Logika Noise
Air Quality
CONSULTANTS

70 years since the great London smog

1952 air quality in a modern context

A report for the Greater London Authority

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1 Introduction

December 5th, 2022 marks the 70th anniversary of the start of the Great London Smog of 1952 which lasted for five days and led to an estimated 4,000 excess deaths during that month. The smog (a combination of smoke and fog), caused mainly by coal burning from domestic fireplaces, power stations and furnaces, led to the introduction of the Clean Air Act of 1956, a pivotal change in the application of pollution control policies in the UK. The Act allowed, for the first time, local authorities to declare smoke control areas, and introduced grants to help people convert their fireplaces. It also controlled dark smoke emissions from factories and furnaces and laid the foundation for future pollution control measures such as the Clean Air Act 1968, and the Environment Act 1995.

This report describes the air quality issues we faced in 1952, the evolution of pollution sources associated with the change in residential heating and the growth in road traffic, and the issues we still face in 2022. It then considers what air quality in London could look like if the Clean Air Acts had not been introduced. Finally, it looks to the future and considers what issues are emerging and what still needs to be done to reduce pollution emissions and improve public health.

2 Air pollution then and now

Historical Emissions and Concentrations

Historically, air pollution was very different to what we experience in London today. Complaints were first recorded hundreds of years ago when coal burning was first introduced into London, and from the mid-19th century smogs were a common event in large British cities during the winter months. In 1952, coal combustion from domestic fireplaces, power stations and industrial furnaces was the main source of pollution, with smoke and sulphur dioxide being the principal pollutants of concern. During the period of the Great London Smog, daily average sulphur dioxide concentrations were in the range of 3,000 to 4,000 $\mu g/m^3$ on three consecutive days[1] (the current WHO air quality guideline is 40 $\mu g/m^3$), and daily smoke (fine particulate matter) concentrations[2] were measured at 490 $\mu g/m^3$ on December 4th, rising to 4,460 $\mu g/m^3$ on December 7th and 8th (compared to an current legal limit value of 50 $\mu g/m^3$, not to be exceeded more than 35 times per year).

Trends in Emissions and Concentrations

Concentrations of sulphur dioxide and black smoke were measured as part of the UK air quality monitoring Networks over many years, and the trend over the period 1962-1982 (when the site was operational) is shown for a site in Westminster in Figure 1.

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[1] QUARG (1993) Urban Air Quality in the United Kingdom.

[2] Wilkins, E.T. (1954). Air pollution and the London Smog of December 1952. *J R Sanit Inst 1954, 74(1)*

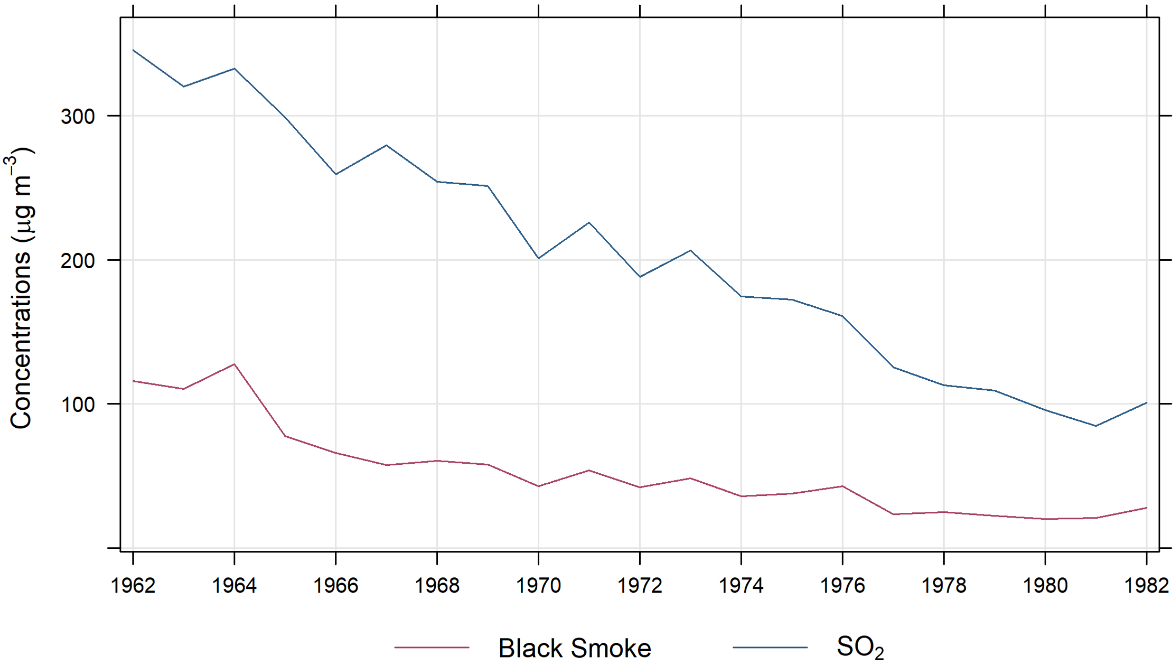
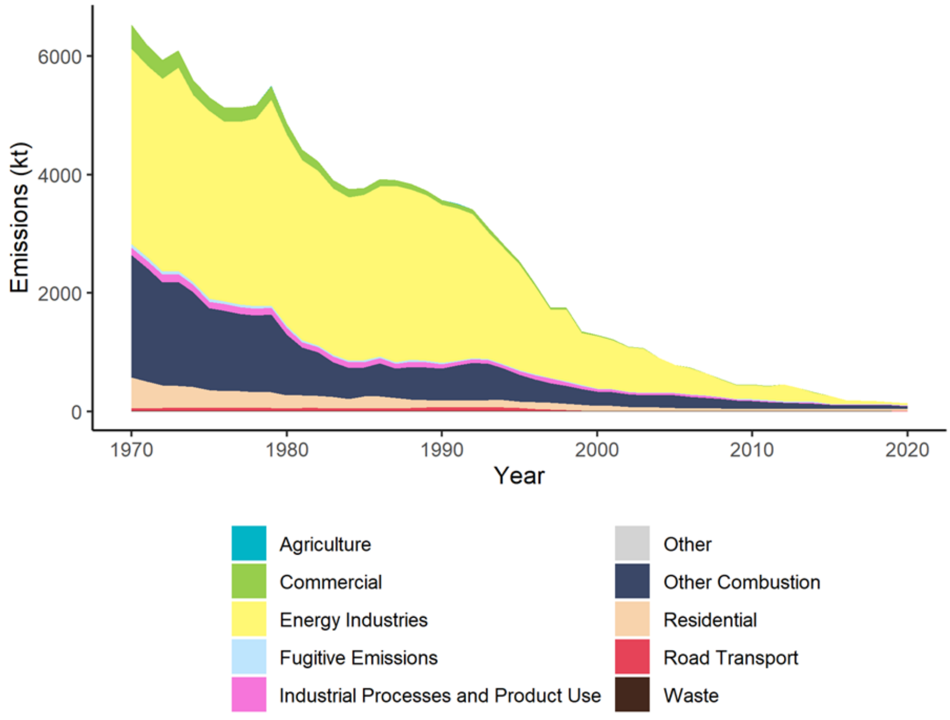


Figure 1: Trend in Annual Mean Black Smoke and Sulphur Dioxide Concentrations at Westminster 7 (1962-1982). Source: uk-air.defra.gov.uk

Concentrations of both sulphur dioxide and smoke reduced dramatically from the mid-1960s onwards. This improvement was brought about by the use of cleaner fuels (such as gas), the progressive closure and relocation of power stations in London, and the overall decline of heavy industry.

Emissions causing air pollution problems in London have now changed considerably, and with the shift from solid fuel burning to gas, the principal source of pollution in London in recent years is now road traffic, contributing 49.1% of all NOx emissions and 34.2% of all $PM_{2.5}$ emissions in London in 2019.

Figures 2 to 4 show the national trends in sulphur dioxide, fine particulate matter (as $PM_{2.5}$), and NO_x (nitrogen oxides) emissions by sector since 1970 to 2020.



Note: “Other” is defined in the NAEI as any sources that are not specifically defined in NFR Codes 1-5. “Other Combustion” includes manufacturing industries and construction, other minor sectors (such as agriculture and fishing) and fugitive emissions from fuels.

Figure 2: Trends in UK Sulphur Dioxide Emissions 1970-2020 (Source: UK National Atmospheric Emissions Inventory (NAEI))

Total emissions of sulphur dioxide (kilotonnes per annum) have declined dramatically since 1970, principally from the Energy Industries sector ((which have been largely located outside of London). However, there has also been a continuing downward trend in emissions from the Residential sector, with emissions falling from 521 kt in 1970 to 43 kt in 2020[3] and associated with the shift from solid fuel combustion to gas.

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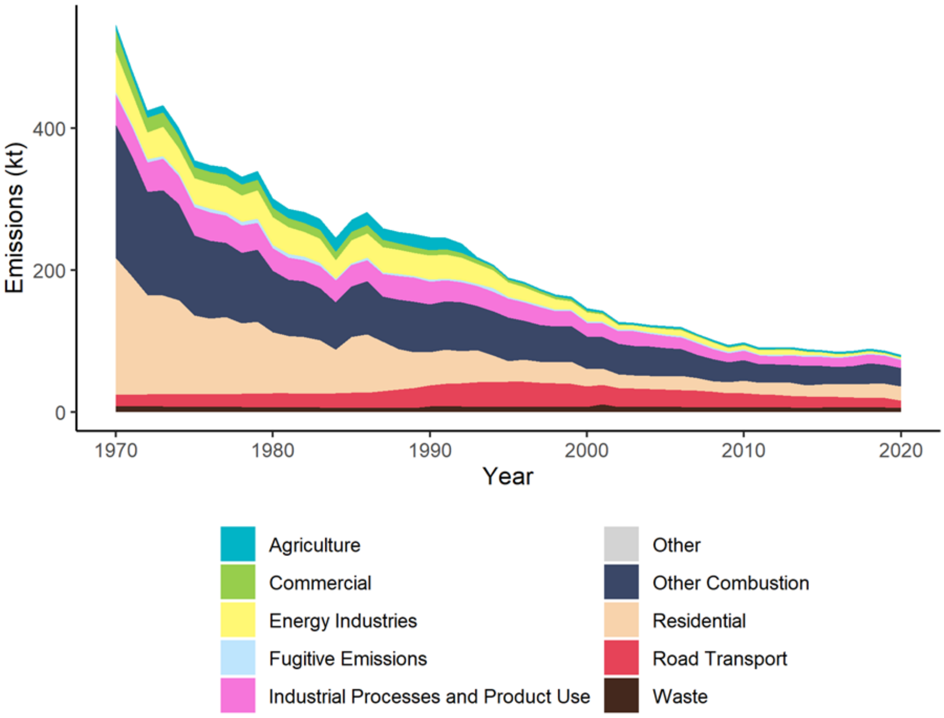
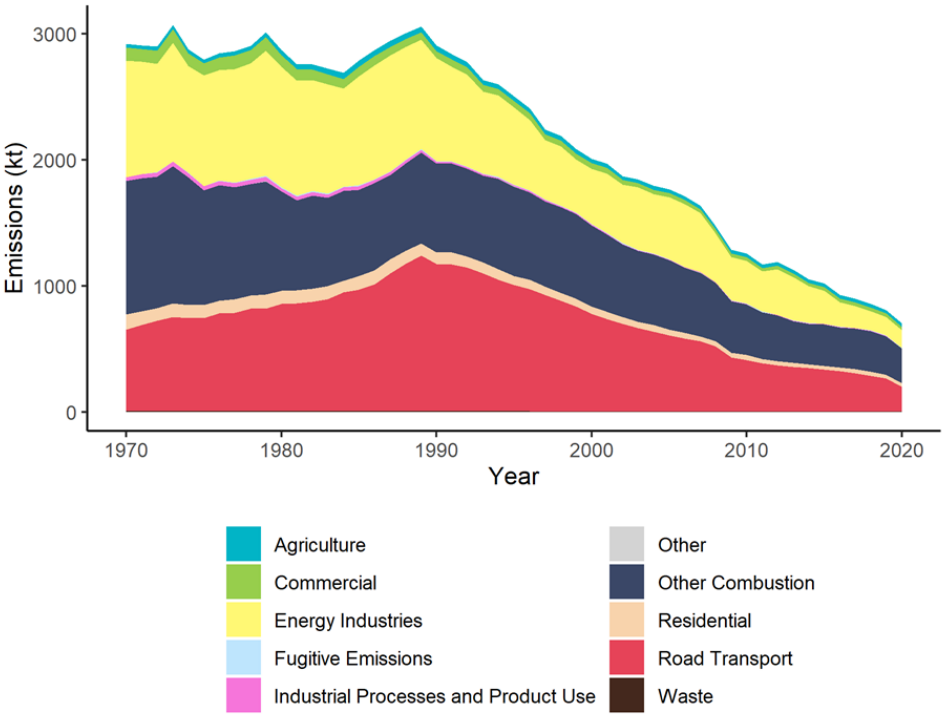
[3] Emissions from the residential sector in 2020 are most likely to be associated with solid and liquid fuel combustion outside of London.



Note: “Other” is defined in the NAEI as any sources that are not specifically defined in NFR Codes 1-5. “Other Combustion” includes manufacturing industries and construction, other minor sectors (such as agriculture and fishing) and fugitive emissions from fuels.

Figure 3: Trends in $PM_{2.5}$ Emissions 1970-2020 (Source: NAEI)

Total emissions of $PM_{2.5}$ (kilotonnes per annum) have declined dramatically since 1970, and emissions within the Residential sector have fallen from 193kt in 1970 to 20kt in 2020.



Note: “Other” is defined in the NAEI as any sources that are not specifically defined in NFR Codes 1-5. “Other Combustion” includes manufacturing industries and construction, other minor sectors (such as agriculture and fishing) and fugitive emissions from fuels.

Figure 4: Trends in Nitrogen Oxides (NO_x) Emissions 1970-2020 (Source: NAEI)

The trend in NO_x emissions (kilotonnes per annum) shows a very different pattern than that for sulphur dioxide and $PM_{2.5}$, with total emissions peaking in 1989. As with sulphur dioxide, the contributions from the Energy Industries sector have reduced due to being largely relocated outside of London. Urban pollution will have been dominated by emissions from the Road Transport sector which also peaked in 1989 (associated with the growth in road traffic over that time). The steady decline in NO_x emissions from 1990 (645kt) to 2020 (196kt) has been principally driven by the introduction of more stringent vehicle emissions standards (Euro standards) as shown in Table 1, and also illustrated in Figure 5 for diesel Light Duty Vehicles (LDVs), and by supporting air quality polices in London.

Table 1: European Emissions Legislation for Light Duty Vehicles

Legislation	Initial Date	THC + NOx (g/km)		NOx (g/km)		PM (g/km)	
		Petrol	Diesel	Petrol	Diesel	Petrol	Diesel
Euro 1	1992	0.97	0.97	-	-	-	0.140
Euro 2	1996	0.50	0.90	-	-	-	0.100
Euro 3	2000	-	0.56	0.15	0.50	-	0.050
Euro 4	2005	-	0.30	0.08	0.25	-	0.025
Euro 5	2009	-	0.23	0.06	0.18	0.005	0.005
Euro 6	2014	-	0.17	0.06	0.08	0.005	0.005

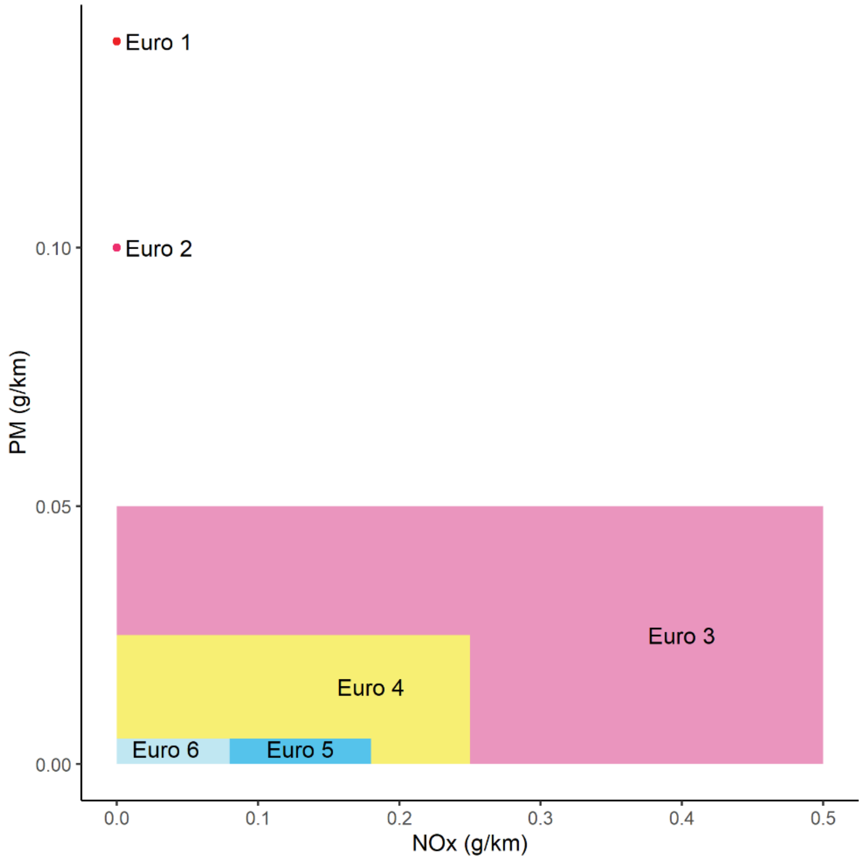
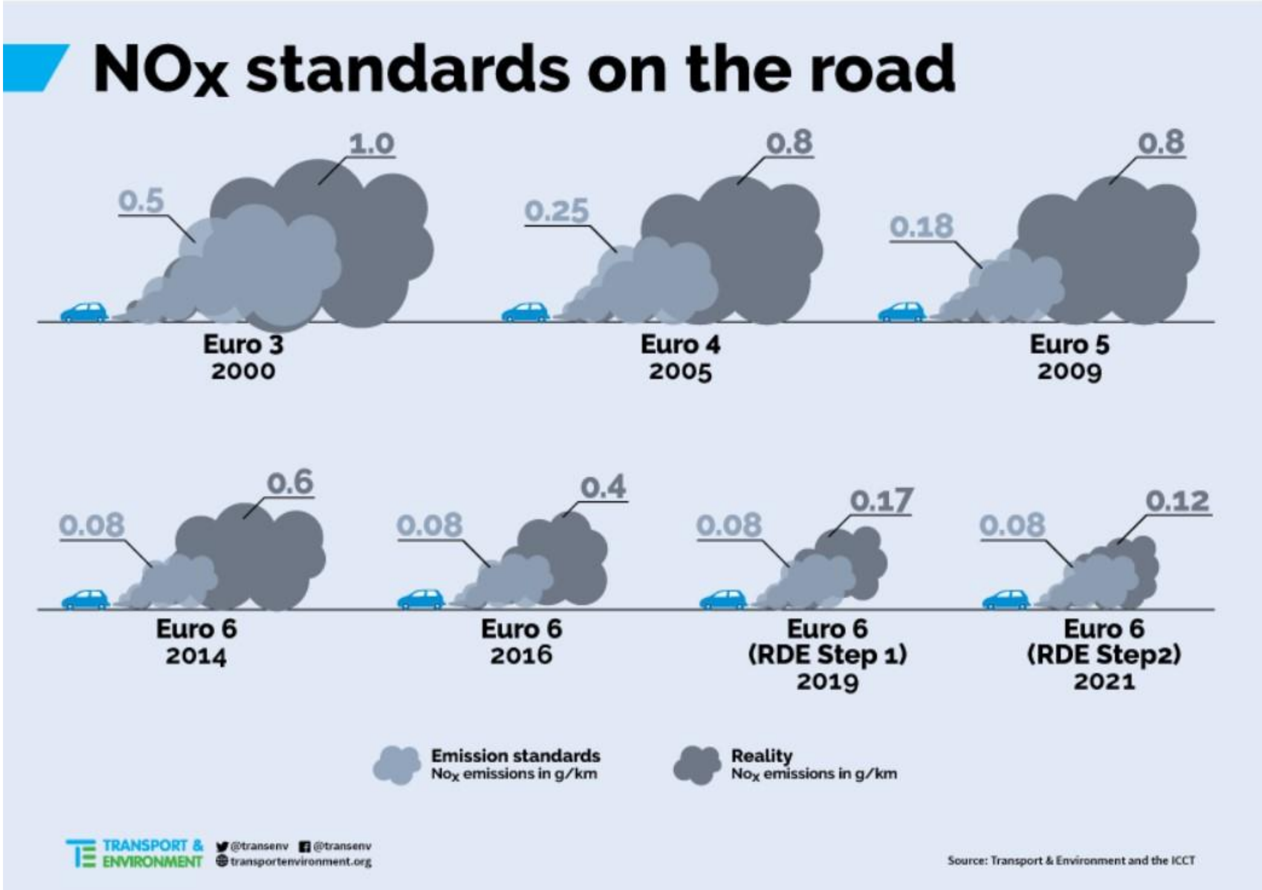


Figure 5: Trends in Euro Emission Standards for NOx and PM for Light Duty Diesels.

Over the period from when the Euro 1 standard was introduced (1992) to the most recent Euro 6 standard (2014) NOx emissions from diesel cars and vans have reduced by over 90%[4] and PM emissions by over 95%. However, it must also be recognised that Euro 3, Euro 4, Euro 5 and the early variants of Euro 6 failed to deliver the intended emissions reductions from diesel cars due to the manner in which the testing was carried out. This is illustrated in Figure 6 which shows the NOx emissions standard for Euro 3 onwards, and the real-world emissions by comparison. This under-performance resulted in nitrogen dioxide levels barely declining at many monitoring sites in London over the period 2004 to 2017. This issue has now been largely rectified in the current variants (Real World Driving Emissions (RDE) Step 1 and Step 2) of the Euro 6 standard that includes an extended on-road test to measure RDE, as illustrated in Figure 6.



Source: Transport & Environment and the ICCT

Figure 6: Comparison of Euro Standards and Real-World Emissions (Source: Transport & Environment – Dieselgate, Who?, What?, How? September 2016)

Continuing "Smogs"

Whilst the historical smogs of the 1950s have disappeared, several smog episodes, primarily associated with NO_x emissions from road traffic, occurred in London during calm, winter days during the 1990s (and coinciding with the peak years in road transport emissions shown in Figure 4). Most notably in December 1991, "Big Ben" was obscured by a brown haze caused by elevated nitrogen dioxide concentrations, and on Friday 13th December 1991, a peak hourly nitrogen dioxide concentration of 809 $\mu g/m^3$ was recorded at a

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[4] Euro 1 and Euro 2 had a combined THC+NOx standard

non-kerbside site – the highest level since monitoring had commenced in the UK. It is estimated that this smog episode caused between 100 and 180 excess deaths[5].

Despite much reduced emissions in London, pollution episodes still occur, driven by different pollutants, sources and mechanisms. . Between 2018 and 2021 the Mayor's Air Quality Alert System issued 163 moderate pollution alerts and 10 high alerts for a range of pollutants. "Photochemical smogs" often occur in London – and are associated with chemical reactions in the atmosphere – principally related to road traffic emissions By way of example, a photochemical smog episode occurred in August 2020, when ozone concentrations across London reached the 'High' band[6] of Defra's daily air quality index[7]. This pollution episode was caused by a combination of soaring ambient temperatures and sunny conditions promoting the formation of ground-level ozone as imported and locally emitted pollutants reacted in the atmosphere.

A pollution episode related to $PM_{2.5}$ concentrations occurred in March 2022, with 'High' $PM_{2.5}$[8] measured across a number of sites on Thursday 24th and Friday 25th. In contrast to the "historical smogs" of the 50's and 60's, this episode was largely driven by transboundary pollution, corresponding with parcels of air that had passed at low altitude over large areas of Europe, accumulating pollution from urban, industrial, and agricultural sources. At the same time, wind speeds dropped in London, resulting in poor dispersion of locally generated emissions allowing a widespread build-up of pollution.

Current air pollution emissions and levels

Current emissions and levels of most pollutants are substantially lower than during the period of the Great London Smog, and the source contributions have also changed.

Emissions and source contributions

Figures 6 and 7 repeat the analysis shown in Figures 2 and 3, but the data have been derived from the London Atmospheric Emissions Inventory (LAEI) (and so are specific to London) and focus on the changes between 2013 and 2019.

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[5] COMEAP (1997) Handbook on air pollution and health.

[6] Above 161 μg/m3 as an 8-hour running mean

[7] https://uk-air.defra.gov.uk/air-pollution/daqi?view=more-info

[8] Above 65 μg/m3 as a daily mean

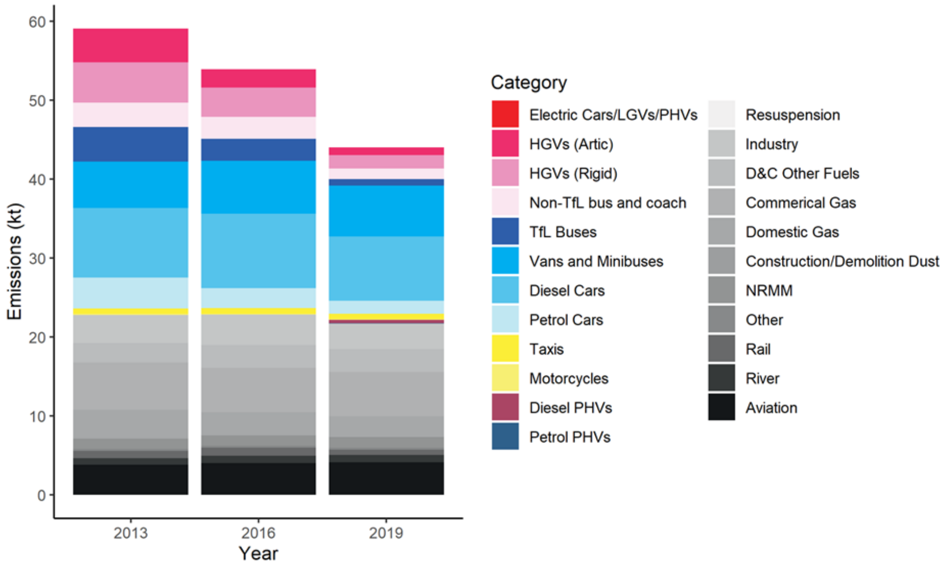

Figure 6: NOx emissions by sector for 2013, 2016 and 2019 (Source: London Atmospheric Emissions Inventory (LAEI))

NOx emissions have continued to decline in London over the period 2013 – 2019 (approx. 59 kt reducing to 44 kt), with the most substantial reductions in the road transport sector (specifically Heavy Goods Vehicles (HGVs), buses and coaches and petrol cars). The road transport sector contributed just over 49% of total NOx emissions LAEI total) in 2019, with diesel cars, vans and minibuses the highest (64% of the road transport sector).

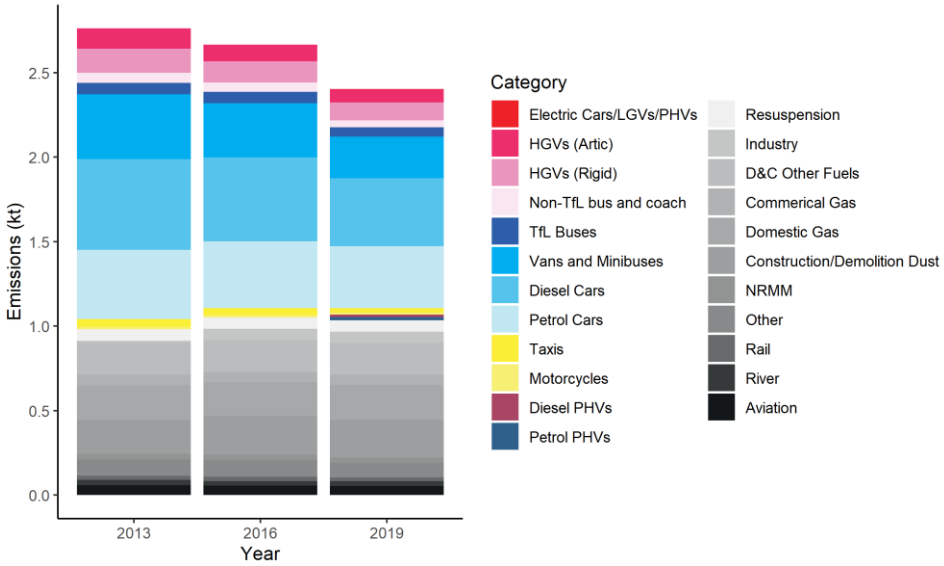

Figure 7: $PM_{2.5}$ emissions by sector for 2013, 2016 and 2019 (Source LAEI)

$PM_{2.5}$ emissions also declined between 2013 and 2019 (approx. 2.8 kt declining to 2.4 kt), with the most substantial reductions in the transport sectors across all vehicle types. The road transport sector contributed just under 57% of total $PM_{2.5}$ emissions (LAEI total) in 2019, with diesel and petrol cars and vans and minibuses the highest (74% of the road transport sector).

Monitoring Data

Monitoring is carried out extensively across London and reported in the London Air Quality Network (londonair.org.uk) and Air Quality England (https://www.airqualityengland.co.uk/). A summary of the monitoring data for 2019[9], is provided below:

Sulphur dioxide: Annual mean concentrations of sulphur dioxide are now extremely low, and approximately 1 µg/m^3. There were no recorded exceedances of the most stringent (15-minute mean) air quality objective.

$PM_{2.5}$: All sites (28 in total) with reference-equivalent samplers achieved the UK limit value of 20 µg/m^3, with levels in the range of 10 – 15 µg/m^3. Only seven sites achieved the Mayor's target[10] of 10 µg/m^3.

Nitrogen dioxide: A total of 48 sites (out of 119) failed to achieve the annual mean air quality objective (40 µg/m^3). These were all roadside or kerbside sites.

In 2021, the World Health Organization (WHO) updated its air quality guidelines, recommending lower levels for outdoor air pollutants to reflect the growing weight of scientific evidence of the health risks of exposure to air pollution – even at low levels. All areas of London currently exceed the new WHO air quality guidelines of 5 µg/m^3 $PM_{2.5}$ and 10 µg/m^3 NO_2, both expressed as an annual average.

3 What would London's air quality be without the Clean Air Acts?

Analyses were undertaken to simulate a hypothetical scenario of what present-day concentrations of NO_2, $PM_{2.5}$ and PM_{10} could have been without the Clean Air Acts. The local combustion component of present-day domestic heating and power demand was replaced with the local combustion energy mix from 1952, effectively switching from natural gas and a small proportion of solid sources (present-day), to coal and oil (1952) (but using present-day emissions factors per unit activity). Subsequently, the health impacts of such a fuel mix were estimated.

Methodology

The approach was not intended to be definitive or precise. Rather, the methodology provides an indication of the effect that replacing present-day domestic combustion with the 1952 energy mix might have. The most recent concentrations and emissions data which can readily be used for this calculation represent 2019. Previously collated demographic information relates to 2017-2018. These datasets are both taken to broadly represent 'present-day'. In the context of comparisons against 1952, the imprecision of combining data over the period 2017-2019 is unlikely to be significant.

The 2019 NOx, $PM_{2.5}$ and PM_{10} emissions associated with domestic heat and power (natural gas, coal, and oil) were extracted from the LAEI[11] for every Output Area within Greater London by taking the 1 km^2 gridded

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[9] Monitoring data in both 2020 and 2021 were severely affected by the lockdown restrictions of the Covid-19 pandemic and have not been included in this analysis.

[10] The Mayor's ambition is to achieve the WHO 2005 air quality guideline for $PM_{2.5}$ by 2030.

[11] GLA and TfL (2022) LAEI 2019: https://data.london.gov.uk/dataset/london-atmospheric-emissions-inventory--laei--2019

LAEI data for the centre of each Output Area. The total energy consumption associated with these sources for each Output Area was then calculated based on the emission factor[12] for NOx, as detailed in the NAEI[13].

The emissions associated with meeting the 2019 energy demand with an estimated energy mix representative of 1952 fuel sources, were then calculated. For the purpose of this analysis, this was assumed to be 85% coal and 15% oil[14].

The GLA provided source-apportioned concentrations by Output Area for 2016, including the contribution of 'domestic and industrial' gas consumption to NOx, $PM_{2.5}$ and PM_{10} concentrations[15]. The 'domestic' gas contribution was isolated by splitting the 'domestic and industrial' pollutant concentrations by the ratio of the domestic and industrial emissions for every Output Area in 2016. The 2016 contribution was subsequently scaled to represent a 2019 contribution based on the relative changes of NOx, $PM_{2.5}$ and PM_{10} emissions from the domestic gas sector between 2016 and 2019 across the whole LAEI. The ratio between the scaled (2019) concentration contribution and the emissions from domestic gas combustion in 2019 was used to estimate pollutant concentrations from the revised calculated emissions.

Using the conversion factor discussed above, the concentrations associated with a 1952 domestic fuel mix were calculated. The total hypothetical concentrations of NOx, $PM_{2.5}$ and PM_{10} in 2019 without the Clean Air Acts were calculated using the equation below:

$$x = A - B + C$$

where 'x' represents the concentration in 2019 without the Clean Air Acts, 'A' represents the 2019 LAEI concentrations, 'B' represents the concentrations associated with modern domestic heat and power sources, and 'C' represents the concentrations associated with a fuel mix from 1952. NO_2 concentrations for each output area were estimated from NOx using the NOx:NO_2 ratio for each Output Area average in the 2019 LAEI.

The resulting changes in concentrations have been used to calculate the health burden for Greater London. Exposure-response coefficients have been applied to the population in the study area. In order to align with previous work relating to health effects from combustion in London[16], the risk coefficients have been taken from Defra[17]. The coefficients are expressed as the Relative Risk per 10 $\mu g/m^3$ of the pollutant (RR10) and are 1.06 for $PM_{2.5}$ attributable mortality, 1.023 for NO_2 attributable mortality, and 1.008 for PM_{10} attributable respiratory and cardiovascular hospital admissions. These are the health outcomes for which Defra states there is strong evidence of an association[17].

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[12] Amount of pollutant emitted (kilotonne) per unit of energy (terajoule). Energy consumption was thus derived in TJ/km^2.

[13] https://naei.beis.gov.uk/data/ef-all-results?q=170872

[14] Warde (2007) *Energy Consumption in England & Wales 1560-2000*: https://histecon.fas.harvard.edu/energyhistory/data/Warde_Energy%20Consumption%20England.pdf

[15] Provided by the GLA.

[16] https://www.london.gov.uk/sites/default/files/gla_efw_study_final_may2020.pdf

[17] Ricardo Energy and Environment (2019) *Air Quality damage cost update 2019:* https://uk-air.defra.gov.uk/assets/documents/reports/cat09/1902271109_Damage_cost_update_2018_FINAL_Issue_2_publication.pdf. This means that the approach does not align precisely with other GLA-commissioned work (https://www.london.gov.uk/programmes-and-strategies/environment-and-climate-change/environment-publications/health-burden-air-pollution-london), but it is not the intention of the current work to provide definitive results.

The Relative Risk (RRc) for the population-weighted concentration (C) is then derived as follows:

$$RRc = RR10^{\left(\frac{C}{10}\right)}$$

The Attributable Fraction (AF) of the health outcome is derived from the RRc as follows:

$$AF = \frac{(RRc - 1)}{RRc}$$

The AF is then applied to the base data described below. In the case of mortality, the base data are the non-accidental deaths in 2017 for the population over 30 years of age, published for each borough by the Office of National Statistics in 2018[18]. For hospital admissions, use has been made of the rate of hospital admissions per resident of England in 2017/2018 derived from national admissions data from the NHS[19].

The same calculation has been applied to the concentrations both with and without the uplifts associated with the 1952 energy mix. This has been done to allow the relative increase in the health burden to be calculated.

The mortality calculations have been carried out for both NO_2 and $PM_{2.5}$. The numbers are greater for $PM_{2.5}$ than for NO_2, thus the results for $PM_{2.5}$ are presented. This follows advice from the Committee on the Medical Effects of Air Pollutants (COMEAP)[20] that the mortality rates based on single pollutant epidemiological models will reflect exposure to $PM_{2.5}$ and other pollutants. It is for this reason that the NO_2 and $PM_{2.5}$ results are not treated as additive because it will likely give an overestimate of the effects of the pollution mix. The results are thus presented as mortality attributable to air pollution and should not be ascribed to $PM_{2.5}$ alone.

Results

On average, the 1952 fuel mix results in a 22% increase in NO_2 concentrations, a 230% increase in $PM_{2.5}$ concentrations, and a 150% increase in PM_{10} concentrations across Greater London.

Over Greater London as a whole, the total burden of mortality from the 1952 domestic fuel mix has been calculated at 1,633 additional deaths brought forward per year, which represents an increase of 22% from present-day mortality associated with air pollution.

The total respiratory hospital admissions attributable to PM_{10} emissions from the 1952 domestic fuel mix is predicted to be 3,392 admissions per year across the whole of Greater London, which represents an increase of 235% from present-day admissions associated with air pollution.

The total cardiovascular hospital admissions attributable to PM_{10} emissions from the 1952 domestic fuel mix is predicted to be 2,979 admissions per year across the whole of Greater London, which also represents an increase of 235% from present-day admissions associated with air pollution.

These relative changes to mortality and hospital admissions associated with air pollution are summarised in Figure 8. The statistics apply to the present-day population, emissions factors and meteorology and does not directly reflect conditions in 1952.

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[18] ONS (2018) *Deaths Registered in England and Wales: 2017*

[19] NHS (2018) *Hospital Admitted Patient Care Activity, 2017-2018*

[20] Committee on the Medical Effects of Air Pollutants (2018) *Associations of long-term average concentrations of nitrogen dioxide with mortality,* PHE publishing gateway number: 2018238

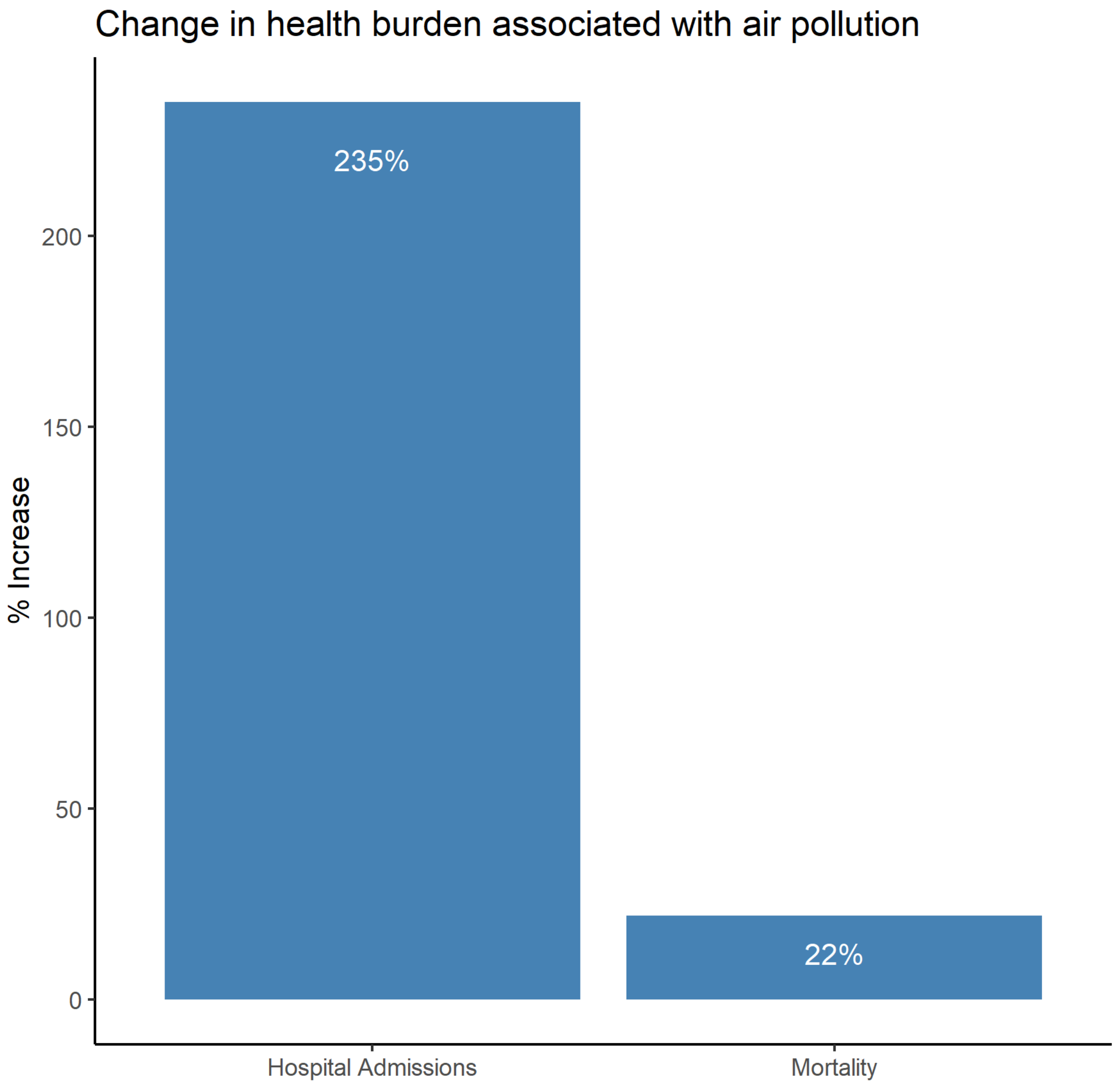

Figure 8: Calculated Change in Present-day Hospital Admissions and Mortality Associated with Air Pollution if 1952 Domestic Combustion Patterns were Resumed

4 How has the challenge changed and what's left to be done?

Air pollution in London in 2022 is very different from that experienced by Londoners in 1952. The air is certainly cleaner, although the nature of the pollutants, especially particulate matter, has also changed. Our understanding of the adverse health effects of air pollution has also changed, with studies showing more associated conditions, effects at lower concentrations, and greater concern over the harms caused by long term exposure. The recent update to the World Health Organisation's (WHO) Air Quality Guidelines[21] greatly reduced the level of pollution which could be considered "safe" and underlined the fact that we still have some way to go to achieving clean air. Indeed, the WHO stated that the available evidence cannot currently identify levels of exposure that are risk free. The ban in England on the sale of house coal[22] has removed the main driver of the 1952 smog from the list of air pollution sources in London. However, challenges remain, both old and new, some of which are explored below.

Air quality and Net Zero

Actions to reduce the emission of air pollutants and greenhouse gases (GHGs) are often very similar. Both are largely, but not exclusively, associated with the combustion of fuels (fossil and non-fossil) and so the removal of combustion, such as switching to renewable energy rather than petrol, diesel or gas power plant, is beneficial to both. However, action to improve air quality or protect the climate is not necessarily good for both topics: the pressure to move from petrol to diesel cars in 1990s and 2000s was motivated by climate policies (diesel power is, generally, more fuel efficient than petrol) but had a detrimental effect on air quality, particularly in light of the failure of the Euro 4 and 5 emission standards to control NO_X emissions from diesel vehicles ("Dieselgate"[23]). Also, historically, the shift towards smaller, more efficient Combined Heat and Power (CHP) plant, provided benefits to GHG emissions, but introduced air pollution sources into urban areas.

If designed in the correct way, measures to reduce GHG can deliver substantial improvements to air quality in cities, by e.g. the promotion of renewable energy solutions, reducing traffic and sustainable means of transport. London's world-leading Ultra Low Emission Zone (ULEZ) has delivered such co-benefits. In the first 10 months of implementing the central London ULEZ, a 44% reduction in roadside NO_2 concentrations and a 27% reduction in $PM_{2.5}$ were delivered alongside a 6% reduction in carbon dioxide (CO_2) emissions in the central zone.[24]

The effect can also be more subtle – investment for GHG emission reduction may focus on the biggest emission sources, but these may not be the key air pollution sources. For example, investment in offshore wind power, while necessary, will do little or nothing for urban air quality, whereas investment in home insulation could reduce the need for home heating and thus reduce urban emissions from gas (and solid fuel) heating.

Further action will be needed to continue improving London's air quality and move the city towards net-zero carbon emissions. This can take into account the lessons learned and also capitalise on synergies between action to tackle these two challenges.

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[21] WHO global air quality guidelines. Particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide: https://www.who.int/publications/i/item/9789240034228

[22] The Air Quality (Domestic Solid Fuels Standards) (England) Regulations 2020: https://www.legislation.gov.uk/uksi/2020/1095/contents/made

[23] 2016, Transport and Environment: https://www.transportenvironment.org/wp-content/uploads/2021/07/2016_09_Dieselgate_report_who_what_how_FINAL_0.pdf

[24] https://www.london.gov.uk/programmes-and-strategies/environment-and-climate-change/environment-publications/central-london-ulez-ten-month-report

Domestic heating

The 1952 Great London Smog clearly illustrates the impact domestic heating can have on urban air quality. However, while the sale of traditional house coal may be banned in England, domestic solid fuel use remains an important emission source, and one which may be on the increase. The most recent emission estimates for the UK[25] show that domestic burning is now the largest source of $PM_{2.5}$ emissions, outweighing all road transport emissions. Survey work commissioned by Defra[26] showed that the great majority (96%) of homes using solid fuel for heating also had other heating sources available and the most common reasons given for choosing to use an indoor burning appliance were: "*to create a homely feel, so they could heat just one room, to save money, and/or because they liked the look of a fire*".

The UK is not alone in having an issue with the air quality impacts of domestic solid fuel use. A report in 2022 by CE Delft[27] estimated that the annual health costs related to domestic burning across the EU and UK were around €29bn, and that coal and wood burning were the main drivers.

Non-exhaust PM

As shown above, diesel powered vehicles were the main source of particulate matter emissions in the UK, up until the introduction of Diesel Particulate Filters (DPFs), effectively mandated by the Euro 5 (cars and vans) and Euro IV (HGV engines) emission standards. For modern diesel vehicles, the total mass of particles emitted from the exhaust pipe is extremely low, effectively removing them as a source. However, exhaust emissions are only one part of the story. Mechanical wear to brakes, tyres and road surfaces also produces particulate matter, some of it extremely fine, i.e. on the PM_{10} and even $PM_{2.5}$ range.

As cars in particular have become larger and heavier, partly to incorporate safety features and partly through consumer choice, so the levels of brake and tyre wear have increased. The latest NAEI estimates show that brake and tyre wear, and road abrasion, now constitutes a larger source of PM emissions than vehicle exhausts. As this is a non-combustion source, switching to electric vehicles will not help. The problem is such that the recently published proposals for the next round of Euro emission standards (Euro 7[28]) includes proposals for limits on brake and tyre emissions – a world first – although the test for tyre wear has yet to be developed. Since the UK's exit from the EU, Euro 7 will not automatically apply, and while it is doubtful that car designs overall will differ between the UK and the EU, components such as tyres and brake pads could meet different standards. The UK, and London, will most likely need to develop approaches to controlling non-exhaust emissions of particulate matter if it is to meet the new Environment Act targets, and WHO air quality guidelines for $PM_{2.5}$ in urban areas.

Future pollutants

Ultra-fine particles (UFP) are so small (less than one-ten millionth of a metre in diameter) that they effectively have no mass. Whilst we have known about UFP for many years, our understanding is still limited, and little monitoring is carried out, although London has two permanent sites to measure this

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[25] UK Informative Inventory Report (1990-2000): https://uk-air.defra.gov.uk/assets/documents/reports/cat09/2203151456_GB_IIR_2022_Submission_v1.pdf

[26] Burning in UK homes and gardens: https://uk-air.defra.gov.uk/library/reports?report_id=1014

[27] Health-related social costs of air pollution due to residential heating and cooking in the EU27 and UK: https://cedelft.eu/publications/health-related-social-costs-of-air-pollution-due-to-residential-heating-and-cooking/

[28] https://ec.europa.eu/commission/presscorner/detail/en/ip_22_6495

pollutant. There is convincing medical evidence that UFP can penetrate very deep into the lung and can even directly the bloodstream or the brain. However, the recent 2021 WHO review was unable to recommend a guideline for UFP, due to the paucity of epidemiological evidence (from studies conducted in the population) and exposure. UFP are emitted from all fossil fuel combustion sources, and so measures to control these sources should also be beneficial in reducing UFP exposure. But as UFP concentrations are poorly correlated with other pollutants (such as $PM_{2.5}$) away from the immediate vicinity of the source, additional monitoring is needed to determine trends and support the development of guidelines.

Interest in microplastics has largely focused on the impacts to rivers and oceans, but there is increasing concern with regard to microplastics in the atmosphere and public exposure, and studies have confirmed the presence of this pollutant in both human lungs and the bloodstream[29]. Whilst there are many sources of microplastics, the emissions of tyre and road wear particles (TRWP) are of increasing concern and is currently unregulated. A study by Emissions Analytics[30] found that the $PM_{2.5}$ emissions from tyre wear to be 400 times greater than from the exhaust. Emissions can be reduced by modal shift to more sustainable transport, the use of smaller and lighter vehicles, and by the improvement of tyre characteristics and setting standards for abrasion performance (see reference to Euro 7 above).

Behaviour shifts

The history of air pollution control has been dominated by technological measures, from the replacement of fireplaces with gas fires or central heating boilers, through industrial abatement systems such as flue gas desulphurisation, to the complex and sophisticated emission control systems on modern vehicles. There are two main reasons for this:

1. Technology changes are more predictable and easier to quantify. This means that their costs and projected benefits can be weighed in economic assessments, they are easier to fit into predictive models and greater confidence can be attached to their effectiveness. In short, they fit better into the policy development process which is itself technological in nature.
2. Persuading people to change their behaviour is difficult, takes time, the outcomes are uncertain and such attempts are often viewed as unpopular (e.g. Government meddling, nanny-statism, etc).

However, relying solely on technological measures to solve air quality (or other problems) is likely to be insufficient to deliver complete solutions. This is both because technology can only take us so far – electric vehicles still emit particles through tyre and brake wear – and because the solutions presented are often narrow. For example, switching to electric vehicles will have a significant impact on air quality and, if the electricity is produced from low or zero carbon sources, on GHG emissions. However, this will do nothing for road safety and will still require the manufacture of complex electronic components (where there is a history of environmental damage), in addition to requiring a huge increase in the total amount of electricity generated. On the other hand, persuading more people to walk, cycle or use public transport benefits both air quality and climate change, in addition to reducing noise, increasing physical activity (and reducing the direct and indirect costs of poor health), increasing social cohesion, and giving a boost to mental health.

The Netherlands is often referred to as an example of where low and no emission transport is favoured over motorised options. School drop-off in Amsterdam can look very similar to its equivalent in London, except

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[29] European Public Health Alliance at https://epha.org/breathe-clean-air-not-microplastics/

[30] https://www.emissionsanalytics.com/news/gaining-traction-losing-tread

the cars are swapped for bikes, and town planning makes it physically difficult to drive through some towns, making walking and cycling both quicker and easier. This has not always been the case – in the 1950s and 60s, the Netherlands had similar approaches to transport planning as the UK and other European countries. However, public concern over road safety prompted the Government to adopt a policy of favouring walking and cycling over motorised transport and, 70 years later, low carbon transport is embedded in Dutch culture.

Achieving such cultural change need not take 70 years, as the shifts in behaviour brought about by Covid-19 lockdowns demonstrated (although some of these shifts are being increasingly reversed). However, behavioural shifts can be enacted through more subtle means. Small scale projects, such as school streets[31,32] can have an incremental effect on both air pollution and people's behaviours. While their effects on air pollution tend to be difficult to isolate when taken individually, small scale behavioural change projects can act as an enabler to more hard-edged measures – they gradually shift attitudes in favour of air pollution control. A recent study by Imperial College showed how behaviour changes can benefit air quality overall and have a beneficial impact on a variety of other issues[33].

Indoor air pollution

As people spend a considerable part of their lives indoors (at home, work/school or other public spaces), exposure to air pollution in these environments can represent a significant fraction of their overall exposure, and is the basis of a recent report published by the Air Quality Expert Group (AQEG)[34]. Indoor air quality is complex and has been studied to a lesser extent than ambient air quality. Indoor air quality is affected by the ingress of outdoor air (that additionally supports measures to reduce ambient levels of pollution), but is also affected to a greater extent by emissions from indoor sources such as building and furnishing materials, combustion appliances for heating and cooking, the use of solvent-containing products, and cleaning and personal care products. Some of these emissions are under control of the individual (e.g. use of personal care products in the home) but others (emissions from building fabrics, or ventilation rates in public spaces or workplace) are not. Many of the key pollutants in ambient air are found indoors (such as $PM_{2.5}$ and NO_2), but others (such as range of Volatile Organic Compounds (VOC)) are found in much greater quantities indoors.

There are many measures at different levels that can be used to control indoor emissions. Some are regulated (e.g. controls on ventilation rates, standards for solid-fuel burners, controls on the VOC content of paints and other products etc.). Measures at the individual level (via actions or behavioural changes) can also improve indoor air quality, but many of the sources are linked to personal choice (such as cooking, cleaning, use of candles and fragrances etc.).

The AQEG report notes that "many of the challenges around indoor air pollution stem from deficiencies in the evidence system and the lack of recognition of its potential importance outside expert communities. As an issue that has had no obvious single owner in either government or the research funders this is perhaps

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[31] The Guardian, 18 November 2022: https://www.theguardian.com/environment/2022/nov/18/pollutionwatch-school-streets-children-exposure-toxic-air-traffic?CMP=Share_AndroidApp_Other

[32] https://www.london.gov.uk/programmes-and-strategies/environment-and-climate-change/environment-publications/school-streets-air-quality-study

[33] Riley *et al*, 2021, *How do we effectively communicate air pollution to change public attitudes and behaviours? A review*; Sustainability Science (2021) 16:2027–2047. https://www.imperial.ac.uk/news/230817/reducing-pollution-changing-behaviours-help/

[34] AQEG (2022) Indoor Air Quality https://uk-air.defra.gov.uk/research/aqeg/

unsurprising. It is noted that the Cross Government Working Level Group on Indoor Air Quality has been set up. It will be important that this Group, or an equivalent, remains active and is effective at raising the profile of indoor air pollution across government."

Clear goals and a positive vision

In common with many environmental issues, air quality is often presented as a negative, either in terms of the need for action (air pollution being responsible for large numbers of additional deaths) or the impact of the actions themselves (increased charging, restricted access, products being banned). Research into health impacts, such as that assessed in the WHO Air Quality Guidelines, has demonstrated that air pollution causes significant health effects at levels which cannot be perceived directly (i.e. they have no noticeable odour or appearance). Thus, the benefits of improved air quality are intangible and may not act as a motivator for action without demonstration of these actions at a local level. Being able to see, in the real world, the link between actions and positive outcomes is a far stronger driver for the acceptance of those actions, than the fear of the consequences of inaction.

Measures designed to improve air quality almost never effect air quality alone. Likewise, measures to reduce GHG emissions, noise level, increase green space, etc will have knock-on effects on air quality. If designed effectively, the benefits of such actions can reinforce each other to create urban environments that are more person- (as opposed to vehicle-) focussed, are better places to live and work, and support more active and vibrant communities. This is encapsulated in the ten indicators on the Mayor of London's Health Streets[35]. However, there are three clear preconditions for the creation of environments like Healthy Streets:

1. A clear, agreed sets of goals and parameters which developers and planners can work to, in order to encourage innovative, positive and integrated development.
2. Strong and extensive community outreach and engagement to ensure that designs meet community needs and address community concerns.
3. A "vision" for what the success looks like which can be (and is) clearly communicated and informs the development of policies and measures to address air quality and other issues.

Community outreach and engagement is particularly important. Solutions which are perceived as being imposed by either national or local authorities with no engagement[36] are much more likely to be resisted by local communities and much less likely to be successful. A failure to engage could result in specific concerns and issues of different community groups not be picked up and addressed in the scheme design, thus leading to a less successful outcome.

If action to improve air quality is to be successful into the future, it has to be accompanied by a positive view of the benefits of success, and it must carry local communities with it.

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[35] https://content.tfl.gov.uk/healthy-streets-for-london.pdf

[36] Note that this is more than simply consultation, i.e. the publication of documents for comments, and involves active participation in discussions on policies and measures.

5 Conclusions

The air pollution climate in London has changed dramatically over the past 70 years since the Great London Smog. The Clean Air Acts, and subsequent legislation, have brought about substantial improvements to air quality.

To illustrate the effect of the Clean Air Acts, an analysis has been undertaken to simulate a hypothetical scenario of what present-day levels of nitrogen dioxide, PM_{10} and $PM_{2.5}$ could have been without the Acts in place, and the subsequent reduction in coal burning In London. The local combustion component of present-day domestic heating and power demand was replaced with the local combustion energy mix from 1952, effectively switching them from natural gas and a small proportion of solid fuels (present day) to coal and oil (representing 1952), but using present-day emission factors per unit activity. On average, the 1952 fuel mix results in a 22% increase in nitrogen dioxide concentrations, a 230% increase in $PM_{2.5}$ concentrations, and a 150% increase in PM_{10} concentrations across Greater London compared to the present-day fuel mix. Over Greater Londin as a whole, this results in an additional 1,633 additional brought-forwards deaths per year, or a 22% increase in mortality. The 1952 fuel mix also represents an additional 3,392 hospital admissions per year attributable to PM_{10} concentrations, or a 235% increase compared to present-day emissions.

As a shift away from solid fuel burning reduced emissions of sulphur dioxide and smoke, so the increasing use of road transport caused a dramatic rise in NOx emissions and nitrogen dioxide concentrations in London. While measures to tackle road transport emissions were introduced, the efficacy was hampered by an inadequate testing regime that allowed real world driving emissions to be many times higher than the standard; this has now been rectified by the latest variants of the Euro standard and there is convincing evidence that levels of nitrogen dioxide are falling.

Despite these improvements, air pollution problems in London remain, and the capital continues to be affected by pollution episodes every year – often driven by pollution emissions arising outside of the city. There are also new challenges related to a rise in domestic solid fuel burning, controlling non-vehicle emissions from road transport, and “new” pollutants such as Ultra Fine Particles and microplastics, that will require continued regulation and policies into the future.