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POLICY SOLUTIONS TO THE CLEAN AIR CHALLENGE

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This collection of policy briefs addresses the global challenge of air pollution, with an emphasis on solutions – policy, technical and behavioural – that can help deliver clean air.

The briefs combine approaches from physical sciences, engineering, medicine, public health, business and law – as the clean air challenge will not be solved by any one approach. The articles are intended as a starting point for discussion: how a particular approach or concept can be best applied to a specific problem will vary, and we encourage those interested to reach out to the authors in each case.

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FOREWORD

Taking a breath of air is such an instinctive human reaction that we rarely pause to consider how clean our air is, or how clean it could or should be. The quality of the air we breathe is linked to human and ecosystem health, wellbeing, economic productivity and healthcare costs, climate and environmental amenity.

The latest science is now able to characterise the particles and gases in our air in great detail, and also detect pollutant fingerprints that can unequivocally identify emission sources – and hence inform policies to deliver cleaner air. It can also quantify the burden from poor air quality: around 30,000 premature deaths each year in the UK, and up to 7 million globally. This challenge represents a call for action – one which requires integrating insights ranging from technological interventions to governance solutions.

In the follow up from the United Nations Climate Change Conference (COP26), the University of Birmingham is pursuing research that matters, to address global environmental challenges, including clean air. How clean can our air be? Who is responsible in law – and who is not? Are electric vehicles the solution? How can natural solutions help? What are the secondary consequences of technical interventions?

This edited collection offers a comprehensive examination of the nexus between different disciplines that are important in addressing air pollution, implementing innovative clear air solutions and their policy implications. Covering a diverse range of topics, including outdoor and indoor pollution, trees, vehicle design and compliance with legal rules on air quality, this collection presents contemporary research to inform evidence-based policy actions.

In this publication, we explore some of these questions and many others. We hope that these briefing papers will not only inform the debate, but will also drive progress towards clean air for all, on scales ranging from the domestic to the global.

Aleksandra Čavoški, Suzanne Bartington, William Bloss and John Bryson

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Air Pollution Solutions? City-Region Public Policy Interventions to Enhance Air Quality, Productivity and Well-being

Author: Professor John R. Bryson

Air Pollution and Productivity

This briefing paper explores policy interventions and recommendations intended to reduce the impacts of air pollution. Air pollution affects human health and well-being as well as contributing to climate change. All public policy interventions must be designed to have a neutral or positive impact on enhancing air quality.

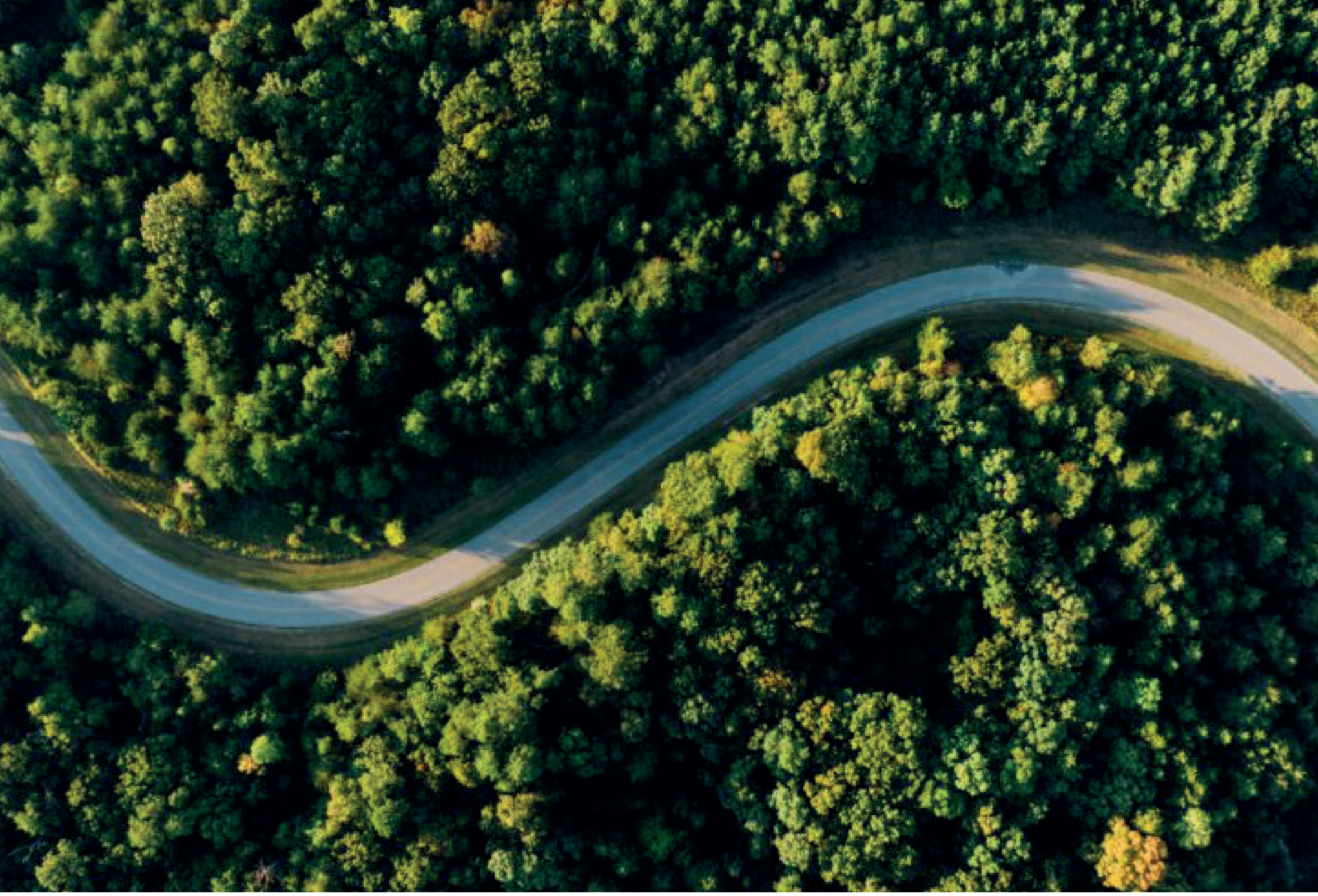
Air pollution emerged as a major problem in London in the nineteenth century as smog and fog came to characterize the city. A government inquiry on air quality in the UK commenced in 1914 with this committee reporting in 1921.[1] London's smog resulted in a major national air quality incident in 1952 and this led to the 1956 Clean Air Act.[2]

Air pollution continues to be a major source of health problems. There are important links between developing policy interventions intended to reduce air pollution and climate change as many air pollutant sources emit carbon dioxide (CO_2) which is the dominant anthropogenic greenhouse gas.[3]

Policy development to reduce exposure to air pollution relies on effective measurement and monitoring.
There are important health outcomes linked to air pollution, but research and policy has tended to focus on extreme impacts including mortality and hospitalizations. Air pollution results in more subtle effects that have negative impacts on everyday living including work-related productivity[4] and on labour supply.[5,6] Research on the impacts of air pollution on productivity has focussed on studies of low-skilled occupations and on service workers.[7] One study of indoor workers in a pear-packing factory identified a link between increases in fine particulate matter ($PM_{2.5}$) and significant decreases in productivity.[8] A study of the impacts of $PM_{2.5}$ on the output of call centre workers in two Chinese cities found that increases in pollution led to significant productivity decreases with a reduction in the number of calls placed or received by workers.[9]

The links between productivity and air pollution imply that effective solutions to enhancing air quality would enhance productivity across the economy as well as having positive impacts on educational attainment. There is evidence that exam performance is negatively impacted when students are acutely exposed to air pollution. A cross-sectional study of students in Cardiff, Wales, identified that short-term exposure to nitrogen dioxide (NO_2) from traffic-related pollution was associated with a negative impact on educational attainment for students aged 15-16.[10]

The link between air pollution and productivity draws attention to the cumulative impacts of daily exposure on individuals and the ways this is reflected in work and worker experiences. Productivity is a standard economic measure and is one that can be monetized enabling calculations to be made regarding the social and economic costs on a society of air pollution. Calculating these costs is critical to support cost-benefit analyses of air quality policies.



UK Local Policy Context

In 2019, a national UK Clean Air Strategy was published setting out comprehensive actions to reduce emissions of five key pollutants by 2020 and 2030: fine particulate matter ($PM_{2.5}$), sulphur oxides (SOx), nitrogen oxides (NOx), ammonia (NH_3) and non-methane volatile organic compounds (NMVOCs).[11] This was followed by the 2021 Environment Act setting targets, plans and policies for improving the natural environment.

In the UK there is a tension between national and local air quality policy. Nationally, air quality is acknowledged as a major problem, but no consensus has emerged amongst the public and across political parties.[12] This has resulted in fragmentation of policymaking and limited agreement regarding policy responses. In the UK, compliance with national air quality objectives is devolved to Local Authorities (LAs), but a policy disconnect exists between UK national and local air quality management. LAs must work towards meeting air quality objectives including Local Air Quality Management (LAQM) responsibilities and identifying local 'hotspots', or Air Quality Management Areas (AQMAs), that exceed air quality objectives and then developing Air Quality Action Plans (AQAP) that are intended to improve local air quality.[13, 14] A key issue for LAs is the need to develop an integrated approach to developing solutions to reducing air pollution and its impacts. This includes developing AQAPs and integrating them with LAQM.[15] In the UK, the two-tier approach to national and local air quality management has failed to enhance air quality.[16] Reducing air pollution requires an integrated, multi-scalar and multi-stakeholder approach.

Clean Air Zones and Liveable Neighbourhoods as Air Pollution Solutions: The Case of Bath

Developing solutions to air pollution is an on-going policy challenge. Solutions include the introduction of Clean Air Zones (CAZ) intended to reduce higher emission vehicles from driving in a designated area. Bath, for example, began to identify AQMAs in 2002. Five areas were identified in the city where levels of NO_2 exceeded the national annual average and local AQAPs were developed. Nevertheless, traffic growth has meant that these action plans struggled to reduce pollutant levels to meet national targets.[17] A CAZ was introduced in Bath from 15 March 2021[18] with the objective to meet government air quality targets whilst minimising the social, economic, and distributional impacts of this zone on residents and businesses. Bath's CAZ was the first charging CAZ to be launched outside London.

For Bath, the CAZ is one element in an evolving policy toolkit intended to enhance air quality and to minimise the negative health and economic impacts of air pollution. In 2020, Bath held a consultation on Liveable Neighbourhoods with a focus on better health, environments and spaces for people and business.[19] This strategy was part of the city's Climate Emergency Action Plan (CEAP) that was approved in October 2019. The CEAP recommended a major shift to mass transport, walking and cycling to reduce transport emissions. The introduction of Liveable Neighbourhoods was an important contribution to enhancing health and wellbeing by reducing the dominance of motor vehicles and emissions, enhancing road safety, and promoting healthy lifestyles. There is an interesting inclusion agenda here as this strategy is intended to provide fairer access for those travelling on foot or bicycle.[20] The outcome of this strategy was the adoption of three Liveable Neighbourhood strategies: Low Traffic Neighbourhoods, Residents' Parking Schemes, and an On-Street Electric Vehicle Charging Strategy. Bath and North East Somerset Council decided to introduce 12 Low Traffic Neighbourhoods in Bath and three in North East Somerset. This has been a controversial policy with concerns over displaced traffic and the need for residents to develop new routines. One Councillor noted that residents will take "weeks and even months" to develop new routines and that the LA will need to "hold our nerve".[21] This highlights tensions between resident expectations and existing liveability and livelihood routines, and policy interventions intended to reduce air pollution.

Recommendations and Public Policy Interventions

There is a large literature on air pollution and public policy interventions which has focussed on exploring the impacts of designated air quality policies, related action plans,[22,23,24,25,26] and the impacts of congestion charges.[27,28] Nevertheless, the key to developing solutions to air pollution lies with the formulation of a systematic or integrated approach.[29] Such an approach must consider the following:

a) Air quality policy must be supported by measurement and monitoring and the development of an appropriate sensor network. Identifying the scale of the problem, including emission source apportionment, is critical to support policy formulation and development. Data must be freely available to inform public awareness and choice.

b) Identification of key pollutant thresholds and health implications.

c) An appreciation of the wider impacts of air pollution on socio-economic activities including the negative impacts on productivity.

d) The development and application of a whole city-region approach rather than one focussed on air pollution hotspots.

e) Developing strategies that result in behavioural change including reductions in car use and increases in mass transport, walking and cycling. This could include, for example, expansion of residents' car parking permit schemes to reduce the supply of free all-day commuter parking to suppress demand for car-commuting and to encourage alternative transport modes including walking and cycling.

f) An acceptance that developing effective solutions to air pollution will disrupt existing household and business behaviours and that policy implementation might be challenging.[30]

g) Appreciate the importance of encouraging micro behavioural adjustment and meso adjustments related to the design of streetscapes including effective deployment of green infrastructure.

h) Green infrastructure as part of the solution to air pollution including the identification and development of strategic movement corridors to encourage walking and cycling.

i) Developing solutions to reduce educational and health related car use to encourage active travel.

j) A focus on creating liveable neighbourhoods and developing streetscapes that are attractive, safe, and convenient for people to walk and cycle. This includes understanding the role that different temporary urbanism solutions can play in enhancing health within urban environments.[31, 32]

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Green Infrastructure for Clean Air and One Health

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Executive Summary

This brief is intended for local authorities, community forests and private developers. It aims to communicate a recent shift in understanding of green infrastructure to enhance its direct value for clean air: away from pollutant *removal* by vegetation, towards careful *alteration* of *the distribution* of pollution, close to its source, using 'vegetation barriers'. Strategic planting, which is the focus of this brief, offers a secondary means of reducing exposure to proximate sources of pollution, such as roadside exposure to vehicular emissions:

- The best way to improve air quality is to reduce the emissions of pollutants at source: all efforts should be made to reduce total vehicle movements and emissions per vehicle.

- Vegetation barriers in the right locations subsequently offer means of reducing the health impacts of remaining emissions, by reducing local exposure to them by up to 50%.

- The efficacy of barriers depends, however, on a complex but predictable interplay of local conditions (e.g., interactions between the wind and local urban form), and on maintaining healthy vegetation to obstruct substantively the flow of polluted air.

- The Green Infrastructure for Roadside Air Quality Platform (www.GI4RAQ.ac.uk) is freely available to estimate the benefits and/or disbenefits of proposed planting.

  Thoughtful implementation of green infrastructure can deliver benefits for local air quality, but also for biodiversity, sustainable urban drainage, and mitigation of the urban heat island effect.[1,2,3,4] Across a raft of environmental, social, and economic outcomes, London's 8.4 million trees are estimated to deliver benefits of over £130 million per year.[5]

- The emerging concept of One Health (https://onehealthinitiative.com) captures the win-wins achievable by jointly considering the health of people, plants, and animals.

Background

The roadside, where many people come into close proximity with vehicles, is a priority environment for exposure reduction. Road transport is the single largest source of urban outdoor air pollution in the UK and globally[6] and one that will remain problematic for many decades. Whilst the electrification of vehicles removes their exhaust emissions, over 75% of the fine particulate matter ($PM_{2.5}$) they emit comes from brake, tyre and road wear[7] that are set to increase. These non-exhaust sources are expected to increase with road traffic volume (the Department for Transport projects a 17–51% increase in traffic in England and Wales by 2050 relative to 2015[8]) and increasing vehicle weight.[9]

Vegetation barriers between vehicles and people have demonstrable ability to reduce local exposure.[10,11,12] It is now recognised that they do so primarily by changing local patterns of polluted air flow and mixing, collectively referred to as 'dispersion', rather than by removing the pollution via deposition to leaf surfaces. Such barrier-induced dispersion can reduce roadside elevations in pollutant concentrations – above their background concentrations – by up to 50% in the barrier's immediate wake.[11]

Deposition of Pollutants to Street-Scale Vegetation

Numerous studies have reported sizeable benefits in local air quality downwind of a hedge and/or line of trees.[10,13,14,15,16] The deposition, or 'filtering', of pollutants is of considerable aggregated value at a national scale[17,18] but is expected to be of limited benefit in most urban contexts where the residence time of air is relatively short.[19,20] Where air resides in a space for longer, there is greater opportunity for deposition (see, e.g., the 'green oases' of Hewitt et al.[21]), but also greater opportunity for accumulation of emissions from any vehicles in these spaces.

A recent review[11] concluded that vegetation at the scale of realistic urban planting schemes typically removes only a few percent of PM, and an even smaller fraction of nitrogen dioxide (NO_2). It cited, amongst other findings, a computational fluid dynamics study of trees in central Leicester, which estimated that they reduced $PM_{2.5}$ concentrations via deposition by just 2.8% - but by 9% via changes in pollution dispersion.[22]

Whilst it is relatively straightforward to separate the effects of deposition and dispersion in a numerical model, it is much more difficult via measurements in the real world. Existing, reliable measurements of deposition efficiency to a variety of vegetated surfaces, such as eddy-covariance measurements from tall towers, cannot explain the marked reductions in pollutant concentrations measured behind hedges and trees in the built environment.[11] Neither can deposition explain the increases in pollutant concentrations observed in the vicinity of vegetation in some locations. Changes in dispersion can potentially explain both.

Changing Pollution Dispersion Close to Point of Emission

Using green infrastructure to alter the dispersion, and thereby distribution, of pollution close to point of emission is a pursuit of net reductions in exposure for net public health benefit. It calls for:

- Careful identification of which people, where within a street, are currently most exposed and/or most susceptible to the health impacts of air pollution (e.g., the young, the elderly and those with certain pre-existing medical conditions);
- Design of a site-specific intervention to reduce their exposure: what is beneficial in one location may not be in another – even an ostensibly similar street environment differing, for example, only with respect to the street's geographic orientation.
- Omission of planting – where undertaken in the name of improving air quality – where it could increase exposure: for clean air, it must be strategic and selective.

In the simplest scenario, where the wind blows from vehicles towards people and a vegetation barrier is introduced between the two, the concentrations of pollutants emitted by those vehicles are expected to (1) increase immediately upwind of the barrier due to the 'blocking' of pollutant dispersion, (2) decrease in the barrier's immediate wake—bypassed by the fraction of polluted air forced around the barrier—and (3) gradually tend, with increasing distance beyond the barrier, towards the same 'urban background' concentrations as encountered before introducing a barrier.11 These simple changes may, however, be markedly modified by the presence of nearby buildings and their influence on local air flow; we can, and must, account for this complexity.

Harman et al.[23] synthesised studies of air flow within streets of variable width (W) and height (H) spanning several decades.[24, 25] When the wind aloft blows perpendicular to a street of W≤3H, it yields a reversal of air flow across the entire base of the street. For a street of W>>3H, it yields a reversal across just a fraction of the street's width, with the direction of low-level air flow matching that aloft across the remainder.[23] Particular care is needed when considering planting in regions of air-flow reversal: these 'recirculation regions' partially trap emissions from any vehicles within them, and the introduction of a barrier therein risks further reducing the volume of air in which those emissions accumulate, increasing their concentrations.

Image by James Levine

The bottom line is, the patterns of air flow within a street, and the impacts of a vegetation barrier on the local distribution of vehicular pollution, are complicated but intelligible.

Green Infrastructure for Roadside Air Quality (GI4RAQ)

To help urban practitioners, not just air quality specialists, quantitatively estimate the site-dependent impacts of roadside vegetation barriers, Pearce et al.[26] have recently developed freely-available, open-source software: the Green Infrastructure for Roadside Air Quality (GI4RAQ) Platform (www.GI4RAQ.ac.uk). Focussing exclusively on the impacts of barriers on the dispersion of pollution close to source, it complements previous natural capital accounting tools focussed solely on deposition, such as i-Tree (www.itreetools.org).

Designed for practitioners, the GI4RAQ Platform was co-developed with partners including: Transport for London (TfL), the Greater London Authority (GLA), Birmingham City Council and AEA Ricardo. The software builds on an earlier qualitative, but still site-dependent, approach developed with TfL by Levine et al.[27] In turn, this elaborated on simpler guidance they wrote with the GLA.[28] The founding principle of Reduce, Extend, Protect was first introduced by Ferranti et al.[29] in a publication with the Trees and Design Action Group.

Recommendations

1. Reduce first, and to the fullest extent possible, emissions of pollutants at source.

For road transport pollutants, this means not only seeking to replace petrol and diesel vehicles with electric ones, but reducing total vehicle movements, for example, by incentivising modal shift to public transport and active travel.

2. Extend the distance between residual sources of pollution and people ('receptors').

The longer the source-receptor pathway, the greater the mixing that takes place en route, diluting the pollutants and reducing their concentrations at point of exposure.

Where it is not possible to distance people from vehicles geographically, roadside vegetation barriers (and grey infrastructure alternatives) can extend pollutant pathways by forcing a fraction of polluted air to take a more circuitous path from source to receptor, creating pockets of much cleaner air in their immediate wake. The benefits of a barrier to people downwind may be accompanied by disbenefits to people upwind. Overall, impacts depend on a complex interplay of local factors (e.g., proximity and geometry of nearby buildings, and their interactions with wind conditions aloft) but can be estimated with the GI4RAQ Platform (www.GI4RAQ.ac.uk).

3. Protect the most vulnerable: the young, the elderly and those with pre-existing medical conditions rendering them more susceptible to health impacts.

More deprived communities, in which Black and Global Majority people are concentrated, tend to live in more polluted areas[30] and show higher incidences of the conditions making them more vulnerable to health impacts.[31] They also have less disposable income to fund amelioration or escape from these environments. Prioritising interventions where the most vulnerable are exposed to higher-than-average (but perhaps not the highest) pollutant concentrations will deliver greatest public health benefits (i.e., value for money) and reduce health inequalities.

If thoughtfully integrated and well maintained, green infrastructure interventions can deliver health benefits from clean(er) air, and substantial co-benefits, not just for human health (e.g., increased thermal comfort[32]), but the health of other fauna and flora (e.g., increased biodiversity): One Health.

This briefing note was written by Dr James Levine, Dr Emma Ferranti and Prof Rob MacKenzie

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Why Battery Electric Vehicles are not Zero Emission Vehicles

Author(s): Professor Roy Harrison OBE FRS

Terminology

The term "zero emission vehicle" (ZEV) has long been used to describe battery electric vehicles (BEV). As pointed out by the UK Government's Air Quality Expert Group, such vehicles are anything but zero emission.[1] If one were to consider the full life cycle of a vehicle of any type, the pollutant emissions during manufacture of the vehicle and its component materials, and the end-of-life disposal alone are inevitably substantial. Despite this, it is the emissions during operational use which lead to descriptions such as low-emission vehicle, ultra-low emission vehicle and zero emission vehicle. However, unfortunately, it is only the exhaust emissions which are considered in applying such a terminology.

Sources of Emissions

Vehicle emissions do not arise only from the exhaust. Non-exhaust emissions of particles arise from abrasion of the brakes, tyres and road surface, and from suspension of road dust into the atmosphere by passing traffic. Vehicle exhaust emissions have been declining fast in recent years. European emissions standards have led to steady reductions in new car and truck emissions since the mid-1990s, but a large change started in 2011 when the Euro 5 emission standard for new light duty vehicles became mandatory and henceforth all new diesels were fitted with Diesel Particle Filters. Since then, as new cars enter the fleet, total emissions of particles from the exhaust have declined. This can be seen clearly in measurements of black carbon (a major component of diesel particles) at roadside sites such as Marylebone Road in London, with a decline from 8.8 µg m^{-3} in 2010 to 1.2 µg m^{-3} in 2021.[2]

Most developed countries maintain inventories of air pollutant emissions, and in Europe these account for emissions from traffic exhaust as well as the brake wear, tyre wear and road surface abrasion components of non-exhaust emissions. The road dust component is not usually included, as this is very hard to measure, and risks some double counting of the abrasion particles which deposit to the road surface after emission. For the UK, the inventory shows that in 2018, exhaust particles accounted for only 33% of $PM_{2.5}$ (particles smaller than 2.5 micrometres diameter, measured by mass) and 21% of PM_{10} (particles <10µm diameter) emissions from road traffic, with brake, tyre and road surface wear accounting for 67% and 79% respectively for $PM_{2.5}$ and PM_{10}.[3] So even without accounting for road dust resuspension, non-exhaust particles account for more than two thirds of the mass of emissions of the finer $PM_{2.5}$ particles which are believed to be more toxic. This inevitably raises the question of which type of particle is more toxic per unit mass. A number of recent reports from authoritative bodies, including the UK Committee on the Medical Effects of Air Pollutants, have concluded that on the basis of current knowledge, it is not possible to rank the relative toxicity of particles on the basis of their source or chemical composition, and hence all types of $PM_{2.5}$ should be regarded as equally toxic per unit mass.[4] In the case of non-exhaust particles, this seems very reasonable, as laboratory tests of toxicity have shown similar effects on cellular and acellular systems for exhaust, brake wear and tyre wear particles.[5]

Particles are not the only non-exhaust pollutant. Volatile Organic Compounds arise from evaporation of screenwash and de-icers, in addition to evaporation of fuel from the fuel tank and fuel lines. In the UK inventory data, the non-exhaust emissions have exceeded evaporative fuel emissions since 2004 and exhaust emissions since 2010. It is also significant that the mixture of compounds is very different from the fuel and exhaust-related emissions.[3]

So-called zero emission vehicles emit much the same mass of non-exhaust particles and organic compounds as internal combustion engine vehicles (ICEV). It has even been argued in a controversial paper by Timmers and Achten[6] that BEV have higher emissions than a modern diesel car, even when including the exhaust emissions in the calculation. This premise was based on the idea that a BEV is typically heavier than the nearest equivalent ICEV and consequently emits more wear particles and resuspended road dust as a consequence. The authors acknowledged that brake wear particles would be much reduced from a BEV due to regenerative braking in which no voltage is applied to the electric motor, which continues to turn due to the inertia of the vehicle and provides resistance to motion as it becomes a generator. Some BEV drivers use the conventional friction brakes only for emergency stops, and hence brake wear emissions from a BEV can be very small, but depend upon driving style, as do tyre wear emissions, which can be large from a BEV if the full acceleration is used. In our research work,[7] we have used the accepted weight dependences of emissions to compare BEV and ICEV emissions on three different road types, finding little overall difference between the total summed emissions from brakes, tyres, exhaust, road surface and road dust of the two vehicle types.

The Future

Can anything be done to reduce non-exhaust emissions? This may soon become mandatory as the EU has supported development of a standard test for brake wear emissions, and a test for tyre wear is under development. There are a number of avenues possible.[3] One is to reduce the weight of the BEV, but with safety requirements and the desire for greater travel range, this is not easy. There are a number of systems being researched for the capture of brake wear particles on the vehicle, as well as development of brake materials which abrade more slowly. Similarly, for tyres, particle capture and improved materials are possible avenues, but more challenging than for brake wear. Better road surface materials may mitigate the wear problem, but at a cost which the highways authorities may find prohibitive. Road dusts can be washed from the road surface, or stuck down with “suppressants”, but neither treatment is effective for long. The consequences of reducing urban speed limits and redistributing traffic through Low Traffic Neighbourhoods are complex, and likely to affect different types of non-exhaust particles in different ways. Hence, non-exhaust emissions will remain a problem for many years to come, and as long as they are, the Zero Emission Vehicle will never live up to its name.

This briefing note was written by Professor Roy Harrison OBE FRS

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Developing Interventions for Non-exhaust Emissions from Transport

Author(s): Run Si, Dr Jose Martin Herreros and Dr Jason Stafford

Background

Reducing exhaust emissions and facilitating net-zero transportation have been primary focus areas over the last decade to curb the climate and air quality issues we face. We have seen the emergence of pure electric and hybrid electric vehicles, as well as developments in combustion of biofuels, electro-chemical fuels, and hydrogen as main fuel sources or as mixture injections for current fossil fuels.[1-3] Furthermore, continuous developments of existing vehicle technologies, such as catalytic exhaust aftertreatment components and vehicle exhaust filtration for harmful particulate capture, have had major impacts on reducing exhaust emissions. Notable progress in the UK has occurred since the Climate Change Act 2008, which requires a 100% reduction in greenhouse gas (GHG) emissions relative to 1990 levels by 2050.[4] Firstly, 200,000 licensed vehicles in the UK in 2018 were ultra-low emissions vehicles, defined as cars or vans with tailpipe CO_2 emissions of 75 g/km or less.[5] Secondly, GHG emissions from road transportation in the UK have increased at a much slower rate than the increase in road traffic. From 1990 to 2017, road traffic in Great Britain increased by 29%, whereas GHG emissions from road transport increased by 6%[6] Thirdly, emissions of other harmful pollutants from road transportation have also reduced dramatically: emissions of nitrogen oxides (NOx) have fallen by 77% while emissions of carbon monoxide (CO) have fallen from 4.8 million tonnes to 0.3 million tonnes, a 93.8% reduction. Coarse mode primary (exhaust) particulate matter (PM_{10}) emissions have reduced by 45.7%, and last but not the least, fine particulate matter ($PM_{2.5}$) primary (exhaust) emissions have reduced by 56.7%.[7]

In the same period, however, other vehicle emissions sources have received far less attention despite warnings from scientific research that they are major contributors to harmful air pollution. Non-exhaust emissions (NEE) are continuously released during driving and are not emitted from the exhaust pipe of the vehicle.[8] These emissions can be categorised into two types – emissions from abrasion (brake, tyre and road surface wear) and road dust re-suspension.[9-10] NEE are considered to be significant according to many studies and have been shown to equal or surpass exhaust emissions.[11] In 2016, NEE particles from brake wear, tyre wear and road surface wear contributed 8.5% and 7.4% of total UK primary PM_{10} and $PM_{2.5}$ emissions, respectively. According to the UK National Atmospheric Emissions Inventory, these NEE are the majority source of primary particulate matter from road transportation, contributing to 60% of $PM_{2.5}$ and 73% of PM_{10} (by mass). Excluded from this is the effect of road dust resuspension, another important contributor which is highly sensitive to the road and environmental conditions.[12] Emissions can, therefore, vary by location with some locations in the UK experiencing above 90% of PM_{10} levels linked to NEE.[10] Even at low concentration levels, PM_{10} and $PM_{2.5}$ are associated with negative health outcomes such as chronic mortality, chronic bronchitis, coronary heart disease, stroke, lung cancer and asthma.[7]

Numerous pathways for these pollutants exist leading to their dispersion among different environmental compartments (air, soil, water) and even indoors.[13,14] Non-exhaust pollutants released from vehicles can also deposit in the soil, vegetation, or surface water run-off. Pollutants such as PM_{10} and $PM_{2.5}$ include chemical compounds, microplastics and micro-metallic particles, which come into contact with humans and animals in various ways through a series of complex environmental pathways. Microplastics have become a serious concern for marine wildlife health. Remarkably, about 34% of coarse mode tyre wear particles and 30% of brake wear particles have found their way into the World Ocean.[15] Airborne ultrafine particles (smaller than $PM_{2.5}$) can enter the human blood stream through the lungs and cause severe health issues such as lung cancer.[10] The evidence suggests that to protect the health of our environment and society, greater attention is urgently needed to create solutions for non-exhaust emissions.

Net-zero Transport and Air Quality

Transportation alone accounts for almost a quarter of UK GHG emissions.[16] Road transport is the biggest portion of the transport sector, and it has accounted for more than half of the GHG emissions across all transportation modes. The electrification of road transport has emerged as the primary direction to reduce transport carbon emissions. Electric vehicles (EVs) can meet the growing demand of road transport for both light duty vehicles (LDVs) and heavy-duty vehicles (HDVs) in some cases.[17] Using the UK for example, upcoming milestones for 2030 will end sales of new fully petrol and diesel cars and vans, followed by the requirement of zero tailpipe emissions for all new cars and vans beyond 2035.[18] Despite these GHG targets, electrification and use of low to zero carbon alternative fuels for future road transport will not solve the issue of ensuring good air quality for health and the environment. Particulate emissions from brakes, tyres and roads will persist unless new policy, planning and technological solutions are introduced (Figure 1).

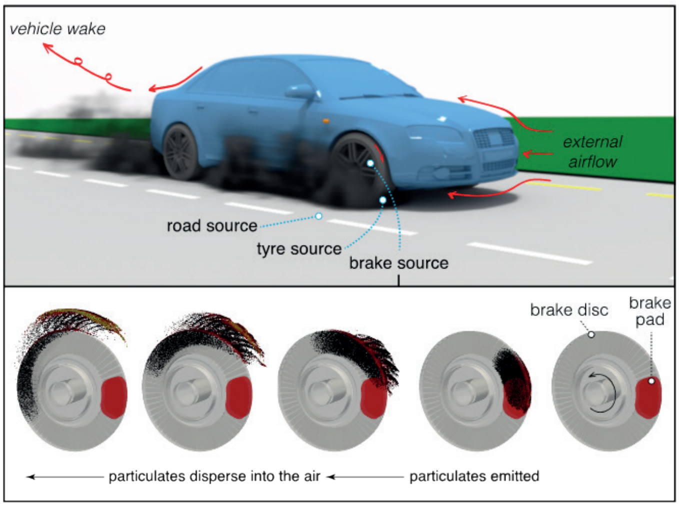

Figure 1: Non-exhaust emissions originate from brake, tyre and road sources. These numerical simulations illustrate the complex paths non-exhaust pollutants take from a rotating disc brake after a braking event (bottom), and from an entire car to the atmosphere (top).

Opportunities for Intervention

The 2021 Environment Act lists air quality as a priority area for the government to address in its long-term environmental plan. This legislation provides a general framework towards addressing the multifaceted air quality challenge, including transport. By establishing a legally binding duty to set targets for the concentration of fine particulates ($PM_{2.5}$), and for population exposure reduction, measures to reduce non-exhaust emissions in urban environments should be encouraged. Interventions and corrective actions to achieve progress, however, will require targeted approaches. The following lists a number of key areas and opportunities to develop solutions:

- Low emission abrasive materials and particle filtration to reduce emissions from NEE sources (brakes, tyres).
- Technologies that reduce or remove NEE sources (e.g. regenerative braking).
- Road planning that limits NEE exposure, particularly in urban areas with high population density – for example to reduce braking, cornering, and acceleration events.
- Automotive regulations that set baseline and progressive NEE standards and provide legislation to ensure these standards are upheld.
- Prioritising investment in interdisciplinary research that fast-tracks the development of sweeping interventions – for example holistic methods identifying the composition, pathways, and fate of NEE, the short- and long-term effects on population health from exposure, and the wider interactions with other environmental compartments.

Developments are emerging in some areas. With regenerative braking, data show that PM_{10} emissions from brakes can be reduced by between 12-26% on all road types, and $PM_{2.5}$ emissions can be reduced between 1.9-27%.[19] Technologies such as brake/tyre dust collectors can also reduce air and water pollution. The 2020 James Dyson Award was given for a tyre particle collector which could capture up to 60% of airborne microplastic pollutants.[20] Automotive filtration companies are also beginning to recognise the NEE problem, developing brake dust filtration concepts that are aimed at reducing emissions at source.[21] Although currently not intended to target NEE issues, urban planning through new city designs could support synergistic solutions that promote active travel and reduce NEE. For example, the Superblock Barcelona contains the functionality of a city in a 400 × 400 metre block and places restrictions on traffic that would also be favourable for reducing NEE. The entire block has a speed limit of 10 km hr-1 for vehicles, and the aim is to reduce private vehicle journeys from 36% to 18.5%, and for 81.5% of journeys to be taken on foot, bicycle, and public transport by 2024.[22] While these different examples of solutions and co-benefits are encouraging, more concerted and collective approaches will be necessary to mitigate the risks non-exhaust emissions pose to public and environmental health.

This briefing note was written by Run Si, Dr Jose Martin Herreros and Dr Jason Stafford

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Preventing Diesel Exhaust Fumes from Reaching Train Interiors

Author(s): Dr Hassan Hemida and Dr David Soper

Background

Diesel trains represent ~30% of the UK's passenger rolling stock. They are regularly used on railway lines which pass through densely populated areas carrying a large number of passengers. Previous studies have highlighted that these passengers may be subjected to significant levels of air pollution, including particulate matter (PM) emitted from the diesel engines. Morawska1 highlighted that all indoor sources contribute between 19% at 76% of daily residual exposure to PM. It is therefore important to assess the concentration of pollutants within train carriages and characterise the exposure commuters could face.

Diesel exhaust is a mixture of gaseous and particulate substances, from both unburned and burned fuel. It has been shown by Andersen et al.[2] that travelling on a diesel train may expose users to a higher risk of exposure to harmful particles than standing near a busy road. This train pollution is caused by a range of factors: positioning of the ventilation units, air contamination levels, and passengers entering and leaving the carriage, etc. However, it is hypothesised by the authors that a large proportion of these problems are caused by the diesel exhaust coming from the exhaust pipe of the actual train being considered. The pollutants enter the carriages through the heating, ventilation, and air conditioning (HVAC) system.

As part of the Rail Safety and Standards Board (RSSB) Clean Air Research programme, our team carried out a research project - Air Quality on Trains – HVAC and Exhaust Interaction Study[3] - to provide a better understanding of engine exhaust's direct contribution to air pollution onboard trains. The project aimed to determine how exhaust emissions and HVAC systems interact and impact levels of air pollution onboard trains and established factors that can be changed to improve air quality.

Current Standard and Regulations

The rail environment policy notes that diesel train emissions include seven dangerous pollutants, including nitrogen oxides and PM.[4] Historically, the UK has used EU concentration limits when considering air pollution; however, these limits apply to outside areas where population exposure occurs, and are not directly applicable for onboard railway vehicles. Recently, the UK government issued the Air Quality Strategy 2019 to protect the nation's health. By implementing the policies in this Strategy, $PM_{2.5}$ concentrations across the UK will be reduced, so that the number of people living in locations where ambient $PM_{2.5}$ levels exceed 10 $\mu g\ m^{-3}$ is reduced by 50% by 2025. Subsequently in 2021 the RSSB established air quality targets for the rail industry, by defining the level of pollutant concentrations to be achieved at various locations across the network by a specific time. The recommendation of the RSSB project is to set a minimum standard of 200 $\mu g\ m^{-3}$ per 1-hour average NO_2 onboard trains, with the aim of eliminating wherever possible engine exhaust ingress into trains. This minimum standard is to be assessed through spot checks on all diesel-powered (including bi-mode, diesel-and-electric) train services and for all classes of passenger trains. Therefore, to achieve these aims, the interaction between exhaust and HVAC units needs to be fully understood.

Understanding the Interaction between Exhaust and the HVAC units

To prevent diesel exhaust from entering train carriages, it was clear that an understanding of how the exhaust interacts with the HVAC system was required, before mitigation measures could be suggested. To overcome these challenges and open up a new capability for the rail industry, the project team at the University of Birmingham:

- developed a robust Computational Fluid Dynamics (CFD) simulation methodology for the interaction between exhaust gases and roof mounted HVAC systems;
- provided thorough validation of simulation techniques through experimental trials, capitalising on a unique aerodynamic capability (TRAIN rig facility) owned by the University of Birmingham;
- established the role of vehicle design and operational factors that influence air quality onboard trains, and
- provided industry guidance for using CFD analysis and recommendations on design considerations to improve air quality on trains.

The project demonstrated the ability of CFD methods to analyse the dispersion of pollutants from exhaust emissions within the highly turbulent aerodynamic flow around a train. To generalise the results for a variety of UK rolling stock, a generic train model was developed that comprises the features of the majority of the UK fleet (shown in Figure 1).

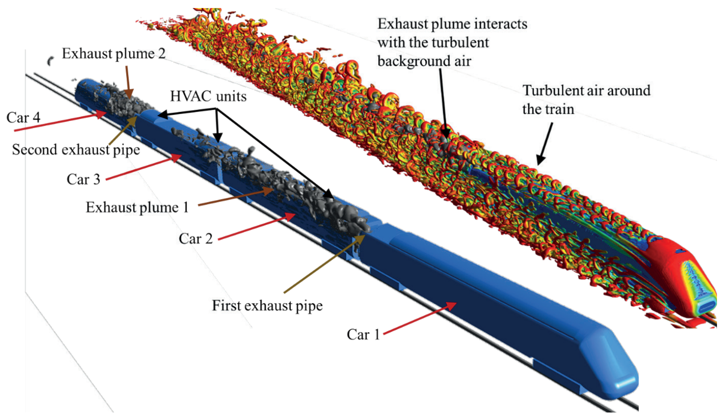

Figure 1: Generic train showing the turbulent flow, the exhaust plume and the interaction with HVAC units.

The results showed that the following factors have a significant effect on the interactions between exhaust plume and HVAC units:

1. position of the HVAC on the roof;
2. exhaust flow rate;
3. position of the exhaust pipe;
4. fresh air flow rate;
5. train roof shape (flat vs rounded);
6. crosswind;
7. length of the train;
8. shape of the exhaust pipe, and
9. idle coasting vs normal operation.

Mitigations and Optimisation Strategies

The results of the research project[3] showed that within carriage, concentrations are highly dependent on exhaust shape/position and on HVAC position on the roof. This project has shown that careful design can substantially reduce passenger exposure to harmful air pollutants. The opportunity now is to implement these findings across the industry, and to apply the research techniques developed to minimise passenger exposure in other transport environments. The key finding was that each train will need careful consideration through a specific CFD analysis. There are however a number of other possibilities.

1. Wherever possible, this issue should be considered in the early stages of design, and the roof profile around the exhaust designed so as to push the exhaust plume away from the train surface as much as is possible within other design constraints. Also, high performance filter systems on the HVAC units are desirable to reduce cabin particulate levels.

2. The results showed that the highest concentrations were in the trailing coach or the coach just before an inter-unit gap in coupled trains. This suggests the possibility of developing a different HVAC system for such coaches that draws air from adjacent coaches rather than from the roof. Again, this would require specific design for each train, together with a cost-benefit analysis of designing and installing different HVAC systems for different vehicles.

3. It may be possible to take advantage of the fact that the concentrations on the different sides of the HVAC system can be very different, and it may be that using intakes on just one side of the system might result in lower cabin concentrations. Intuitively one would hypothesise that intakes on the side of the HVAC system furthest from the exhaust would be lower than on the near side.

4. If possible, apply an after-treatment to the exhaust. Essentially this can reduce the total emission of nitrogen oxides, but also change the balance between NO and NO_2. The results of the project showed that, depending on the running condition, NO_2 levels can either decrease by 33% or increase by 67%, the latter being during idling while coasting.

5. Place the fresh air intake far away from the roof—preferably on the sides, above windows.

This briefing note was written by Dr Hassan Hemida and Dr David Soper

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Court Supervision of Air Pollution Safeguards

Author(s): Professor Aleksandra Čavoški and Professor Robert Lee

Case Background

Over time, case law has exposed the caution on the part of courts in England and Wales to review the technical and scientific judgement exercised by the Environment Agency (EA).[1] This has arisen recently in relation to the exposure thresholds to air pollutants and identification of appropriate guideline values in assessing the need for regulatory enforcement. In the widely reported case of *R. (on the application of Richards) v Environment Agency*[2] the claimant was a five and half-year old boy Mathew, living with his mother in the Staffordshire former mining village of Silverdale. Mathew was prematurely born and as result developed a lung condition known as bronchopulmonary dysplasia ("BPD"). Matthew is now continuously exposed to emissions of hydrogen sulphide above ambient levels together with bad odours, resulting from operations at Walleys Quarry Landfill Site (WQLS). Such exposures are said to not only affect his quality of life but to place him at risk of further developing chronic obstructive pulmonary condition (COPD). The landfill facility operates under an environment permit issued by the Environment Agency. The claimant applied for a judicial review of the EA's discharge of its duty as a public body, in line with section 6 of the 1998 Human Rights Act, to protect Mathew's right of life under Article 2 and his right to respect for private and family life under Article 8 of the European Convention on Human Rights (ECHR). The High Court declared that "in order to comply with its legal obligations, the Agency had to implement guidelines produced by Public Health England"[3] with the aim of reducing off-site odours and daily hydrogen sulphide concentrations to identified guideline levels.[4] On appeal, the Court of Appeal set aside the declaration as it failed to find actual or proposed unlawfulness on the part of the EA which called for a remedy.[5]

Reviewing Expert Determination

This reluctance of courts to engage with technical and scientific issues is not a recent phenomenon. It is often explained by the ingrained approach of the courts not to interfere with the discretion of the executive by adhering to specific and limited grounds for judicial review. It is a policy based to some degree on deference to scientific and technical expertise which the judge is unlikely to possess. However, as environmental issues are becoming more prominent, and there is more information and greater understanding of science and technology, there is a growing call for courts to engage more profoundly with the substantive content of environmental determinations in order to prevent wider harm to community wellbeing and to protect the environment. This is particularly relevant in environmental judicial review, in which it is often the case that in order to find a breach on the part of the regulator it is necessary to identify some form of procedural error because of the limited grounds of challenge to the substantive decision reached by a regulator. The *Richards*' case provides a good illustration of this challenge.

In considering the EA's conduct, the judge, Mr Justice Fordham, in the High Court spent some time reviewing significant scientific and technical evidence relating to the guidelines issued by Public Health England (PHE). This evidence was presented in a 'hot tubbing' process, in which concurrent evidence is presented by experts acting as witnesses.[6] The procedure aims to narrow down the issues and perhaps to iron out differences of opinion, often created in the adversarial setting of the court room. In *Richards*, this exercise, recognised by the judge as useful to the better understanding of experts' statements and conclusions, highlighted differences arising from the different disciplinary backgrounds of the experts and their understanding of safe levels of exposure. The witness called by the company operating WQLS was an experienced toxicologist and pathologist who relied predominantly on epidemiological studies, which were said to offer solid basis for setting a ‘good reliable safety level’. The expert acting for the claimant was a respiratory paediatrician who argued that there are no safe levels and that a ‘zero-tolerance’ approach might be necessary to protect children, “which accepts no increased emissions of hydrogen sulphide above ambient levels”.[7] This latter view is aligned with an approach informed by the precautionary principle which argues that in the face of threat of serious harm, lack of full certainty should not constitute a reason for taking cost effective measures.

The Limits of Review

In his judgment, Fordham J, did not accept the zero tolerance approach but he did not accept that the PHE guidelines were unduly precautionary either, or that Mathew’s condition was unrelated to air pollution. Rather, the judge accepted the evidence that levels of hydrogen sulphide were significantly impairing Mathew’s health. He did not expressly rule that the EA had acted unlawfully, but did grant a declaration requiring the EA to adopt the PHE guidelines, using these to “design and apply such measures” that (in the EA’s judgement) would achieve specified air quality outcomes in relation to emissions of hydrogen sulphide, by specified dates. This declaration was granted on the basis that there was a real and immediate risk to life in Mathew’s case, in the sense of shortened life expectancy, and that air pollution had a direct effect on Mathew’s home, and his family and private life. In the light of this there was a “positive operational duty” on the EA to take action but that compliance with human rights’ obligations would be met by taking the steps laid out in the declaration on the basis of the PHE guidelines.

While Fordham J endorses the PHE guidelines as based on “impressive, health-orientated documented sources”[8] he goes on to emphasise that it is not his task to identify appropriate exposure levels as this is a regulatory task drawing on evidence-based professional and scientific expertise and support. It remained inappropriate for the court to identify measures that EA should require the company to undertake to address the breach.[9] Such disclaimers, however, were found to have little traction in the Court of Appeal in allowing the appeal of the EA. The Appellate Court emphasised that the High Court went beyond its role by attempting to define the substance of the regulator’s action.[10] It is not for the court to set standards that the regulator needs to follow but “to adjudicate on whether a claim as brought was made out, and if so what remedy was appropriate”.[11] The Court’s role was to exercise the margin of appreciation by evaluating whether the regulator successfully struck a fair balance between the interests of the company and local residents.[12] This again would entail compliance with measures prescribed by law without any profound engagement with scientific or technical issues.

The High Court decision caused a brief flurry of excitement in legal circles as it might have heralded a more interventionist approach to reviewing the technical content of regulatory decision-making. Such an approach is not without precedent in other jurisdictions. In India, the National Green Tribunal engages technical experts in judicial decision-making in the hope of determining more effective environmental protection.[13] In the Netherlands, the Supreme Court ordered the Dutch Government to pursue more ambitious greenhouse gas emission targets based, as in *Richards*, on rights-based arguments arising out of Articles 2 and 8 ECHR.[14] More than 20 years after incorporating the rights in the ECHR into English Law,[15] the procedural limitations in judicially reviewing the scientific and technical content of environmental protection measures in areas such as air pollution, still constrain to some degree the oversight of those rights.

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Clean Air for All: The New Environment Act Targets and Way Forward

Author(s): Professor William Bloss, Professor Aleksandra Čavoški and Dr Suzanne Bartington

The 2021 Environment Act and New Air Quality Targets

Poor air quality can be obvious, as historical images of the 'Pea Souper' smogs of the 1950s and plumes from poorly regulated industrial chimneys remind us. However, air pollution exerts significant impacts on human and ecosystem health and wellbeing, even at levels too dilute for us to sense. We cannot personally perceive the pathway from emission to receptor (from the polluter to the polluted); thus, the externalities of many of our activities as a society upon clean air as a public good are neglected. Air quality policy seeks to protect public health through establishing appropriate standards for pollutant levels, compliance with which drives action for clean air. Here, we reflect on the nature and process for setting air quality targets in the UK, focussing on the contemporary Environment Act 2021 for England, and how developments in air quality information may shift the ambition of the debate.

The 2021 Environment Act includes a number of measures intended to improve air quality, including adoption of new legally binding targets for Particulate Matter (PM), improved provision and powers for local Government to effectively undertake Local Air Quality Management (LAQM) and establishment of a new independent regulator, the Office for Environmental Protection (OEP). However, implementation of the Environment Act has illustrated challenges in setting the numerical air pollution targets and sparked debates about best approaches to ensure protection of human health and enhance the quality of the natural environment, and perceived tensions with regulatory burdens and impacts upon individual choice and economic growth.

With regard to air quality, the Environment Act includes new governance systems and the potential for more ambitious targets. The Act prescribes the legal obligation for the Secretary of State to set long-term targets in respect of any matter which relates to the natural environment, or people's enjoyment of the natural environment (section 1(1)). Air quality is recognised as one of the priority areas (section 1(3)). This power must be exercised "in respect of at least one matter within each priority area" (section 1(2)). Of particular significance is the obligation conferred onto the Secretary of State to set "the $PM_{2.5}$ air quality target" in respect of the annual mean level of $PM_{2.5}$ in ambient air" (section 2(1)). This target may but does not necessarily have be a long-term target (section 2(2)).

How should new targets should be determined?

How this target will be set has been extensively discussed. In its Advice on health evidence relevant to setting $PM_{2.5}$ targets, the Committee on the Medical Effects of Air Pollutants (COMEAP) reflected on some of the approaches that Defra might seek to pursue and the $PM_{2.5}$ target concentrations supported by the latest science.[1] Related to this is the question of concentration thresholds and whether there is evidence to support a threshold of effect (i.e., is there any pollutant level below which no health impact occurs).

This leads to wider discussion on which threshold should be regarded as safe. If we apply a cost benefit approach coupled with threshold of effect, there are some concerns about the extent to which the precautionary approach will be applied to addressing air pollution. There is no doubt that there is no identified threshold below which air pollutant levels are safe: health benefits continue to accrue with cleaner air. The 2021 update to the World Health Organisation Air Quality Guidelines[2] found that adverse health effects persisted for NO_2 at annual mean concentrations of 10 µg m^{-3}, a level well below the 40 µg m^{-3} limit in force currently; similar considerations apply for $PM_{2.5}$.

A target consisting of a single threshold concentration limit encourages action in the most polluted locations (where levels exceed the threshold) but does not drive improvement elsewhere; the wider population may not benefit – despite exposure to air pollution at levels that cause harm. Combining a limit value with a Population Exposure Reduction Target (PERT) – effectively, the product of the annual average PM level and the population of a given area – will drive the public health benefits for the wider population. A single threshold value provides equity (focus on the most polluted areas), while the PERT approach provides efficiency (in achieving the greatest health benefit for the wider population). A PERT approach also allows the relevant authorities to demonstrate progress to the public on an ongoing (e.g. annual) basis.

There is the more significant question of what target levels are appropriate, and how should these be determined. The current UK/EU $PM_{2.5}$ limit value (25 µg m^{-3} as an annual mean) is significantly out of step with most recent WHO guideline (5 µg m^{-3}). This policy brief emphasises the need for new $PM_{2.5}$ threshold targets to at least reflect the WHO health-based guidelines, to be achieved by 2030. Thus, it is key that $PM_{2.5}$ targets combine both threshold and population-exposure-reduction approaches and reflect WHO guidelines in the level and timeline for compliance. One difficulty may be the national level of the targets: annual mean $PM_{2.5}$ levels are typically higher in London and the South East, due to concentration of sources and inflow from continental Europe. This should not preclude setting targets which might be challenging for London, but which would drive meaningful action (i.e., cleaner air) for those living elsewhere in England – rather, engagement with the challenge in the SE of England, from local to international dimensions, will deliver the greatest benefit across the country. A regional approach, balanced with national commitments, would permit the most efficiently tailored measures, but would also be legislatively challenging.

Which species should we focus on? Transport electrification will reduce NO_2 levels in urban areas (see brief by Zhong and Hodgson3) – but the WHO guidelines identify health impacts well below present day levels, as noted above. Separating the impacts of NO_2 and $PM_{2.5}$ is difficult: they have many common sources (notably, diesel traffic), challenging epidemiological approaches, and synergistic effects, potentially limiting inferences from human exposure studies. This has, arguably, been less important in the recent UK context – initiatives to tackle one pollutant were likely to bring benefits through reductions of the other in parallel (and the health benefits from reducing $PM_{2.5}$ are significantly greater). In the future UK context however, achieving the ambition of the Environment Act – if the level of the targets, and their timeline, reflect the science evidence of the levels at which harms occur – this may become more important. Widespread transport electrification will reduce tailpipe NOx and PM emissions, and wider combustion will become a more significant source of the latter, while hydrogen use (for example, in heating systems) may increase the former. The effect will be to separate sources of the two pollutants.

In a future Net Zero economy, neither NO_2 nor $PM_{2.5}$ may be effective metrics for a basket of wider pollutants including ultrafine particles, soot, carcinogenic polycyclic aromatic hydrocarbons (PAHs) and heavy metals. The Environment Act does not specifically require new targets for NO_2 or any air pollutants other than $PM_{2.5}$ (existing legislation will continue in force) – although it does allow the government to introduce these.

One factor which may affect views in this regard is the increasing availability of air quality information – from small, inexpensive indicative monitoring devices now widely available and disseminated through the web, to model tools providing predicted levels at postcode and household level. While such approaches may lack the rigour necessary to assess regulatory compliance, they underpin a growth in awareness of the challenge, and help empower individuals to act to reduce their exposure. We are seeing a shift in ownership of air quality information from central and local authorities to individuals, groups, and communities: this may begin to address the "public good" challenge outlined at the start of this brief – and translate into greater appetite – or demand – for cleaner air. Finally, the series of cases initiated by Client Earth demonstrates the power of civil society organisations and citizens in ensuring compliance with legal targets and holding government accountable.

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Reimagining Breathing Clean Air in Lower and Middle-income Countries

Author: Dr Nana Osei Bonsu

Air pollution in Lower and Middle-Income Countries

Air pollution and its impact on public health is a primary global concern. Yet, there is a vast disparity in the regulation and monitoring of air quality between wealthier nations and lower- and middle-income countries (LMICs). Drawing on a study in Ghana, West Africa, this policy brief outlines how LMICs can gather data on ambient air pollution to inform coherent policies that improve health impacts from air pollution.

Key messages:

- Air pollution increases poverty for lower-income people in LMICs and limits the possibility of social mobility due to health impacts, lost income, and related medical costs.
- Citizen science techniques via decentralised, locally-led regulatory air monitoring can help LMICs gather data on ambient air pollution concentration levels to inform coherent policies that improve health impacts from air pollution.
- To achieve clean air in LMICs, national air quality legislation must address the health effects of outdoor air pollution and transition to net-zero emissions. For example, banning import of high-polluting second-hand vehicles for commercial passenger functions.

According to the World Health Organisation (WHO), outdoor ambient air pollution was estimated to cause 4.2 million premature deaths worldwide in 2016 alone 91% of these from LMICs.[1] In the most developed countries, air pollution levels are monitored by networks of stations equipped with high-level instruments maintained by government agencies, producing high-quality data necessary for regulation.

However, in LMICs like Ghana, the full impact of air pollution on public health is unknown, due to substantial data gaps and hence a lack of policy priorities. So, what steps can LMICs such as Ghana take to clean up the air their citizens breathe?

Case Study – Ghana, West Africa

Ghana encounters a range of human, environmental and economic challenges, with air pollution remaining one of the country's major ill-health issues, causing early deaths and a mortality rate of 203.8 for every 100,000 people.[2] With no national monitoring scheme for air pollution, three major urban hotspots experiencing heavy traffic were selected in line with Ott's criteria for locating air monitoring stations.[3] The study areas were:

- Western Region – Tarkwa-Tamso Estate Junction
- Greater Accra Region – Accra – Kaneshi
- Ashanti Region – Kumasi – Mile 3 Junction and Alaba.

The study used a Low-Cost real-time Sensor (LCS) to provide indicative data on the spatial distribution of emissions of air pollutants from road transport, e.g. Particulate Matter ($PM_{2.5}$, PM_{10}), Nitrogen Oxides (NOx), and to raise awareness. Preliminary data were collected for an initial two to three-week period. However, LCS monitoring in the two most urbanised cities was continuous to ensure data consistency. Thirty people from groups who live and work in the case study areas were interviewed, including policymakers and those in positions of authority. These interviews explored views on the health effects, experiences and causes of living with high levels of air pollution.

What does the New Research tell us about why People in LMICs Breathe Dirty Air?

- The study revealed high traffic congestion on roads, with often old, privately owned commercial vehicles releasing harmful emissions of black soot/smoke.
- In some study areas, traffic build-up was due to insufficient infrastructure. Roads were not suitable for the number of vehicles using them, and dry and unpaved surfaces meant wind could blow dust particles and exhaust across the area.
- Many people depend on roadside locations for their livelihoods, food, shopping, cooking, and selling to the public, and hence are directly exposed to transport emissions.
- There is no financial assistance to raise awareness or monitor air pollution locally, with no viable strategy for improving communication to the public and decision-makers about its impact.
- There is a lack of local level epidemiological studies on air pollution and its effects on human health. Such gaps make it hard for local agencies and decision-makers to argue for prioritising pollution control measures, despite the estimated health burdens from air pollution.
- A lack of policy integration and coordination between government agencies that must deal with the causes and results of dirty air, such as planning authorities and health service providers, is also a significant issue.

Other findings:

- Apart from transport emissions, the public is exposed to ambient air pollution from burning rubbish, biomass, and charcoal.
- Pollutants, such as PM_{10} and NO_2 levels across the hotspots, are likely to be significantly higher than the WHO guidelines (but are not measured).
- Anecdotally, people from these areas shared their experiences of ill health such as catarrh, exhaustion, headaches, dizziness, coughs, sore throat, and asthma, which was particularly prevalent. All these conditions are caused or exacerbated by breathing polluted air.
- Interviewees understood the complex situation around poor air quality, citing people's dependency on old polluting vehicles and the government's difficulty in creating meaningful change.

Policy Recommendations

As a first step, LMICs can use citizen science to create more decentralised governance and a structured way for local policymakers and stakeholders, including the public, to monitor air pollution and shape its management. As well as building trust among the general public, this can also help raise awareness by engaging communities and local stakeholders and bridging health impact data gaps. Notably, decentralisation of environmental pollution management[4] also promotes regional green development. As a potential pathway, this study recommends:

- Decentralisation of air quality management in LMICs adhering to national and international standards since air pollution health impacts are primarily locally felt. A decentralised governance structure will help build more robust technical capabilities at the local level to respond more effectively to emissions, health impacts and priorities while also allowing policies and instruments to be better tailored to local conditions. For example, the central authority (i.e., Environmental Protection Agency) could empower, train and develop the technical capacities at local and provincial levels to implement locally-led policy measures, such as higher rates on high-emission vehicles and establishing emission zones.
- Integrating different forms of knowledge in local policymaking by bringing together relevant regional or local multi-stakeholder groups such as the EPA, public health professionals, transport planners and associations, community groups, the public, and city planners to co-design, and implement and monitor a coherent local air quality management plan. This could follow tried-and-tested models elsewhere[5] that integrate cross-sectoral knowledge in local air quality policymaking and implementation.[6]
- Measures should aim to strengthen the capacity of local legal and judicial authorities, including courts and district councils, to enforce regulations on local air pollution control.

New Air Pollution Legislation & Dealing with Political Feasibility

The study stresses the importance of politicians and national governments' developing policies and enforcing new national legislation that addresses the health effects of air pollution, such as:

- Regulatory instruments for the importation of second-hand vehicles

  Though importation of second-hand vehicles from developed countries creates jobs, contributes to regional economies and livelihoods, and provides affordable mobility/transport in LMICs, the poor quality of these vehicles hinders efforts to mitigate the climate crisis and health impacts of health air pollution. This study reveals "weak" policies to regulate the import of used polluting and unsafe vehicles. Thus, it calls for stricter regulatory instruments to control environmental externalities from exporting and dumping old, polluting, and hazardous vehicles from wealthier nations to LMICs. This unethical practice damages the health of those living in LMICs, whilst richer nations benefit from exporting their old vehicles to aid those countries. Hence, breathing clean air in LMICs will require substantial international leadership and cooperation and deal with the moral obligation of decision-makers to address the political feasibility of air pollution policymaking in the developing world.[7] Authorities in exporting and importing countries should fill the current policy vacuum by advocating for a UN charter or harmonised quality standards guarantee to control transport sector externalities, i.e. the desired level of protection of public health and environmental quality.

- Emission control and recalling of highly polluting vehicles

  The transport sector is responsible for nearly a quarter of energy-related greenhouse gas emissions. Thus, new legislation is recommended for decarbonising LIMC's transport sector through a transition to low and net-zero emission vehicles. Decarbonisation measures to reach net-zero emissions by 2050 should strategically enable vehicle emissions testing and recall old high polluting vehicles. In addition, a funded scrappage scheme is recommended to gradually phase out and subsidise or compensate old polluting commercial vehicle owners towards a shift to low and net-zero emission vehicles. For example, introducing hybrid and electric commercial minibuses use in urban areas, including embracing emissions standards mirroring Euro 5 and 6.[8]

LMIC decision-makers must develop transformative policies to reduce the impact of air pollution and improve related public health outcomes. New, innovative, and future-oriented thinking and integrated mechanisms are crucial to help reimagine and realise a different future that averts the worst air pollution and climate change effects. This policy brief stresses the urgent need for LMICs' to focus on sustainability and the co-benefits of decarbonisation and clean air while transforming vulnerable populations' livelihoods and boosting economic activities.

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Social and Environmental Impacts of Domestic Solid Fuel Burning

Author: Dr Deepchandra Srivastava

Effects and Use of Solid Fuel

Exposure to high levels of airborne particles is one of the five greatest health risks worldwide. According to the World Health Organisation (WHO),[1] approximately 3.8 million deaths per year globally can be attributed to exposure to indoor air pollution, which is mostly linked to cooking or heating activities involving the use of solid fuels (the other 4.2 million deaths per year come from outdoor or ambient air pollution). Globally, half of pneumonia deaths amongst children aged under 5 years are linked to household air pollution, as well as 17% of lung cancer deaths in adults.

The burning of solid fuels, such as wood, crop waste, coal and dung, releases harmful pollutants, such as carbon monoxide (CO), oxides of nitrogen (NO and NO_2 = NOx), sulphur dioxide (SO_2), as well as tiny particles collectively referred to as particulate matter (PM), much of which is easily inhaled and can go on to cause adverse health effects. A group of toxic compounds called polycyclic aromatic hydrocarbons (PAHs) are a common component of particles associated with burning and are known carcinogens. Researchers from Lund University found that exposure to wood smoke particles has an adverse effect on pregnancy outcomes, preterm delivery, and increased risk of preeclampsia.[2] Exposure to such PM has also been linked to respiratory problems, heart disease, strokes, cancers. Thus, exposure to these particles should be kept to a minimum. Emissions of soot particles also causes nuisance and loss of amenity by darkening buildings and even impacts clothes drying. Despite the common perception that the use of biomass fuel is less harmful to climate than fossil fuels, it should be noted that soot particles have light absorbing properties that can warm the atmosphere, so any reduction in net carbon emissions by burning biomass will be somewhat offset by this effect.

For people living in lower- and middle-income countries (LMICs), cooking practices which use solid fuels are very common. The progression from solid fuels to cleaner fuels, like LPG (liquid petroleum gas), natural gas and electricity occur with increasing wealth, however the poorest communities still have no access to alternative fuels with an estimated 2.6 billion people still using solid fuels globally. Recent research suggests that women in Uganda and Ethiopia are at seven times higher risk of developing health problems associated with indoor air pollution exposure than men, due to their greater role in households.[3] The Global Alliance for Clean Cookstoves report in 2017 suggests that despite the distribution of over 80 million improved cookstoves, a sustainable improvement in health has not materialised as policies did not consider the historical, cultural and behavioural aspects of the use of solid fuels.[4] For example, many social and religious occasions in LMICs involve the preparation of meals in a traditional way. This suggests that any policy change, or sustainable solutions, should be based on an in-depth understanding of the social and cultural context of solid fuel usage in cooking, including the influence of non-cooking factors.

The use of solid fuels to heat domestic housing during colder seasons is common place in many countries, irrespective of GDP. Domestic wood burning activity has become the biggest source of PM pollution indoors in the UK,[5] and exposure to wood burning PM is calculated to cost £1bn a year in health-related damages.[6] Closed stoves and open fires were found to be responsible for 38% of human exposure to $PM_{2.5}$ pollution in 2019, whereas road traffic was only responsible for 12%.[7] Annual primary emissions of $PM_{2.5}$ have fallen by 80% over the past 50 years in the UK,[8] through reductions in the use of coal and higher emission standards for transport and industry. However, further reductions have levelled off in recent years, due in part to increases in emissions from domestic wood burning and use of biofuels by industry. Emissions of PM from domestic wood burning have increased at a rate of around 3% each year since 2003.[9]

Challenges of Cutting Solid Fuel Burning Emissions

Reducing the health impacts of domestic wood burning emissions is complex. Small-scale domestic heating involving the burning of wood and other biomass is popular in many western countries and is often considered a sustainable source of fuel that can assist in climate change mitigation and energy security. It should be recognised that in some rural areas burning wood to heat homes may be the most cost-effective and, in some cases, the only option – particularly in the context of gas, electricity and heating oil inflation and fuel poverty. In addition, indoor wood burning stoves have also become something of a "fashion statement" for many households in urban areas that are used more as a home accessory which can provide a nostalgic and comforting focal point. The challenge is to balance this choice with the negative impacts on the health of households, their neighbours, and the environment around them. It may be that wood burning should not be considered as acceptable, at least where it is not a necessity. One simple first step is to ensure that any wood burned is dry, as this substantially reduces emissions. Within the UK, legislation passed in 2021 requires solid fuel sold in volumes of up to 2 m^3 to have a moisture content of 20% or less so it will produce less smoke when burnt.[10] Despite modifications in the design of wood burners to reduce PM emissions, researchers from the University of Sheffield found wood burning stoves tripled indoor PM concentrations when operational.[11] A report by the Air Quality Expert Group suggests that domestic stoves are likely to produce more PM than old vehicles.[12]

Thus, any future policy to be implemented with the aim of reducing human exposure to particles from the burning of solid fuels needs to balance health and environmental objectives with the necessity of heating and cooking in some contexts, and personal choice regarding domestic behaviour in others. In order to strike this balance, we must fully understand all the health impacts associated with exposure, which will require more clinical and epidemiological studies. We also need a conversation about the real climate and "eco" credentials of burning biomass to heat homes. However, we can start with a few simple steps by providing energy efficient housing or by developing initiatives intended to incentivise smoke-free ways to heat homes and to cook (e.g., move from coal to gas) in LMICs. We should reach out to communities to raise awareness on the negative impact of exposure to solid fuel PM so people can make informed choices if possible. Strategies for moving away from solid fuel burning should recognise individual needs and be tailored according to where the strategy will be implemented. Working with industry to develop new, easy to use and affordable abatement technologies should also be explored. While the debate will undoubtedly continue, it is likely there will never be such a thing as a clean wood stove, and this needs to be more widely recognised in terms of the health impacts caused.

This briefing note was written by Dr Deepchandra Srivastava

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Cleaner Cooking Fuels – Improving Health in a Time of Climate Crisis

Author: Katherine Woolley

Effects and Use of Cleaner Fuels

Should we accept solutions to household air pollution which damage climate?

Currently, over half the world's population cook using solid biomass fuels (wood, dung, charcoal, and crop residue), which is the main source of Household Air Pollution (HAP), due to high levels of Particulate Matter (PM) associated with biomass combustion in poorly ventilated settings.[1] Cooking using cleaner fuel sources such as Liquid Petroleum Gas (LPG), electricity, biogas and solar, plays an important role in mitigating the health impacts of HAP. Despite advances in accelerating access to cleaner fuels, the absolute number of solid biomass users has not decreased over time, due to population growth.[2] A high reliance on solid biomass fuels has led to significant health, socioeconomic and environmental impacts, which limits progress towards multiple UN Sustainable Development Goals, including good health and wellbeing (SGD 3), gender equality (SDG 5), affordable and clean energy (SDG 7), climate action (SDG 13) and life on land (SDG 15).[3]

The primary cleaner fuel alternative (in terms of reduced PM emissions) in low and middle-income countries is LPG, which is a non-renewable energy resource. LPG is readily used and can be stored in cylinders and therefore is easier to deploy in settings which lack mains gas or electricity infrastructure. The adverse climate impacts of using fossil fuels for domestic energy are well known, as demonstrated by trends in some high-income countries away from these to meet net zero commitments. However, there are potential climate benefits of using LPG compared with solid biomass fuels (e.g., lower production of short-lived climate pollutants and a negligible increase in CO_2 emissions).[4] In addition, the direct health impacts associated with PM exposure are significantly decreased with sole use of a cleaner fuel, with attendant wellbeing and economic benefits.[5] While the transition to non-renewable clean fuels would help achieve SDGs 3 (health and wellbeing), 5 (gender equality) and 7 (affordable and clean energy), it would not support climate action (SDG 13). It is also worth noting that increasing reliance on LPG could have an impact on energy prices in the longer term and increase the exposure to global energy price volatility.[6]

Transition to Sustainable Energy Resources

Sustainable alternative energy sources to LPG include solar, electricity (if produced from renewable resources) and biogas (production of gas from decomposing animal waste or biomass), all of which require infrastructure investment and local knowledge to deploy. Solar and electricity from renewable resources (e.g. wind, hydroelectric) produce less climate driving gasses, but biogas does still release greenhouse gasses; and the animals also emit methane. While biogas programmes have been deployed at small scale with some success in India[7] and Rwanda,[8] there are still barriers to scale up the use of biogas (e.g. gender equality, stakeholder engagement, maintenance, implementation strategies).[9] While cleaner cooking fuels remain inaccessible to many due to cost, lack of supply, maintenance and awareness of the harms of HAP, new technologies will be hard to deploy at scale, without educational and governmental support.

The consequences of not transitioning to cleaner fuels are clear, despite considering the negatives. Using traditional biomass cooking methods has significant impacts on gender inequality due to risks for women and children who typically collect fuels.[10,11] This is coupled with the increased health hazards of HAP exposure due to spending more time undertaking cooking and domestic tasks, alongside opportunity costs for educational development or alternative employment due to the time associated with solid biomass cooking. Incremental solutions such as improved cookstoves, and improved biomass fuels do not lead to substantive health and gender equality improvements. Conversely, reliance on solid biomass fuels causes major environmental degradation including deforestation, desertification, and erosion.[12] These impacts on land quality not only add additional physical hazards but could also lead to food insecurities,[13] which are particularly prevalent issues associated with climate change. Therefore, a move to cleaner fuels generated by renewable sources – such as wind and solar - would achieve both climate and health benefits. This energy transition provides an opportunity to invest in renewable production and thereby avoid the negative climate implications of fossil fuel reliance, whilst achieving major clean air benefits for those living in resource poor settings.

Having access to a source of domestic energy for cooking is not a luxury, as it is a necessity to eat. Thus, many living in resource poor households have no other option but to use polluting solid biomass fuels. Tackling climate action is a core SDG and transitioning to cleaner energy solutions away from fossil fuel sources needs to account for this. There should be an aim to create longer-term sustainable and renewable energy sources rather than just applying short-term LPG solutions which may hinder attaining future climate change objectives. Full attainment is a challenge due to infrastructural weaknesses in resource poor settings and the need for more detailed research on the effectiveness and acceptability of renewable cleaner energy sources which considers social and cultural factors. There is a balance between health objectives and climate action if fossil fuel alternatives are deployed in the immediate term to mitigate HAP impacts. However, a drive to LPG reliance will lead to further climate challenges in the longer term. Ultimately transition to renewable energy sources whilst delivering clean air benefits at a household level is critical for achieving a sustainable development trajectory whilst protecting the health of citizens.

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Co-benefits of Decarbonisation Policies on Future Ambient Air Quality and Health

Author(s): Dr Jian Zhong and Dr James Hodgson

Introduction

Climate change (long-term shifts in global average temperatures and weather patterns) is linked to impacts including flooding, wildfires and heatwaves, crop failures, loss of biodiversity and rising sea levels, which can significantly affect the planet's ecosystems and human society. Climate change is a global challenge and therefore requires international efforts to develop effective interventions. The 2015 Paris Agreement[1] brought more than 190 countries together to commit to a long term goal of "limiting the global temperature increase to well below 2°C, compared to pre-industrial levels", which if achieved would limit the most damaging impacts due to climate change. The Conference of the Parties (COP-26)[2] in Glasgow in 2021 included the Glasgow Climate Pact[3] as a somewhat enhanced commitment to mitigate climate change.

Climate change is mainly caused by activities such as burning fossil fuels, which emits carbon dioxide (CO_2) into the atmosphere. CO_2 as the most important greenhouse gas remains in the Earth's atmosphere system for many years, driving warming. According to the Intergovernmental Panel on Climate Change (IPCC),[4] significant reductions in carbon emissions are needed by 2030 to retain the prospect of limiting global warming to 1.5°C and avoid the most damaging climate impacts, while there are ambitions to achieve net zero by 2050 and to limit global warming to below 2°C.

Decarbonisation aims to remove or reduce CO_2 emissions via low carbon technologies and policies in a variety of sectors (e.g. transport, energy, industry, residential). Frequently, CO_2 is co-emitted with short-lived air pollutants, formed during the fuel combustion process. Decarbonisation will therefore also reduce emissions of air pollutants and bring co-benefits of cleaner air and improved health. This article investigates the co-benefits of decarbonisation policies on ambient air quality and health.

UK Net Zero Strategy

In 2019 the UK became the first major economy to adopt a net zero target[5] to avoid increasing impacts due to man-made climate change. This legislation requires the UK to take actions to achieve the binding target of net zero emissions by 2050. Net zero does not mean that carbon emissions will cease entirely. It is acknowledged that it is difficult to completely decarbonise some sectors (e.g. aviation, agriculture, and industry). The residual emissions from these sectors will be compensated by greenhouse gas removal (e.g. trees, and carbon capture and storage technology).

Following the launch of Ten Point Plan for a Green Industrial Revolution[6] in November 2020, the UK government launched its Net Zero Strategy[7] in October 2021, to fulfil the UK's commitment to the Paris Agreement. This strategy includes UK decarbonisation pathways to meet Nationally Determined Contributions (i.e. to cut carbon emissions by 68% by 2030 compared with 1990 levels) and to reach net zero emissions by 2050 by establishing carbon budgets for all sectors (e.g. decarbonisation policies in power, fuel supply and hydrogen, industry, heat and building, transport, Natural Resources, waste and fluorinated gases sectors) of the UK economy and associated actions for the transition.

Air Quality and Health

The key air pollutants of concern in urban areas are nitrogen dioxide (NO_2) and particulate matter ($PM_{2.5}$) – fine inhalable particles less than 2.5 micrometres in diameter, 20 times finer than a human hair. Local road transport represents the largest source of NO_2 emissions in urban areas. The major primary emission sources of $PM_{2.5}$ are combustion in commercial, industrial, residential and agriculture, road transport (exhaust from tailpipe and non-exhaust from tyre wear, brake wear, and road surface wear). The implementation of clear air zones[8], in cities such as London and Birmingham, is intended to reduce the highest NO_2 roadside concentrations, but these emissions control measures will not address the majority of air quality health impacts, notably those due to PM exposure.

There are about 4.2 million premature deaths attributed to ambient air pollution worldwide each year, as estimated by the World Health Organisation (WHO)9. 99% of the world's population[10] is exposed to air with pollution levels exceeding health-based WHO guidelines. The latest WHO Air Quality Guidelines[11] highlight that even exposure to lower levels of air pollutant can affect human health. In the UK, the premature mortality burden attributed to the long-term exposure to harmful air pollutants is 28–36,000 per year.[12]

Assessing Climate, Clean Air and Health Co-benefits

This brief quantifies potential air quality and health co-benefits of 2030 decarbonisation policies, using the West Midlands, UK, as an example. Through the WM-Air project[13] we have configured an air quality model14 for the West Midlands, applied here to conduct air quality modelling scenarios (e.g. impacts of decarbonisation policies). We compare two scenarios: A 2030 business-as-usual (BAU) case uses emissions projection for 2030 based on the National Emission Ceiling Directive (NECD),[15] which is the most recent projection of national emission reduction of certain air pollutants for the UK. An alternative 2030 decarbonisation scenario incorporates carbon reduction measures as projected in the Net Zero Strategy, across all sectors (such as power, fuel supply and hydrogen, industry, heat and building, transport, and Natural Resources, waste, and fluorinated gases).

The model's predictions show that reductions of annual mean NO_2 of 5-7 $\mu g\ m^{-3}$, or 17-21%, could be achieved through decarbonisation policies relative to the BAU scenario. The distribution of NO_2 is significantly influenced by changes in emissions from road transport. When averaged to the ward level, a 7% reduction in the proportion of the population exposed to NO_2 levels higher than the 2021 WHO guideline of 10 $\mu g\ m^{-3}$ is achieved. For $PM_{2.5}$, reductions in the annual mean of 1-1.4 $\mu g\ m^{-3}$, or 8-12% could be achieved through decarbonisation policies, and the influence of road emissions is less significant than for NO_2. An overall reduction of 16% in the proportion of the population exposed to $PM_{2.5}$ levels above 10 $\mu g\ m^{-3}$ from decarbonisation measures is predicted. This translates to prevention of 736 lost life-years (or 68 annual premature deaths) due to the PM air quality benefits achieved across the West Midlands.

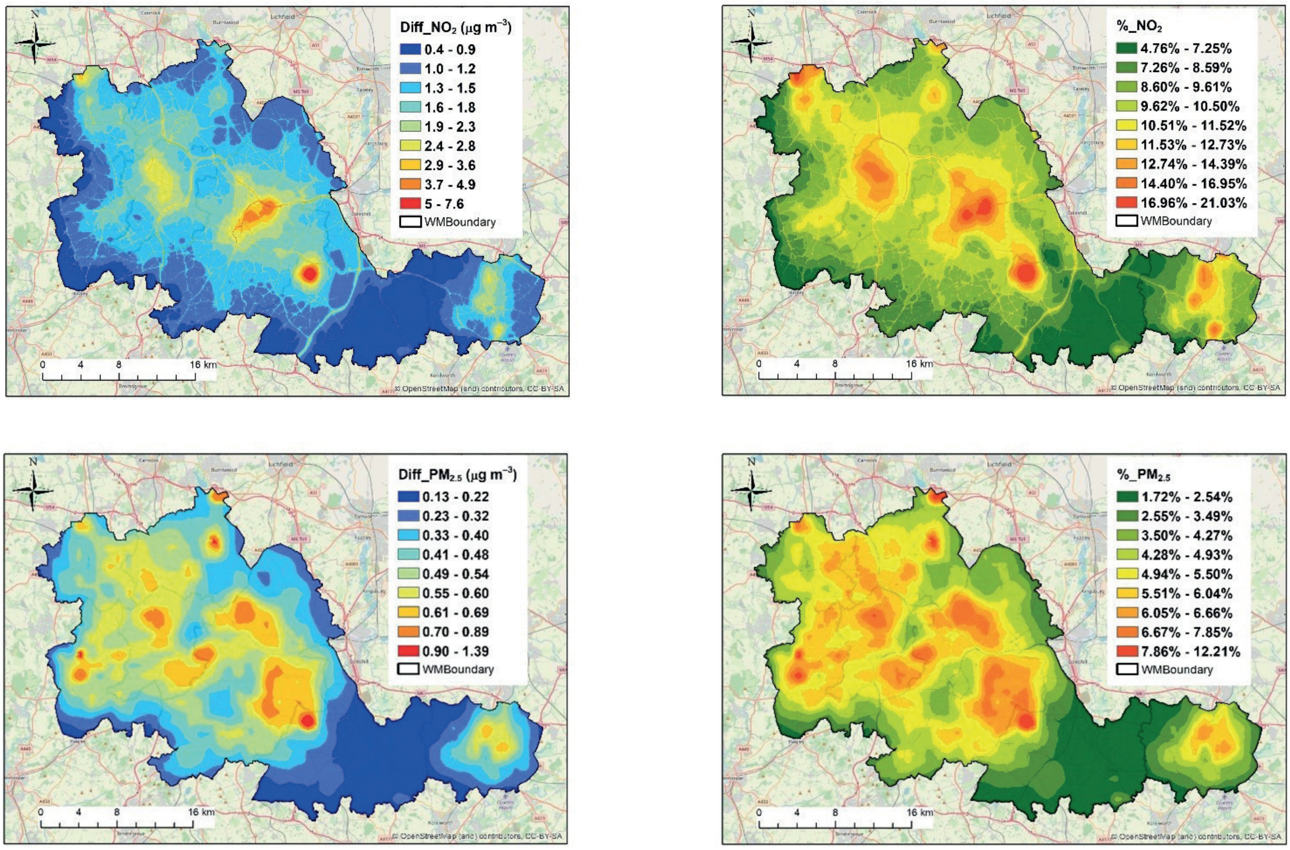

Figure 1: Impact of decarbonisation policies on $PM_{2.5}$ and NO_2 levels across the West Midlands in 2030. Top panels: absolute and percentage reductions in annual mean NO_2 for the decarbonisation scenario, relative to business-as-usual. Lower panels: corresponding absolute and percentage changes in annual mean $PM_{2.5}$.

This briefing note was written by Dr Jian Zhong and Dr James Hodgson

Concluding Remarks

We have investigated the air quality and health co-benefits which an NDC-driven decarbonisation scenario would achieve across the West Midlands in 2030, relative to a business-as-usual case. Decarbonisation of the road transport sector has a significant impact on NO_2 concentrations, especially for these who live near roads. Decarbonisation in other sectors (such as residential and industry combustion) has a larger impact on $PM_{2.5}$.

Poor air quality is experienced locally, and the density, demography and health geography of the affected population matters for determining health effects. The pathway to net zero requires careful management of the decarbonisation polices, to maximise air quality and health benefits. Detailed transition scenarios for key major individual sectors, such as the environmental response to hydrogen emissions, transport electrification and clean energy, also need further exploration, alongside the behavioural changes associated with this transition. Explicitly quantifying air quality and health co-benefits underpins setting priorities for future decarbonisation policies, and the mitigation of environmental justice consequences.

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Why a Transition to Green Ammonia is Imperative for Climate Change Goals

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The Need to Decarbonize Ammonia Manufacture

As the impetus to limit global warming gains urgency, nations across the globe are formulating policies to decarbonise various sectors of the economy.[1] Fossil fuel consumption is fundamentally linked to global warming and many aspects of air pollution, thus moving away from these is critical. This document outlines why a transition to greener, non-fossil fuel-based methods for ammonia manufacture is imperative to achieving net-zero goals.

Ammonia has played a pivotal (if largely unrecognised) role in feeding the world population and supporting human life since the turn of the 20th century.[2] Ammonia production (presently, primarily for fertiliser manufacture) is a multi-billion dollar global industry with annual global production being approximately 176 million tonnes. It is responsible for over 1.5% of global greenhouse gas (GHG) emissions (approximately 350 million tonnes of GHG per year).[3] 96% of ammonia is manufactured using the conventional Haber–Bosch (HB) technology for ammonia synthesis from nitrogen and hydrogen. The hydrogen supply for manufacture is currently almost exclusively fossil fuel-based (most commonly, derived from natural gas), which is the primary source of its carbon footprint. Replacing natural gas with a green hydrogen source, such as renewable electricity-powered water electrolysis would reduce CO_2 emissions by an estimated 75%.[3] Alongside moving to a green hydrogen source, powering the entire manufacturing process by sustainable electricity will yield ammonia that is 100% renewable and carbon-free, often referred to as 'green ammonia'.[4]

The potential benefits of green ammonia extend far beyond its current use for fertiliser, into its use in the green energy transition. Although there is much enthusiasm currently about hydrogen as a green fuel and energy store, ammonia has many advantages for these applications compared to hydrogen. It is easier to compress and liquefy, making it easier to store and transport than hydrogen. Furthermore, this is an already-mature industry with robust global infrastructure: large-scale ammonia manufacture for fertilisers is ongoing. The existing manufacturing, storage and distribution technologies can be readily adapted for the green ammonia transition. Green ammonia may be used directly as a zero-carbon fuel, such as in maritime transport, or as a hydrogen carrier for applications where hydrogen is used, as is the case in many types of fuel cells. Green ammonia can therefore contribute in multiple ways as a potential clean air solution.

With the evolving energy landscape, and the UK's binding climate change targets enshrined in legislation,[5] there is now a pressing need to move away from fossil fuel-based hydrogen. The UK government has legally binding targets to reduce greenhouse gas emissions by 100% of 1990 levels by 2050.[6] The UK's Ten Point Plan for a Green Industrial Revolution highlights the critical importance of low carbon hydrogen for decarbonizing our energy and industrial sectors. The UK Hydrogen Strategy[7] aims for 5 GW of low carbon hydrogen production capacity by 2030. This will require the engagement of the industrial sector with a rapid ramp up of green hydrogen production over the coming decade. A parallel transition to green ammonia is now indispensable to meeting the Paris Agreement's aspiration to limit temperature rise to 1.5 degrees by 2050.

Challenges for Policymakers in the Transition to Green Ammonia

Achieving a safe and sustainable transition at the pace needed does, however, require policy measures to encourage manufacturers and markets to prioritise green ammonia, and the addressing of regulatory gaps. Green ammonia manufacture is being piloted in various existing manufacturing facilities around the world with this initiative being currently driven almost entirely by a few interested industry actors. However, there are, presently, no specific regulatory frameworks for its use or manufacture in the UK, and inadequate incentives for manufacturers to engage with the transition. Despite the contribution that green ammonia can make regulation appears to have lagged behind in shaping this transition. We contend that the need to deliver on net zero targets requires a mandate for a more interventionist approach on the part of policymakers. Resolving the air pollution crisis requires policies to facilitate a safe and sustainable green ammonia transition. Policymakers will need to engage with a number of challenges:

- Evolving technologies: Government policy seeks guidance from science, but because this is an emerging technology, regulators will need to navigate a degree of scientific uncertainty. While manufacturing technology is per se mature, establishing a renewable hydrogen source poses a techno-economic barrier (arguably, more economic than technical: legislative measures will be critical for ensuring the availability of green hydrogen). Furthermore, unlike ammonia synthesis, which has been performed on an industrial scale for several decades, ammonia cracking to yield hydrogen is less established and remains an area of research. While the decarbonisation of the fertiliser sector is not reliant on ammonia cracking technology, the development of an efficient process to convert ammonia back to hydrogen is key to energy-related applications where ammonia will serve as a hydrogen carrier.

- Lack of definitional clarity: when is ammonia 'green'? Green ammonia is predominantly defined by the colour of the constituent hydrogen, and we have no way of knowing the hydrogen input into ammonia after manufacture. This raises definitional complexities. Hydrogen comes in a spectrum of colours denoting environmental impact, ranging from brown, grey, blue, and green. The industrial uses of hydrogen have historically employed cheap fossil fuels without carbon capture ('brown' or 'grey' hydrogen, rather than green). The transition to 'green' hydrogen is likely to be incremental rather than immediate, thus the transition to green ammonia is anticipated to follow a similar pathway. Until sufficient quantities of green hydrogen become available at viable cost, it is entirely foreseeable that ammonia manufacturers may in the early stages only be able to achieve partial transition; for example, by using a mix of fossil-fuel based and renewable hydrogen. Although such a partial transition would reduce the carbon footprint of the manufacturing process, the produced ammonia would not, under strict definitions, be classified as 'green' ammonia. Likewise, producers who incorporate carbon capture, storage, and utilization mechanisms, to whatever degree, are also contributing to manufacturing cleaner ammonia. It is important that these early partial efforts to decarbonise ammonia manufacture do not go unrecognised, thus some industry and scientific consensus on defining and labelling these various grades of cleaner ammonia is critical. The Ammonia Energy Association aims to formulate definitional clarity, and the UK will need to consider whether to follow these or develop national standards.

- Standards and certification: Manufacturers will want clear licensing and certification mechanisms, as lack of objective monitoring makes it difficult to distinguish genuine green ammonia from disingenuous claims or 'greenwashing.' There is currently no authorised regulatory body for green ammonia certification (nor, indeed for green hydrogen certification). This is a significant regulatory barrier for a credible green ammonia transition.

- Incentives and markets: Until green hydrogen becomes more widely available, green ammonia is likely to be a premium product. If this is reflected in premium pricing, market demand for a more expensive, even if more environmentally friendly, product is uncertain. There is no regulatory requirement for UK manufacturers to manufacture green ammonia, nor an incentive for purchasers to buy this, but these may be imperative for enabling the shift. The UK and EU Emissions Trading Scheme (ETS) provide some incentives as ammonia producers are allocated free allowances of carbon credits based on a determined benchmark. An ETS works on the cap-and-trade principle. A cap is put on the total quantity of greenhouse gases that can be produced, this cap is gradually reduced over time which results in lower total emissions.[8] Within the cap, installations purchase or receive emission allowances, which they can trade with one another as needed. The EU also proposes to introduce the Carbon Border Adjustment Mechanism (CBAM), which imposes a carbon price on imports of certain goods, including ammonia.[9] The CBAM will incentivise both green and blue ammonia by applying the same carbon costs to importers and domestic producers in the EU, and the UK should consider similar measures.

Ammonia manufacture is indispensable for the fertiliser industry, and for meeting global food production needs. Green ammonia will not only help to decarbonize this vital industry and reduce dependence on fossil fuels, but also holds great potential for building a UK net zero energy strategy. To exploit this potential, policymakers cannot afford to wait for this transition to happen by itself. Robust policies will be needed to support low carbon ammonia manufacture in this competitive global industry, along with definitional clarity, clearer regulation, and certification mechanisms.

This briefing note was written by Dr Jyoti Ahuja and Dr Manoj Ravi.

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Policy Recommendations: Interventions for Reduction of the Health Impacts of Air Pollution

Author(s): William Bloss, Suzanne Bartington, Zongbo Shi, Alice Turner, Rob MacKenzie, Roy Harrison.

EMISSIONS / EXPOSURE - AMBIENT	
Ammonia emissions	Reduce ammonia emissions by better management of animal waste and more efficient use of fertiliser / improved application: agricultural practices. National level action required owing to the spatial scales involved. Longer term, transition to green ammonia and encourage manufacturers and markets to prioritise green ammonia.
Domestic wood burning	Reduce both outdoor and indoor wood burning. Note potential tension with some decarbonisation trajectories; there is a need to avoid (foreseen) consequences. Ensure focus upon burning dry fuels where unavoidable. Both national and regional actions can be effective. Educate consumers on pollutants linked to wood burning and the necessity to only burn seasoned wood, where essential.
Road Transport Emissions – non-exhaust particulate matter, PM	Actions to reduce production of, and trap brake and tyre wear particles from road vehicles.
Road Transport Emissions – exhaust nitrogen dioxide, NO_2 and PM	Measures to reduce traffic levels, promote fleet renewal to the latest standards (including Electric Vehicles), and target the highest emitting vehicles.

Rail Transport Systems	Rail electrification, hydrogen hub technology (such as the Tees Valley Multi-Modal Transport Hub), or fuel hybridisation (e.g., Hydroflex). However, rolling stock lifetimes are such that retrofit options such as exhaust after-treatment (noting potential trade-offs with fuel consumption), or retrofitting stop-start technologies to prevent engine idling (beyond driver guidance) may be more immediately realisable.
Vegetation and air pollution	UK afforestation will increase pollution deposition efficiency, but deposition is not usually sufficient to reduce air pollution concentrations demonstrably in these environments. Reduce exposure by modified flow paths (e.g. hedges, fences, green infrastructure). A tool now exists to help implement this inexpensive intervention to reduce exposure: www.gi4raq.ac.uk Other than in limited applications of green infrastructure, devices which claim to clean the outside atmosphere (e.g. photocatalytic paint, green benches, solar towers) are generally ineffective, and should not be endorsed. Emissions reductions are far more effective.
BEST PRACTICE, LOCAL POLICY CONTEXT and EVALUATION	
Practitioner Guidance – planning and green infrastructure	Introduce the above vegetation / air quality recommendations into planning guidance, reflecting the three-word strategy Reduce-Extend-Protect to guide use of green infrastructure, and wider urban design and planning approaches: Reduce Emissions / Extend the distance from Source to Receptor / Protect the receptor – as a hierarchy, in order.
Local Air Quality Management	Local Authorities should be encouraged to move beyond threshold compliance, in line with the health evidence, to focus upon PM and to increase focus on non-transport sources alongside roadside NO_2, and to adopt best practice guidance (see above).
Lower- and middle-income countries (LMICs) and air quality	Lower- and middle-income countries must focus on sustainability and the co-benefits of decarbonisation and clean air while transforming vulnerable populations' livelihoods and enhancing economic activities. This includes action to reduce reliance upon solid fuels for domestic cooking and heating as a key priority.
Intervention Assessments	Promote robust policy evaluation, employing new methods to quantitatively evidence policy benefits.[1]

Public Awareness	Develop a public awareness campaign that highlights small actions that can be taken by citizens that would enhance air quality.
Planning / Neighbourhoods	Developing effective solutions to air pollution will disrupt existing household and business behaviours and effective policy implementation might be challenging. The emphasise must be on creating liveable neighbourhoods and developing streetscapes that are attractive, safe, and convenient for people to walk and cycle.
TRANSPORT ENVIRONMENTS	
Travel Mode & Exposure Reduction	Macro: The policy emphasis should be on encouraging behavioural change including increased active travel by walking and cycling and public transport. This is about encouraging people to consider carefully their travel modes and patterns to reduce air and noise pollution. Current technological solutions including electric vehicles are only partial solutions as pollution is still produced. Micro: Retrofit vehicle cabin with active charcoal air filters. Careful design can substantially reduce passenger exposure to harmful air pollutants.
LEGAL RECOMMENDATIONS	
Legal targets and compliance	Set $PM_{2.5}$ targets to both address the most polluted areas, and deliver improvements across the population. Reflect the ambition of the WHO guidelines in the level and timeline for target achievement – for example, 2030). Courts to develop a more of an interventionist approach to reviewing the technical content of regulatory decision-making.

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