to a clustering of environmental risk factors that include greater air pollution, more noise from traffic and less access to high-quality green spaces (see Figure 4). These factors exacerbate health inequalities.[6]

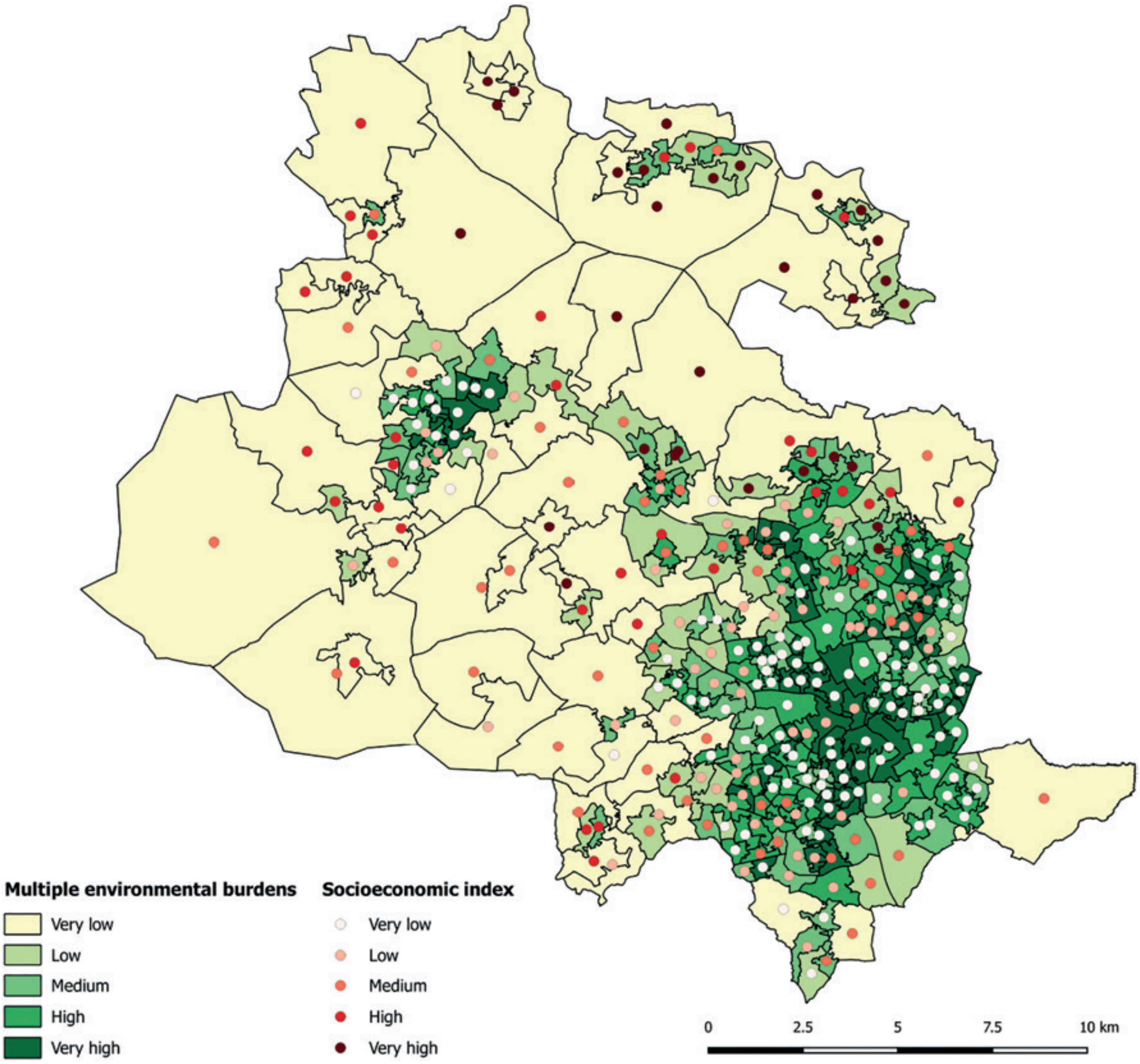
Source: Bradford Metropolitan District Council

Figure 2: Pollution on Manchester Road, Bradford



Source: Dr Kimon Krenz, University College London. Contains data from the City of Bradford Metropolitan District Council, Department of Health and Wellbeing, Environmental Health and Ordnance Survey data © Crown copyright and database right 2022

Figure 3: Concentrations of particulate matter (PM$_{10}$) for the City of Bradford, at 1x1 metre resolution



Source: Mueller et al. (2018)[6]

Figure 4: Multiple environmental burdens including noise, pollution and lack of green space in Bradford by socio-economic position

A City Collaboratory approach to improve air quality

For over 15 years, the Born in Bradford (BiB) research programme has been working to find out what keeps families healthy and happy, and to find ways to reduce health inequalities. Over 50,000 Bradford residents are actively involved in BiB cohort studies, and this is linked to a routine dataset of health, social care, environmental and education data for around 600,000 citizens living in Bradford and Airedale.[7]

The BiB City Collaboratory[8] provides an environment in which the public, scientists, the local authority, policy leaders and practitioners can work with each other. This system-wide work involves co-producing and testing solutions for early life and upstream disease prevention, and the evaluation of these solutions is supported by efficient data platforms to enable evaluation. The City Collaboratory co-production model consists of a multistep interactive cycle that places local communities at the heart of decision-making (see Figure 5).There is active participation in both shaping and using the research, and this also connects academic expertise with policymakers.[8]

Source: Born in Bradford

Figure 5: The Born in Bradford City Collaboratory approach

The Collaboratory infrastructure, connecting researchers and communities with policymakers, means we can add value to the development, implementation and evaluation of interventions to improve health by ensuring a strong focus on scientific evidence and community co-production.

The Collaboratory in action: the Bradford Clean Air Plan

Communities, clinicians and policymakers in Bradford have been working closely with BiB to study how air quality is affecting health across the life course. Early BiB research found links between pollution and low birth weight of babies in Bradford.[9] As the children involved in the study grew up, BiB found exposure to air pollution during early life to be related to higher blood pressure,[10] and poorer cognitive development[11] at ages 4 to 5 and indoor air quality to be related to childhood obesity at ages 6 to 11.[12] At a molecular level BiB found exposure to pollution relates to shorter telomere length (an indicator of biological ageing).[13] Through health impact assessments, the team have shown that there is a greater burden of pollution on health among the more deprived communities in Bradford.[6]

Poor air quality does not affect Bradford's communities in isolation. The term 'urban exposome' is used to refer to a whole set of environmental factors that are experienced in the outdoor urban environment and that may influence health. In addition to pollution, these factors include traffic noise, poor access to natural space, the built environment, public transport, facilities and walkability, all of which have been linked to health outcomes.[10,12,14]

The Bradford Clean Air Plan and Clean Air Zone

In 2018, Bradford was one of 28 local authorities to receive a ministerial direction to explore ways of improving air quality as quickly as possible. The Bradford Clean Air Programme board was formed, comprising representatives from health, planning, transport and researchers. With a clear focus on health and the reduction of inequalities, the board has worked with communities and stakeholders to identify a range of innovative approaches within the Bradford Clean Air Plan. Crucially, these have been based on science and evidence, recognising that everything is connected, and that a whole-city approach is needed to address the clustering of environmental risk factors.

On 26 September 2022, Bradford switched on a 'class C' clean air zone (CAZ) which charges non-compliant buses, coaches, heavy goods vehicles, vans, minibuses, taxis and private hire vehicles a daily fee to enter the zone. About 85% of these older commercial vehicles entering the city, the target of the CAZ, are registered outside the Bradford district. The CAZ includes exemptions and support packages for locally registered vehicles and those that are regularly in the zone. These include financial support for upgrade or retrofit, and the provision of infrastructure for low-emission technologies. The CAZ is the third largest in the country, and encompasses an area of 22.4km^2. Around 20% of the Bradford population live within the zone.[15]

BiB research from seldom-heard communities informed the development of the CAZ plans. Communities reported that they were worried about how pollution affects health, but also about the impact that charging the taxi trade would have on families that were already on low incomes.[16] As a result of this, appropriate mitigation strategies were planned, including obtaining £12 million in grants for taxi drivers to cover up to £10,000 towards the cost of replacing or upgrading a vehicle.

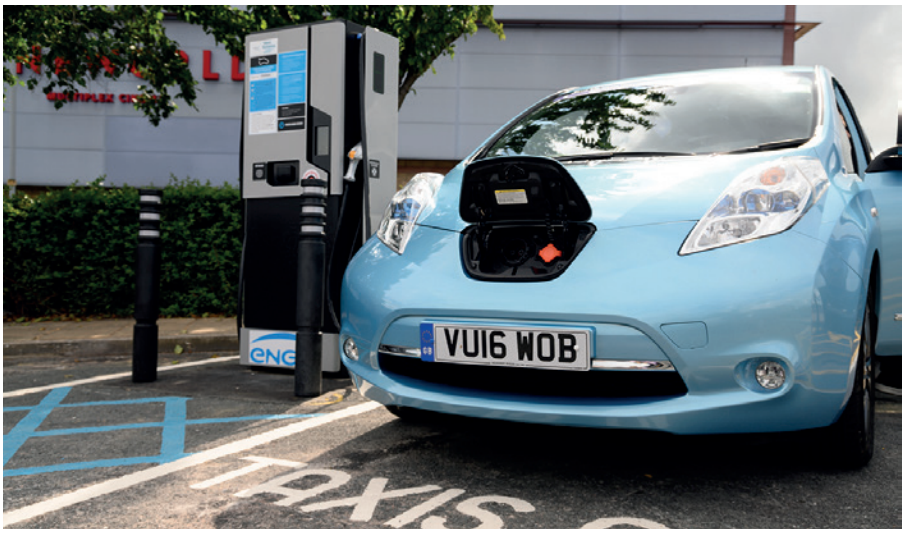
Source: Bradford Metropolitan District Council

Figure 6: Clean air zone road sign, Bradford

The CAZ will have limited effects if it is implemented in isolation, without considering wider infrastructure within the city (for example electric vehicle charging points) and sources of emissions unrelated to traffic (for example wood burning and industrial sources). However, the CAZ investment has been instrumental as a springboard to focus the city's attention on problems with pollution and has enabled the attraction of greater investment for more ambitious initiatives; this was evidenced in the successful Zero Emission Bus Regional Area (ZEBRA) scheme bid for 30 new electric buses for Bradford in March 2022. Further examples are highlighted below, ranging from high-level policy action to grassroots work with communities.

Planning development control: designing clean air into new infrastructure plans

In Bradford, the planning department works closely with the Clean Air Plan team to assess every new domestic and commercial development for its air quality impact and apply mitigations. Bradford led the development of innovative planning and development control guidance which has now been applied across the 5 local authorities of West Yorkshire. This includes consideration of air quality mitigation at the design stage and offset mitigation contributions informed by air quality damage costs.[17] To date, this has resulted in the provision of over 5,000 electric vehicle charging points and site-specific mitigation on development schemes, for example low-NO_x heating plants and electric mini-bus provision for disconnected sites. Future work will involve engaging with construction sites to introduce cleaner non-road mobile machinery.



Source: Bradford Metropolitan District Council

Figure 7: Charging point for an electric vehicle

School Streets: reducing exposure on the school run

Over 40% of Bradford schools are located within the CAZ, with many of them on busy, congested roads. Bradford Council estimates that children in these schools will benefit from an average relative reduction in NO_2 of 30% as a result of the CAZ.[18] This is important, as epidemiological research has found associations between exposure to traffic-related air pollution and poorer academic attainment.[19]

More than a third of school journeys are made by car, with around half of primary-aged children driven to school.[20] BiB research found that school travel choices in the city are complex, with safety a key concern. Parents are concerned about speeding traffic and dangerous parking outside the school gate, and schools fail to enforce parking restrictions to improve safety.[21] To address these issues a School Streets pilot was launched across 9 schools in June 2021. The scheme legally closes roads outside schools for set times at morning drop-off and afternoon pick-up, with exceptions for residents and those who have other access needs. Many of the schools have reported reductions in the amount of traffic outside their grounds at these crucial times, allowing children, parents and carers to walk, scoot or cycle to school. Further research is being conducted into barriers and enablers to implementation to help refine the model before this is rolled out across the district. Working with the BiB team, the impacts of this initiative on air quality and active travel will be evaluated.

Pupil power: co-production in action

The City Collaboratory has been working with communities and schools across the district to co-produce and implement interventions to reduce exposure to air pollution. As part of the BiB Breathes project,[15] over 200 primary school pupils have been trained to be 'citizen scientists', monitoring their pollution exposure using mobile sensors on their journey to and from school. Indoor and outdoor pollution monitors have been installed in 14 schools, and creativity labs and co-production workshops have supported children to come up with their own ideas about how to address pollution. These insights have led to local authority investment in anti-idling campaigns. The 'We Care about Clean Air' campaign works with schools and provides them with materials, banners and posters to raise awareness among parents and other road users and reduce idling near their schools. The campaign is supported by environmental wardens who regularly patrol near local schools and encourage drivers to switch engines off when they are stationary.

Source: Born in Bradford

Figure 8: Co-production workshop

Source: Bradford Metropolitan District Council

Figure 9: We care about clean air

Housing and indoor air quality: behaviours in the home

Poor housing conditions (for example lack of ventilation, damp or mould), heating sources (for example wood burners) and occupant behaviours (for example the use of household or personal care products, cooking) all contribute to indoor air pollution,[22] which in turn contributes to ill health. Surveys with the BiB cohort have shown that 23% of families report the presence of damp or mould in their homes, but there is currently limited information on the extent of indoor pollution issues or how housing characteristics or occupant behaviours contribute to this.

Indoor air quality will be monitored in over 300 homes across the district, following investment from the Natural Environment Research Council (NERC)[23] and Department for Environment, Food & Rural Affairs (Defra)/Department for Transport (DfT).[24] The team will monitor air quality in locations within the home, including kitchens, living spaces and bedrooms, using a variety of sensors which assess pollutants, including PM, carbon dioxide and volatile organic compounds (VOCs). To explore factors affecting air quality, they will conduct audits of building quality, record occupant behaviours which may affect levels of indoor air quality, such as cooking and cleaning, and collect detailed information on symptoms and health over a two-week period. The findings will enable a greater understanding of the burden of indoor air pollution, what causes it, and how it affects health. Information will be used to develop a range of policy, enforcement and behaviour-change approaches aimed at reducing indoor pollution, for example by reducing pollution from solid fuel burning in residential areas. These activities will be complemented by a low-emission energy plan for the district to include ground source heat pumps and solar sources in preference to biomass burning.

Evaluating the impact of the 'City Collaboratory'

The rich research infrastructure of BiB, including cohorts and linked data, will allow us to provide vital evidence of the effects the activities within the Bradford Clean Air Plan. For example, the National Institute for Health Research (NIHR)-funded BiB Breathes project[15] will evaluate the effects the CAZ and Bradford Clean Air Plan have on respiratory and cardiovascular health, and birth outcomes across all Bradford residents. It will investigate the impact of the plan on health inequalities and will explore value for money. The council has invested in an extensive monitoring network of 199 sites to explore how activities are affecting air quality and providing research calibre measurements at a city scale.

Lessons learned: tackling the multiple interacting sources of pollution

Air pollution needs to be addressed at a system level to tackle the multiple interacting factors which contribute to its pervasive presence. Ambitious policies are needed to stop emissions at source, supported by attitudinal and modal behaviour shifts within communities to reduce behaviours contributing to pollution. Good data to measure harm and evaluate how changes affect health and inequalities are important. BiB has created a whole-population testbed by combining routine health, education and social care data with environmental indicators. This enables evaluation of the effect of citywide initiatives, and we are working to spread this approach to other localities. Our longitudinal cohorts with embedded qualitative and quantitative evaluations allow us to dive deeper into the differential effects of interventions for different population groups.

The City Collaboratory has learned the importance of building strong partnerships between policymakers and researchers. By working together from the outset, they can define the priorities and health need, identify and evaluate solutions, make the political case for change and implement change. Timely feedback to policymakers, in contrast to the typically slow pace of research, helps to ensure decision-making is predicated on the best possible evidence.

While science and evidence can help to make the case for investment and justification for change, efforts will fail if we do not also win the hearts and minds of communities. Understanding how to engage with different stakeholder groups with differing motivations is challenging, and messages need to be tailored to these different groups. Communities must also be ready for the changes which policymakers affect, to ensure there are no unintended consequences. By working with the BiB research programme, the City Collaboratory was able to quickly conduct bespoke research with seldom-heard communities in relation to the planned CAZ. This provided a powerful voice for these communities which enabled further investment in mitigation strategies through, for example, the provision of grants to taxi drivers to allow them to upgrade their vehicle. It also helped to highlight the need for a systems approach. For example, the research found community priorities often centred on more visible aspects of their environments, such as fly-tipping or a lack of green space. Without also acknowledging and acting upon these concerns, efforts to address air pollution may be seen as misjudged by communities. Co-production within our collaborative approach is built on the values of trust, agency and reciprocity, which take time and commitment to develop. To make this work, it is important that community engagement infrastructure is properly supported, including voluntary, community and social enterprise (VCSE) and faith organisations, community groups, schools and workplaces.

In Bradford, we have taken a systems approach to deal with high levels of pollution in the city to improve the health of our population. Our City Collaboratory places communities at the centre of our work, and enables decision-makers, policymakers, statutory health partners, the third sector and researchers to work together towards a common goal. Our city of research infrastructure means that we are well placed to evaluate how our plans affect health and inequalities. We hope this learning will be useful to other cities, nationally and internationally, that are experiencing similar issues.

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6.3 London

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Introduction

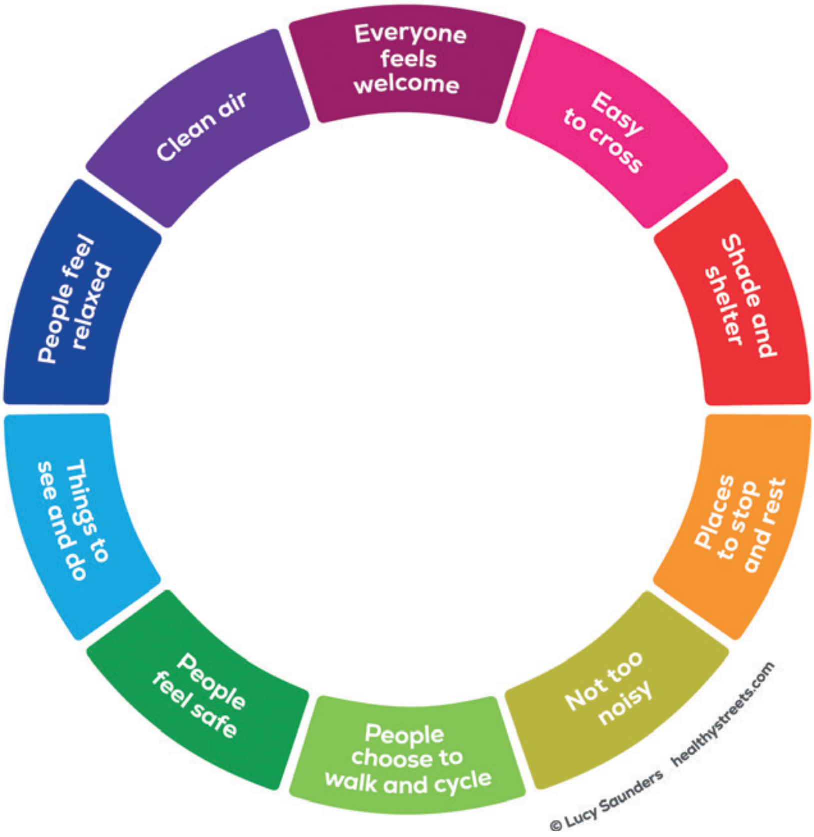
Improving air quality is a strategic priority for London across local and regional government and health and care partners, with overall coordination provided by the Mayor of London. The 2018 London Environment Strategy (LES) sets out the aim for London to have the best air quality of any major world city, going beyond the legal requirements to protect health and minimise inequalities.[1] In addition, the London Health and Care Vision (2019) includes action to improve air quality, with an ambition that every Londoner breathes safe air.[2]

Following the second inquest into the death of Ella Adoo-Kissi-Debrah, a 9-year-old girl from South East London in 2013, a Prevention of Future Deaths (PFD) report was published in April 2021. In this report the coroner raised 3 matters of concern including that national limits for Particulate Matter were set at a level far higher than the World Health Organization Guidelines; low public awareness of the sources of information about national and local pollution levels; and that the adverse effects of air pollution on health were not being sufficiently communicated to patients and their carers by medical and nursing professionals.

The PFD report was sent to central government departments, the Mayor of London, the London Borough of Lewisham and medical professional organisations. The responses from the Mayor and the London Borough of Lewisham, published in June 2021, highlight the ambition of London's air quality programme and its importance in protecting people's health.[3]

London's strategic approaches to improving air quality

When developing all Mayoral strategies, there is a statutory requirement to include policies and proposals to promote Londoners' health and reduce health inequalities. This 'health in all policies' approach means that work to improve air quality is embedded within the environment, health inequalities, transport and development strategies. The Healthy Streets Approach, for example, provides the framework for putting people's health and experience, including clean air, at the heart of planning the city. The Healthy Streets Approach is shown in Figure 1.



Source: Saunders (2014)[25]

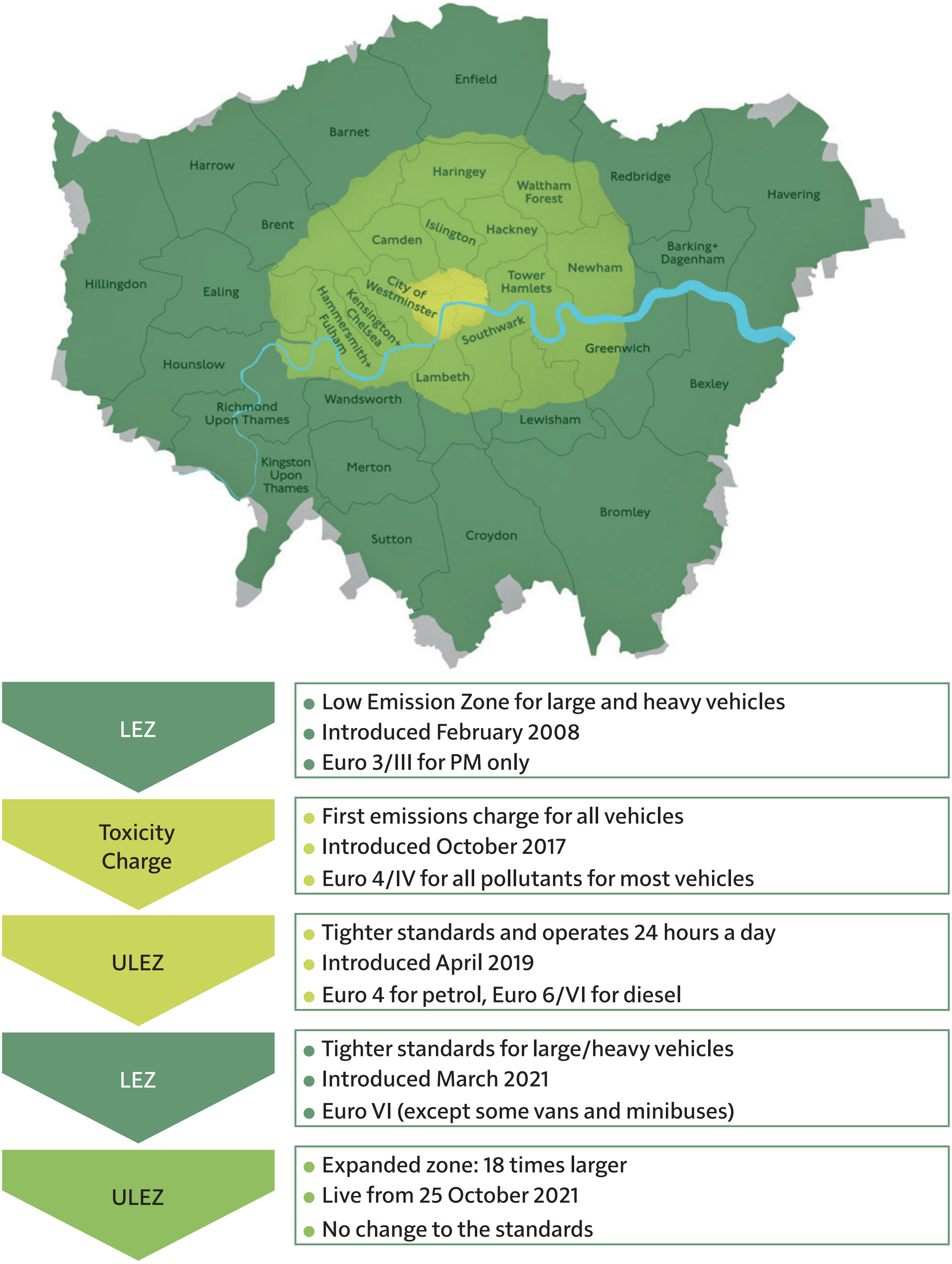
Figure 1: The 10 Healthy Streets indicators

From policy to implementation: improving air quality in London

London's air quality programme reflects action at national, regional and local levels, with partnership working across organisations in health, environment, transport and planning. The examples outlined below are part of a holistic approach to reducing air pollution and health inequalities.

Road user charging

Successive road user charging schemes have been implemented in London, and the stages are presented in Figure 2. The Low Emission Zone (LEZ) requires large and heavy vehicles to meet emission standards or pay a daily charge to operate in London. Similarly, the Ultra Low Emission Zone (ULEZ) (and its precursor, the 'Toxicity Charge') requires smaller vehicles, including private cars and motorcycles, to meet emission standards or pay a daily charge to operate in a specific area of the city.



LEZ	● Low Emission Zone for large and heavy vehicles ● Introduced February 2008 ● Euro 3/III for PM only
Toxicity Charge	● First emissions charge for all vehicles ● Introduced October 2017 ● Euro 4/IV for all pollutants for most vehicles
ULEZ	● Tighter standards and operates 24 hours a day ● Introduced April 2019 ● Euro 4 for petrol, Euro 6/VI for diesel
LEZ	● Tighter standards for large/heavy vehicles ● Introduced March 2021 ● Euro VI (except some vans and minibuses)
ULEZ	● Expanded zone: 18 times larger ● Live from 25 October 2021 ● No change to the standards

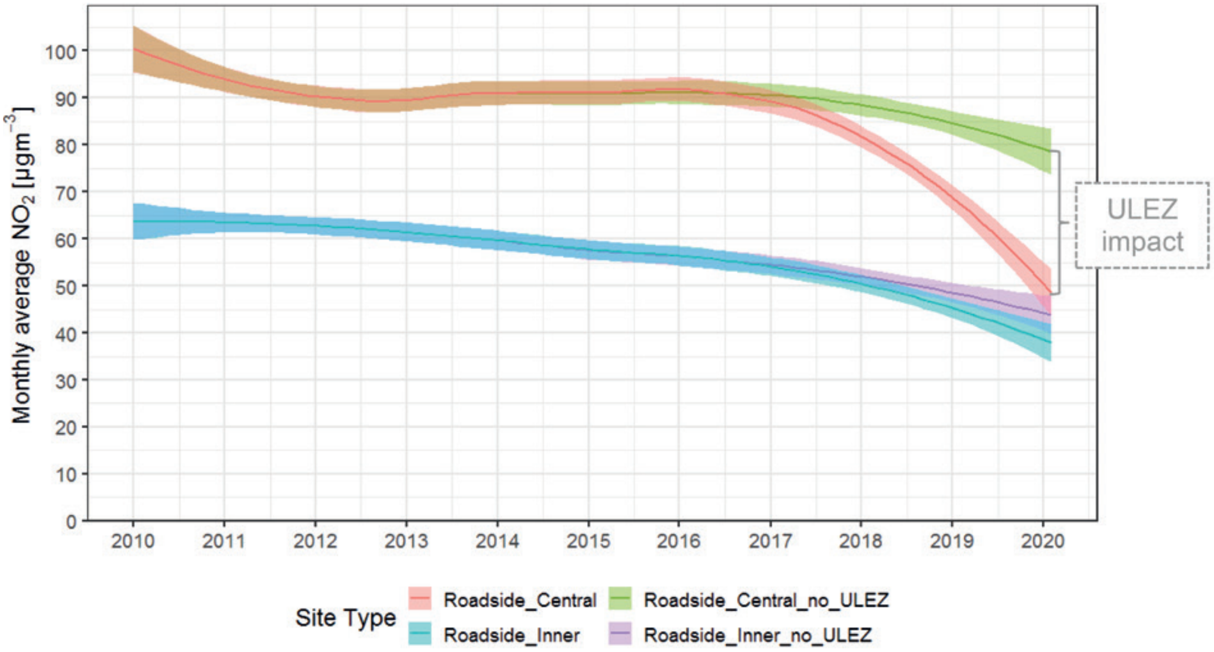
Source: Greater London Authority

Figure 2: Progressive emission-based road charging schemes in London

The LEZ and ULEZ schemes were designed to reduce the pollutants most harmful to health. The emission standards for the vehicles in the zones correspond to the Euro standards for permitted air pollution emissions from vehicle engines. The Euro standards and engineering solutions to reduce air pollution emissions are described further in Section 4.1.1.

Since the introduction of the central London ULEZ, vehicle air pollution emissions have reduced. While the ULEZ was not introduced until April 2019, the introduction of the Toxicity Charge was confirmed as a stepping stone for the ULEZ in February 2017. The effects of the ULEZ can be measured from this date, as it marked the beginning of an accelerated change in the vehicle fleet, with Londoners and businesses preparing for the new schemes and buses on routes in central London starting to undergo upgrades to become ULEZ compliant. Between February 2017 and February 2020, NO_2 concentrations at roadside sites within the original central zone reduced by 44% and fine particulate matter ($PM_{2.5}$) reduced by 27%.[4]

Figure 3 shows the monthly average NO_2 concentrations at roadside sites in central and inner London as well as a 'no ULEZ' scenario estimates for each. The 'no ULEZ' estimate reflects the changes that would have occurred in central and inner London without ULEZ restrictions, based on the trends shown on roadside sites in outer London (where the effects of the ULEZ were less significant). The divergence between the measured concentrations and the 'no ULEZ' scenario in central London (as shown by the red and green lines) from 2017 (when changes associated with the ULEZ began) up to the end of February 2020 (before the introduction of COVID-19 restrictions) highlight the impact of the scheme.



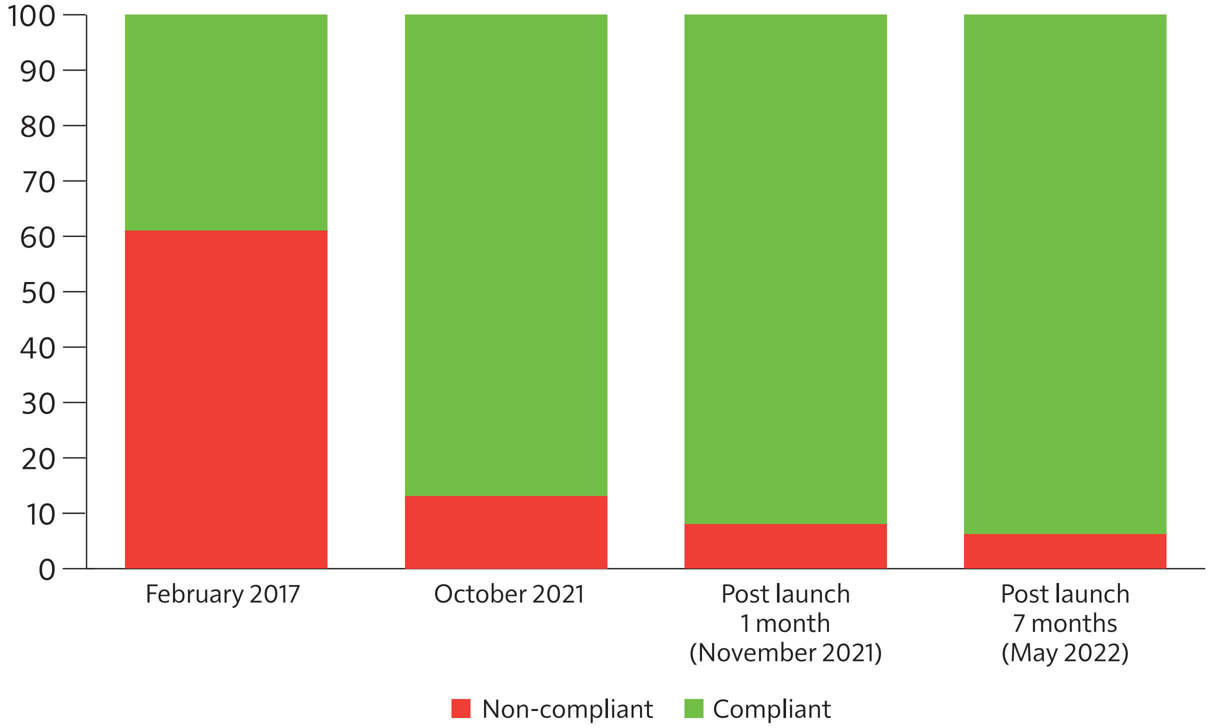
Source: Greater London Authority (2020)[4]

Figure 3: Monthly average NO_2 concentrations in London with and without the central ULEZ

The ULEZ expanded in October 2021, and since then there has been a reduction in the number of older, more polluting vehicles in the zone. After 7 months of operation, nearly 94% of vehicles in the ULEZ met the emission standards, meaning that 67,000 fewer non-compliant vehicles were driving in the zone on an average day. NO_2 concentrations alongside roads are estimated to be

20% lower in inner London and 44% lower in central London than they would have been without the ULEZ and its expansion.[5]

Figure 4 shows the share of vehicles meeting the ULEZ standards one month and 7 months after the launch of the expanded ULEZ, compared to indicative figures prior to its launch and figures from 2017 when the Toxicity Charge was confirmed and plans were announced to expand the ULEZ. This illustrates the effects of pre-compliance behaviours when Londoners were preparing for the scheme and the influence of the scheme following the launch.



Note: Bars show compliance one month and 7 months after the launch of the expanded ULEZ compared to rates recorded prior to the launch and in 2017 when the Toxicity Charge was confirmed.

Source: Greater London Authority (2022)[5]

Figure 4: Compliance rates with ULEZ standards (all vehicles)

To help Londoners prepare for the ULEZ and its expansion, the Greater London Authority (GLA) allocated £61 million in funding for scrappage schemes, providing grants for small businesses, charities and low-income and disabled people. These schemes helped remove over 15,200 more polluting vehicles from London's roads. Grace periods also gave disabled drivers and community transport minibuses longer to adapt to the change. These supporting measures were an important part of building public support for the scheme.

As a result of these road user interventions, GLA and Transport for London (TfL) modelling suggests that Greater London is on track to meet legal pollution limits for NO_2 by 2025 at the latest. This contrasts with the estimated 193 years it would have taken to achieve compliance had the ULEZ and other measures not been implemented.[6] However, despite the successes of the ULEZ and LEZ schemes, air pollution has improved more slowly in outer London (outside the expanded ULEZ). The highest proportion of premature deaths attributable to air pollution is also in outer London; this is mainly due to the higher proportion of older people living in these areas, who are more vulnerable to the health impacts of air pollution.[7]

To address air pollution from vehicles in outer London, a consultation was conducted between May and July 2022 to discuss further expansion of the ULEZ in 2023. A decision on whether to implement this policy is expected by the end of 2022. In addition, TfL is exploring what the future of road user charging could look like in London. This could include ending existing charges, such as the Congestion Charge, LEZ and ULEZ, and replacing them with a single road user charging scheme that uses more sophisticated technology to make it as simple and fair as possible for drivers.

Walking, cycling and public transport

The road user charging schemes have been supported by policies to provide convenient, affordable and safe alternatives to private car use. TfL and the London boroughs are investing in sustainable modes of transport to fulfil one of the central aims of the Mayor's Transport Strategy: for 80% of all trips in London to be made on foot, by bike or using public transport by 2041.[8]

In addition to reducing harmful emissions, more walking, cycling and public transport use will help address physical inactivity and improve the health of Londoners. If all Londoners walked or cycled for 20 minutes a day, this would save £1.7 billion in NHS treatment costs over 25 years.[9] More than a third of car trips made by Londoners could be walked in under 25 minutes and two-thirds could be cycled in under 20 minutes.[10]

Since 2016, the network of protected cycle space across the city has tripled, 250 new or improved pedestrian crossings have been installed and 25 of the capital's most dangerous and intimidating junctions have been changed to make them safer for walking and cycling.

The most recent data showed that in 2020 bike journeys accounted for 3.4% of all journeys in London – a 48% increase since 2019 – and journeys made on foot peaked at 57% of all journeys, up from 35% in 2019.[11] While driven by the unique circumstances of the COVID-19 pandemic, this also shows how behaviour can be changed and active travel more widely adopted.

TfL has supported London boroughs to deliver over 100 Low Traffic Neighbourhoods (where residential streets are closed to through traffic) and over 500 school streets (where streets are closed to vehicle traffic at pick-up and drop-off times) to make it easier and safer to walk and cycle locally. There is public debate around Low Traffic Neighbourhoods. A study published in March 2021 found that school streets reduced NO_2 by up to 23% during morning drop-off.[12] Walking is now the main way that 58% of children aged 5–11 in London travel to school.[13]

Reducing air pollution emissions from private and public vehicles

Not all journeys will be able to be made by walking, cycling or public transport, and the GLA, TfL and London boroughs have developed a strategy to support the expansion of electric vehicle charging infrastructure across the city. London now has over 11,000 electric vehicle charge points, a third of the UK's total, delivered through effective collaboration between the public and private sectors.

While private cars and vans account for the largest share of road transport emissions in London, there has been parallel work to reduce emissions from public transport, specifically buses and taxis.

Since 2018, all new double decker buses have been hybrid or zero-exhaust emission, and over 800 zero-exhaust emission buses currently operate in London. A comprehensive programme to phase out or retrofit the remaining diesel buses resulted in all 9,000 TfL buses meeting or exceeding the cleanest Euro VI emission standards by 1 January 2021, reducing bus-related NO_x emissions by up to 90%.[14] Since September 2021, TfL has only procured zero-exhaust emission buses.

Since January 2018, all newly registered taxis have been required to be Zero Emission Capable (ZEC). A taxi de-licensing fund has helped retire the oldest, most polluting diesel black cabs from London's fleet. There are currently over 5,000 ZEC taxis, from a baseline of zero in 2017. This also demonstrates the ability of environmental and health policies to encourage economic growth, with 500 jobs created in Coventry to build the new ZEC taxis.

While London traffic has reduced over the last 20 years, there have been increases in the numbers of delivery vehicles. Larger vans and heavy vehicles have been subject to emissions restrictions throughout London since the introduction of the LEZ in 2008, with tighter restrictions enforced from 2021. Smaller vans and other vehicles used for deliveries are subject to the ULEZ. To encourage further reductions in emissions from the delivery sector, the Mayor's Air Quality Fund has supported a number of initiatives, including local consolidation centres with zero-emission onward delivery and 'Zero Emission Network' projects which support businesses to transition to zero-emission modes, including cargo bikes and electric vans, for first- and last-mile deliveries.

Other action to reduce air pollution in London

Schools

The GLA has audited the air quality at 50 primary schools and 20 nurseries in the city's most polluted areas, supported by a £1 million fund to help schools reduce local pollution. These programmes supported measures such as the installation of green screens and air filtration systems, building equipment upgrades and behaviour change campaigns which have all helped reduce emissions from schools and children's exposure to air pollution.

The London Schools Pollution Helpdesk helps more schools conduct air quality audits and implement recommendations to reduce student and teacher exposure. Over half of London's schools participate in TfL's sustainable travel accreditation scheme, STARS.[15] Air quality is one of the key issues addressed through London's School Superzones programme, which supports the creation of 400m healthy zones around schools.[16]

Construction sources

London's Non-Road Mobile Machinery Low Emission Zone (NRMM LEZ) requires all engines with a power rating between 37kW and 560kW to meet an emission standard based on the engine emission 'stage'. The standards that need to be met depend on where the construction site is. The NRMM LEZ has eliminated over 16.5 tonnes of particulate matter (PM) and 297 tonnes of NO_x emissions from construction projects between 2016 and 2019. The supporting enforcement project has since been expanded from the initial 13 boroughs to cover the whole of London. Additional powers are being sought to make this system more efficient and broaden it to cover a wider range of NRMM uses in London.

Local action

The Air Quality Action Plans produced by the London boroughs set out local actions being taken across the city, including increased monitoring, raising public awareness and improving sustainable travel infrastructure. An annual summary of work by London's local authorities shares best practice and recommendations for further action.[17] The Mayor's Air Quality Fund has supported a variety of borough- and business-led local and pan-London projects to improve air quality.[18]

Planning

London's Spatial Development Strategy, the London Plan,[19] sets out that developments should not lead to further deterioration of existing poor air quality, create new areas that exceed air quality limits or create unacceptable risk or high levels of exposure to poor air quality. The GLA is currently developing guidance to ensure that all new developments meet 'air quality neutral' standards and all large-scale developments take an 'air quality positive' approach. 'Air quality neutral' ensures developments do not contribute to air pollution beyond specific building and transport emissions benchmarks, while 'air quality positive' requires developers to seek ways to maximise benefits to local air quality and reduce exposure to pollution during design stages.

Impact and innovation: achievements and next steps

Data, awareness raising and community empowerment

The coroner's finding that exposure to excessive air pollution contributed to the death of Ella Adoo-Kissi-Debrah has led to increasing public awareness of the inequalities in exposure to air pollution. Focusing on the health and social justice impacts of pollution and the benefits of tackling it, including for children and communities in areas of deprivation, has been a crucial part of building public support for action. A growing body of academic research, including studies commissioned by the GLA,[20] has informed this framing by highlighting the strong case for action. Extensive marketing and communications activity has helped to raise public awareness of the health impacts of air pollution and encourage behaviour change (see Figure 5).

Source: Left: Greater London Authority campaign. Right: Idling Action London

Figure 5: Examples of pan-London awareness-raising campaigns

Air quality alerts system

The London-wide air quality alerts system was launched in 2016. Through this system, air quality alerts are displayed at 2,500 bus countdown signs and river pier signs, at the entrances of all 270 London Underground stations and at 140 roadside signs on the busiest main roads on high- and very high-pollution days. Information is provided directly to over 3,000 schools and every London borough. In addition to health messaging to encourage the most vulnerable to reduce their exposure, the alerts also seek to encourage people to reduce emissions by walking, cycling, avoiding unnecessary car journeys and engine idling, and avoiding burning wood and garden waste.

Source: Transport for London

Figure 6: Photo of air quality alert on a bus countdown sign

London has one of the world's most comprehensive air quality monitoring networks with sites operated and funded by the London boroughs, TfL and Heathrow and London City airports. A number of these sites are included in the national Automatic Urban and Rural Network (AURN), which is the main network used for compliance reporting against the Ambient Air Quality Directives. Additionally, the Breathe London network, consisting of almost 350 low-cost sensors, provides user-friendly information to Londoners. The monitoring sites are chosen by community groups and London boroughs and sites include hospitals and schools. Live data from all monitors in London are available through the Breathe London website.

Impact of policies and interventions

There has been a significant reduction in total NO_x emissions across the whole of London over the last decade, and the largest emissions reductions have come from road transport. This has contributed to a significant drop in NO_2 concentrations over the same period. It has been harder to reduce concentrations of $PM_{2.5}$ in London, with this declining at a slower rate than NO_2. Around half the $PM_{2.5}$ in London comes from sources outside the city, and the Mayor and the London boroughs have limited powers to address non-transport sources such as woodburning and commercial cooking. Table 1 shows the changes in air pollution from 2016 to 2019 across Greater London.

Pollutant	**Change in emissions 2019 vs 2016**	**Change in road transport emissions 2019 vs 2016**	**Change in concentrations 2019 vs 2016**
NO_x emissions/NO_2 concentrations	–18%	–31%	–22%
PM_{10}	–4%	–9%	–24%
$PM_{2.5}$	–5%	–14%	–19%

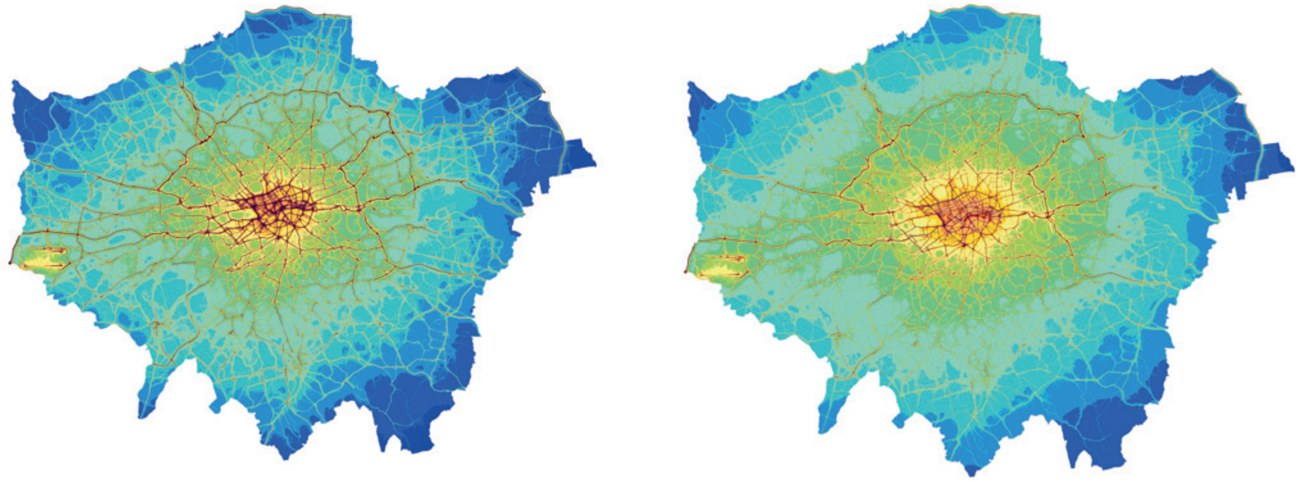
Source: London Atmospheric Emissions Inventory (2019)[21]

Table 1: Reductions in emissions and concentrations of key pollutants across Greater London since 2016

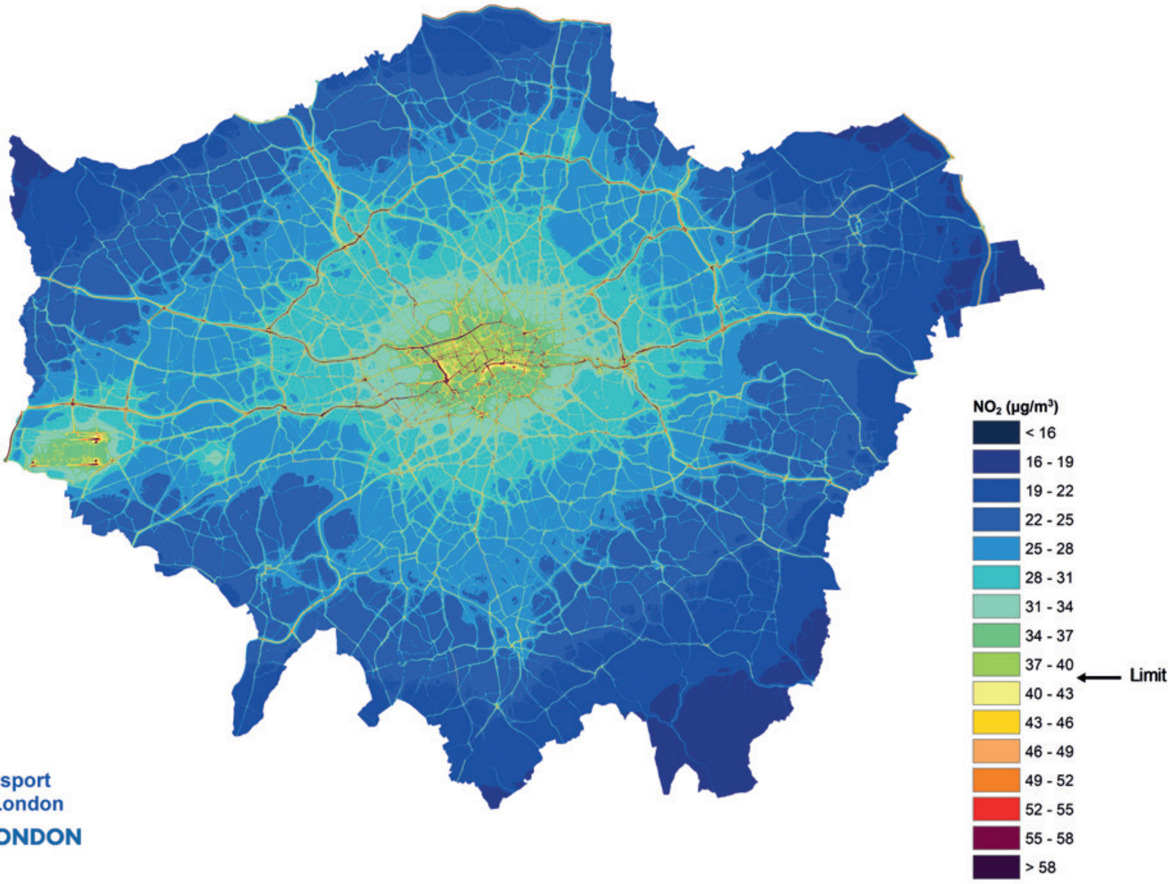
The maps in Figures 7 to 9 show the changes in air pollution concentrations in Greater London from 2013 to 2019 for NO_2, PM_{10} and $PM_{2.5}$.

NO_2 concentrations 2013

NO_2 concentrations 2016

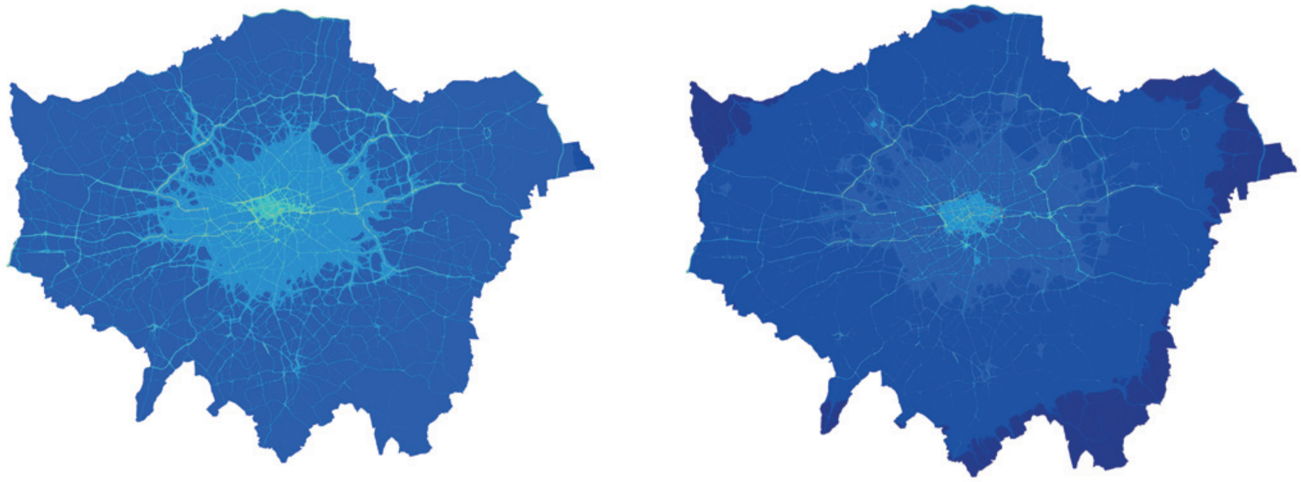


NO_2 concentrations 2019



Source: London Atmospheric Emissions Inventory (2019)[21]

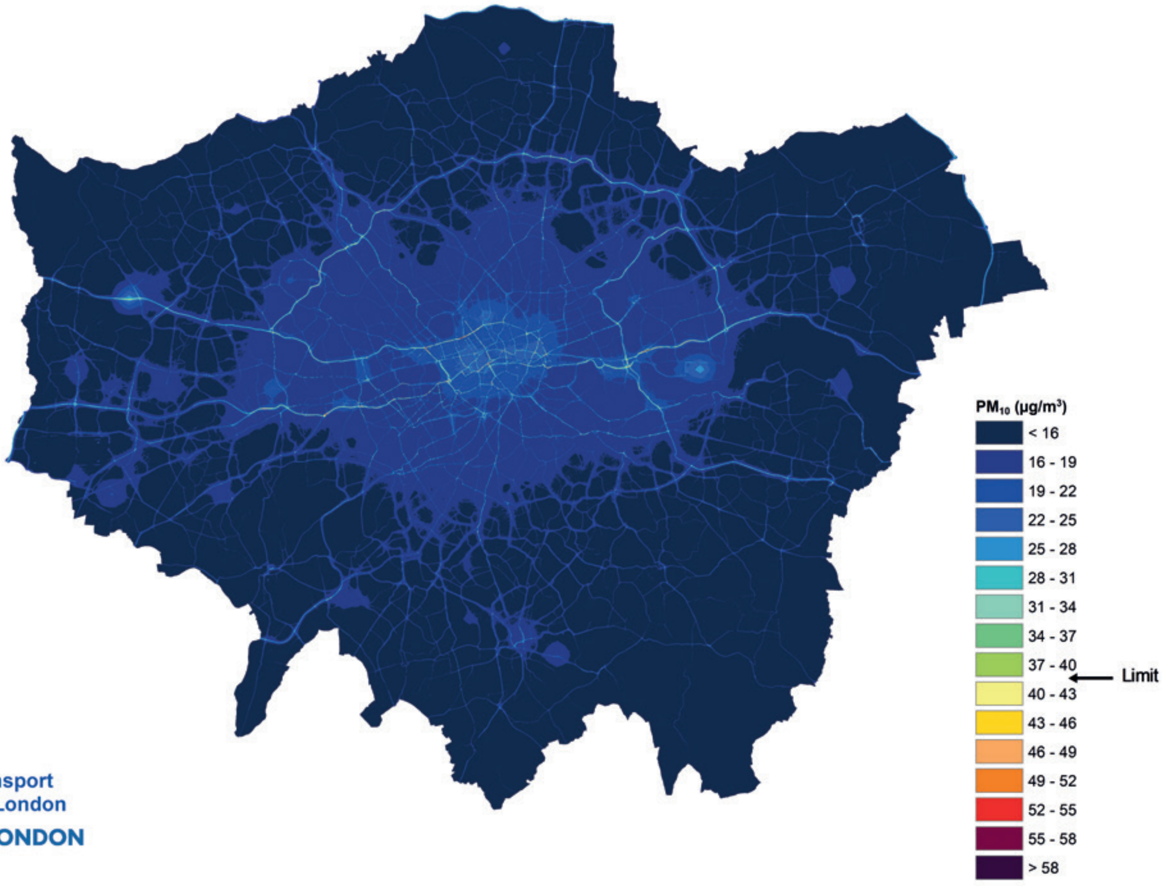
Figure 7: NO_2 concentrations across the Greater London area in 2013, 2016 and 2019



PM$_{10}$ concentrations 2013

PM$_{10}$ concentrations 2016

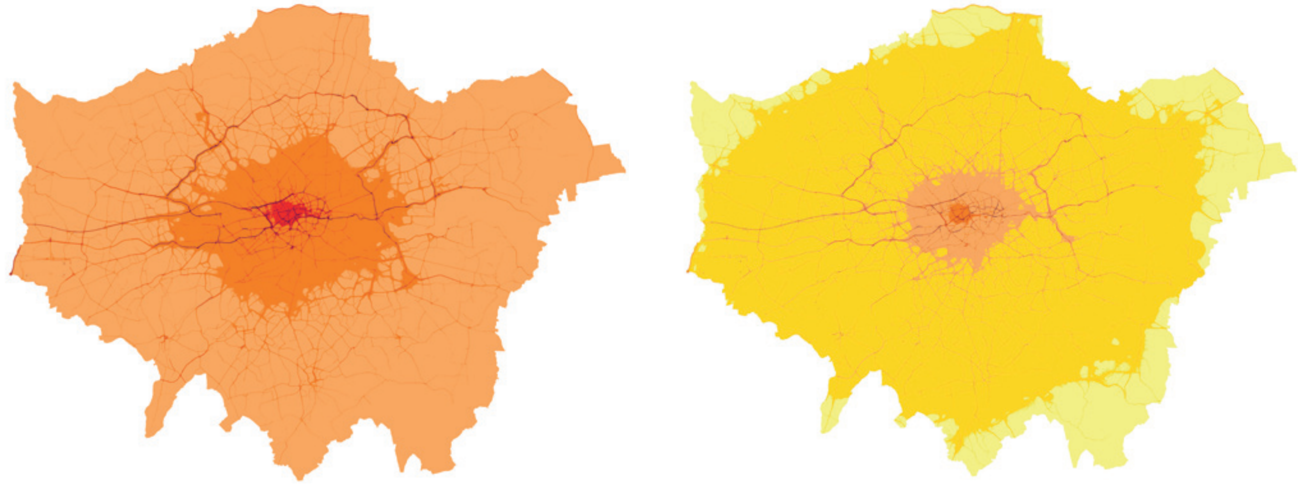
PM$_{10}$ concentrations 2019



Transport for London
MAYOR OF LONDON

Source: London Atmospheric Emissions Inventory (2019)[21]

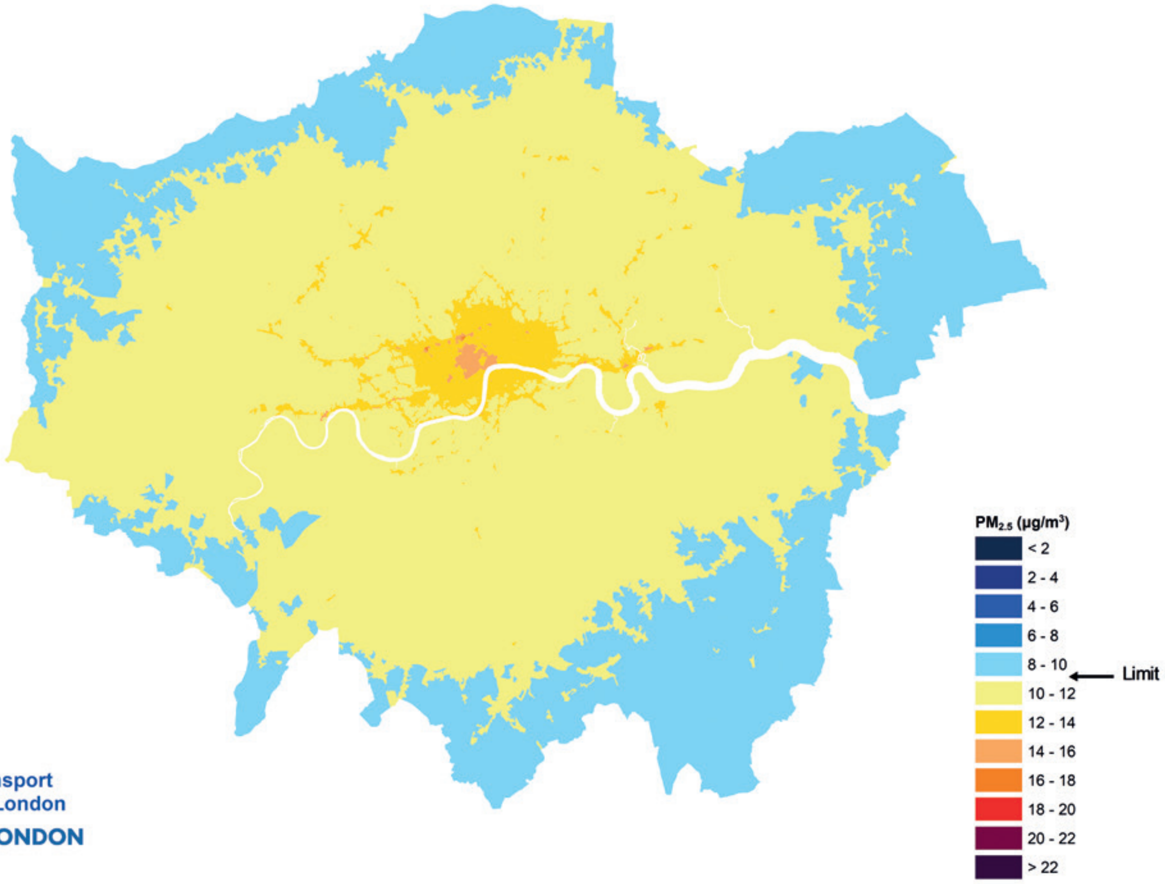
Figure 8: PM$_{10}$ concentrations across the Greater London area in 2013, 2016 and 2019



PM$_{2.5}$ concentrations 2013

PM$_{2.5}$ concentrations 2016

PM$_{2.5}$ concentrations 2019



Transport for London
MAYOR OF LONDON

Source: London Atmospheric Emissions Inventory (2019)[21]

Figure 9: PM$_{2.5}$ concentrations across the Greater London area in 2013, 2016 and 2019

Over 2 million Londoners were living in areas exceeding the annual average legal limit of 40µg/m^3 for NO$_2$ in 2016, reducing to 174,000 in 2019. The number of state primary and secondary schools in London in areas exceeding the legal limit for NO$_2$ fell from 455 in 2016 to just 20 in 2019.[21] Nearly 1.2 million Londoners lived in areas meeting the WHO interim guideline for PM$_{2.5}$ of 10µg/m^3 in

2019 – up from zero in 2016. For the first time, 12% of state primary and secondary schools are in areas meeting the interim target.[21] The WHO interim guideline for $PM_{2.5}$ is much lower than the legal annual average limit of 20µg/m^3 and reflects the latest evidence that long-term exposure to even low levels of air pollution is harmful to health.

It is estimated that the improvement in air pollution levels has reduced the number of hospital admissions for asthma and serious lung conditions attributable to air pollution in London by 30% – from 2,450 (2014–2016) to 1,700 (2017–2019). The largest percentage improvement was among children under the age of 14.[22] London's air quality programme is expected to save the NHS in London almost £5 billion and prevent more than 1 million hospital admissions related to air pollution by 2050.[23]

Air quality and the health system

The GLA and London boroughs have developed broad partnerships to deliver local air quality and health improvements and raise awareness of the negative effects of pollution on health, including working directly with the NHS, businesses, community organisations, charities and academics as well as international partners such as the WHO and C40 (the global network of mayors). The support of this wide range of stakeholders, including health professionals, has been an important part of addressing local concerns and encouraging public support for air quality policies. For example, the GLA regularly commissions and publishes research on the effects of air quality on health and how policies to address pollution are improving air quality in London.

The health and care system has an important role to play in raising awareness of the importance of tackling air pollution and communicating its health impacts to patients. London's health leaders have reiterated their commitment to raise awareness of air pollution and tackle health inequalities. Further action in London, for example investigating how air quality alerts could be disseminated to GPs and other medical professionals, will be initially coordinated through a fixed-term Air Quality and Health Programme Office.

Tackling inequalities

Communities with higher levels of deprivation, or a higher proportion of people from a non-white ethnic background, are more likely to be exposed to higher levels of air pollution. However, London's air quality policies have helped to narrow this gap since 2013. The difference in exposure to NO_2 between the most and least deprived socio-economic groups (measured as annual average concentration) reduced by 50%, from 7.6µg/m^3 in 2013 to 3.8µg/m^3 in 2019.

The exposure to NO_2 in those Lower Super Output Areas (LSOAs) with the highest proportions of black, Asian and ethnic minority groups was compared to the LSOAs with the highest proportions of white residents between 2013 and 2019. The gap in exposure to NO_2 between areas narrowed by 15% for Asian, 36% for Black, 37% for mixed and 35% for other ethnic groups, from 2013 to 2019.[24]

Local and regional government and partners across London will continue to prioritise addressing the health inequalities relating to poor air quality through city-wide and local action.

Next steps

Through effective partnership working, ambitious policies and taking a 'health in all policies' approach, London has made important progress over recent years in reducing air pollution and tackling health inequalities. But there is clearly more to do to ensure all Londoners can breathe clean air. Partners across the city are committed to addressing the sources of air pollution, reducing individual exposure to it and raising public awareness of its effects on health, including through mobilising health professionals.

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7 Air pollution research and innovation

Introduction

This report highlights many areas where air pollution has improved. In almost all these areas, research underpins the understanding that there was a problem and the solutions that have been applied. However, further research is needed to understand several aspects of the scope of the remaining problem, and even more importantly, find ways to prevent or mitigate the effects of air pollution on human health. We should also be clear that many of the causes of anthropogenic air pollution are unintended by-products of earlier eras of science to improve manufacturing, transport, agriculture and heating, among others. New industries and products run the risk of unintentionally increasing air pollution health harms if it is not considered as part of the development process.

Air pollution is an area of environmental human health where much of the relevant science comes from disciplines outside traditional biomedicine. Identifying the level of risk in the population has required epidemiology, cellular science and pathology, among others. Understanding air pollution itself draws on insights from atmospheric chemistry, physics and meteorology.

Many of the solutions to prevent air pollution and mitigate its effects on human health have come from engineering in many forms, agricultural sciences and social and economic sciences. For example, the sections on transport, urban planning and active travel demonstrate the remarkable impact of vehicle engine redesign in response to regulation, but also the importance of patterns of travel.

This point is important because the research disciplines most familiar to clinical and public health scientists, who see and manage the effects of air pollution on human health, are generally not the disciplines that are best able to tackle the sources of air pollution emissions. Those interested in reducing air pollution therefore need to collaborate with scientists from many unfamiliar areas. This includes funding by research councils in engineering, agricultural, environmental and social sciences. Research also needs to be undertaken by many different industries, including transport, building, heavy and light industry, agriculture and heating.

The UK already has a significant body of publicly funded work examining air pollution and its prevention, summarised in the report Appendix. There are examples of research from different academic disciples, and also cross-sector collaborations such as those funded by the UK Research and Innovation Clean Air Strategic Priorities Fund.[1] This is in addition to substantial work undertaken in multiple parts of the third sector, private sector and wider industry. There are however some significant gaps and opportunities that are worth highlighting.

Understanding the problem

From a public health perspective, while it is always useful to refine estimates of size of health effects of existing air pollution, some areas are more relevant to finding a better solution than others. For example, it is widely accepted that $PM_{2.5}$ is a significant risk factor for cardiovascular and respiratory disease and cancer, it is associated with increased mortality, and that exposure to it needs to be decreased. Repeating observational studies of risk will be unlikely to lead to change unless they result in a substantially different estimation of risk. There are, however, some gaps that have important practical implications, and we highlight a few below. These examples are simply illustrative to indicate the range of areas where improving our knowledge base would potentially lead to better outcomes. In every area covered by this report, further advances in science could or will improve our countermeasures to air pollution.

1) The role of different forms of particulate matter (PM) at $PM_{2.5}$ size or below in chemical composition, shape and size. As engineering solutions to reduce PM are developed, understanding that particular materials, or sizes of particle, are especially hazardous (or not) will be important to developing less hazardous outcomes and products. There are sufficient data to make it clear that this is an issue to be understood, but not yet to provide guidance on clear solutions in many areas.

2) Understanding the indoor air pollution environment on human health, including the impact of building design, the building materials used, consumer products such as personal care products, cleaning products, paints or glues, and ventilation. Our understanding of the sources and exposure to air pollution outdoors is now substantially better than our understanding of indoor sources, whether in the public or private indoor spaces. As outdoor air pollution has improved, the relative importance of the indoor environment (where most people spend most time), has become more prominent, but is not as well-researched.

3) Understanding the relative importance of peak concentrations of air pollution compared to cumulative (area-under-the-curve) exposure on different acute and chronic health conditions. This has important policy implications as well as helping provide evidence-based advice and information to the public and those at greatest risk of harm. The age at which exposure has its effects is also important – for example, if children of a particular age are especially vulnerable, this may have policy implications.

4) Economic analyses. Air pollution has a major societal and human cost, as well as increasing the cost of healthcare; countermeasures to air pollution also have a cost whether to the public or private sector. Economic factors are always going to be considered in decisions in both sectors, but currently much of the economic analysis is insufficient to base major policy decisions on. An example in the report is the capital investment likely to be needed in agriculture to reduce ammonia emissions; will they save costs and over what time period are important questions for farmers.

Countermeasures and mitigations

5) With the electrification of the passenger fleet, we are likely to see significant improvements in tailpipe emissions from road transport. This is a major win for air pollution reduction, as laid out in Section 4.1.1. This is in addition to the contribution to reducing carbon emissions. Brake wear should decrease due to regenerative braking, but it remains a source of air pollution, with less known about the health effects. There is relatively little known about tyre wear impact on health, but this will remain the same, or may get worse if there are heavier vehicles in the future. Having tyres that minimise PM emissions while maintaining road safety is relatively poorly researched as, to date, it has been relatively less important. This is an example of an area becoming more important as other risks decline.

6) Non-road forms of transport will become relatively more important and may need research to reduce their air pollution impacts. Obvious examples include air pollution emissions from trains (especially in urban areas), underground transport, aviation and shipping. Several industry-specific, road-based challenges also need to be addressed, including refrigerated vehicles and 'last mile' deliveries (where items are despatched from a local warehouse for the final delivery to customers) – each one has a relatively small contribution to air pollution, but collectively can make a significant impact.

7) The increased relative importance of indoor air pollution, as outdoor pollution has decreased, means ventilation indoors needs to be optimised. In the UK, especially in colder months, there is a potential trade-off between improving air quality through ventilation and optimising heat retention and reducing energy use for space heating (this is also important for net zero targets). This will involve identifying improved engineering solutions for air quality, building heating and energy efficiency, and identifying where air pollution emissions can be reduced.

8) Many interventions to reduce greenhouse gas emissions also improve air quality, but not all. We need to ensure that air pollution implications are considered in the important net zero transition – for example, changes to energy systems so that (as a minimum) air quality is not worsened and ideally improved by net zero initiatives.

9) We need better evaluations of interventions to reduce air pollution at local, regional and national levels, including their impact on health and on disparities. This includes interventions by local and national government to change traffic flows, the use of green spaces, improved active transport infrastructure, among other considerations.

The examples of UK research laid out in the Appendix are necessary, but some way from sufficient if we are to tackle the remaining areas of uncertainty in air pollution. Research is, of course, an international endeavour, but as a highly research-active and relatively densely populated country, the UK should aim to play a major part in developing the evidence base needed to improve air pollution.

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8 Appendix – Air pollution research and innovation, further information

Introduction

There is a great deal of research and innovation taking place in the UK to better understand air pollution and how it affects health, and the results of different actions to reduce it. This work involves many academic disciplines and collaborations between them, reflecting the cross-sector nature of air pollution research. The health harms of air pollution underpin much of the work to reduce pollution and people's exposure to it.

This appendix provides a summary of air pollution research and innovation that is being funded by UK Research and Innovation (UKRI) and the UKRI Councils, Department of Health and Social Care (DHSC) through the National Institute for Health and Care Research (NIHR), Department for Environment, Food & Rural Affairs (Defra), Department for Transport (DfT), Department for Levelling Up, Housing and Communities (DLUHC), Department for Business, Energy & Industrial Strategy (BEIS) and the Wellcome Trust.

Key research and innovation areas are described to demonstrate the breadth of work in this field, but this is not a comprehensive list of projects funded by these organisations. There is also significant work on air pollution funded by other government departments and arm's-length bodies, industry and third sector organisations. In addition to this appendix, a brief overview of air pollution research and innovation is presented in Chapter 7.

8.1 UK Research and Innovation (UKRI)

Caroline Culshaw and **Heather Birch** – Natural Environment Research Council (NERC)
Alexandra Hughes-Johnson – Economic and Social Research Council (ESRC)
Graham Campbell – Medical Research Council (MRC)
Kevin O'Malley – Innovate UK
Stephen Loader – Science and Technology Facilities Council (STFC)
Neil Robinson – Engineering and Physical Sciences Research Council (EPSRC)

UK Research and Innovation (UKRI)[1] is composed of 7 disciplinary research councils, plus Innovate UK and Research England. For air pollution, UKRI supports the underpinning research, training, infrastructure and innovation that enables the study of air pollution, its health impacts, and the development of new solutions for cleaner air. UKRI operates across the whole country and works with many partners in higher education, research organisations, businesses, government and charities.

The UKRI Councils come together to support challenge-focused multidisciplinary and interdisciplinary research and innovation, such as through the UKRI Strategic Priorities Fund (SPF) Clean Air Programme.[2] This £42.5 million investment supports high-quality research and innovation that develops practical solutions for air quality issues and equips the UK to tackle future air quality challenges to protect health and support clean growth. They also support disciplinary-focused research and innovation on air pollution. Summaries of the different roles are provided below.

Some of the air pollution research and innovation funded as part of the UKRI SPF Clean Air Programme and individual UKRI Councils is described in this section. While it is not possible to include all areas, the summary aims to demonstrate the breadth of current work.

UKRI Councils – air pollution research and innovation

The **Economic and Social Research Council (ESRC)**[3] supports research into the social, economic and behavioural drivers and impacts of air quality, such as transport choices, regulation, tax policy, housing, planning and land use decisions. ESRC funds research that explores solutions, risks and the benefits and opportunities in addressing these areas.

The **Engineering and Physical Sciences Research Council (EPSRC)**[1] supports research, training, infrastructure, and innovation across the UK that addresses and develops solutions to understanding, mitigating, and reducing air pollution through engineering and physical sciences. EPSRC supports a wide breadth of work – from combustion engineering that develops novel low-pollution fuels to digital twins of air quality, where information from sensors combines with computational models and algorithms to provide advice for minimising exposure to pollutants.

Innovate UK[4] is the UK's national innovation agency, supporting business-led innovation in all sectors, technologies and UK regions. Innovate UK helps businesses grow through the development and commercialisation of new products and services across the whole of the UK clean air technology sector.

The **Medical Research Council (MRC)**[5] supports research into air quality and environmental exposures and how they affect human health. This includes aiming to understand the molecular mechanisms and the biological pathways associated with disease and determining the health effects of air pollution on the population – in particular disadvantaged groups, to develop interventions that improve public health and wellbeing.

The **Natural Environment Research Council (NERC)**[6] supports research on the sources and emissions of different air pollutants and how those chemicals are transformed and transported in the atmosphere. NERC supports technology development of instrumentation, sensors and software for air pollution measurement and modelling, and also supports research on the ecological effects of air pollution.

The **Science and Technology Facilities Council (STFC)**[7] supports research in astronomy, particle physics, nuclear physics, and space science, and provides access to world-leading, large-scale facilities across a range of physical and life sciences. Capabilities relevant to air pollution research are focused around analysing and integrating large and complex data, earth observations and remote sensing, access to and experience of using STFC facilities, and development and application of technology.

Research and innovation supported by UKRI Councils

Pollutants, measurements and models

Fundamental atmospheric research supported by NERC uncovers the chemical and meteorological processes controlling the formation of particulate matter (PM) and secondary pollutants such as ozone (O_3). Past research on PM formation has meant the impacts of interventions on future air quality can be made with high confidence. NERC also supports an outdoor air pollution measurement capability for the UK that includes consistent long-term data sets of outdoor air pollution, 'supersites' (see Figure 1) that provide detailed measurements of air pollution composition, networks of low-cost sensors that provide dense geographical coverage, airborne measurements from research aircraft, and access to satellite-derived data of key pollutant concentrations across the UK. These different types of measurements are important for identifying emerging pollutants, evaluating the effectiveness of interventions on different sources of pollution, and understanding long-term changes in air pollution at a national scale.

Source: National Centre for Atmospheric Science

Figure 1: Manchester Air Quality Supersite

Air pollution measurement data is integrated into different models, supported by NERC, which range from collaborations with the UK Met Office on the interactions between weather and air quality that affect air quality forecasts, through to integrated modelling and assessment of the impacts of air pollution and climate change on human health and ecosystems.

The combination of computer models and air quality sensors has been used by the UK's national institute for AI and Data Science, the EPSRC-funded Alan Turing Institute,[8] in partnership with Lloyd's Register Foundation, to forecast London's air quality.[9] Nightly, short-term air pollution forecasts can then be shared with Londoners via an app, providing insights on when and where to travel to limit pollution exposure.

Research supported by ESRC is linking movement, travel, air pollution and sustainability in cities. The ESRC-funded Urban Big Data Centre (UBDC), is a research centre and national data service that generates insights to improve social, economic and environmental wellbeing in cities using new and emerging forms of data. In using such data, the UBDC has opened up possibilities for near-real-time analysis of city movement. They have developed a range of innovative tools that will contribute to better understanding of travel behaviours in cities and the impact of that movement on carbon emissions, air pollution, urban planning and sustainability. In addition, low cost and wearable sensors to measure personal exposure to air pollution[10] have been developed through support from NERC and MRC, and the SPF Clean Air Programme is supporting the development of models to assess personal exposure to air pollution[11] based on behaviour and concentrations in micro-environments (e.g. public transport).

For indoor air pollution, there is a paucity of data on sources and emissions, especially in homes, which are heterogenous and difficult to access for research. Through the SPF Clean Air Programme, researchers will use analytical methods and develop unobtrusive ways to collect detailed information on air pollution composition indoors[12] to fill this knowledge gap and determine reasons for ill health. The research will also explore how behaviours affect air pollution production and exposure. To study aerosols in different indoor environments, the EPSRC-funded Chamber for Environmental Control of Airborne Microorganisms[13] will allow scientists to pave the way for improved air quality through enhanced building design and ventilation. From late 2022, this facility will provide new insights into how ventilation and room layouts change how aerosols spread and deposit on to surfaces. It will help develop new solutions to mitigate indoor air pollution, such as better design of air conditioning units and drainage systems.

Air pollution health effects, toxicology and epidemiology

The MRC Toxicology Unit[14] explores fundamental and applied toxicological challenges and advances the mechanistic links between adverse outcome and exposures, including environmental factors. Understanding the adverse health effects on the lungs linked to short and long-term environmental exposures, including $PM_{2.5}$ and PM_{10}, is an important aim of the unit. Also, the UKRI SPF Clean Air Programme funded a toxicology research platform to identify the most hazardous components of air pollution to health.[15] A recent report by the Clean Air Programme on air pollution toxicology[16] highlights the importance of this type of research and the current gaps in our knowledge.

The MRC Centre for Environment and Health[17] takes a multidisciplinary and systems approach to gain insights into how air pollution causes health harms, to inform policies and practice. The centre takes advantage of its extensive cohort resources as well as the UK Biobank (partly funded by MRC) and uses multi-omic technologies to improve understanding of the environmental causes of non-communicable disease. It also works to identify downstream molecular signals and biomarkers of exposures, with a focus on the critical periods of life, such as in utero and childhood/adolescence and vulnerable populations. The links between air quality as a risk factor in the exacerbation of airborne microbes and infectious disease is an important area of research supported by MRC, brought to prominence by the observed correlation between air pollution and COVID-19 related deaths during the pandemic.

Tracing pollution particles on their journey from the wider environment, through an individual person down to the cellular level is an outstanding problem. It is a challenge that has the potential to shed light on how pollutants interact with cells and tissues, what the possible damage is, and how this relates to health outcomes. Funded through the Physics of Life Programme, health assessment across biological length scales for personal pollution exposure and its mitigation (INHALE)[18] is assessing how pollution affects personal health in urban environments (including schools) and how interventions, such as green infrastructure, can reduce exposure to pollutants and minimise public health impacts.

The integration of environment, health and social data for epidemiological studies is supported by NERC, MRC, ESRC and others. ESRC is the primary funder of Understanding Society,[19] the UK household longitudinal study that collects data on tens of thousands of households every year, including information about health conditions, modes of transport, and will include energy use in the future. The data can be analysed at different geographic scales and through different social lenses. When combined with air quality data, it can help to understand what social factors lead to air pollution and the links between pollution and health outcomes. Research on health inequalities linked to air pollution is a new area of research supported by UKRI. A new UKRI SPF Clean Air Programme project will work with children in ethnic minority and disadvantaged communities, seeking to improve outcomes linked to air pollution for people with asthma.[20]

Rapid urbanisation across the globe is recognised as playing a critical role in shaping population exposure to environmental hazards, including poor air quality in high-income, and more noticeably, in low-income countries. To understand pathways of urban environmental exposure in human health, MRC and NERC have partnered with local funders to support studies in Indian and Chinese megacities. Work includes identifying components of air pollution associated with non-communicable diseases, and their exacerbation, while focusing on the most vulnerable populations.

Source: Thomas Angus, Imperial College London

Figure 2: Researchers in the laboratory at the MRC Centre for Environment and Health, Imperial College London

Evaluating the impact of interventions to reduce and remove air pollution

Research supported by MRC, NERC and ESRC has supported local government to develop clean air public health policies. Modelling by the MRC Centre for Environment and Health supported the recent expansion of the Ultra Low Emission Zone (ULEZ) in London. The ULEZ continues to be used to study the health impacts of air pollution, applying these results to predict the effect of clean air zones across UK cities. The West Midlands Air Quality Improvement Programme is working with local authorities to quantify potential air quality benefits of active travel policies. The ESRC Centre for Climate Change and Social Transformations (CAST)[21] is collaborating with Cardiff City Council on low-carbon behaviours and air pollution. MRC coordinates the UK Prevention Research Partnership, a multi-funder initiative that supports novel research into the primary prevention of non-communicable diseases (NCDs) to improve population health and reduce health inequalities. Research to improve the urban environment, including transport systems and air quality is exemplified by investment in community innovation to maximise the contribution of urban green and blue spaces to the primary prevention of NCDs.[22]

Sustainable transport, including decarbonisation and air quality impacts, is a major area of investment for EPSRC, supporting diverse work across road, marine, rail and air transport. For example, EPSRC's Network Plus in Decarbonising Transport is tackling problems across whole system approaches to electrification,[23] hydrogen-fuelled transportation,[24] freight transport,[25] aviation,[26] and transport networks.[27] Across UKRI, the Faraday Institution[28] is investing in future battery technologies. During the COVID-19 pandemic, UKRI supported research to link air pollution data to measures of mobility, to understand how lockdowns affected air quality. This research will be used to learn lessons on how to implement air quality policy to best promote and achieve healthy mobility patterns to support a green recovery.

To develop cleaner products and services, Innovate UK has supported businesses that reduce tyre wear,[29] provide clean gas engines for use on construction sites,[30] and reduce use of fuel in refrigerated transport.[31] These products are now flourishing in the marketplace and attracting international partnerships.

By 2050, how do we develop cities with no air pollution and no heat-island effect? This was the central question of the EPSRC-funded Managing Air for Green Inner Cities project.[32] The project brought together computer models and air quality sensors with a management and decision support system with the aim of allowing a city to manage its air so that it can become its own heating, ventilation, and air conditioning system. This will help cities eliminate harmful pollution while providing cool air at a low energy cost, improving health and comfort.

The air pollution emitted by transport and energy generation is influenced by technical details, and also by user behaviour and wider socio-cultural factors. The UK Energy Research Centre[33] has developed a strategic transport, energy, emissions, and environmental impacts systems model[34] that incorporates technical details and wider factors such as policy influences on energy demand reduction, external costs, and local air pollution emissions. These models have been used to explore the alternative transport futures and policies that will be required to meet air quality targets and net zero requirements. In addition, research supported by ESRC considers public behaviours and people as agents of transformation in everyday life. The ESRC Centre for Climate Change and Social Transformations (CAST)[21] provides insight into sustainable habits and low carbon patterns of behaviour. In exploring travel behaviours, particularly our reliance as a society on planes and cars, CAST research suggests that changing the way we travel has the potential to benefit our health – in reducing air pollution experienced by families that live in cities, and from increasing physical activity through walking and cycling.

Indoors, fluid dynamics and aerodynamics are critical in proposing interventions that reduce air pollution, providing insights from flow around small objects in rooms to the global trajectory of atmospheric pollution. The UK Fluids Network,[35] supported by EPSRC[36] includes groups working on low-energy ventilation and urban fluid mechanics. These groups focus on developing and enabling ventilation strategies for modern buildings, understanding the flow of air and pollutants around buildings, quantifying the effect of pedestrians and vehicles on air flow, and the exchange of indoor and outdoor air, all with the aim of better controlling air flows and improving air quality. Innovate UK is also supporting innovations for the consumer market that will help householders to visualise and mitigate indoor air pollution risks in the home.

Public engagement activities supported across UKRI use citizen science[37] and art-based playful approaches[38] to raise awareness of the largely invisible hazard of air pollution. The UKRI SPF Clean Air Champions also support the national Clean Air Day campaign[39] and have an active workstream on engaging with health professionals as advocates.

Working with national governments, research funded by the SPF Clean Air programme is exploring forthcoming policy initiatives for their consequences (intended or unintended, positive or negative) on air quality. The ANTICIPATE[40] (Actively anticipating the unintended consequences on air quality of future public policies) project has developed a policy briefing that offers recommendations to avoid or mitigate air quality impacts associated with the NHS App.[41]

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8.2 National Institute for Health and Care Research (NIHR)

Jasmine Parkinson and Charlotte Hall – NIHR

The Department of Health and Social Care (DHSC) funds research to understand and reduce the public health risks associated with air pollution. The research portfolio is delivered through long-standing National Institute for Health and Care Research (NIHR) programmes, and in collaboration with other funders, principally the UK Research and Innovation (UKRI) Strategic Priorities Fund (SPF) Clean Air Programme, as discussed in Section 8.1.

Air pollution health effects, toxicology and epidemiology

The NIHR has funded two waves of Health Protection Research Units (HPRUs)[1] since 2014 to inform government health policy in a number of areas, including the health impacts of air pollution. Researchers at the NIHR HPRU in Environmental Exposures and Health[2] based at Imperial College London, and the UK Health Security Agency (UKHSA), are determining human exposure to chemicals, particles and biologicals and their associated hazards using some of the most advanced biological and biophysical methods available. Using this information in mathematical and epidemiological models enables researchers to make more accurate predictions about the wider UK population's risk from pollution – mainly from air, but also land and water. This HPRU works with King's College London and the Medical Research Council (MRC) Toxicology Unit as well as with the MRC Centre for Environment & Health and the HPRU in Chemical and Radiation Threats and Hazards.

To better understand the effects of air pollution on morbidity, the NIHR HPRU in Environmental Exposures and Health is investigating the impact of air pollution on health across the life course.[2] This includes adverse birth outcomes, early life cognitive development (also being investigated by the NIHR HPRU in Environmental Change and Health[3] based at the London School of Hygiene & Tropical Medicine and UKHSA), adult mental health,[4] and dementia risk in the elderly. The impact of air pollution on cellular processes within the body and the causal pathways that link air pollution and disease outcomes are also being investigated to identify potential biomarkers of human exposure and disease outcome. Recent research supported by the NIHR Maudsley Biomedical Research Centre (BRC)[5] and Applied Research Collaboration (ARC) South London, has shown that UK adults exposed to high levels of traffic-related air pollution over a long period of time are more likely to experience mental health disorders such as depression and anxiety.[6]

For indoor air pollution, working in partnership with UKHSA and the Health and Safety Executive (HSE), researchers at the University of Leicester are addressing the lack of information on exposure to less well-studied indoor air pollutants, as part of an NIHR HPRU development award. These include carbon monoxide and volatile organic compounds (VOCs). Research is also underway to better characterise bioaerosols in both indoor and outdoor built environments and investigate associations with health outcomes.

Impact of air pollution interventions

The effectiveness of current air quality interventions in improving public health is being investigated by a collaborative study led by Queen Mary University of London. The Children's Health in London & Luton or 'CHILL' study[7] has recruited more than 3,000 primary school aged children and will record their height, weight, and lung volume, over a 5-year period. Researchers at Imperial College London are monitoring how much air pollution each child is exposed to and will link this to their health records to determine how often they experienced respiratory illnesses. The lung growth and health data will be compared for children living inside (London) or outside (Luton) of London's Ultra Low Emission Zone (ULEZ) to investigate if the ULEZ is influencing lung development and respiratory health in children growing up in high-traffic urban environments. The study results are anticipated in 2024.

Source: Children's Health in London & Luton (CHILL) study

Figure 1: Assessing lung function of a young participant using spirometry in the CHILL study

To evaluate how the introduction of Bradford's Clean Air Zone (CAZ) has affected air quality and health in the city, (as discussed in Section 6.2), the NIHR is funding the Born in Bradford research programme at Bradford Teaching Hospitals NHS Foundation Trust.[8] The city's schools will participate in air quality data collection before and after the introduction of the CAZ, including sampling by 240 school children using mobile air quality sensors. Air quality data will be linked to health datasets for more than 500,000 Bradford residents to assess the impact of the CAZ on lung and heart health and birth outcomes across the city. The team will also examine whether the impact differs based on ethnicity or socio-economic background, and they will assess the cost-effectiveness of the scheme. This research study is expected to finish in 2025.

The Places & Communities Programme,[9] funded through the NIHR School for Public Health Research (SPHR), has been investigating the impact of place-centred public health initiatives such as the development and implementation of 'School Superzones' in Local Authorities in London,[10] as well as studying the impact of environmental pollution on young people's mental health. The programme has also been funding research to investigate the health impacts of Road User Charging policies,[11] and understand public perspectives on approaches to promote alternatives to car use.[12] The NIHR SPHR's new Healthy Places, Healthy Planet Programme[13] will build on this research over the next five years to consider the wider issues of planetary health, the environment and human health.

For agricultural air pollution, the AMPHoRA study[14] led by the UK Centre for Ecology & Hydrology, and the AIM-HEALTH study[15] led by the Institute of Occupational Medicine, will assess the public health benefits and cost-effectiveness of interventions to reduce air pollution from agricultural sources. These awards are expected to complete in 2024.

Considering the impacts of net zero policies, research led by Imperial College London, which builds on previous NIHR-funded research, is modelling the air quality, health, and economic impacts of possible interventions to achieve the UK's net zero target. The net zero policy scenarios have been identified by the Climate Change Committee,[16] a project collaborator and the UK's independent adviser on tackling climate change. In consultation with the public, the research team will model policies that have strong public support and are likely to affect air pollution – from transportation and logistics, to how we cook our meals and heat our homes.

The NIHR has also been supporting air pollution research in low- and middle-income countries (LMICs). For example, the NIHR CLEAN-Air (Africa) Unit[17] is focusing on household air pollution related disease burden, with the aim to strengthen community prevention of related disease and provide evidence for the transition to clean household energy. Other NIHR Units and groups have been examining air pollution as a risk factor as part of a broader focus on chronic respiratory diseases in LMICs. The NIHR-funded Global Health Research Group, Achieving Control of Asthma in Children in Africa (ACACIA),[18] has developed a low-cost, school-based intervention aimed at addressing the barriers to good asthma control among children in Africa. In Asia, the NIHR Global Health Research Unit on Respiratory Health (RESPIRE-2)[19] is looking to develop an air pollution 'early warning system' to help individuals with respiratory conditions in LMICs improve their health and quality of life.

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8.3 Department for Environment, Food & Rural Affairs (Defra)

John Newington – Deputy Head of Air Quality & Industrial Emissions, Defra
Shaun Brace – Air Quality & Health lead, Air Quality & Industrial Emissions, Defra

To meet the statutory responsibility to safeguard outdoor air quality, the Department for Environment, Food & Rural Affairs (Defra) set out their ambition in the Clean Air Strategy and the National Air Pollution Control Programme.[1] This is currently under review, and a consultation was undertaken between 25 July and 4 September 2022.[2] The department invests in a core evidence base, as part of delivering emission reductions across different sectors, through policy development, and by collaborating with other government departments and stakeholders. On top of statutory requirements, Defra invests in research, development and innovation to address evidence gaps identified in the department's Areas of Research Interest,[3] and evaluates the effectiveness of interventions and new abatement technologies. This investment underpins wider research, including projects within the UK Research and Innovation (UKRI) Clean Air Strategic Priorities Fund research programme.

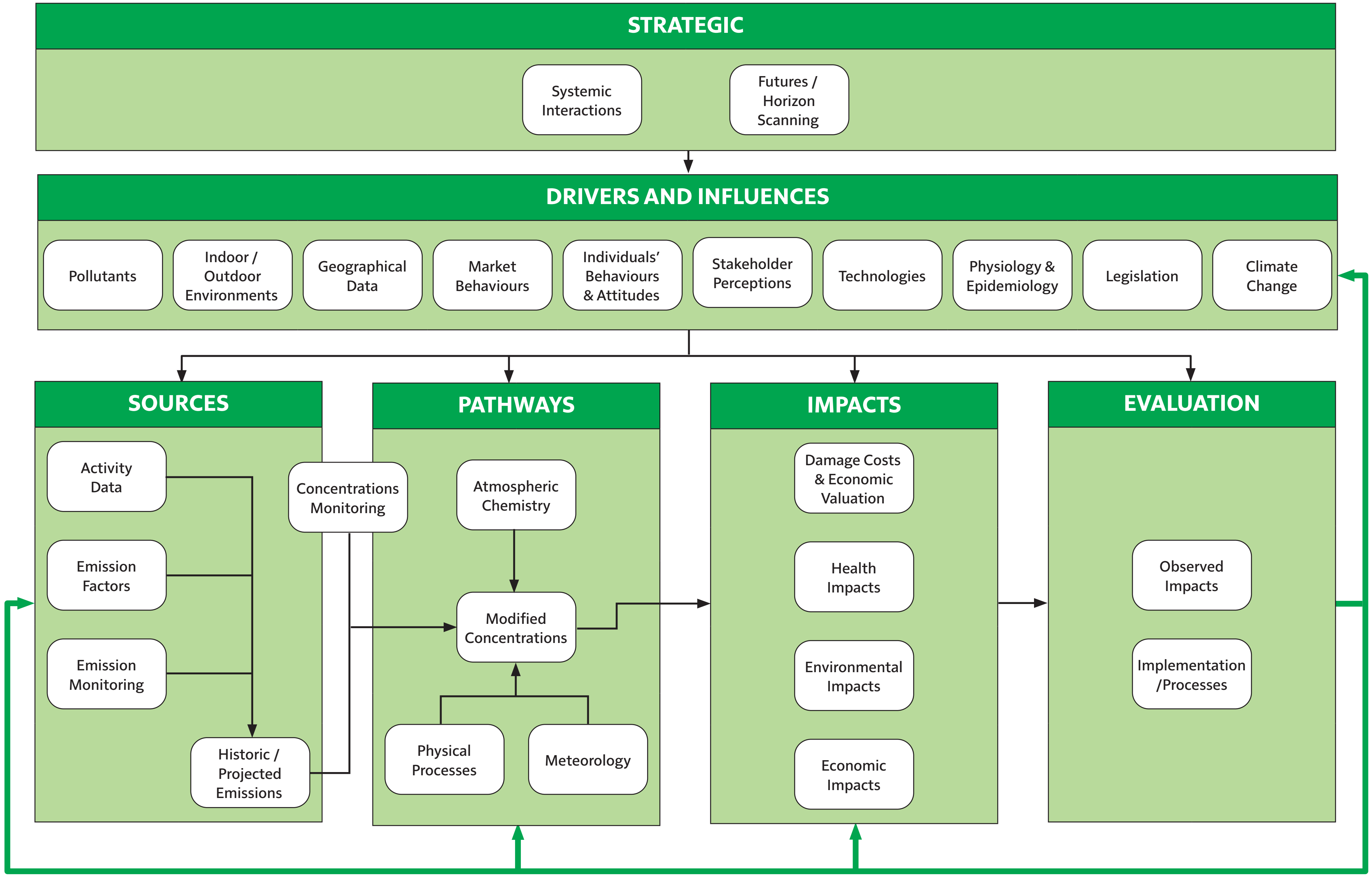
Defra provides funding and secretariat support for their independent Air Quality Expert Group (AQEG),[4] which publishes advice, guidance and in-depth reports on challenging scientific issues. Their highly cited work supports research in this field. They also fund a Knowledge Exchange Fellowship with the National Centre for Atmospheric Science, sit on the Steering group for UKRI's Clean Air Strategic Priorities Fund, fund a PhD and support early career scientists through placements and internships. Defra are committed to expanding this support for early career scientists.

Assessment of air quality across the UK

Defra's air quality evidence landscape is described by the framework in Figure 1 and the Areas of Research Interest report[2] highlights aspects of this system where further research would help to meet Defra's evidence needs.

To assess current pollutant concentrations against legal requirements across the UK, Defra invests in and uses a combination of a national monitoring networks and a compliance model called the Pollution Climate Mapping model (PCM). There are 14 national networks, with more than 500 individual monitoring sites. This statutory monitoring also provides added evidential value and supports a range of UKRI-funded research and development work.[5] Compliance against pollutant concentrations across the UK are annually reported in the Air Pollution in the UK report[6] and the compliance data is published on the UK-AIR website.[7]

To support Defra's ability to meet new targets for $PM_{2.5}$ introduced by the Environment Act 2021, the department has invested to expand $PM_{2.5}$ monitoring. Continued investment will mean that by end of 2025, this will at least double the size of the current $PM_{2.5}$ monitoring network.



Source: Defra

Figure 1: Defra Air Quality Evidence Framework

A major element of Defra's core evidence is the award-winning National Atmospheric Emissions Inventory (NAEI).[8] This allows for statutory assessment of UK emissions to be carried out from different anthropogenic activities. The latest National Statistics[9] cover national emissions and trends of key air pollutants and are published annually. This work also provides an annual estimation of future emission projections, which sets out the trajectory for Defra's 2030 emissions reduction commitments. The latest projections can be found on the NAEI webpage.[10] The assessment of economic impacts follows the HMG Green Book[11] and uses damage costs[12] which Defra continues to invest in, to improve and update in line with the latest research.

Access to air pollution data and information

The UK-Air website provides a significant amount of data and information, including forecasting,[13] the latest local measurements from Defra's nationwide monitoring and local authority networks,[14] as well as health advice informed by the work of the Committee on the Medical Effects of Air Pollutants (COMEAP).[15] Defra is undertaking a major overhaul of the UK-Air website and other Air Quality Web services over the next 3 years. The department is also undertaking a comprehensive review of how air quality information is communicated and has established an expert steering group to guide this work.[16]

Defra also funds work to improve the department's communications, message content and empower key message providers. Recent examples include a series of pilot projects to investigate the effectiveness of training health professionals to deliver air quality information to patients and carers through a 'Clean Air Champions' model.

Air pollution innovation

A report commissioned by Defra in 2016 'Investigating the Feasibility of Innovative Technologies to Improve Air Quality Monitoring over the Medium to Long Term',[17] identified the potential for both satellite and low-cost sensors (LCS) to enhance the statutory evidence base and evaluation capability at a national and potentially local scale. To support new fit for purpose sensor technology come to market, Defra have invested in projects to look at the performance of LCS technologies, including lab-based and real-world trials.

In conjunction with the British Standards Institution, academia, industry and other government departments, Defra is developing a publicly available specification for the selection, use, operation and decommissioning of LCS in pollutant monitoring. This will explain how users of the sensors – from citizen scientists to local authorities – can ensure that they gather quality data that is fit for purpose. Public consultation of the draft will be completed in summer 2023.

In 2020/21, Defra funded a research and development project to explore whether satellites, Earth Observation (EO), could be used to evaluate the NAEI. The work provided further assurance that the NAEI reflects real world emissions in most cases, but has also helped identify several areas for improvement – for example, ammonia emissions from dairy and cattle farming. The promising role that EO data can play to strengthen our evidence base continues to be explored.

In 2022/23 to 2024/25, Defra will explore a collaboration with Innovate UK to run two Small Business Research Initiatives (SBRI) programmes[18] to stimulate and accelerate abatement innovation to reduce particle emissions from domestic combustion and ammonia emissions from agricultural practices including anaerobic digestion.

Air pollution interventions and evaluation

Defra provides grant funding to local authorities to carry out practical interventions and research. This funding seeks to help English councils develop and implement measures to benefit schools, businesses and communities and reduce the impact of polluted air on people's health.

To evaluate the effectiveness of interventions, Defra will develop an evaluation framework to help local authorities evaluate local schemes. This builds on Public Health England's 'Review of interventions to improve outdoor air quality and public health', published in 2019[19] and AQEG's 2020 report 'Assessing the Effectiveness of Interventions on Air Quality' which outlines best practice methods to effectively evaluate interventions.[20] Defra has also commissioned a comprehensive evaluation of the Domestic Solid Fuels Standards Regulations 2020, which will investigate the implementation and impact of the regulations.

The Joint Air Quality Unit (JAQU), a joint venture between Defra and the Department for Transport, has a comprehensive evaluation programme to evaluate the impacts of Local NO_2 Plans. Together with detailed case study assessments of individual plans and specific issues, this programme collects and analyses local air quality and traffic data to understand whether Local Plans are having the required effect. The second evaluation annual report was published in May 2022.[21] JAQU's work is discussed in Section 4.2.

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8.4 Department for Transport (DfT)

The Department for Transport (DfT) and its arm's-length bodies commission research to understand air pollution sources from transport, and the effect of interventions to reduce it. This research informs policy development and the operation and delivery of transport to reduce emissions and improve air quality for passengers and transport staff, alongside local communities.

Understanding of air pollution emissions from vehicles

DfT's research includes tracking how trends change over time with advances in vehicle technology. In February 2021, DfT's International Vehicle Standards division commenced a research project to better understand the measurement techniques, materials properties and control parameters of brake and tyre wear emissions from road vehicles. The project considers differences in particulate emissions from tyre and brake wear in battery electric, petrol and diesel vehicles. The project will report in 2023 and evidence will inform policy decisions and any potential legislation that may be required to control and reduce these emissions.

Impact of air pollution interventions – road, rail and maritime

DfT and its arm's-length bodies fund research to understand emissions interventions. In 2019, National Highways (formerly Highways England) concluded a wide-ranging research programme to explore opportunities to address poor air quality alongside the strategic road network. This work primarily examined nitrogen oxides (NO_x).[1] National Highways are reviewing individual road links with high air pollution concentrations continuously, to understand the most appropriate measure to be used in that location. For example, they are currently working with Birmingham University to research the movement of air flow in relation to the A3 in Guildford.

For rail, since 2018, DfT has invested in a programme of research delivered by the Rail Safety and Standards Board aimed at improving air quality across the railway through better monitoring, modelling and emission mitigation methods.[2] DfT has also funded an air quality monitoring network, working with the rail industry to monitor the impact of diesel trains on air quality in stations.[3] This is being rolled out in phases, with the first phase of monitors installed in more than 100 stations across England and Wales, and expanded to 9 stations across Scotland. Once fully established, this network will help to identify priority locations on the rail network where air quality improvements should be targeted to ensure cleaner and healthier travel for passengers and staff.

Through the Transport Research Innovation Grant, the Connected Places Catapult and DfT Accelerator, DfT is funding the company Pluvo to pilot their pioneering air filtration system on Birmingham New Street Station platforms.[4] This technology removes several pollutants, including particulate matter (PM), NO_x, sulphur oxides (SO_x) and ozone (O_3). There is also the potential that this technology could be used on the roadside in congested urban settings. This research will help to understand the potential to scale these technologies across the transport network.

For the maritime sector, to inform the development of the Clean Maritime Plan (CMP), the government commissioned a major programme of research related to reducing the maritime sector's contribution to climate change and air pollution.[5] Reports about this research were published alongside the CMP in 2019.[6]

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8.5 Department for Levelling Up, Housing and Communities (DLUHC)

This section provides examples of research that includes indoor and outdoor air pollution, commissioned by the current Department for Levelling Up, Housing and Communities (DLUHC) and its predecessors.

Ventilation and indoor air quality in new homes

The government commissions reviews and research to help inform the future development of the building regulations and associated guidance. Indoor air quality research was commissioned by the Department for Communities and Local Government, now DLUHC, to investigate ventilation and indoor air quality in 80 new homes during winter 2015/16. This study was undertaken by AECOM, supported by Four Walls Consultants Limited and Indoor Air Quality (IAQ) Consulting Limited. The primary aim was to evaluate whether the ventilation provisions recommended in the 2010 edition of the guidance on building regulations (Approved Document F) continued to provide satisfactory indoor air quality in new homes, in light of enhanced energy efficiency standards, as set out in the 2010/13 edition of the guidance (Approved Document L).

The main findings from the research are set out in the report 'Ventilation and Indoor Air Quality in New Homes' which was published in 2019.[1] Its findings have led to revisions to the building regulations guidance on ventilation. A new edition of Approved Document F was published in December 2021 and came into force in June 2022. This guidance includes a methodology that helps maintain adequate levels of ventilation when energy efficiency measures are installed, such as asking for trickle ventilators to be installed in replacement windows. A copy of the new publication 'Ventilation: Approved Document F Volume 1: Dwellings' is available on the government's website.[2]

Indices of Deprivation – including outdoor air quality

The former Ministry of Housing, Communities and Local Government, now DLUHC, commissioned Oxford Consultants for Social Inclusion (OCSI) and Deprivation.org to update the English Indices of Deprivation 2015. The Indices of Deprivation provide a set of relative measures of deprivation for small local areas across England, with the aim of encompassing a wide range of information on aspects of an individual's living conditions.

The main findings of the research are in 'The English Indices of Deprivation 2019 Research Report'.[3] The Living Environment Deprivation Domain measures the quality of the local environment. The indicators fall into two sub-domains: the indoors living environment measures the quality of housing; and the outdoors living environment includes measures of outdoor air quality. The air quality indicator is an estimate of the concentration of four pollutants – nitrogen dioxide, benzene, sulphur dioxide and particulates – and data was sourced from the UK-Air Information Resource.[4] A higher score for the indicator represents a higher level of deprivation.

More detail on how the air quality indicator was constructed and incorporated as part of the Indices of Deprivation can be found in 'The English Indices of Deprivation 2019 Technical Report'.[5] Data for small local areas is also available in map form.[6] The government aims to update the Indices of Deprivation every three to four years, but the dates of publication for future Indices have not yet been scheduled.

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8.6 Department for Business, Energy & Industrial Strategy (BEIS)

Peter Coleman – BEIS

The principal interest of the Department for Business, Energy & Industrial Strategy (BEIS) in air pollution research is to understand how air quality could be impacted by potential policy interventions to the industrial and energy systems of the UK to decarbonise society. The research informs policy development and innovation investment to improve outcomes for society. Research themes supported by BEIS are discussed below.

Air pollution and decarbonisation

A study, carried out by the Energy System Catapult, investigated energy system scenarios that could deliver the UK's previous target of an 80% reduction in greenhouse gas (GHG) emissions by 2050 and their the effect on UK air pollution emissions.[1] This study assumed that there were no developments in reducing the quantity of pollution per unit of energy consumed, and that non-energy emissions, such as from agriculture, were constant. Using the Energy Systems Modelling Environment (ESME) model, the research found that the lowest cost energy system to meet the GHG emission target delivered significant reduction in air pollution emissions. Also, the existing air quality emission targets for 2020 and beyond could support decarbonisation.

Hydrogen economy

Expanding the use of hydrogen is widely thought to have a potentially significant role in decarbonising energy use. While hydrogen leakage (fugitive emissions) would be minimised for economic and safety reasons, fugitive emissions would increase if there was significantly increased consumption of hydrogen as a fuel. BEIS is therefore developing a programme of evidence for a robust assessment of the atmospheric impacts of hydrogen.

Using hydrogen to power fuel cells will not result in significant air pollution emissions. However, when hydrogen is burnt, as with other combustion processes, there is likely to be emissions of nitrogen oxides (NO_x), but a reduction in emission of carbon dioxide, carbon monoxide and volatile organic compounds compared to combustion of natural gas. When compared with coal combustion, there will also be reductions of primary particulate matter and sulphur dioxide emissions. Our work supports hydrogen policy teams developing standards for domestic and industrial appliances for hydrogen combustion, to ensure that the NO_x emissions are no higher than from the current natural gas appliances.

Hydrogen in the atmosphere can act – by changing atmospheric composition – as an indirect GHG. BEIS commissioned a literature review of the atmospheric impacts of hydrogen emissions to quantify this effect. This review concluded that hydrogen could act as an indirect GHG through increasing the lifetime of methane in the atmosphere, but that the literature quantifying this impact used older climate models.[2]

BEIS funded a study from the University of Cambridge to use current scientific understanding and modern global climate models to examine the atmospheric impacts of hydrogen emissions.[3] This study established that the potential impacts of the hydrogen economy on the atmosphere are a function both of the extent of emissions (which can be reduced through effective fugitive emission control) and how hydrogen is used. The findings also indicated that hydrogen emissions would have trivial impacts on stratospheric ozone recovery but would increase regional concentrations of tropospheric ozone. BEIS are now working with the Natural Environment Research Council (NERC) on projects to deepen our understanding of the environmental impacts of hydrogen.

Future work

Increased deployment of anaerobic digestion to deliver biomethane could, if poorly implemented, lead to pressure on ammonia emissions, water quality, and plastics entering the environment. BEIS has commissioned the Waste and Resources Action Programme (WRAP) to carry out a review of the technoeconomic options to reduce these pressures, expected to be published in 2023. BEIS also commissioned three short literature reviews of the air pollution impacts of developments in the energy system. These are reviews of the air pollutant emissions from using hydrogen as a diesel replacement, from the combustion of future fuels for aviation and a review of biogenic air pollution emissions from different tree and energy crop planting. The reviews are expected to be published by the end of 2022.

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8.7 Wellcome

Irini Pantelidou – Research Manager, Climate and Health, Wellcome Trust

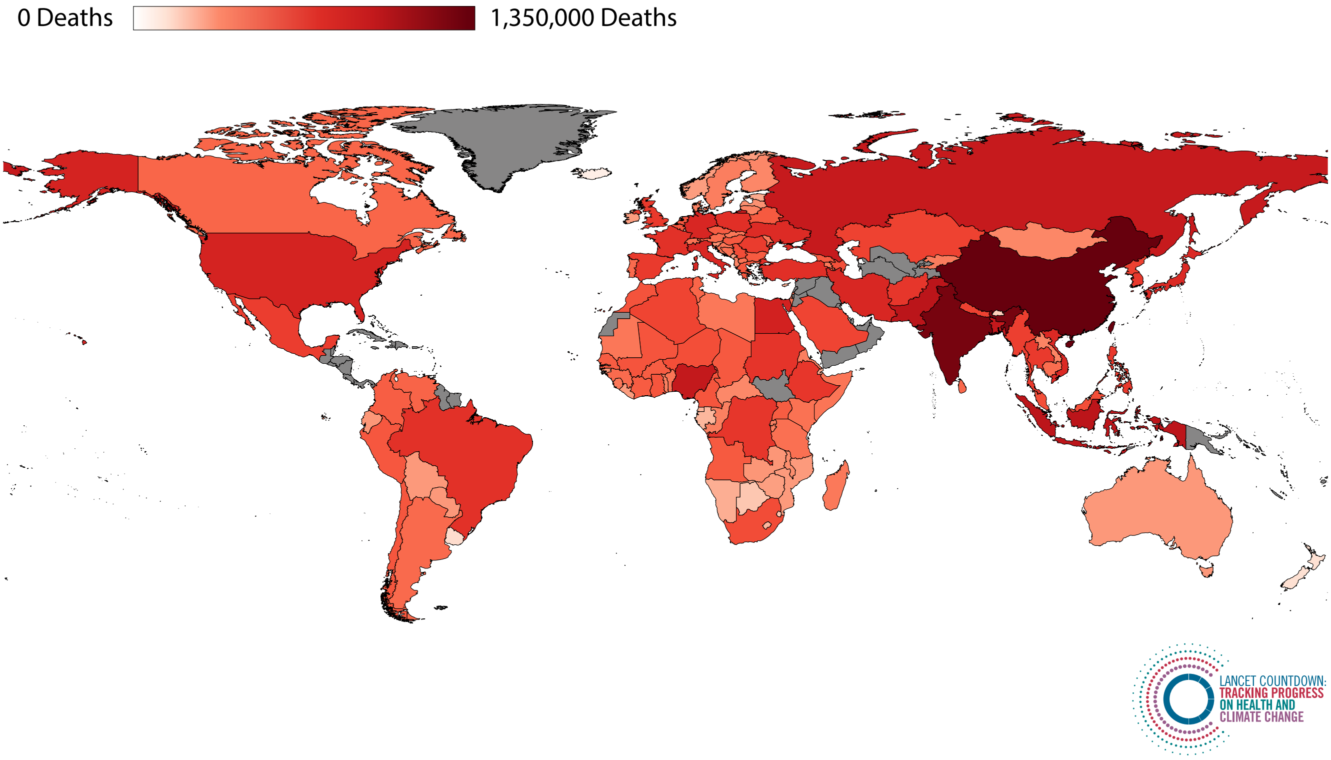
Wellcome[1] is a global charitable foundation that supports discovery research into life, health and wellbeing, and is taking on three worldwide health challenges: mental health; infectious disease; and climate and health.

Wellcome has a history of funding research into climate-related challenges, including air pollution. Between 2015 and 2020 research was funded under three themes: climate change; food systems; and cities. The latter involved the development of tools and metrics to enable policymakers to model and assess the health impacts of environmental sustainability strategies in areas including housing, transport, and infrastructure. Wellcome's air pollution research funding was linked to our cities portfolio. Some specific examples of Wellcome's historical portfolio of relevant funded projects are described below.

The Complex Urban Systems for Sustainability and Health (CUSSH)[2] project led by University College London (UCL) led to the development and application of models for specific policies on human health and sustainability in the target cities. This is to help policymakers understand how the choices they make can benefit the environment and human health. These include:

- The Cities Rapid Assessment Framework for Transformation (CRAFT) tool[3] investigates the connections between climate change policies and determinants of health, including air quality. It provides quantitative estimates of the health impacts of city policies in reducing greenhouse gas emissions, decreasing health hazards and improving public health, helping to support and prioritise policy actions. To date the tool has been applied to London in the UK and Rennes in France.
- The Greenhouse Gas – Air Pollution Interactions and Synergies (GAINS) model generates first source apportionment estimates of ambient fine particulate matter ($PM_{2.5}$) for cities. So far it has been applied in the analysis of waste management options in Kisumu, Kenya[4] and air pollution co-benefits of greenhouse gas mitigation in Beijing, China.
- The MicroEnv[5] microsimulation model aims to quantify the health impact of multiple environmental risks at high spatial resolution and aid the uptake of policies likely to have the greatest potential benefit to health. This tool has been applied to an assessment of the impact of air pollution on health in London, and can be adapted to cities in different contexts, where underpinning data is available.

The Lancet Countdown led by UCL tracks the relationship between health and climate change across 5 key domains and over 40 indicators, including: exposure to air pollution in cities; premature mortality from ambient air pollution; and the economic costs of the health impacts of air pollution. The sixth annual report[6] published in October 2021 highlighted that, globally, 3.3 million deaths were attributable to ambient $PM_{2.5}$ pollution from human sources in 2019. It also revealed that countries from the medium and high Human Development Index groups had the highest mortality rates.[7] Findings from the work are shown in Figure 1.



Source: 2021 Report of the Lancet Countdown[7]

Figure 1: Deaths attributable to exposure to $PM_{2.5}$ ambient air pollution in 2019

C40 and George Washington University have led the development of tools to help large cities incorporate air pollution and health into their climate action plans (CAPs). The Pathways–Air Quality scoping tool[8] and related instruments allow city staff to test complex climate change mitigation scenarios, projecting emissions, local air quality, and public health impacts. Working directly with cities, C40 has used these tools to inform climate action – often over months-long processes involving collaborative data gathering, scenario planning and analysis, refinement of air quality and health benefits estimates, and discussion of policy implications.

The University of Cambridge, Vivid Economics and Planetrics have conducted an economic analysis to estimate the extent to which a carbon price on energy could transform road transport, by increasing active travel, including the use of public transport, and bringing benefits to both the climate and health. The modelling assesses health determinants such as physical activity, air pollution and traffic injuries, and consequent health outcomes including body mass index, and mental health and wellbeing.

The Clean Air Fund has published research[9] into how air pollution is perceived by more than 1,000 healthcare professionals in the UK, Bangladesh, India, Ethiopia and Mexico. Findings show that, while the majority of healthcare professionals agree that they have the ability to do more about air pollution, they have not engaged with policy, public health officials or campaigns to exercise their influence. Barriers include lack of prioritisation, lack of access to information on long-term impacts of air pollution, and cultural barriers. There are opportunities in mobilising the health sector to take greater action on air pollution, including through providing credible data for action, communication and campaigns to prioritise air pollution as a health issue.

Internationally, Wellcome-funded research has been generating knowledge, tools and frameworks to better quantify the effects of climate change on air pollution, and its health effects. The Pathways to Equitable Healthy Cities project led by Imperial College London has conducted the largest air and noise pollution measurement campaign in a Sub-Saharan African city which will allow for an assessment of both the temporal and spatial variability of pollution in Accra, Ghana and serve as a prototype for other cities in Sub-Saharan Africa.[10] Yale University is researching how air pollution and weather are associated with health effects in major Brazilian cities and evaluating how climate change policies could affect air quality in the short term.

The Urban Health in Latin America project[11] led by Drexel University has built a dataset of 371 cities with more than 100,000 inhabitants in 11 Latin American countries to look at how urban environments and urban policies affect the health of city residents throughout Latin America. One of the outputs includes a study on green spaces, air pollution, and climate-related heat mortality in Latin American cities. The study examines the associations between extreme heat events and excess mortality in cities, and how air pollution and green spaces affect the outcomes. The study is due to report in 2022.[11]

A Wellcome-funded study at George Washington University led to the creation of the Clean Air, Healthy Planet[12] framework for integrating air quality management and climate action planning at the city level to meet local air quality goals while improving quality of life for residents. The 9-step framework includes assessing existing data, developing planned and ambitious policy scenarios, ranking multiple benefits, prioritising actions, and developing an integrated plan.

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