Modelling the long-term health impacts of changing exposure to NO_2 and $PM_{2.5}$ in London

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Glossary

Terms	Meaning
Baseline	This refers to the 'steady state' of the risk factor assuming no change from current exposure levels. However, changes in the population (e.g. ageing) occur.
COMEAP	Committee on the Medical Effects of Air Pollutants. An expert committee that provides advice to the UK Government on the health effects of air pollutants.
Cumulative incidence	Successive additions of annual cases of a disease. For example, the cumulative incidence between 2016 and 2025 would be the sum of the all new disease cases in each of those years.
Distribution	The possible values for a variable and how frequently it occurs. In the current context, the frequency of outcomes (or diseases) in the sample population. The probability distribution describes all the possible values and likelihoods that a variable can take within a specified range.
Dose -response	Also referred to as exposure response. Describes the change in health effect on an individual caused by a change in levels of exposure to a stressor (in this case an air pollutant) after a certain exposure time.
$\mu g/m^3$	Microgramme per metres cubed. This is the unit used to measure concentration of a pollutant in the air. Microgramme is a unit of mass equal to one millionth (1×10^{-6}) of a gram.
Microsimulation	A computer model that replicates real life as closely as possible using national population and disease statistics. It can test the long-term impact of a range of different scenarios on future outcomes.
Incidence	The occurrence of new cases of the disease – not to be confused with prevalence.
NO_2	Nitrogen dioxide is a noxious gas. It is a local, primary traffic pollutant and a biologically relevant indicator of exposure to traffic-related air pollution with known health effects.
$PM_{2.5}$	Fine particulate matter. It is an urban background pollutant which often disperses over a large area. PM consists of finely divided solids or liquids such as dust, fly ash, soot, smoke, aerosols, fumes, mists, and condensing vapours that can be suspended in the air.
Prevalence	This is the total number of cases of a disease in a particular population. This indicates how widespread the disease is.
Probability	This is the chance of a disease occurring. Probability always lies within 0 and 1.
Regression	A statistical technique for estimating the relationships between variables.

Key Findings

This study estimates the long-term health impacts of exposure to air pollution in London from 2016 to 2050 for three scenarios: a baseline scenario where pollution remains at 2016 levels; a "ULEZ" scenario which models the health benefits of the central London Ultra Low Emission Zone, expansion to the North and South circular roads and tightening of the emissions standards for the Londonwide Low Emission Zone for heavy vehicles; and a scenario which models the health benefits of all the policies included in the London Environment Strategy. Key findings from this study include:

- If no action is taken to reduce current levels of pollution, by 2050 the number of new diseases attributable to exposure to man-made NO_2 and $PM_{2.5}$ in London is estimated to be 850,000. This equates to 1 in every 4 cases for the diseases considered in this study.
- By 2050 if no action is taken to reduce current levels of pollution the cumulative cost of air pollution to the NHS and social care system in London is estimated to be £15.4 billion.
- The ULEZ policies are predicted to result in the avoidance of over 250,000 new cases of NO_2 and $PM_{2.5}$ related disease and 1.1 million new air pollution related hospital admissions Londonwide by 2050. This is a reduction of around 1 in every 3 air pollution related diseases, and will result in a cost saving to the NHS and social care system of £4.2 billion.
- The policies in the London Environment Strategy (including the ULEZ) are predicted to result in the avoidance of around 300,000 new cases of NO_2 and $PM_{2.5}$ related disease and 1.2 million new air pollution related hospital admissions Londonwide by 2050. This equates to a cost saving to the NHS and social care system of £5.0 billion.

Executive Summary

Air pollution has many adverse effects on people's health, both in the long and short-term (1–4). In London, the London Environment Strategy (LES) and Mayor's Transport Strategy (MTS) include policies to improve air quality and reduce impacts on health.

This study used a computer simulation to estimate the long-term health impacts of the Ultra Low Emission Zone (ULEZ) and the wider suite of policies included in the London Environment Strategy (LES). Specifically, this study estimates the health impacts of the change in concentration of two pollutants: Nitrogen Dioxide (NO_2) and Particulate Matter ($PM_{2.5}$). These pollutants are known to have long-term health effects.

This study estimates the number of new cases of disease and the resulting costs to the National Health Service (NHS) and social care system under three scenarios:

Scenario	Assumption
Baseline	There is no change in pollution levels from 2016
ULEZ	The central London Ultra Low Emission Zone is introduced in April 2019, there is tightening of the restrictions of the Londonwide Low Emission Zone (LEZ) in 2020, and the boundary of the ULEZ is expanded to the North and South Circular in 2021
LES	All policies in the London Environment Strategy (including the policies in the 'ULEZ' scenario, which are also modelled within the LES scenario) are implemented

The baseline year for the simulation is 2016 and the simulation runs from 2016 to 2050. The study focuses on the health impacts of long-term or "chronic" exposure to air pollution and does not include the impact of short-term exposure to high levels of pollution during high pollution episodes. Other studies have focused on short term impacts (5). The chronic health impacts of air pollution accumulate over many years, and as a result the health benefits of policies such as the ULEZ are not fully realised until many years later. This is why results in this study are presented as a cumulative figure over many years, rather than on a year by year basis. The study also distinguishes between diseases for which there is established evidence, such as childhood asthma, and diseases for which there is emerging evidence, such as diabetes. The three scenarios were run for NO_2 and $PM_{2.5}$ separately. Adjustments have been made to account for the overlap between each pollutant, in line with recommendations from the Committee on the Medical Effects of Air Pollutants (COMEAP) (6). The simulations were run for London as a whole as well as individually for each London borough. This report includes analysis for London as a whole and also for Lambeth as a borough-level case study. Results for all other boroughs are included in the data that accompanies this report.

The results from this study show that the ULEZ policies and broader, more all-encompassing LES policies have important impacts on the health of Londoners. Ensuring continued implementation of these policies is therefore key if air pollution related diseases are to be abated. However, these results highlight that additional policies to address $PM_{2.5}$ from non-transport sources will also be required if air pollution-related diseases are to be reduced still further. Pan-London action is required alongside national legislation and action if larger health benefits are to be realised.

Introduction

Air pollution has a significant impact on public health, causing short (3-5) and long-term health effects (6-8), increasing risks of cardiovascular and respiratory diseases, as well as the risk of death. It is also a significant contributor to health inequalities (7). Tackling air pollution will improve both the environment and public health. The Mayor's Transport Strategy (MTS) and London Environment Strategy (LES) include policies to improve London's air quality to benefit health and reduce health inequalities. There are simulation tools which can model the impacts of such public health policies (8).

Transport for London (TfL) and the Greater London Authority (GLA) commissioned the UK Health Forum and HealthLumen to quantify the health impacts of policies included in the LES and MTS using their bespoke microsimulation model. This model has been developed over the last 12 years and was recently adapted in collaboration with Imperial College London for Public Health England, in order to model health impacts of air pollution.

The model considers the impacts of both nitrogen dioxide (NO_2) and fine particulate matter ($PM_{2.5}$). NO_2 is a local, primary traffic pollutant and a biologically relevant indicator of exposure to air pollution with known health effects. $PM_{2.5}$ is largely an urban pollutant from vehicle exhaust, tyres and brake wear and road abrasion. It is also generated from heat and power sources such as wood burning stoves. It comprises a mixture of primary and secondary particles which disperses over a large area. In this study each pollutant has been simulated independently. Adjustments have been made to account for the overlap between each pollutant, in line with recommendations from the Committee on the Medical Effects of Air Pollutants (COMEAP).

Air pollution generally, and NO_2 and $PM_{2.5}$ in particular, are named as an attributing factor for a number of non-communicable diseases. There is established evidence that air pollution is a factor in the causation of a number of diseases including coronary heart disease (CHD), stroke, asthma, and lung cancer. There are also diseases for which the evidence for a robust association with air pollution exposure is weaker for example, Chronic Obstructive Pulmonary Disease (COPD), and there are diseases for which the association with air pollution is currently emerging, including, diabetes, dementia and low birthweight. There is a separate evidence base on the impacts of air quality on exacerbations of pre-existing cardiovascular and respiratory disease, however this study did not model impacts from disease exacerbation.

The findings of this study build on the existing body of knowledge on this topic, including those of *Walton et al* (9) *(2015) 'Understanding the health impacts of air pollution in London'*, which estimated the health burden of air pollution in London in 2010; PHE's *'Estimation of costs to the NHS and social care due to the health impacts of air pollution'* (2018); and Walton et al's '*Health impact assessment of air pollution on asthma in London'* (2019) (10).

The results will enable TfL and GLA to better understand the health impacts of their policies, communicate the rationale for implementing them, and support the development and delivery of future policies to further improve air quality.

Method

The detailed methods used for this study have been described in '*Estimation of costs to the NHS and social care due to the health impacts of air pollution*' (11,12) and are provided in appendix 1. A summary is provided below.

Microsimulation model

This study uses a dynamic microsimulation model that simulates a virtual London population and predicts the future health and economic impact of NO_2 and $PM_{2.5}$ in London. The model has a base year of 2016 and an end year of 2050. Health impacts that are modelled to occur beyond 2050 are therefore not captured. The impact of the central London Ultra Low Emission Zone (ULEZ) and its expansion, as well as other policies in the London Environment Strategy (LES) have been quantified relative to a 'baseline' (no change) scenario. This simulation utilises geography-specific data on air pollution exposure extrapolated by age and sex, making use of disease data from the literature and population data collected from the Office for National Statistics (ONS), a publicly available database. The microsimulation method is an advanced method for modelling chronic diseases because of its capacity to simulate entire populations at an individual level over time. Further technical detail can be found in previous reports (12).

Data inputs

The model requires data inputs relating to population and air pollution exposure. **Table 1** and **Figure 1** summarise the data sources included in the model. Appendix 2 provides the input data and appendix 3 provides a summary of the data references.

Table 1. Data sources included in the model

Parameter	**Data source**
Population data	Office for National Statistics
Concentration data	London Atmospheric Emission Inventory (LAEI) 2013 interpolated to 2016 + Forecast concentrations for the ULEZ expansion / LEZ Strengthening proposals and the London Environment Strategy (LES)
Exposure-response coefficients	Literature review
New disease cases (incidence), prevalence, mortality, survival data	Literature review. National level disease data by age and sex.
Cost-per-case data	Literature review for costs to the NHS and social care per disease.
Annual probability of hospitalisation by disease	Literature review and online databases

Note that exposure-response coefficients were only available for adults, with the exception of asthma where $PM_{2.5}$ exposure-response coefficients were available for children. Therefore, exposure to pollution was only associated with increased risk of asthma in children.

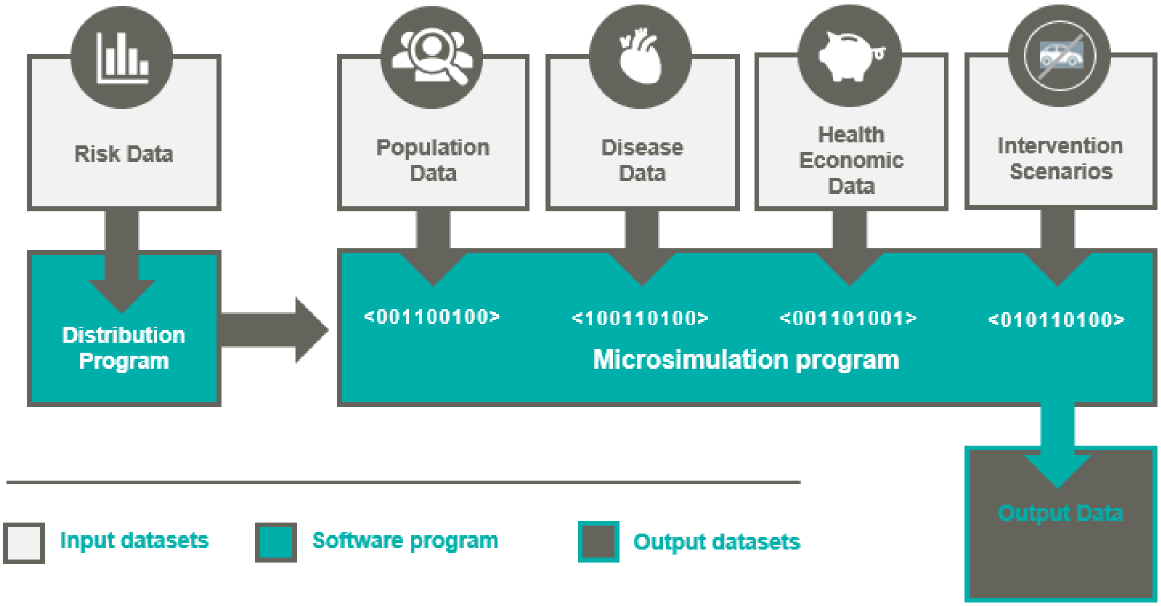

Figure 1. Schematic of the data inputs required for the microsimulation software

Population data

Population projections by age and sex provided by the Greater London Authority and are publicly available (https://data.london.gov.uk/dataset/projections). Births by mother's age and total fertility rate by London borough were taken from the Office of National Statistics database 2016. The age-sex population distribution for London and Lambeth are illustrated in Figure 2. Lambeth has a greater number of 20-40 year olds than London as a whole, which has a higher proportion of 50+ year olds, and 0-10 year olds than Lambeth.

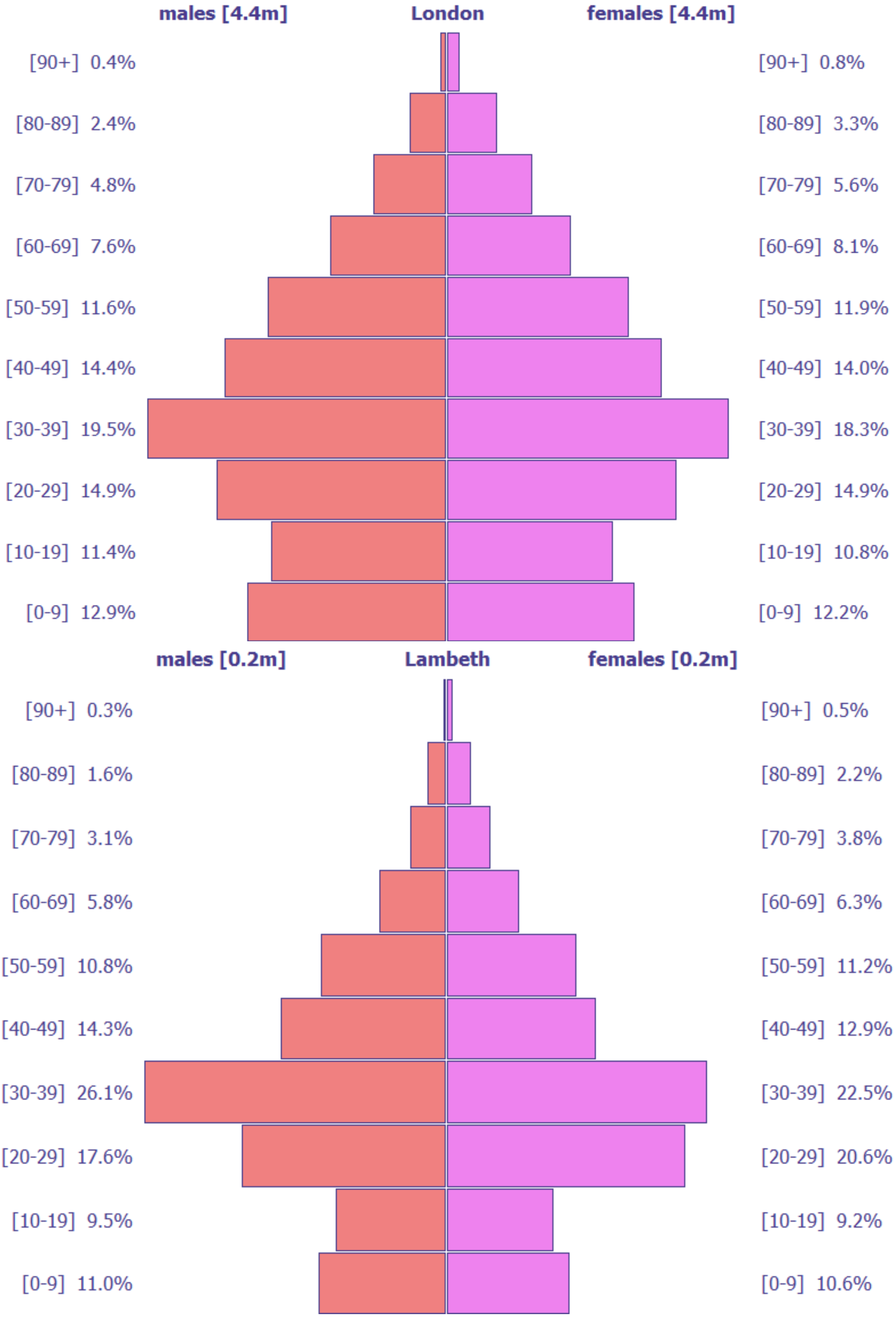

Figure 2. Population distribution by age and sex for Lambeth and London respectively

Concentration data

NO_2 and $PM_{2.5}$ concentration data for the baseline scenario was taken from 2016 concentrations across London, interpolated from the baseline 2013 and forecast base 2020 concentrations published by the GLA as part of the London Atmospheric Emissions Inventory (LAEI) 2013 update (13). The LAEI is a comprehensive inventory of all air pollutant emission sources across London, updated on a regular basis. It includes both total emissions by source type, as well as ground level concentrations based on detailed dispersion modelling of emissions.

Concentration data for the ULEZ scenario includes detailed forecast NO_2 and $PM_{2.5}$ concentrations for 2016, 2019 (for Central ULEZ), 2020 (LEZ strengthening), 2021 and 2025 (both LEZ strengthening and ULEZ expansion), which informed the proposals for Central ULEZ, LEZ strengthening and ULEZ expansion, based on the same dispersion modelling methodology used for the LAEI.

Concentration data for the LES scenario, which builds upon the ULEZ scenario, includes forecast NO_2 and $PM_{2.5}$ concentrations for 2025, 2030 and 2050 that informed the London Environment Strategy (LES) published in 2018, and includes additional measures to tackle air pollution across London beyond the ULEZ proposals.

Concentration data for all other years were interpolated from the above-mentioned data, using linear interpolation. For example, concentrations from 2016 to 2019 in the baseline scenario were interpolated using the 2013 baseline concentrations and 2020 baseline forecast concentrations published in the LAEI 2013. For the ULEZ/LES scenario, concentrations from 2016 to 2018 were interpolated using the 2013 baseline concentrations from the LAEI 2013 and the 2019 concentrations forecast which supported the Central ULEZ consultation documents.

All concentrations, originally available across London at a 20m resolution grid level, were averaged at Output Area (OA) level before being combined with population data to calculate population exposure at Borough level for each of the years required by the microsimulation model to determine health impacts

Disease data

Asthma, Chronic Obstructive Pulmonary Disease (COPD), Coronary Heart Disease (CHD), stroke, type 2 diabetes, lung cancer, low birth weight, and dementia data were included in the model. It is acknowledged that the strength of evidence for each disease varies as described in **Table 2**. Dose-response estimates for NO_2 were adjusted and reduced by 60% to take account of overlaps between risks based on COMEAP recommendations for mortality (6).

Table 2. Summary of established robust associations ('established evidence') and less robust associations ('weaker evidence') for $PM_{2.5}$ and NO_2

	Long term exposure to $PM_{2.5}$	**Long term exposure to NO_2**
Established evidence for an association	Coronary heart disease Stroke Lung cancer Asthma (children)	Asthma (children)
Evidence less certain or emerging evidence of associations	Chronic Obstructive Pulmonary Disease (as chronic bronchitis) Diabetes Low birth weight	Asthma (adults) Diabetes Lung cancer Low birth weight Dementia

Incidence (or prevalence), survival, mortality, and relative risk data were extracted from the literature (Appendix 1) as well as cost data. For COPD and dementia no incidence data were available, therefore prevalence was converted to incidence using WHO Dismod II equations (14). Annual cost-per-case to the NHS and social care were found from the literature for each disease, with the exception of low-birth weight. The impact of low birthweight is heterogeneous and as such is a risk factor for other diseases, making it too complex to cost with any degree of accuracy. Therefore, only epidemiological outputs are provided for this condition. The data references can be found in appendix 3. The dose-response estimates that were included in the model are illustrated in **Table 3**.

Table 3. Dose-response estimates included in the model by disease and pollutant

Disease	**Relative Risk**	
	NO_2	**$PM_{2.5}$**
Asthma	Khreis *et al.* 2016 (15) In children =<6 years: OR 1.08 (1.04; 1.12) per 4$\mu g/m^3$→*Converted to OR 1.212 (1.103; 1.328)* per 10$\mu g/m^3$→*REDUCED by 60%* → **1.08 (1.01; 1.12) per 10$\mu g/m^3$** In children >6 years: OR 1.03 (1.00; 1.06) per 4$\mu g/m^3$→*Converted to OR 1.08 (1.00; 1.16)* per 10$\mu g/m^3$→ *REDUCED by 60%* → **1.03 (1.00; 1.06) per 10$\mu g/m^3$** Jaquemin *et al.* 2015 (16) *In adults:* OR 1.10 (0.99;1.21) per 10$\mu g/m^3$ →*REDUCED by 60%* → **1.04 (0.996; 1.08) per 10$\mu g/m^3$**	Khreis et al. 2016 (15) In children >6 years: OR 1.04 (1.02; 1.07) per 1$\mu g/m^3$ →Converted OR **1.48 (1.22 ; 1.97) per 10$\mu g/m^3$**

COPD	NA	COMEAP 2016 (6) COMEAP recommend using PM_{10} estimate based on Cai et al. 2014 estimate for chronic phlegm in never smokers in sensitivity analyses: OR 1.32 (1.02; 1.71) per 10µg/m^3 of PM_{10} → scale to $PM_{2.5}$ using the conversion factor of $PM_{2.5}$-> PM_{10}: 0.7 (or PM_{10} -> $PM_{2.5}$:1.42) recently used in the air quality index, COMEAP: Converted to **1.49 (1.03; 2.14) per 10µg/m^3 of $PM_{2.5}$**
CHD	NA	Cesaroni et al. 2014 (17) Estimate used in CAPTOR tool from subgroup analysis of participants with additional information on CVD risk factors: HR 1.19 (1.01; 1.42) per 5µg/m^3→ Converted to **1.41 (1.00 - 2.01) per 10µg/m^3**
Diabetes	Eze *et al.* 2015 (8) RR 1.12 (1.05; 1.19) per 10µg/m^3→*REDUCED by 60%* → **1.05 (1.02; 1.07) per 10µg/m^3**	Eze et al. 2015 (8) RR **1.10 (1.02; 1.18) per 10µg/m^3**
Stroke	NA	Scheers et al. 2015 (3) HR 1.064 (1.021; 1.109) per 5µg/m^3 →Converted to **1.13 (1.04; 1.23) per 10µg/m^3**

Dementia	Oudin et al. 2016 (18) HR 1.08 (1.00; 1.16) per 10µg/m^3 NOx. Scaling factor: NOx → NO2: 0.44 which was developed by Anderson et al. based on the ratio that fell midway between the average or roadside vs urban background monitoring sites in London for 2001 (see Online Supp 2) Converted from NOx to NO2:HR 1.03 (1.00; 1.07) →REDUCED by 60% → **1.01 (1.01; 1.03) per 10µg/m3 of NO2**	
Low birth weight	Pedersen et al. 2013 (19) OR 1.09 (1.00; 1.19) per 10µg/m^3→*REDUCED by 60%* → **1.04 (1.00; 1.07) per 10µg/m^3**	Pedersen et al. 2013 (19) OR 1.18 (1.06; 1.33) per 5µg/m^3→Converted OR **1.39** **(1.12; 1.77) per 10µg/m^3**
Lung cancer	Hamra et al. 2015(20) RR 1.04 (1.01; 1.08) per 10µg/m^3→*REDUCED by 60%* → **1.02 (1.00; 1.03) per 10µg/m^3**	Hamra et al. 2014 (21) **RR 1.09 (1.04; 1.14) per 10µg/m^3**

Annual probability of hospitalisation for COPD (22), stroke (23), CHD (24), asthma (22) and lung cancer (25) was calculated based on data from the literature and online databases (see appendix 1). For COPD, child and adult asthma, emergency hospitalisation rate per 1000 was converted to number of emergency hospitalisations in the population. Emergency hospitalisation rate per case was then calculated by dividing the number of emergency hospitalisations of the disease in the population by the disease in prevalence. For CHD and stroke, emergency hospital admission rate per 100,000 were scaled to the population and divided by the prevalence of the respective diseases in the population to get the emergency hospitalisation probability per case. For lung cancer, emergency hospitalisation data per person was not altered since it was already presented as a rate per 1.

Scenarios

The baseline scenario includes “business as usual” NO_2 and $PM_{2.5}$ concentration projections that were forecast as part of the LAEI 2013 to the year 2016 and held static over time.

The ULEZ scenario includes estimated improvements in air quality due to the progressive greener vehicle fleet that will result from the introduction of more stringent emission standards for road vehicles in Central London, due to the introduction of the ULEZ (in 2019), the strengthening of the LEZ emission standards for HGVs, buses and coaches (in 2020) as well as the widening of the Central London ULEZ in 2021 up to the North/South Circular Road, which will reduce emissions from cars and LGVs.

The LES scenario includes all the measures already included in the ULEZ scenario to tackle air quality, but also include additional measures that will further reduce air pollution, such as road transport measures proposed in the Mayor’s Transport Strategy (26) that will help increase the proportion of hybrid, plugin electric and fully electric vehicles and reduce total road traffic on London roads. This scenario also includes other measures not related to road-transport proposed in the LES 2018 (27). This includes reducing construction emissions, energy efficiency programmes and the progressive phasing out of fossil fuels to reduce emissions generated by the heating and power consumption of homes and workplaces, which will further improve air quality. Prior modelling projected the expected impact of these different policies on NO_2 and $PM_{2.5}$ exposure in each borough and London as a whole as described in Appendix 1.

Table 4 provides a summary of the scenarios that were included in the model. The model was adapted to make use of the projections of exposure produced by Transport for London.

Table 4. Summary of scenarios included in the model

Scenario	Description	From	To
Static 2016 baseline scenario	The baseline scenario assumes air pollution levels remain at 2016 levels throughout the period to 2050.	2016	2050
Ultra Low Emission Zone (ULEZ) scenario	The Ultra Low Emission Zone (ULEZ) scenario includes modelled air quality improvements resulting from the introduction of the central ULEZ in 2019, the tightening of the restrictions of the Low Emission Zone (LEZ) in 2020, and the expansion of the ULEZ in 2021, as well as additional policy measures in the period 2016-2024[1].	2016	2050
London Environment Strategy (LES) scenario	The London Environment Strategy (LES) scenario which includes modelled air quality improvements as a result of the central ULEZ, LEZ tightening and ULEZ expansion, as well as those resulting from additional policies in the LES over the period 2025-2050.	2016	2050
Attributable Scenario	A final scenario was run which reduces exposure to non-anthropogenic levels for the whole population to compute the total number of new diseases attributable man made to air pollution.		

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[1] The central ULEZ was introduced in London in April 2019 and is a defined area within which all vehicles will have to meet strict emission standards or face a daily charge to travel.

Outputs

Appendix 1 provides a detailed methodology of how each output is generated. In summary, the outputs are defined in the following ways:

A. Epidemiological outputs

Cumulative incidence per population over the simulation period / New cases of disease: The total number of new cases of disease, divided by the total number of people in the population in a given year, and accumulated over a specified period of the simulation from year 2016. Therefore, the cumulative number of incident cases represents a sum of all of the incident cases from the start of the simulation as a rate per population, by scenario.

Attributable incidence cases per total population over the simulation period/ New cases of disease attributable to air pollution: The number of new cases of disease attributable to air pollution per population. This reflects the difference in cases between baseline and if air pollution was reduced to non-anthropogenic levels.

Cumulative incidence avoided per population over the simulation period/ New cases of disease avoided: The total number of incident cases of disease avoided since the start year 2016 as compared to baseline “no-change” scenario. A positive value represents the number of cases avoided.

Cumulative hospitalisations avoided per population/ Hospitalisations avoided: The number of emergency hospitalisations as a function of change in disease prevalence. These figures represent the number of hospitalisations avoided as a result of the decreased prevalence of disease and do not take into account hospitalisations avoided due to a reduction in air-pollution-related exacerbations of disease.

B. Economic outputs

Attributable NHS and social care costs per population over the simulation period: These are costs attributable to air pollution each year of the simulation calculated from change in disease prevalence and cost-per-case.

NHS costs avoided per population over the simulation period: The annual and cumulative costs avoided as a result of each scenario relative to baseline calculated from change in disease prevalence and cost-per-case.

Social care costs avoided per population over the simulation period: The annual and cumulative social care costs avoided as a result of each scenario relative to baseline calculated from change in disease prevalence and cost-per-case.

The confidence limits that accompany the sets of output data represent the accuracy of the microsimulation (stochastic or aleatoric uncertainty) as opposed to the confidence of the input data itself (parameter uncertainty). Errors around the input data were not available.

‘Disease cases’ refers to the diseases listed above only, not total of all possible disease cases. There are other diseases with emerging evidence of association with air pollution exposure that have not been included in this study including pneumonia, depression and neurological development in children. As a result, this may be a conservative estimate.

Note that costs are not included for low birth weight since the costs are frequently related to other conditions later in the child’s life.

Results

This report presents the results for the whole of London and an example borough (Lambeth) to illustrate the scale of impacts at borough-level. The results for the remaining 33 local authorities can be found in appendix 4. Results from the microsimulation are presented as rates per 100,000 population then scaled to the respective population (e.g. London, Lambeth) for that year, as estimated by Office for National Statistics population projections (28).

Londonwide disease cases attributable to air pollution

New cases of disease Londonwide

The model has calculated the cumulative new cases of disease which is the total number of new cases of disease accumulated over a specified period of the simulation from the year 2016. Therefore, the cumulative number of incident cases represents a sum of all the incident cases from the start of the simulation as a rate per population, by scenario. These represent all the new ‘incident’ cases of disease that would be expected to occur in the population in a scenario where air pollution remains at 2016 levels.

Table 5 and **Table 6** show the total new cases of disease for the conditions included in this study, many of these will not be attributable to air pollution.

Table 5 shows the total new cases of disease between 2016 and 2050 in a scenario where NO_2 remains at 2016 levels is 3.45 million.

Table 6 shows the estimated total new cases of disease between 2016 and 2050, in a scenario where $PM_{2.5}$ remains at 2016 levels is 3.45 million.

Table 5. Cumulative new cases per London population (NO$_2$ baseline)

Year	Child asthma	Adult asthma	Type 2 diabetes	Lung cancer	Low birth weight	Dementia	Total
2020	54,133 [±176]	57,561 [±176]	158,797 [±264]	20,476 [±88]	41,127 [±88]	66,085 [±176]	398,179 [±352]
2025	103,697 [±176]	116,791 [±176]	334,204 [±352]	43,764 [±88]	73,818 [±176]	135,949 [±264]	808,222 [±527]
2030	146,934 [±264]	177,867 [±264]	530,086 [±439]	71,533 [±176]	102,203 [±176]	217,940 [±264]	1,246,475 [±703]
2050	289,737 [±439]	433,682 [±527]	1,475,048 [±967]	240,173 [±352]	213,106 [±352]	794,601 [±703]	3,446,348 [±1,406]

Table 6. Cumulative new cases per population, London (PM$_{2.5}$ baseline)

Year	CHD	Stroke	Child asthma	Lung Cancer	COPD	Type 2 diabetes	Low birth weight	Total
2020	45,785 [±88]	36,646 [±88]	590,55 [±176]	20,564 [±88]	32,427 [±88]	159,149 [±264]	41,655 [±88]	395,192 [±352]
2025	95,876 [±176]	77,949 [±176]	114,946 [±176]	44,027 [±88]	69,424 [±176]	334,555 [±352]	74,785 [±176]	811,562 [±527]
2030	152,558 [±264]	125,579 [±264]	164,334 [±264]	71,885 [±176]	111,958 [±176]	529,910 [±439]	103,521 [±176]	1,259,832 [±703]
2050	480,873 [±527]	410,746 [±527]	322,691 [±439]	240,525 [±352]	312,146 [±439]	1,471,445 [±967]	216,534 [±352]	3,454,960 [±1,406]

New cases of disease attributable to air pollution Londonwide

Not all of the cases of diseases in **Table 5** and **Table 6** are attributable to air pollution. Some people who are not exposed to air pollution are still at risk to air pollution related diseases for other reasons, such as smoking, poor diet and genetics. This section estimates the number of new cases of diseases within the population which are attributable to air pollution.

The cumulative new cases of cases attributable to air pollution have been calculated by comparing the baseline scenario (which assumes no improvement from 2016 levels of air pollution) to a scenario where pollution was lowered to non-anthropogenic background levels. The difference between these two scenarios is an estimate of the number of new cases of disease which are attributable to air pollution.

Table 7 shows the cumulative number of disease cases attributable to NO_2 between 2016 and 2050, scaled to the London population.

By 2050 the model predicts 40,073 new cases of disease attributable to NO_2 exposure when diseases with established evidence are included (childhood asthma only), increasing to 297,294 new cases of disease attributable to NO_2 exposure when both established and emerging evidence is included. Type 2 diabetes cases were the greatest contributors to the total cases attributable, with 159,500 cases attributable to NO_2 between 2016 and 2050.

By comparison with the figures in **Table 5**, this equates to around 9 per cent of the total cumulative new cases of cases by 2050. In other words, 9 per cent of the total cases of these diseases in London are attributable to NO_2 exposure.

Table 8 shows the cumulative number of new disease cases attributable to $PM_{2.5}$ for the London population between 2016 and 2050.

By 2050 the model predicts 266,273 total new cases attributable to $PM_{2.5}$ when established evidence is included, increasing to 552,319 when established and emerging evidence is included. CHD and Type 2 diabetes are the greatest contributors, with 133,927 and 111,167 cases attributable to $PM_{2.5}$ respectively.

By comparison with the figures in **Table 6** this equates to around 16 per cent of the total cumulative new cases of cases by 2050. In other words, 16 per cent of the total cases of these diseases in London are attributable to $PM_{2.5}$ exposure.

In a baseline scenario if no action is taken to reduce current levels of pollution the model predicts a total 849,613 new cases of disease attributable to air pollution by 2050 (297,294 for NO_2, 552,319 for $PM_{2.5}$) when established and emerging evidence are included. This is equivalent to approximately 25 per cent, or 1 in 4 of all cases for the diseases included in this study.

If no action is taken to reduce current levels of pollution, by 2050 the number of new diseases attributable to exposure to NO_2 and $PM_{2.5}$ exposure in London is estimated to be 849,613 (297,294 for NO_2, 552,319 for $PM_{2.5}$) equating to 1 in every 4 of all cases for the diseases included in this study.

Table 7. Cumulative new cases attributable to NO$_2$ by disease, per London population

Year	Child asthma	Adult asthma	Type 2 diabetes	Lung cancer	Low birth weight	Dementia	Total
2020	7,909 [±176]	6,152 [±264]	19,245 [±352]	1,055 [±88]	4,745 [±88]	1,582 [±264]	40,688 [±527]
2025	14,500 [±264]	12,479 [±264]	40,073 [±527]	2,285 [±88]	8,524 [±264]	3,076 [±352]	80,849 [±703]
2030	20,124 [±352]	18,894 [±352]	62,130 [±615]	3,779 [±264]	11,864 [±264]	4,833 [±352]	121,537 [±967]
2050	40,073 [±527]	44,555 [±703]	159,500 [±1318]	11,952 [±527]	24,694 [±527]	16,521 [±967]	297,294 [±2,021]

Table 8. Cumulative new cases attributable to PM$_{2.5}$ per London population

Year	CHD	Stroke	Child asthma	Lung Cancer	COPD	Type 2 diabetes	Low birth weight	Total
2020	13,621 [±88]	4,130 [±88]	12,742 [±176]	1,670 [±88]	11,161 [±88]	14,324 [±352]	13,270 [±88]	70,743 [±527]
2025	28,033 [±264]	8,524 [±264]	25,661 [±264]	3,603 [±88]	23,552 [±264]	29,264 [±527]	23,815 [±264]	142,540 [±703]
2030	44,203 [±352]	13,533 [±352]	37,524 [±352]	5,800 [±264]	38,052 [±264]	44,467 [±615]	33,130 [±264]	216,709 [±967]
2050	133,927 [±703]	41,127 [±703]	73,467 [±527]	17,752 [±527]	104,927 [±527]	111,167 [±1318]	69,952 [±439]	552,319 [±1,933]

Hospitalisations attributable to air pollution Londonwide

This section estimates the number of hospitalisations as a result of exposure to air pollution.

Table 9 presents the cumulative hospitalisations attributable to NO_2 for the London population between 2016 and 2050 respectively. In total, by 2050, an estimated 31,719 hospitalisations are attributed to NO_2 exposure when diseases with established evidence are included (childhood asthma), increasing to 99,476 when established and emerging evidence is included.

The condition with the largest number of cumulative hospitalisations attributable to NO_2 by 2050 was lung cancer with 49,375 cases.

Table 10 presents the cumulative hospitalisations attributable to $PM_{2.5}$ for the London population between 2016 and 2050 respectively. In total, by 2050, an estimated 306,586 hospitalisations are attributed to $PM_{2.5}$ when established evidence is included, increasing to 3.83 million when diseases are included where there is less emerging evidence.

The largest number of cumulative hospitalisations attributable to $PM_{2.5}$ by 2050 were estimated to be for COPD and CHD with 3.53 million and 150,047 respectively.

If no action is taken to reduce current levels of pollution, by 2050 the total number of hospitalisations attributable to exposure to NO_2 and $PM_{2.5}$ exposure in London is estimated to be 3.93 million (99,476 for NO_2, 3.83 million for $PM_{2.5}$).

Table 9. Cumulative hospitalisations attributable to NO$_2$ in London

Year	Child asthma	Adult asthma	Lung cancer	Total
2020	996 [±66]	492 [±27]	2,700 [±303]	4,188 [±311]
2025	3,509 [±98]	1,740 [±40]	7,266 [±470]	12,515 [±481]
2030	7,164 [±124]	3,729 [±52]	13,239 [±633]	24,132 [±6,48]
2050	31,719 [±225]	18,382 [±102]	49,375 [±1,437]	99,476 [±1,458]

Table 10. Cumulative hospitalisation attributable to PM$_{2.5}$ in London

Year	CHD	Stroke	Child asthma	Lung cancer	COPD	Total
2020	4,618 [±75]	811 [±40]	1522 [±69]	4599 [±302]	162,169 [±2,017]	173,719 [±2,042]
2025	15,636 [±112]	2,765 [±61]	5,518 [±101]	12,156 [±469]	501,595 [±3,065]	537,670 [±3,105]
2030	32,198 [±145]	5,671 [±80]	11,833 [±129]	21,542 [±632]	962,947 [±4,069]	1,034,191 [±4,123]
2050	152,047 [±303]	26,620 [±173]	55,375 [±233]	72,544 [±1431]	3,525,199 [±8,514]	3,831,785 [±8,643]

NHS and social care costs attributable to air pollution exposure Londonwide

This section includes an estimate of the costs to the NHS and social care system as a result of diseases attributable to air pollution exposure in a baseline scenario where pollution stays at 2016 levels. This does not include change in costs due to change in exacerbations. That is, daily spikes in air pollution may exacerbate e.g. asthma resulting in a spike in attendance at hospital. The present model is annual and thus accounts for an average cost per disease per year. Therefore, the output figures refer to annual average costs.

Table 11 presents the cumulative NHS direct healthcare costs attributable to NO_2 in London between 2016 and 2050 for a scenario where NO_2 remains at 2016 levels. By 2050 it is predicted that there would be £106.41 million in NHS costs attributable to NO_2 exposure when established evidence is included (childhood asthma) increasing to £3.13 billion when both established and emerging evidence is included.

Table 12 presents the cumulative social care costs attributable to NO_2 in London between 2016 and 2050 for a scenario where NO_2 remains at 2016 levels. By 2050 it was predicted that there would be £2.07 billion in social care costs attributable to NO_2 when both established evidence and emerging evidence are included.

The combined NHS and social care costs attributable to NO_2 in London between 2016 and 2050 in the baseline scenario where NO_2 remains at 2016 levels is £106.80 million when established evidence is considered, increasing to £5.20 billion when emerging evidence is included.

Table 13 shows the cumulative NHS direct healthcare costs attributable to $PM_{2.5}$ for the London population between 2016 and 2050. The total costs attributable to $PM_{2.5}$ is estimated to be £5.21 billion when established evidence is included, increasing to £9.04 billion when diseases with emerging evidence are included, with the largest contributor being Coronary Heart Disease with £2.94 billion in cost.

Table 14 shows the cumulative social care costs attributable to $PM_{2.5}$ for the London population between 2016 and 2050. The total cumulative social care cost by 2050 is projected to be £167.08 million when established evidence is included, increasing to £1.12 billion when disease with emerging evidence are included. The majority of the cost being attributable to type 2 diabetes with £905.62 million in cost.

The combined NHS and social care costs attributable to $PM_{2.5}$ exposure in London between 2016 and 2050 in a scenario where $PM_{2.5}$ remains at 2016 levels is £5.38 billion when established evidence is considered, increasing to £10.16 billion when emerging evidence is included.

If no action is taken to reduce current levels of pollution, by 2050 the cumulative cost to the NHS and social care attributable to exposure to NO_2 and $PM_{2.5}$ in London is estimated to be £5.49 billion (£106.80 million for NO_2, £5.38 billion for $PM_{2.5}$) for diseases where there is established evidence, increasing to £15.40 billion (£5.20 billion NO_2, £10.16 billion $PM_{2.5}$) when diseases are included where the evidence is associative or emerging.

Table 11. Cumulative NHS costs attributable to NO_2 in London

Year	Child asthma	Adult asthma	Type 2 diabetes	Lung cancer	Low birth weight	Dementia
2020	3,340,991 [±218,114]	2,644,134 [±141,648]	67,253,362 [±1,806,110]	900,049 [±100,912]	4,145,717 [±545,809]	78,284,253 [±1,907,292]
2025	11,771,681 [±320,246]	9,346,982 [±211,804]	248,437,244 [±2,704,743]	2,422,507 [±156,542]	12,149,847 [±807,363]	284,128,261 [±2,852,962]
2030	24,034,852 [±408,230]	20,023,900 [±275,735]	544,666,830 [±3,535,314]	4,414,034 [±211,119]	22,713,247 [±1,051,242]	615,852,865 [±3,727,038]
2050	106,409,956 [±734,786]	98,719,541 [±540,730]	2,802,662,343 [±7,150,103]	16,462,156 [±478,863]	101,637,959 [±2,415,921]	3,125,891,956 [±7,617,234]

Table 12. Cumulative social care costs attributable to NO_2 in London

Year	Child asthma	Adult asthma	Type 2 diabetes	Lung cancer	Low birth weight	Dementia
2020	12,295 [±803]	9,730 [±521]	33,594,012 [±902,178]	145,352 [±16,297]	27,286,624 [±3,592,450]	61,048,013 [±3,704,037]
2025	43,320 [±1,179]	34,397 [±779]	124,097,940 [±1,351,058]	391,218 [±25,281]	79,968,880 [±5,313,972]	204,535,755 [±5,483,092]
2030	88,448 [±1,502]	73,688 [±1,015]	272,068,836 [±1,765,940]	712,836 [±34,094]	149,495,950 [±6,919,155]	422,439,758 [±7,141,037]
2050	391,587 [±2,704]	36,3287 [±1,990]	1,399,969,741 [±3,571,578]	2,658,525 [±77,333]	668,969,215 [±15,901,313]	2,072,352,355 [±16,297,666]

Table 13. Cumulative NHS costs attributable to $PM_{2.5}$ in London

Year	CHD	Stroke	Child asthma	Lung cancer	COPD	Type 2 diabetes	Total
2020	89,408,429 [±1,446,895]	62,615,053 [±3,107,100]	5,107,501 [±225,834]	1,533,388 [±100,827]	92,766,061 [±1,152,570]	49,838,693 [±1,811,318]	301,269,126 [±4,051,917]
2025	302,760,634 [±2,155,978]	213,456,143 [±4,666,170]	18,512,171 [±331,456]	4,053,003 [±156,298]	286,928,590 [±1,751,501]	176,572,908 [±2,716,483]	1,002,283,449 [±6,082,985]
2030	623,440,729 [±2,806,306]	437,839,470 [±6,137,977]	39,698,845 [±422,463]	7,182,179 [±210,606]	550,836,557 [±2,325,006]	376,095,810 [±3,554,293]	2,035,093,590 [±7,988,216]
2050	2,944,037,003 [±5,854,679]	2,055,406,884 [±13,283,603]	185,772,666 [±759,814]	2,4186,875 [±476,887]	2,016,526,528 [±4,863,240]	1,813,003,728 [±7,204,660]	9,038,933,684 [±16,943,858]

Table 14. Cumulative social care costs attributable to $PM_{2.5}$ in London

Year	CHD	Stroke	Child asthma	Lung cancer	COPD	Type 2 diabetes	Total
2020	4,118,267 [±66,646]	819,023 [±40,642]	18,796 [±831]	247,632 [±16,283]	2,251,802 [±27,977]	24,895,137 [±904779]	32,350,656 [±908,718]
2025	13,945,542 [±99,307]	2,792,069 [±61,035]	68,125 [±1,220]	654,532 [±25,241]	6,964,901 [±42516]	88,200,681 [±1,356,922]	112,625,849 [±1,362,817]
2030	28,716,477 [±129,262]	5,727,069 [±80,287]	146,091 [±1,555]	1,159,873 [±34,011]	13,370,999 [±56,437]	187,865,211 [±1,775,420]	236,985,719 [±1,783,147]
2050	135,606,106 [±269,674]	26,885,324 [±173,753]	68,3641 [±2,796]	3,906,015 [±77,014]	48,949,136 [±118,050]	905,621,173 [±3,598,830]	1,121,651,396 [±3,615,849]

Londonwide scenario assessment

This section estimates the impact of the Ultra Low Emission Zone and London Environment Strategy polices on the new cases of disease, attributable hospitalisations and the NHS and social care costs in the years 2016 to 2050.

New cases of disease avoided Londonwide by scenario

The new cases of disease avoided is the total number of incident cases of disease avoided due to the intervention since the start year of 2016 as compared to the baseline scenario (when pollution remains at 2016 levels). A positive value represents the number of cases avoided as a result of the intervention. The cases avoided are equal to the baseline number of cases minus the scenario number of cases.

Cases avoided as a result of reductions in NO_2:

As presented earlier in this report, it is predicted that will be a total of 3.45 million new disease[2] cases by 2050 if baseline trends continue (see **Table 5**) of which 297,294 (or 9 per cent) are attributable to NO_2 (see **Table 7**).

Table 15 presents the cumulative new cases of disease avoided as a result of reduction in NO_2 for each scenario in London.

Table 15 shows that the ULEZ and LES scenarios are estimated to avoid 103,170 and 125,052 of NO_2 attributable cases respectively. This represents the avoidance of 35 per cent and 42 per cent of NO_2 attributable cases as a result of the policies in the ULEZ and LES scenarios respectively by 2050 (i.e. an additional 7 per cent of attributable diseases are avoided by policies in the LES).

The largest number of disease cases avoided are estimated for type 2 diabetes and adult asthma.

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[2] Disease cases refers only to the list of diseases included within the model and reflect the number expected in the population.

Cases avoided as a result of reductions in $PM_{2.5}$:

It is predicted that there will be a total of 3.45 million new disease cases[3] by 2050 if baseline trends continue (see **Table 6**) of which 552,319 (or 16 per cent) are attributable to $PM_{2.5}$ (**Table 8**). **Table 16** presents the cumulative new cases of disease avoided as a result of reduction in $PM_{2.5}$ by scenario in London.

Table 16 shows that the ULEZ and LES scenarios are estimated to avoid 147,461 and 169,167 of these cases respectively when both established and emerging evidence is included. This translates to the avoidance of 27 per cent and 31 per cent of $PM_{2.5}$ attributable cases as a result of policies in the ULEZ and LES scenarios respectively by 2050.

Total diseases avoided by scenario:

- As presented earlier in this report, if no action is taken to reduce current levels of pollution the model predicts there will be 849,613 cases of disease attributable to air pollution by 2050 (297,294 for NO_2, 552,319 for $PM_{2.5}$)
- The ULEZ policies are predicted to result in the avoidance of 250,631 new cases of NO_2 and $PM_{2.5}$ related diseases Londonwide by 2050 (103,170 for NO_2 and 147,461 for $PM_{2.5}$). This equates to a 29 per cent reduction in the number of cases attributable to air pollution compared to the baseline scenario, or a reduction of approximately 1 in every 3 new attributable cases
- The LES policies are predicted to result in the avoidance of 294,219 new cases of NO_2 and $PM_{2.5}$ related diseases Londonwide by 2050 (125,052 for NO_2 and 169,167 for $PM_{2.5}$). This equates to a 35 per cent reduction in the number of cases attributable to air pollution compared to the baseline scenario, or a reduction of approximately 1 in every 3 new attributable cases

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[3] Disease cases refers only to the list of diseases included within the model and reflect the number expected in the population.

The ULEZ policies are predicted to result in the avoidance of 250,631 new cases of NO_2 and $PM_{2.5}$ related diseases Londonwide by 2050. This equates to a 29 per cent reduction in total new cases of disease attributable to air pollution in London.

The policies in the London Environment Strategy (LES) are predicted to result in the avoidance of 294,219 new cases of NO_2 and $PM_{2.5}$ related diseases Londonwide by 2050. This equates to a 35 per cent reduction in total new cases of disease attributable to air pollution in London.

Table 15. Cumulative new cases avoided for ULEZ and LES relative to baseline, for NO_2 in London

	Year	Child asthma	Adult asthma	Type 2 diabetes	Lung cancer	Low birth weight	Dementia	Total
ULEZ Rel Baseline	**2020**	527 [±264]	527 [±264]	1582 [±352]	88 [±88]	352 [±88]	88 [±264]	3,164 [±527]
	2025	1670 [±264]	2,109 [±264]	7470 [±527]	439 [±88]	1,318 [±264]	527 [±352]	13,621 [±703]
	2030	2,285 [±352]	4,306 [±352]	15,291 [±615]	967 [±264]	2,285 [±264]	1,142 [±352]	26,188 [±967]
	2050	4,042 [±615]	15,994 [±703]	63,976 [±1318]	5,097 [±527]	6,942 [±527]	7,030 [±967]	103,170 [±2,021]
LES Rel Baseline	**2020**	615 [±264]	527 [±264]	1,406 [±352]	88 [±88]	352 [±88]	88 [±264]	3,076 [±527]
	2025	2,021 [±264]	2373 [±264]	8,261 [±527]	527 [±88]	1,406 [±264]	615 [±352]	15,203 [±703]
	2030	3,076 [±352]	5,273 [±352]	18,542 [±615]	1,142 [±264]	2,636 [±264]	1,406 [±352]	31,988 [±967]
	2050	4,833 [±615]	19,773 [±703]	77,246 [±1,318]	6,064 [±527]	8,876 [±527]	8,261 [±967]	125,052 [±2,021]

Table 16. Cumulative new cases avoided for ULEZ and LES relative to baseline, for $PM_{2.5}$ in London

	Year	CHD	Stroke	Child asthma	Lung Cancer	COPD	Type 2 diabetes	Low birth weight	Total
ULEZ Rel Baseline	**2020**	791 [±88]	176 [±88]	703 [±264]	88 [±88]	703 [±88]	703 [±352]	791 [±88]	3,867 [±527]
	2025	2,724 [±264]	791 [±264]	2461 [±264]	352 [±88]	2,636 [±264]	2,636 [±527]	2197 [±264]	13,797 [±703]
	2030	5,976 [±352]	1,670 [±352]	4,042 [±352]	791 [±264]	5,624 [±264]	5,185 [±615]	3515 [±264]	26,891 [±967]
	2050	41,742 [±703]	12,567 [±703]	10,194 [±615]	5,536 [±527]	32,779 [±615]	31,636 [±1,406]	13,006 [±527]	147,461 [±2,021]
LES Rel Baseline	**2020**	791 [±88]	176 [±88]	703 [±264]	88 [±88]	791 [±88]	703 [±352]	703 [±88]	3,867 [±527]
	2025	2,900 [±264]	791 [±264]	2,548 [±264]	352 [±88]	2,724 [±264]	2,812 [±527]	2,285 [±264]	14,500 [±703]
	2030	7,030 [±352]	1,933 [±352]	4,921 [±352]	879 [±264]	6,591 [±264]	6,327 [±615]	4,130 [±264]	31,900 [±967]
	2050	47,894 [±703]	14,324 [±703]	11,688 [±615]	6,415 [±527]	37,524 [±615]	36,206 [±1,406]	15,115 [±527]	169,167 [±2,021]

Hospitalisations avoided Londonwide by scenario

This section provides estimates for the number of hospitalisations avoided as a result of the two policy scenarios. These represent the number of hospitalisations avoided as a result of the decreased number of cases of disease, not a reduction in hospitalisations due to a reduction in daily air-pollution-related exacerbations of disease. For NO_2 hospitalisation rates were available for asthma and lung cancer only, for $PM_{2.5}$ hospitalisation rates were available for all diseases except for diabetes and low birth weight. Therefore, numbers are higher for $PM_{2.5}$ as compared to NO_2.

Reduction in hospitalisations in London attributable to NO_2 as a result of ULEZ and LES policies:

As presented earlier in this report, in a scenario where pollution stays at 2016 levels an estimated 99,476 hospitalisations are attributable to NO_2 from 2016 to 2050 (see **Table 9**).

Table 17 shows that the ULEZ and LES scenarios are estimated to avoid 29,383 and 35,397 hospitalisations respectively. This translates to a reduction of 30 per cent and 36 per cent of NO_2 attributable hospitalisations for ULEZ and LES scenarios respectively by 2050.

Reduction in hospitalisations in London attributable to $PM_{2.5}$ as a result of ULEZ and LES policies:

In a baseline scenario where pollution stays at 2016 levels an estimated 3.8 million hospitalisations are attributable to $PM_{2.5}$ from 2016 to 2050 (see **Table 10**).

Table 18 shows that the ULEZ and LES scenarios are estimated to avoid 1.06 million and 1.23 million hospitalisations attributable to $PM_{2.5}$ respectively. This translates to a reduction of 28 per cent and 32 per cent of $PM_{2.5}$ attributable hospitalisations for ULEZ and LES scenarios respectively by 2050.

The majority of hospitalisations avoided in the case of both scenarios are COPD hospitalisations.

Total hospitalisations avoided by scenario in London:

- As presented earlier in this report, in a baseline scenario if no action is taken to reduce current levels of pollution the model predicts 3.93 million hospitalisations attributable to air pollution (99,476 for NO_2, 3.83 million for $PM_{2.5}$)
- The ULEZ policies are predicted to result in the avoidance of 1.09 million hospitalisations due to of NO_2 and $PM_{2.5}$ related diseases Londonwide by 2050 (29,383 for NO_2, 1.06 million for $PM_{2.5}$). This equates to a 28 per cent reduction in the cumulative hospitalisations attributable to air pollution compared to the baseline scenario
- The LES policies are predicted to result in the avoidance of 1.23 million hospitalisations due to NO_2 and $PM_{2.5}$ related diseases Londonwide by 2050 (35,397 for NO_2 and 1.23 million for $PM_{2.5}$). This equates to a 32 per cent reduction in the cumulative hospitalisations attributable to air pollution compared to the baseline scenario

The ULEZ policies are predicted to result in the avoidance of 1.09 million new air pollution related hospital admissions Londonwide by 2050. This equates to a 28 per cent reduction in total new cases of disease attributable to air pollution in London.

The policies included the LES (which includes the ULEZ policies) are predicted to result in the avoidance of 1.23 million air pollution related hospital admissions Londonwide by 2050. This equates to a 32 per cent reduction in total new cases of disease attributable to air pollution in London.

Table 17. Cumulative hospitalisations avoided due to reduction in NO_2 following ULEZ and LES relative to baseline

	Year	Childhood asthma	Adult asthma	Lung cancer	Total
ULEZ Rel Baseline	2020	154 [±67]	56 [±27]	314 [±305]	524 [±313]
	2025	516 [±98]	265 [±40]	1,543 [±474]	2,324 [±485]
	2030	1,028 [±125]	708 [±52]	3,445 [±639]	5,180 [±653]
	2050	3,936 [±226]	5,542 [±103]	19,906 [±1,447]	29,383 [±1,468]
LES Rel Baseline	2020	172 [±67]	61 [±27]	303 [±305]	537 [±313]
	2025	580 [±98]	282 [±40]	1,566 [±474]	2,428 [±485]
	2030	1,233 [±125]	808 [±52]	3,841 [±639]	5,882 [±653]
	2050	4,949 [±226]	6,831 [±103]	23,616 [±1,446]	35,397 [±1,467]

Table 18. Cumulative hospitalisations avoided due to the reduction in to $PM_{2.5}$ following ULEZ and LES relative to baseline

	Year	CHD	Stroke	Child asthma	Lung cancer	COPD	Total
ULEZ Rel Baseline	2020	311 [±76]	34 [±41]	320 [±69]	299 [±307]	8,603 [±2,100]	9,568 [±2,125]
	2025	1,398 [±115]	220 [±61]	914 [±101]	1,235 [±476]	46,463 [±3,240]	50,230 [±3,279]
	2030	3,693 [±151]	589 [±81]	1,810 [±130]	2,878 [±642]	121,971 [±4,335]	130,942 [±4,388]
	2050	37,920 [±318]	6,490 [±175]	8,060 [±235]	20,994 [±1,450]	985,535 [±9,056]	1,058,998 [±9,182]
LES Rel Baseline	2020	306 [±76]	38 [±41]	325 [±69]	336 [±307]	9,313 [±2099]	10,317 [±2,124]
	2025	1,456 [±115]	231 [±61]	954 [±101]	1,355 [±476]	48,664 [±3239]	52,660 [±3,278]
	2030	4,125 [±150]	658 [±81]	1,985 [±130]	3,267 [±642]	136,175 [±4330]	146,210 [±4,383]
	2050	44,381 [±317]	7,586 [±175]	9,609 [±235]	24,333 [±1,449]	1,144,606 [±9019]	1,230,515 [±9,145]

NHS and social care costs avoided Londonwide by scenario

This section presents an estimate for the cumulative costs to the NHS and social care system avoided as a result of each scenario relative to the baseline. These are calculated by multiplying the change in disease prevalence by the cost-per-case. The costs from each scenario are then subtracted from the baseline costs to calculate the costs avoided.

Costs avoided as a result of reductions in NO_2 in London:

Table 19 presents the cumulative NHS costs avoided in London for both scenarios compared to the baseline (where NO_2 remains at 2016 levels). Overall, it is predicted that the NHS will avoid £1.01 billion in costs as a result of reducing NO_2 due to the ULEZ policies. The reduction in cases of type 2 diabetes and dementia are predicted to be the highest contributor to cost savings.

For LES policies, it is estimated that the NHS will avoid £1.24 billion in costs relative to baseline trends by 2050 for the London population. The highest costs avoided were again observed for diabetes and dementia.

Table 20 shows the cumulative social care cost avoided as a result of the ULEZ and LES scenarios relative to baseline. The ULEZ policies are predicted to avoid a total of £722 million in social care costs by 2050. The largest costs avoided are attributed to a reduction in cases of dementia and diabetes respectively.

For the LES scenario, it is predicted that there will be £873 million social care costs avoided by 2050, with the largest contributor to this cost again being dementia and diabetes respectively.

Costs avoided as a result of reductions in $PM_{2.5}$ in London:

Table 21 presents the cumulative NHS costs avoided in London for diseases attributable to $PM_{2.5}$. For the ULEZ scenario it is predicted a cumulative total of £2.20 billion NHS costs will be avoided by 2050. The largest cost savings were seen in Coronary Heart Disease with £734.22 million in costs avoided.

For the LES scenario, it is predicted that the NHS will avoid £2.57 billion relative to the baseline scenario where $PM_{2.5}$ stays at 2016 levels. Similar to ULEZ, the largest cost savings were seen in CHD with £859.34 million.

Table 22 shows the cumulative social care cost avoided under ULEZ and LES scenarios relative to baseline. Under ULEZ, it is predicted that a total of £237.25 million would be avoided Londonwide. Most of the cost savings are for type 2 diabetes, which makes up £181.96 million of savings.

For LES, it is predicted that a total of £280.23 million social care costs would be avoided. Again, most of the cost savings are for type 2 diabetes, which makes up £215.67 million of the total for the LES scenario social care cost savings.

Total cost avoided by scenario:

- As presented earlier in this report, in the baseline scenario if no action is taken to reduce current levels of pollution the model estimates the total cost to the NHS and social care system from diseases attributable to air pollution will be £15.36 billion (£5.20 billion for NO_2, £10.16 billion for $PM_{2.5}$)
- The ULEZ policies are predicted to result in the avoidance of £4.17 billion costs to the NHS and social care system (£1.74 billion for NO_2, £2.43 billion for $PM_{2.5}$). This equates to a 27 per cent reduction in total cost compared to the attributable scenario
- The LES policies are predicted to result in the avoidance of £4.96 billion costs to the NHS and social care system (£2.11 billion for NO_2, £2.85 billion for

$PM_{2.5}$). This equates to a 32% reduction in total cost compared to the attributable scenario

The ULEZ policies are predicted to result in the avoidance of £4.17 billion in cost to the NHS and social care system from air pollution related diseases Londonwide by 2050. This equates to a 27 per cent reduction in total new cases of disease attributable to air pollution in London.

The policies in the London Environment Strategy (LES) are predicted to result in the avoidance of £4.96 billion in cost to the NHS and social care system from air pollution related diseases Londonwide by 2050. This equates to a 32 per cent reduction in total new cases of disease attributable to air pollution in London.

Table 19. Cumulative NHS cost avoided as a result of reductions in NO_2 (£) in London

	Year	Child asthma	Adult asthma	Type 2 diabetes	Lung cancer	Low birth weight	Dementia
ULEZ Rel Baseline	**2020**	515,054 [±218,378]	303,113 [±142,028]	5,539,880 [±1,812,434]	104,581 [±101,694]	310,706 [±546,980]	6,773,334 [±1,913,716]
	2025	1,731,571 [±320,950]	1,420,974 [±212,744]	35,835,837 [±2,720,534]	514,567 [±157,855]	1,764,715 [±809,701]	41,267,664 [±2,868,816]
	2030	3,447,811 [±409,476]	3,801,346 [±277,356]	105,611,140 [±3,562,385]	1,148,560 [±212,940]	4,603,861 [±1,054,664]	118,612,718 [±3,754,044]
	2050	13,205,629 [±739,471]	29,760,537 [±545,821]	925,788,093 [±7,228,333]	6,636,695 [±482,324]	39,251,299 [±2,423,448]	1,014,642,253 [±7,694,106]
LES Rel Baseline	**2020**	577,630 [±218,373]	329,795 [±142,024]	5,249,345 [±1,812,464]	100,996 [±101,697]	339,921 [±546,972]	6,597,687 [±1,913,741]
	2025	1,945,050 [±320,935]	1,514,500 [±212,733]	36,962,891 [±2,720,439]	522,269 [±157,849]	1,789,287 [±809,695]	42,733,997 [±2,868,721]
	2030	4,135,719 [±409,432]	4,341,637 [±277,298]	119,417,226 [±3,561,466]	1,280,478 [±212,857]	5,379,989 [±1,054,498]	134,555,049 [±3,753,111]
	2050	16,603,973 [±739,298]	36,684,884 [±545,267]	1,130,541,540 [±7,219,210]	7,873,884 [±481,837]	46,676,289 [±2,422,468]	1,238,380,570 [±7,685,141]

Table 20. Cumulative social care cost avoided as a result of reductions in NO_2 (£) in London

	Year	Child asthma	Adult asthma	Type 2 diabetes	Lung cancer	Dementia	Total
ULEZ Rel Baseline	**2020**	1,895 [±804]	1,115 [±523]	2,767,249 [±905,337]	16,889 [±16,423]	2,045,033 [±3,600,160]	4,832,182 [±3,712,285]
	2025	6,372 [±1,181]	5,229 [±783]	17,900,511 [±1,358,945]	83,099 [±25,493]	11,615,148 [±5,329,356]	29,610,359 [±5,499,948]
	2030	12,688 [±1,507]	13,989 [±1,021]	52,754,268 [±1,779,462]	185,485 [±34,388]	30,302,076 [±6,941,675]	83,268,506 [±7,166,207]
	2050	48,597 [±2,721]	10,9518 [±2,009]	462,444,333 [±3,610,655]	1,071,781 [±77,892]	258,347,481 [±15,950,851]	722,021,709 [±16,354,588]
LES Rel Baseline	**2020**	2,126 [±804]	1,214 [±523]	2,622,122 [±905,352]	16,310 [±16,423]	2,237,321 [±3,600,105]	4,879,092 [±3,712,235]
	2025	7,158 [±1,181]	5,573 [±783]	18,463,490 [±1,358,898]	84,343 [±25,491]	11,776,878 [±5,329,316]	30,337,443 [±5,499,897]
	2030	15,219 [±1,507]	15,977 [±1,020]	59,650,604 [±1,779,003]	206,788 [±34,375]	35,410,464 [±6,940,582]	95,299,053 [±7,165,034]
	2050	61,102 [±2,721]	135,000 [±2,007]	564,721,594 [±3,606,098]	1,271,578 [±77,813]	307,217,903 [±15,944,405]	873,407,178 [±16,347,295]

Table 21. Cumulative NHS cost avoided as a result of reductions in $PM_{2.5}$ (£) in London

	Year	CHD	Stroke	Child asthma	Lung cancer	COPD	Type 2 diabetes	Total
ULEZ Rel Baseline	**2020**	6,023,680 [±1,471,078]	2,650,611 [±3,127,139]	1,074,770 [±226,196]	99,753 [±102,238]	4,921,337 [±1,199,873]	2,457,243 [±1,816,181]	17,227,394 [±4,091,808]
	2025	27,063,924 [±2,214,617]	16,972,282 [±4,714,306]	3,067,868 [±332,518]	411,838 [±158,821]	26,578,363 [±1,851,515]	12,814,567 [±2,728,860]	86,908,842 [±6,175,742]
	2030	71,513,993 [±2,905,269]	45,490,821 [±6,218,863]	6,073,117 [±424,498]	959,457 [±214,124]	69,771,548 [±2,476,914]	34,308,291 [±3,576,117]	228,117,227 [±8,140,308]
	2050	734,224,314 [±6,131,934]	501,104,683 [±13,507,281]	27,040,234 [±768,009]	6,999,583 [±483,350]	563,757,471 [±5,172,585]	364,282,590 [±7,271,215]	2,197,408,875 [±17,334,847]
LES Rel Baseline	**2020**	5,928,881 [±1,471,106]	2,898,568 [±3,127,061]	1,089,192 [±226,195]	111,923 [±102,226]	5,327,087 [±1,199,658]	3,546,347 [±1816073]	18,901,997 [±4,091,648]
	2025	28,194,046 [±2,214,368]	17,807,932 [±4,714,107]	3,201,362 [±332,509]	451,638 [±158,794]	27,837,374 [±1,851,040]	15,491,934 [±2,728,669]	92,984,285 [±6,175,273]
	2030	79,880,009 [±2,903,683]	50,814,887 [±6,217,718]	6,657,718 [±424,463]	1,089,238 [±214,047]	77,896,251 [±2,474,215]	41,466,115 [±3,575,679]	257,804,218 [±8,137,850]
	2050	859,342,241 [±6,115,199]	585,742,477 [±13,494,232]	32,236,460 [±767,727]	8,112,816 [±482,895]	654,751,047 [±5,151,544]	431,754,024 [±7,267,986]	2,571,939,065 [±17,311,111]

Table 22. Cumulative social care cost avoided as a result of reductions in $PM_{2.5}$ (£) in London

	Year	CHD	Stroke	Child asthma	Lung cancer	COPD	Type 2 diabetes	Total
ULEZ Rel Baseline	2020	277,458 [±67,760]	34,671 [±40,904]	3,955 [±832]	16,109 [±16,511]	119,460 [±29,126]	1,227,428 [±907,208]	1,679,082 [±911,270]
	2025	1,246,599 [±102,008]	222,002 [±61,664]	11,290 [±1,224]	66,509 [±25,648]	645,163 [±44,944]	6,401,059 [±1,363,105]	8,592,622 [±1,369,285]
	2030	3,294,026 [±133,820]	595,033 [±81,345]	22,349 [±1,562]	154,946 [±34,579]	1,693,634 [±60,125]	17,137,480 [±1,786,321]	22,897,467 [±1,794,514]
	2050	33,819,310 [±282,445]	6,554,596 [±176,679]	99,508 [±2,826]	1,130,385 [±78,058]	13,684,641 ±125,559]	181,964,340 [±3,632,075]	237,252,779 [±3,650,319]
LES Rel Baseline	2020	273,092 [±67,761]	37,914 [±40,903]	4,008 [±832]	18,075 [±16,509]	129,310 [±29,120]	1,771,451 [±907,155]	2,233,849 [±911,216]
	2025	1,298,654 [±101,997]	232,933 [±61,662]	11,781 [±1,224]	72,936 [±25,644]	675,724 [±44,932]	7,738,441 [±1,363,009]	1,0030,470 [±1,369,189]
	2030	3,679,375 [±133,747]	66,4674 [±81,330]	24,500 [±1,562]	175,904 [±34,567]	1,890,852 [±60,059]	20,712,915 [±1,786,102]	27,148,221 [±1,794,288]
	2050	39,582,402 [±281,674]	7,661,683 [±176509]	118,630 [±2,825]	1,310,164 [±77,984]	15,893,418 [±125,049]	215,667,281 [±3,630,462]	280,233,578 [±3,648,627]

Summary by borough

Table 24 presents the cumulative new disease cases avoided, cumulative hospitalisations avoided, and cumulative social care costs avoided by borough relative to baseline. Note that these figures are scaled to the population in each respective borough so cannot be directly compared as some boroughs have higher populations than others. Health benefits and costs are avoided Londonwide[4]. The borough where the lowest impact is seen is City of London, this is because this because whilst there are significant air quality improvements in City, the resident population is much smaller than any other borough. Barnet is the borough with the greatest number of diseases avoided and largest costs avoided. This is because Barnet has the largest population of all the London boroughs. The prevalence of disease is also affected by the age profile of the borough. In general, the outer London boroughs have an older population than the inner London boroughs. As a result, populations in the outer boroughs are more vulnerable to disease, and thus more impacted by changes in air pollution in this time period.

Table 25 presents the percentage of diseases and costs attributable to air pollution that have been avoided in each scenario. There are larger reductions in the proportion of diseases and costs attributable to air pollution in the outer London boroughs as compared to the inner boroughs. This is because there are fewer cases of disease attributable to air pollution in the outer London boroughs than inner. For example, the largest reduction in disease cases as a percentage of attributable cases was found for Harrow and Hillingdon. The smallest percentage of cases avoided as a percentage of attributable cases was found in Tower Hamlets and City of London. Therefore, this illustrates need for more work to be carried out in inner

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[4] Note that the cases avoided for London are not the sum of each borough because the concentrations in the baseline 2016 and ULEZ/LES 2016 scenarios are not identical. This is described in more detail in Appendix 1.

city boroughs where greater exposure to air pollution results in a higher incidence of disease.

Table 23. Summary table of cumulative new cases of disease, hospitalisations and costs avoided relative to baseline per borough by 2050

	Cumulative disease cases avoided		Cumulative hospitalisations avoided		Cumulative NHS and social care costs avoided	
Borough	**ULEZ**	**LES**	**ULEZ**	**LES**	**ULEZ**	**LES**
Barking	3,291	3,910	10,830	12,638	£38,851,245	£47,194,032
Barnet	8,281	9,633	29,973	34,836	£118,631,822	£140,271,390
Bexley	3,693	4,295	12,067	14,047	£51,876,643	£61,416,733
Brent	8,082	9,552	28,931	33,008	£111,266,828	£131,760,764
Bromley	5,217	6,008	18,417	21,264	£74,640,424	£87,095,304
Camden	6,472	8,035	21,388	26,327	£91,681,245	£115,393,846
City of London	256	320	867	1,097	£3,646,680	£4,567,985
Croydon	7,581	8,690	29,191	33,114	£105,326,366	£121,680,058
Ealing	7,488	8,972	26,498	30,904	£103,060,238	£125,447,411
Enfield	5,521	6,432	17,329	20,352	£75,415,816	£89,254,004
Greenwich	5,749	6,952	20,956	24,745	£78,290,868	£95,706,613
Hackney	6,012	7,531	18,803	23,278	£74,615,992	£95,125,103
Hammersmith and Fulham	4,617	5,668	15,523	19,010	£64,683,187	£80,244,254
Haringey	6,962	8,276	26,242	30,451	£93,064,469	£112,711,286
Harrow	3,932	4,527	13,362	15,281	£55,624,365	£65,260,467
Havering	3,448	3,986	11,546	13,320	£47,671,936	£56,423,049
Hillingdon	4,613	5,290	14,831	16,979	£60,698,772	£71,106,247
Hounslow	5,287	6,348	17,519	20,555	£71,557,616	£87,217,205
Islington	5,409	6,730	17,529	21,760	£71,799,928	£90,344,767
Kensington and Chelsea	5,004	6,210	16,933	20,943	£74,971,251	£94,075,918
Kingston upon Thames	3,026	3,533	9,972	11,760	£42,514,464	£50,230,873
Lambeth	7,385	8,988	23,844	29,009	£100,069,136	£123,834,772
Lewisham	7,794	9,168	30,968	35,391	£105,593,697	£126,597,137
Merton	5,206	5,976	20,948	23,555	£74,105,869	£85,525,920
Newham	7,236	8,914	21,442	26,295	£82,571,048	£105,354,271
Redbridge	5,177	6,129	17,137	20,387	£68,274,498	£81,515,974
Richmond upon Thames	4,099	4,820	14,631	17,322	£59,871,507	£71,929,318
Southwark	7,320	9,124	24,979	30,815	£97,844,081	£123,788,605
Sutton	3,300	3,816	11,497	13,203	£47,881,400	£56,038,742
Tower Hamlets	6,289	7,997	19,747	24,766	£77,298,277	£100,007,935
Waltham Forest	6,874	7,988	26,538	29,821	£90,628,876	£106,449,805
Wandsworth	7,952	9,388	27,566	31,802	£103,454,664	£123,254,364
Westminster	7,250	8,973	24,197	29,929	£107,000,431	£133,846,181
Londonwide	250,631	294,219	1088381	1,265,912	£4,171,325,616	£4,963,960,391

Table 24. Summary table of cumulative new cases avoided per borough as a percentage of attributable cases for each scenario

	Cumulative disease cases avoided		**Cumulative hospitalisations avoided**		**Cumulative NHS and social care costs avoided**	
Borough	**ULEZ**	**LES**	**ULEZ**	**LES**	**ULEZ**	**LES**
Barking	26.2%	31.1%	26.6%	31.0%	26.9%	32.6%
Barnet	27.5%	32.1%	27.1%	31.5%	27.1%	32.1%
Bexley	32.5%	37.7%	28.3%	33.0%	31.5%	37.3%
Brent	25.2%	29.7%	26.2%	29.9%	25.9%	30.7%
Bromley	30.9%	35.6%	27.8%	32.1%	30.7%	35.8%
Camden	19.6%	24.3%	18.2%	22.4%	19.3%	24.3%
City of London	17.0%	21.3%	15.3%	19.3%	17.2%	21.6%
Croydon	28.9%	33.1%	29.3%	33.3%	29.5%	34.1%
Ealing	24.5%	29.3%	24.8%	28.9%	24.5%	29.9%
Enfield	28.7%	33.5%	26.6%	31.2%	29.1%	34.4%
Greenwich	24.1%	29.1%	24.6%	29.1%	24.8%	30.3%
Hackney	18.0%	22.6%	17.6%	21.8%	18.8%	24.0%
Hammersmith and Fulham	18.9%	23.2%	18.0%	22.1%	19.3%	23.9%
Haringey	25.8%	30.7%	27.4%	31.8%	25.9%	31.4%
Harrow	33.5%	38.6%	30.9%	35.3%	33.0%	38.8%
Havering	32.2%	37.2%	29.2%	33.7%	31.1%	36.8%
Hillingdon	32.5%	37.3%	30.5%	34.9%	31.4%	36.8%
Hounslow	23.8%	28.5%	24.0%	28.1%	23.5%	28.7%
Islington	18.2%	22.7%	17.6%	21.8%	18.5%	23.2%
Kensington and Chelsea	20.0%	24.9%	17.4%	21.5%	18.9%	23.8%
Kingston upon Thames	29.5%	34.5%	26.7%	31.5%	28.5%	33.7%
Lambeth	19.3%	23.5%	18.2%	22.2%	20.1%	24.8%
Lewisham	26.2%	30.8%	28.3%	32.3%	26.9%	32.3%
Merton	29.6%	33.9%	31.4%	35.3%	30.4%	35.1%
Newham	21.4%	26.3%	19.2%	23.6%	20.3%	25.9%
Redbridge	25.6%	30.4%	24.2%	28.8%	26.2%	31.2%
Richmond upon Thames	26.8%	31.5%	24.7%	29.2%	25.8%	31.0%
Southwark	18.5%	23.0%	18.2%	22.5%	18.8%	23.8%
Sutton	31.4%	36.3%	28.4%	32.6%	31.6%	37.0%
Tower Hamlets	16.6%	21.2%	17.2%	21.5%	17.6%	22.8%
Waltham Forest	29.6%	34.4%	33.4%	37.5%	30.6%	35.9%
Wandsworth	23.2%	27.3%	25.0%	28.8%	24.5%	29.2%
Westminster	20.2%	25.0%	18.0%	22.3%	19.9%	24.9%
Londonwide	29.5%	34.6%	27.7%	32.2%	27.2%	32.3%

The full results are available for all London boroughs in the data that accompanies this report.

Table 23 shows ULEZ and LES are expected to have a larger impact on absolute disease cases avoided in those boroughs where populations are larger. For example, The City of London has the smallest population and the least number of cases avoided. However, the findings are different when considering the number of attributable diseases per 100,000 residents. The rate of attributable diseases per 100,000 residents is provided in Appendix 4. This enables comparison between the boroughs of attributable rates per 100,000 residents.

The number of new diseases avoided per 100,000 residents is higher in central and inner boroughs, where the ULEZ will be in place, than outer boroughs. This is particularly true for NO_2 related diseases, with less pronounced differences seen between inner and outer London for $PM_{2.5}$ related disease. For example, the largest reduction in new air pollution related disease per 100,000 residents is expected in Kensington and Chelsea, Westminster, City of London, Camden, and Hammersmith and Fulham. The smallest reduction in new air pollution related disease per 100,000 residents is expected in Havering, Bexley, Bromley, Sutton, Harrow and Hillingdon.

Central and inner London boroughs have higher levels of air pollution, and therefore higher numbers of air pollution related disease. In outer London, where there are less air pollution related diseases per 100,000 residents, the improvements in air quality as a result of the ULEZ and LES therefore reduce a higher proportion of the air pollution related disease.

Therefore, continued work to reduce air pollution in inner boroughs is required since exposure to pollutants is much higher and thus burden of related disease likely to rise the most. However, there are health benefits in every borough, even though not every borough is included in the expanded ULEZ.

Borough case study: Lambeth

The following section includes the borough level results for Lambeth. These are available for all London boroughs in the data that accompanies this report.

New cases of disease in Lambeth

The model has calculated the cumulative incidence of cases which is the total number of new cases of disease, divided by the total number of people in the population each year, and accumulated over a specified period of the simulation from year 2016. Therefore, the cumulative number of incident cases represents a sum of all the incident cases from the start of the simulation, by scenario. These represent all the new ‘incident’ cases of disease that would be expected to occur in Lambeth in a scenario where air pollution remains at 2016 levels.

Table 25 shows the total new cases of disease between 2016 and 2050 in Lambeth in the baseline scenario where NO_2 remains at 2016 levels is 124,045.

Table 26 shows the estimated total new cases of disease between 2016 and 2050 in Lambeth in the baseline scenario where $PM_{2.5}$ remains at 2016 levels is 125,048.

Table 25: Cumulative new cases of disease for the Lambeth population (NO$_2$ baseline)

Year	Child asthma	Adult asthma	Type 2 diabetes	Lung cancer	Low birth weight	Dementia	Total
2020	5,830 [±10]	2,722 [±7]	6,329 [±13]	633 [±3]	1984 [±7]	2017 [±7]	19,517 [±20]
2025	11,477 [±16]	5,404 [±10]	12,775 [±16]	1,289 [±7]	3,840 [±10]	3,984 [±10]	38,766 [±30]
2030	16,209 [±20]	8,076 [±13]	19,357 [±20]	1,994 [±7]	5,584 [±10]	6,053 [±10]	57,273 [±33]
2050	26,000 [±23]	18,419 [±20]	45,947 [±30]	5,270 [±10]	12,120 [±16]	16,294 [±16]	124,045 [±49]

Table 26: Cumulative new cases of disease for the Lambeth population (PM$_{2.5}$ baseline)

Year	CHD	Stroke	Child asthma	Lung cancer	COPD	Type 2 diabetes	Low birth weight	Total
2020	1705 [±7]	1243 [±7]	6,414 [±13]	639 [±3]	1,203 [±7]	6,191 [±13]	2122 [±7]	19,520 [±20]
2025	3,440 [±10]	2,505 [±7]	12,631 [±16]	1,305 [±7]	2,479 [±7]	12,490 [±16]	4,102 [±10]	38,952 [±30]
2030	5,243 [±10]	3,827 [±10]	18,147 [±20]	2,020 [±7]	3,807 [±10]	18,901 [±20]	5,968 [±10]	57,909 [±33]
2050	13,192 [±16]	9,821 [±13]	29,692 [±23]	5,292 [±10]	9,319 [±13]	44,756 [±30]	12,972 [±16]	125,048 [±49]

New cases of disease attributable to air pollution in Lambeth

Not all of the cases of diseases in **Table 25** and **Table 26** are attributable to air pollution. Some people who are not exposed to air pollution are still at risk to air pollution related diseases for other reasons, such as smoking, obesity and genetics. This section estimates the number of new cases of diseases within the population which are attributable to air pollution.

The cumulative new cases of disease attributable to air pollution have been calculated by comparing the baseline scenario (which assumes no improvement from 2016 levels of air pollution) to a scenario where pollution was lowered to non-anthropogenic background levels. The difference between these two scenarios is an estimate of the number of new cases of disease which are attributable to air pollution.

Table 27 shows the cumulative number of disease cases attributable to NO_2 between 2016 and 2050, scaled to the Lambeth population.

By 2050 the model estimates 2,879 new cases of disease attributable to NO_2 for diseases where established evidence is included (childhood asthma only), increasing to 14,904 new cases of disease attributable to NO_2 when both established and emerging evidence is included. Type 2 diabetes cases were the greatest contributor to the total cases attributable, with 7,024 cases.

By comparison with the figures in **Table 25**, this equates to 12 per cent of the total cumulative new cases of disease in Lambeth by 2050.

Table 28 shows the cumulative number of new cases of disease attributable to $PM_{2.5}$ for the Lambeth population between 2016 and 2050.

By 2050 the model estimates 10,346 new cases attributable to $PM_{2.5}$ for diseases where established evidence is included, increasing to 23,360 when both established and emerging evidence is included. CHD and type 2 diabetes are the greatest contributors, with 4,565 and 4,515 cases attributable to $PM_{2.5}$ respectively.

By comparison with the figures in **Table 26** this equates to 18 per cent of the total cumulative new cases of disease by 2050.

In a baseline scenario if no action is taken to reduce current levels of pollution the model predicts 38,264 new cases of disease attributable to air pollution in Lambeth by 2050 (14,904 for NO_2, 23,360 for $PM_{2.5}$) when established and emerging evidence is included.

If no action is taken to reduce current levels of pollution, by 2050 the number of new diseases attributable to exposure to NO_2 and $PM_{2.5}$ exposure in Lambeth is estimated to be 38,264 (14,904 for NO_2, 23,360 for $PM_{2.5}$)

Table 27. Cumulative new cases of disease attributable to NO_2 for Lambeth population

Year	Child asthma	Adult asthma	Type 2 diabetes	Lung cancer	Low birth weight	Dementia	Total
2020	423 [±13]	351 [±10]	980 [±16]	43 [±3]	275 [±10]	62 [±10]	2,141 [±26]
2025	872 [±23]	705 [±13]	1,984 [±23]	92 [±10]	531 [±13]	121 [±13]	4,302 [±39]
2030	1,292 [±26]	1,049 [±20]	2,984 [±26]	138 [±10]	774 [±13]	177 [±13]	6,417 [±46]
2050	2,879 [±30]	2,446 [±26]	7,024 [±39]	380 [±13]	1,695 [±20]	485 [±23]	14,904 [±69]

Table 28. Cumulative new cases of disease attributable to $PM_{2.5}$, Lambeth

Year	CHD	Stroke	Child asthma	Lung cancer	COPD	Type 2 diabetes	Low birth weight	Total
2020	590 [±10]	164 [±7]	541 [±16]	62 [±3]	508 [±7]	643 [±16]	728 [±10]	3,243 [±26]
2025	1,177 [±13]	334 [±10]	1,085 [±23]	131 [±10]	1,056 [±10]	1,308 [±23]	1,407 [±13]	6,496 [±39]
2030	1,790 [±13]	505 [±13]	1,672 [±26]	203 [±10]	1,623 [±13]	1,961 [±26]	2,046 [±13]	9,801 [±46]
2050	4,565 [±20]	1,285 [±20]	3,984 [±33]	512 [±13]	3,978 [±16]	4,515 [±39]	4,519 [±20]	23,360 [±66]

Hospitalisations attributable to air pollution in Lambeth

These figures represent the number of hospitalisations as a result of the prevalence of disease due to air-pollution-related exacerbations of disease.

Table 29 presents the cumulative hospitalisations attributable to NO_2 for the Lambeth population between 2016 and 2050 respectively. In total, by 2050, an estimated 1,665 hospitalisations are attributed to NO_2 when established evidence is included (childhood asthma), increasing to 3,933 when established and emerging evidence is included.

The largest number of cumulative hospitalisations attributable to NO_2 by 2050 in Lambeth was for lung cancer 1,491.

Table 30 presents the cumulative hospitalisations attributable to $PM_{2.5}$ for the Lambeth population between 2016 and 2050 respectively. In total, by 2050, an estimated 9,681 hospitalisations are attributed to $PM_{2.5}$ when established evidence is included, increasing to 126,881 when diseases are included where there is less certain/emerging evidence.

The largest number of cumulative hospitalisations attributable to $PM_{2.5}$ by 2050 were estimated to be for COPD with 117,200 cases.

Table 29. Cumulative hospitalisation cases attributable to NO_2 in Lambeth

Year	Child asthma	Adult asthma	Lung Cancer	Total
2020	48 [±3]	26 [±1]	106 [±12]	180 [±13]
2025	173 [±5]	89 [±2]	287 [±18]	549 [±18]
2030	365 [±5]	183 [±2]	494 [±22]	1,042 [±23]
2050	1,665 [±8]	777 [±3]	1,491 [±35]	3,933 [±36]

Table 30. Cumulative hospitalisation attributable to $PM_{2.5}$ in Lambeth

Year	CHD	Stroke	Child asthma	Lung cancer	COPD	Total
2020	194 [±3]	32 [±2]	66 [±3]	156 [±12]	7,140 [±90]	7,587 [±91]
2025	622 [±4]	103 [±2]	226 [±5]	400 [±18]	21,008 [±126]	22,358 [±127]
2030	1,219 [±5]	199 [±3]	479 [±6]	688 [±22]	38,078 [±154]	40,663 [±156]
2050	4,701 [±8]	742 [±4]	2,276 [±8]	1,962 [±35]	117,200 [±234]	126,881 [±237]

NHS and social care costs attributable to air pollution in Lambeth

This section provides estimated for the costs to the NHS and social care system as a result of the prevalence of disease attributable to air pollution in a baseline scenario where pollution stays at 2016 levels. This does not necessarily include change in costs due to change in exacerbations.

Table 31 presents the cumulative NHS direct healthcare costs attributable to NO_2 in Lambeth between 2016 and 2050 for a scenario where NO_2 remains at 2016 levels. By 2050 it was predicted that there would be £5.59 million in NHS costs attributable to NO_2 when established evidence is included (childhood asthma) increasing to £112.30 million when emerging evidence is included.

Table 32 presents the cumulative social care costs attributable to NO_2 in Lambeth between 2016 and 2050 for a scenario where NO_2 remains at 2016 levels. By 2050 it was predicted that there would be £20,559 in social care costs attributable to NO_2 when established evidence is included, increasing to £67.27 million when conditions with emerging evidence are included.

The combined costs to the NHS and social care system attributable to NO_2 in Lambeth between 2016 and 2050 in a scenario where NO_2 remains at 2016 levels is £5.61 million when established evidence is considered, increasing to £179.57 million when emerging evidence is included.

Table 33 shows the cumulative NHS direct healthcare costs attributable to $PM_{2.5}$ for the Lambeth population between 2016 and 2050. The total costs attributable to $PM_{2.5}$ is estimated to be £156.63 million when established evidence is included, increasing to £282.70 million when conditions with emerging evidence are included, with the largest contributor being CHD with £91.02 million.

Table 34 shows the cumulative social care costs attributable to $PM_{2.5}$ for the Lambeth population between 2016 and 2050. The total cumulative social care cost by 2050 is projected to be £5.08 million when established evidence is included, increasing to £36.19 million when emerging evidence is included. The majority of the cost being attributable to type 2 diabetes with £29.48 million cost.

The combined costs to the NHS and social care system attributable to $PM_{2.5}$ in Lambeth between 2016 and 2050 in a scenario where $PM_{2.5}$ remains at 2016 levels is £161.71 million when established evidence is considered, increasing to £318.89 million when less certain/emerging evidence is included.

If no action is taken to reduce current levels of pollution, by 2050 the cumulative cost to the NHS and social care attributable from man-made air pollution in Lambeth is estimated to be £167.2 million (£5.61 million for NO_2, £161.71 million for $PM_{2.5}$) (based on data where there is more robust evidence for an association), increasing to £498.46 million (£179.57 million for NO_2, £318.89 million for $PM_{2.5}$) when diseases are included where the evidence is emerging.

Table 31. Cumulative NHS costs attributable to NO_2, by population, Lambeth

Year	Child asthma	Adult asthma	Type 2 diabetes	Lung cancer	Low birth weight	Dementia
2020	161,378 [±10,734]	141,399 [±6,497]	3,359,481 [±80,027]	35,303 [±4,082]	143,190 [±20,873]	3,840,752 [±83,750]
2025	579,520 [±14,883]	479,711 [±9,056]	11,553,129 [±111,591]	95,772 [±5,857]	411,047 [±28,704]	13,119,180 [±116,681]
2030	1,223,046 [±17,925]	985,051 [±10,971]	23,772,806 [±135,487]	164,570 [±7,298]	737,625 [±34,824]	26,883,098 [±141,648]
2050	5,586,658 [±25,943]	4,172,288 [±16,185]	99,386,855 [±202,563]	497,005 [±11,741]	2,659,512 [±55,981]	112,302,317 [±212,693]

Table 32. Cumulative social care cost (£) attributable to NO_2, by population, Lambeth

Year	Child asthma	Adult asthma	Diabetes	Lung cancer	Dementia	Total
2020	594 [±40]	520 [±24]	1,678,108 [±39,975]	5,701 [±659]	942,458 [±137,387]	2,627,382 [±143,086]
2025	2,133 [±55]	1,765 [±33]	5,770,953 [±55,741]	15,467 [±946]	2,705,464 [±188,924]	8,495,781 [±196,978]
2030	4,501 [±66]	3,625 [±40]	11,874,855 [±67,678]	26,577 [±1179]	4,854,964 [±229,206]	16,764,522 [±238,991]
2050	20,559 [±95]	15,354 [±60]	49,645,149 [±101,183]	80,263 [±1,896]	17,504,596 [±368,458]	67,265,921 [±382,103]

Table 33. Cumulative NHS costs attributable to $PM_{2.5}$ (£) by population, Lambeth

Year	CHD	Stroke	Childhood Asthma	Lung Cancer	COPD	Type 2 Diabetes	Total
2020	375,0177 [±62,725]	2,441,833 [±130,112]	221,751 [±11,208]	51,877 [±4,076]	4,084,555 [±51,214]	2,125,624 [±79,512]	12,675,817 [±173,063]
2025	12,035,860 [±86,786]	7,930,675 [±181,182]	757,102 [±15,535]	133,401 [±5,855]	12,017,290 [±71,937]	7,287,411 [±111,055]	40,161,739 [±241127]
2030	23,602,680 [±104,918]	15,376,296 [±220,591]	1,606,120 [±18,705]	229,232 [±7,295]	21,782,053 [±88,004]	14,815,186 [±134,983]	77,411,568 [±293,320]
2050	91,020,665 [±157,865]	57,321,851 [±340,452]	7,636,023 [±27,054]	654,086 [±11,720]	67,041,901 [±1,33,480]	59,026,543 [±202,343]	282,701,068 [±447,726]

Table 34. Cumulative social care costs attributable to $PM_{2.5}$ (£), Lambeth

Year	CHD	Stroke	Child asthma	Lung cancer	COPD	Type 2 diabetes	Total
2020	172,738 [±2,889]	319,40 [±1,702]	816 [±41]	8,378 [±658]	99,148 [±1,243]	1,061,779 [±39,717]	1,374,799 [±39,883]
2025	554,387 [±3997]	103,736 [±2,370]	2,786 [±57]	21,543 [±946]	291,708 [±1,746]	3,640,166 [±55473]	4,614,325 [±55,703]
2030	108,7170 [±4833]	201,126 [±2,885]	5,911 [±69]	37,019 [±1,178]	528,737 [±2,136]	7,400,396 [±67,426]	9,260,360 [±67,704]
2050	4,192,528 [±7,271]	749,787 [±4,453]	28,100 [±100]	105,630 [±1,893]	1,627,374 [±3,240]	29,484,598 [±101,073]	36,188,018 [±101,502]

Lambeth scenario assessment

This section estimates the impact of the Ultra Low Emission Zone and London Environment Strategy polices on the new cases of disease, hospitalisations and the NHS and social care costs in the years to 2050 in Lambeth.

New cases of disease avoided in Lambeth by scenario

New cases of disease avoided is the total number of incident cases of disease avoided since the start year 2016 as compared to baseline scenario when pollution remains at 2016 levels. A positive value represents the number of cases avoided. The cases avoided are equal to baseline number of cases minus the scenario number of cases.

Cases avoided as a result of reductions in NO_2 in Lambeth:

Table 35 presents the cumulative new cases of disease avoided as a result of reduction in NO_2 for the two scenarios (ULEZ and LES) in Lambeth. As presented previously, it is predicted there will be a total of 124,045 new disease[5] cases by 2050 if baseline trends continue (see Table 25) of which 14,904 are attributable to NO_2 (see Table 27).

Table 35 shows that the ULEZ and LES scenarios are estimated to avoid 3,653 and 4,532 cases respectively. This represents the avoidance of 25 per cent and 30 per cent of NO_2 attributable cases in Lambeth from 2016 to 2050.

The largest number of disease cases avoided are estimated for type 2 diabetes and adult asthma.

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[5] Disease cases refers only to the list of diseases included within the model and reflect the number expected in the population.

Cases avoided as a result of reductions in $PM_{2.5}$ in Lambeth:

Table 36 presents the cumulative new cases of disease avoided as a result of reduction in $PM_{2.5}$ for the two scenarios. As presented previously, it is predicted there will be a total of 125,048 new disease cases[6] by 2050 if baseline trends continue (see Table 25) of which 23,360 are attributable to $PM_{2.5}$ (see Table 28). Table 36 shows that the ULEZ and LES scenarios are estimated to avoid 3,732 and 4,456 cases respectively when both established and emerging is included. This translates to the avoidance of 16 per cent and 19 per cent of $PM_{2.5}$ attributable cases in Lambeth from 2016 to 2050.

Total diseases avoided by scenario in Lambeth:

- As presented previously, if no action is taken to reduce current levels of pollution the model predicts 38,264 cases of disease attributable to air pollution between 2016 and 2050 (14,904 for NO_2, 23,360 for $PM_{2.5}$)
- The ULEZ policies are predicted to result in the avoidance of 7,385 new cases of air pollution related diseases in Lambeth by 2050 (3,653 for NO_2 and 3,732 for $PM_{2.5}$). This equates to a 19 per cent reduction in the number of cases attributable to air pollution compared to the baseline scenario
- The LES policies are predicted to result in the avoidance of 8,988 new cases of air pollution related diseases in Lambeth by 2050 (4,532 for NO_2 and 4,456 for $PM_{2.5}$). This equates to a 23 per cent reduction in the number of cases attributable to air pollution compared to the baseline scenario

The ULEZ policies are predicted to result in the avoidance of 7,385 new cases of air pollution related diseases in Lambeth by 2050. This equates to a 19 per cent reduction in new cases of disease attributable to air pollution in Lambeth.

The policies in the London Environment Strategy (including ULEZ) are predicted to result in the avoidance of 8,988 new cases of air pollution related diseases in Lambeth by 2050 (relative to the baseline scenario in which these policies were not implemented). This equates to a 23 per cent reduction in total new cases of disease attributable to air pollution in London.

Table 35. Cumulative new cases of disease avoided in ULEZ and LES relative to baseline, Lambeth NO_2

	Year	Child asthma	Adult asthma	Type 2 Diabetes	Lung cancer	Low birth weight	Dementia	Total
ULEZ Rel Baseline	2020	39 [±13]	30 [±10]	89 [±20]	3 [±3]	23 [±10]	3 [±10]	193 [±26]
	2025	108 [±23]	115 [±13]	341 [±23]	16 [±10]	79 [±13]	23 [±13]	675 [±43]
	2030	144 [±26]	207 [±20]	646 [±26]	30 [±10]	125 [±13]	33 [±13]	1180 [±46]
	2050	252 [±33]	630 [±26]	2190 [±43]	131 [±13]	282 [±23]	167 [±23]	3,653 [±69]
LES Rel Baseline	2020	36 [±13]	33 [±10]	89 [±20]	3 [±3]	23 [±10]	3 [±10]	193 [±26]
	2025	118 [±23]	128 [±13]	380 [±23]	16 [±10]	89 [±13]	26 [±13]	754 [±43]
	2030	177 [±26]	249 [±20]	784 [±26]	36 [±10]	157 [±13]	46 [±13]	1,449 [±46]
	2050	302 [±33]	787 [±26]	2709 [±43]	164 [±13]	361 [±23]	216 [±23]	4,532 [±69]

Table 36. Cumulative new cases of disease avoided under ULEZ and LES relative to baseline, Lambeth $PM_{2.5}$

	Year	CHD	Stroke	Child asthma	Lung cancer	COPD	Type 2 diabetes	Low birth weight	Total
ULEZ Rel Baseline	2020	30 [±10]	7 [±10]	23 [±20]	0 [±3]	20 [±10]	36 [±20]	36 [±10]	151 [±26]
	2025	95 [±13]	26 [±10]	82 [±23]	7 [±10]	85 [±10]	105 [±23]	102 [±13]	498 [±43]
	2030	184 [±13]	46 [±13]	134 [±26]	16 [±10]	174 [±13]	174 [±26]	164 [±13]	889 [±46]
	2050	898 [±23]	239 [±20]	416 [±33]	92 [±13]	803 [±20]	754 [±43]	525 [±23]	3,732 [±69]
LES Rel Baseline	2020	33 [±10]	7 [±10]	23 [±20]	0 [±3]	23 [±10]	33 [±20]	33 [±10]	157 [±26]
	2025	102 [±13]	26 [±10]	85 [±23]	7 [±10]	95 [±10]	108 [±23]	105 [±13]	528 [±43]
	2030	220 [±13]	59 [±13]	171 [±26]	20 [±10]	210 [±13]	216 [±26]	193 [±13]	1,082 [±46]
	2050	1,079 [±23]	295 [±20]	485 [±33]	115 [±13]	961 [±20]	908 [±43]	613 [±23]	4,456 [±69]

Hospitalisations avoided in Lambeth by scenario

This section estimates the number of hospitalisations avoided as a result of the decreased prevalence of disease resulting from the introduction of the Ultra Low Emission Zone and London Environment Strategy. This does not necessarily take into account hospitalisations avoided due to a reduction in air-pollution-related exacerbations of disease. For NO_2 hospitalisation rates were available for asthma and lung cancer only, for $PM_{2.5}$ hospitalisation rates were available for all diseases except for diabetes and low birth weight. Negative cases of lung cancer suggest that there are more cases in the scenario than baseline, however these figures are not significant. There are a significant number of cases avoided due to the scenario relative to baseline later in the simulation.

Reduction in hospitalisations in Lambeth attributable to NO_2 as a result of ULEZ and LES policies:

As presented previously, in a scenario where pollution stays at 2016 levels an estimated 3,933 hospitalisations are attributed to NO_2 in Lambeth from 2016 to 2050 (see **Table 29**).

Table 37 shows that the ULEZ and LES scenarios are estimated to avoid 905 and 1,097 hospitalisations respectively. This translates to a reduction of 23 per cent and 28 per cent of NO_2 attributable hospitalisations for ULEZ and LES scenarios respectively by 2050.

Reduction in hospitalisations in Lambeth attributable to ULEZ and LES policies for $PM_{2.5}$:

As presented previously, in a baseline scenario where pollution stays at 2016 levels an estimated 126,881 hospitalisations are attributed to $PM_{2.5}$ from 2016 to 2050 (see **Table 30**).

For $PM_{2.5}$ **Table** 38 shows that the ULEZ and LES scenarios are estimated to avoid 22,939 and 27,912 hospitalisations to respectively. This translates to a reduction of

18 per cent and 22 per cent of $PM_{2.5}$ attributable hospitalisations in Lambeth for ULEZ and LES scenarios respectively by 2050.

The majority of hospitalisations avoided in the case of both scenarios are for COPD.

Total hospitalisations avoided by scenario:

- As presented previously, in a baseline scenario if no action is taken to reduce current levels of pollution the model predicts 130,814 hospitalisations attributable to air pollution in Lambeth (3,933 for NO_2, 126,881 for $PM_{2.5}$)
- The ULEZ policies are predicted to result in the avoidance of 23,844 hospitalisations due to of NO_2 and $PM_{2.5}$ related diseases in Lambeth by 2050 (905 for NO_2, 22,939 for $PM_{2.5}$). This equates to an 18 per cent reduction in the cumulative hospitalisations attributable to air pollution compared to the baseline scenario
- The LES policies are predicted to result in the avoidance of 29,009 hospitalisations due to NO_2 and $PM_{2.5}$ related diseases in Lambeth by 2050 (1,097 for NO_2 and 27,912 for $PM_{2.5}$). This equates to a 22 per cent reduction in the cumulative hospitalisations attributable to air pollution compared to the baseline scenario

The ULEZ policies are predicted to result in the avoidance of 23,844 NO_2 and $PM_{2.5}$ related hospital admissions in Lambeth by 2050 (relative to the baseline scenario). This equates to an 18 per cent reduction in total hospitalisations attributable to air pollution.

All of the policies in the LES (which includes the ULEZ policies) are predicted to result in the avoidance of 29,009 NO_2 and $PM_{2.5}$ related hospital admissions in Lambeth by 2050 (relative to the baseline scenario in which these policies were not implemented). This equates to a 22 per cent reduction in total new cases of disease attributable to air pollution in London.

Table 37. Cumulative hospitalisations avoided due to reduction in NO_2 following ULEZ and LES relative to baseline

	Year	Child asthma	Adult asthma	Lung cancer	Total
ULEZ Rel Baseline	2020	17 [±3]	3 [±1]	5 [±12]	25 [±13]
	2025	44 [±5]	14 [±2]	37 [±18]	96 [±18]
	2030	76 [±5]	33 [±2]	92 [±22]	202 [±23]
	2050	226 [±8]	187 [±3]	492 [±36]	905 [±37]
LES Rel Basleine	2020	17 [±3]	4 [±1]	0 [±12]	21 [±13]
	2025	45 [±5]	15 [±2]	37 [±18]	96 [±18]
	2030	83 [±5]	38 [±2]	104 [±22]	225 [±23]
	2050	263 [±8]	231 [±3]	603 [±36]	1,097 [±37]

Table 38. Cumulative hospitalisations avoided due to reduction in $PM_{2.5}$ following ULEZ and LES relative to baseline

	Year	CHD	Stroke	Child asthma	Lung cancer	COPD	Total
ULEZ Rel Baseline	2020	10 [±3]	0 [±2]	8 [±3]	-9 [±12]	219 [±95]	228 [±96]
	2025	46 [±5]	5 [±2]	24 [±5]	-1 [±18]	1,396 [±135]	1,470 [±137]
	2030	110 [±6]	14 [±3]	50 [±6]	27 [±22]	3,465 [±167]	3,666 [±169]
	2050	772 [±9]	117 [±5]	236 [±8]	288 [±36]	21,526 [±255]	22,939 [±258]
LES Rel Baseline	2020	11 [±3]	1 [±2]	8 [±3]	-8 [±12]	236 [±95]	248 [±96]
	2025	48 [±5]	6 [±2]	25 [±5]	-1 [±18]	1,475 [±135]	1,553 [±137]
	2030	122 [±6]	17 [±3]	55 [±6]	34 [±22]	3,921 [±167]	4,148 [±169]
	2050	941 [±9]	147 [±5]	289 [±8]	368 [±36]	261,67 [±254]	27,912 [±257]

NHS and social care costs avoided in Lambeth by scenario

This section presents the cumulative costs avoided as a result of each scenario relative to baseline. These are calculated by multiplying the change in disease prevalence and cost-per-case. The costs from each scenario are subtracted from the baseline costs to calculate the costs avoided.

Costs avoided as a result of reductions in NO_2 in Lambeth:

Table 39 presents the cumulative NHS costs avoided in Lambeth for both scenarios in comparison to the baseline (where pollution remains at 2016 levels). Overall, it is predicted that the NHS will avoid £30.57 million in NHS costs in Lambeth as a result of reducing NO_2 due to the ULEZ policies. The reduction in cases of type 2 diabetes and asthma are predicted to be the highest contributor to cost savings.

For LES relative to baseline, it is predicted that the NHS will avoid £37.94 million in NHS costs by 2050 for the Lambeth population. The highest costs avoided were again observed for diabetes and asthma.

Table 40 shows the cumulative social care cost avoided as a result of the ULEZ and LES scenarios relative to baseline. The ULEZ policies are predicted to avoid a total of £19.55 million in social care costs in Lambeth by 2050. The largest costs avoided are attributed to a reduction in cases of dementia and diabetes respectively.

For the LES scenario, it is predicted that there will be £24.52 million social care costs avoided by 2050, with the largest contributor to this cost again being dementia and diabetes respectively.

The combined cost avoided to the NHS and social care system for reductions in NO_2 as a result of the ULEZ in Lambeth is £50.11 million. For the policies in the LES the combined saving is £62.46 million.

Costs avoided as a result of reductions in $PM_{2.5}$ in Lambeth:

Table 41 presents the cumulative NHS costs avoided in Lambeth for diseases attributable to $PM_{2.5}$. For the ULEZ scenario it is predicted that a cumulative total of

£44.96 million NHS costs will be avoided by 2050. The largest cost savings were seen for CHD.

For the LES scenario relative to baseline, it is predicted that the NHS will avoid £55.20 million in the Lambeth population. Similar to ULEZ, the largest cost savings were seen in CHD.

Table 42 shows the cumulative social care cost avoided by reductions in $PM_{2.5}$ under ULEZ and LES scenarios relative to baseline. Under ULEZ, it is predicted that a total of £5.0 million of social care costs will be avoided in Lambeth due to reductions in $PM_{2.5}$. Most of the cost savings are from type 2 diabetes, which makes up £3.87 million of the total saving.

For the LES scenario, it is predicted that a total of £6.17 million would be avoided in social care costs in Lambeth by 2050. Again, most of the cost savings are for type 2 diabetes, which makes up £4.80 million of the total for the LES scenario.

The combined cost avoided to the NHS and social care system for reductions in $PM_{2.5}$ as a result of the ULEZ in Lambeth is £49.96 million. For the policies in the LES the combined saving is £61.37 million.

Total cost avoided by scenario in Lambeth:

- As presented earlier, in the baseline scenario (if no action is taken to reduce current levels of pollution) the model estimates the total cost to the NHS and social care system from diseases attributable to air pollution will be £498.46 million (£179.57 million for NO_2, £318.89 million for $PM_{2.5}$)
- The ULEZ policies are predicted to result in the avoidance of £100.07 million in costs to the NHS and social care system (£50.11 million for NO_2, £49.96 million for $PM_{2.5}$). This equates to a 19 per cent reduction in total cost to the NHS and social care system in Lambeth attributable to air pollution
- The LES policies are predicted to result in the avoidance of £123.83 million in costs to the NHS and social care system (£62.46 million for NO_2, £61.37 for million for $PM_{2.5}$). This equates to a 23 per cent reduction in total cost compared to the attributable scenario.

The ULEZ policies are predicted to result in the avoidance of £100.07 million in cost to the NHS and social care system from air pollution related diseases in Lambeth by 2050. This equates to a 18 per cent reduction in total new cases of disease attributable to air pollution in Lambeth.

The policies in the London Environment Strategy (LES) are predicted to result in the avoidance of £123.83 million in cost to the NHS and social care system from air pollution related diseases in Lambeth by 2050. This equates to a 22 per cent reduction in total new cases of disease attributable to air pollution in Lambeth.

Table 39. Cumulative NHS cost avoided as a result of reductions in NO_2 (£) in Lambeth

	Year	Child asthma	Adult asthma	Type 2 Diabetes	Lung cancer	Dementia	Total
ULEZ Rel Basleine	2020	57,856 [±10,746]	18,392 [±6,523]	356,661 [±80,449]	1,530 [±4,131]	6,299 [±20,939]	440,737 [±84,176]
	2025	148,359 [±14,916]	76,350 [±91,15]	1,745,519 [±112,536]	12,395 [±5,939]	57,274 [±28,823]	2,039,897 [±117,626]
	2030	256,117 [±17,984]	179,692 [±11,064]	4,462,004 [±136,957]	30,607 [±7,400]	124,228 [±34,988]	5,052,648 [±143,116]
	2050	757,859 [±26,121]	1,005,730 [±16,402]	27,783,903 [±205,759]	163,875 [±11,884]	855,992 [±56,250]	30,567,359 [±215,855]
LES Rel Baseline	2020	56,051 [±10,746]	19,316 [±6,523]	392,661 [±80,443]	72 [±4,133]	3,941 [±20,940]	472,042 [±84,171]
	2025	150,021 [±14,915]	80,830 [±9,114]	1,903,978 [±112,520]	12,237 [±5,939]	63,720 [±28,820]	2,210,786 [±117,610]
	2030	276,930 [±17,983]	202,981 [±11,061]	5,160,678 [±136,905]	34,805 [±7,397]	155,652 [±34,980]	5,831,046 [±143,063]
	2050	882,645 [±26,117]	1,242,556 [±16,387]	34,516,819 [±205,473]	200,929 [±11,869]	1,100,381 [±56,215]	37,943,330 [±215,571]

Table 40. Cumulative social care cost avoided as a result of reductions in NO_2 (£) in Lambeth

	Year	Child asthma	Adult asthma	Type 2 diabetes	Lung cancer	Dementia	Total
ULEZ Rel Baseline	2020	213 [±40]	68 [±24]	178,157 [±40,185]	247 [±667]	41,458 [±137,818]	220,143 [±143,559]
	2025	546 [±55]	281 [±34]	871,912 [±56,213]	2,002 [±959]	376,972 [±189,707]	1,251,712 [±197,862]
	2030	943 [±66]	661 [±41]	2,228,834 [±68,412]	4,943 [±1,195]	817,657 [±230,287]	3,053,038 [±240,237]
	2050	2,789 [±96]	3,701 [±60]	13,878,455 [±102,780]	26,465 [±1,919]	5,634,042 [±370,231]	19,545,452 [±384,237]
LES Rel Baseline	2020	206 [±40]	71 [±24]	196,140 [±40,183]	12 [±667]	25,941 [±137,824]	222,370 [±143,564]
	2025	552 [±55]	297 [±34]	951,064 [±56,205]	1,976 [±959]	419,397 [±189,691]	1,373,287 [±197,845]
	2030	1,019 [±66]	747 [±41]	2,577,832 [±68,386]	5,621 [±1,195]	1,024,481 [±230,233]	3,609,700 [±240,177]
	2050	3,248 [±96]	4,573 [±60]	17,241,643 [±102,637]	32,449 [±1,917]	7,242,581 [±370,002]	24,524,493 [±383,978]

Table 41. Cumulative NHS cost avoided as a result of reductions in $PM_{2.5}$ (£) in Lambeth

	Year	CHD	Stroke	Child asthma	Lung cancer	COPD	Type 2 diabetes	Total
ULEZ Rel Baseline	2020	190,777 [±64,140]	12,516 [±131,265]	26,279 [±11,229]	-2842 [±4156]	125,367 [±54,052]	63,559 [±79,806]	415,656 [±175,438]
	2025	899,621 [±89,837]	365,067 [±183,659]	80,350 [±15,585]	-465 [±5986]	798,692 [±77,382]	443,121 [±111,729]	2,586,385 [±246,072]
	2030	2,138,214 [±109,593]	1,078,756 [±224,310]	166,982 [±18,791]	9,062 [±7,463]	1,982,071 [±95,565]	1,111,002 [±136,058]	6,486,087 [±300,631]
	2050	14,942,074 [±167,626]	9,057,826 [±347,803]	790,610 [±27,306]	96,174 [±11,965]	12,313,638 [±145,914]	7,757,134 [±204,755]	44,957,454 [±461,703]
LES Rel Baseline	2020	213,600 [±64,131]	57,839 [±131,243]	26,940 [±11,229]	-2,662 [±4,155]	135,112 [±54,046]	60,012 [±79,807]	490,842 [±175,417]
	2025	925,608 [±89,830]	435,916 [±183,634]	83,465 [±15,584]	-208 [±5,986]	843,972 [±77,361]	442,668 [±111,729]	2,731,420 [±246,044]
	2030	2,355,056 [±109,548]	1,305,609 [±224,252]	184,062 [±18,790]	11,336 [±7,461]	2,242,933 [±95,473]	1,247,259 [±136,048]	7,346,255 [±300,537]
	2050	18,213,004 [±167,235]	11,317,281 [±347,474]	969,590 [±27299]	122,773 [±11,954]	14,968,402 [±145,363]	9,604,586 [±204,670]	55,195,636 [±461,101]

Table 42. Cumulative social care cost avoided as a result of reductions in $PM_{2.5}$ (£) in Lambeth

	Year	CHD	Stroke	Childhood asthma	Lung cancer	COPD	Type 2 diabetes	Total
ULEZ Rel Baseline	2020	8,787 [±2,954]	164 [±1,717]	97 [±41]	-459 [±671]	3,043 [±1,312]	31,748 [±39,864]	43,380 [±40,038]
	2025	41,438 [±4,138]	4,775 [±2,402]	296 [±57]	-75 [±967]	19,387 [±1,878]	221,345 [±55,810]	28,7166 [±56,055]
	2030	98,489 [±5,048]	14,110 [±2,934]	614 [±69]	1,463 [±1,205]	48,113 [±2,320]	554,961 [±67,963]	717,751 [±68,263]
	2050	688,251 [±7,721]	118,479 [±4,549]	2,909 [±100]	15,531 [±1,932]	298,901 [±3,542]	3,874,799 [±102,278]	4,998,871 [±102,749]
LES Rel Baseline	2020	9,839 [±2,954]	757 [±1,717]	99 [±41]	-430 [±671]	3280 [±1312]	29,977 [±39,865]	43,521 [±40,038]
	2025	42,635 [±4,138]	5,702 [±2,402]	307 [±57]	-34 [±967]	20487 [±1878]	221,119 [±55,810]	290,216 [±56,055]
	2030	108,477 [±5,046]	17,078 [±2,933]	677 [±69]	1,831 [±1,205]	54445 [±2318]	623,024 [±67,958]	805,531 [±68,258]
	2050	838,914 [±7,703]	148,033 [±4,545]	3,568 [±100]	19,827 [±1,930]	363,343 [±3,529]	4,797,628 [±102,236]	6,171,313 [±102,705]

Discussion

What this study shows

This study quantified the attributable burden of air-pollution related diseases in London and simulated the long-term (2016-2050) health impact of the Ultra Low Emission Zone (ULEZ) and London Environment Strategy (LES) policies on morbidity, hospital admissions, and costs to the NHS and social care relative to a baseline where these policies were not implemented and where NO_2 and $PM_{2.5}$ remained at 2016 levels.

Between 2016 and 2050, the total number of new disease cases attributable to NO_2 and $PM_{2.5}$ in London is estimated to be 849,613 (297,294 for NO_2 and 552,319 for $PM_{2.5}$). When diseases with established and emerging evidence are considered the total cumulative NHS and social care costs attributable to NO_2 and $PM_{2.5}$ combined between 2016 and 2050 is estimated as £15.40 billion (£5.20 billion for NO_2, £10.16 billion for $PM_{2.5}$.

In London for the ULEZ policy scenario, the disease burden is estimated to be reduced by 250,631 between 2016 and 2050, which corresponds to 29% of the total attributable disease cases. These changes in disease due to ULEZ result in a reduction of £4.17 billion in NHS and social care costs and 1.09 million hospitalisations by 2050.

In Lambeth for the ULEZ policy scenario, the disease burden is estimated to be reduced by 7,385 cases between 2016 and 2050 in the Lambeth population, which corresponds to 18% of the total attributable disease cases. These changes in disease due to ULEZ result in a reduction in £100.07 million in NHS and social care costs and 23,844 hospitalisations by 2050.

In London for the LES policy scenario, the disease burden is estimated to be reduced by 294,219 between 2016 and 2050, which corresponds to 35% of the total attributable disease cases. These changes in disease due to the LES result in a reduction of £4.96 billion in NHS and social care costs and 1.22 million fewer hospitalisations by 2050.

In Lambeth for the LES policy scenario, the disease burden is estimated to be reduced by 8,988 between 2016 and 2050, which corresponds to 22% of the total attributable disease cases. There changes in disease prevalence due to the LES result in a reduction of £123.83 million in NHS and social care costs and 27,912 hospitalisations by 2050.

The impacts of the policies on the number of new cases of disease, and associated hospital admissions and health and social care costs vary depending on the prevalence of disease in the population and how strong the relationship is between exposure to air pollution and new cases of the disease. Therefore, diseases that are both prevalent and have a high exposure-response coefficient will be more affected by changes in air pollution.

The findings show that while ULEZ and other policies within LES are predicted to have large impacts on reducing related disease burden, they are insufficient to completely eliminate all air quality related disease. This is particularly true for $PM_{2.5}$ related disease since many of the current policies primarily address NO_2 as opposed to $PM_{2.5}$.

The ULEZ scenario is embedded in the LES scenario. The majority of health benefits are associated with the ULEZ policies, identifying the importance of these key measures. However, as anticipated the full suite of LES policies resulted in health benefits beyond those of the policies in the ULEZ scenario alone. The ULEZ policies are the centre piece of the 2018 London Environment Strategy and deliver a large share of the benefits, reducing the burden of disease attributable to air pollution by 29%. However, the wider policies in the Environment Strategy also contribute a large

(6%) reduction in the number of diseases to air pollution. In addition, is important to recognise that health benefits accrue over time, therefore policies introduced earlier in the simulation period (as is the case of the ULEZ scenario policies) will have had a greater impact by 2050, as the population will have been exposed to the effects of those policies for a longer period of time. Further simulation beyond 2050 would be required in order for the lifetime impact of all of the policies to be observed, as such this modelling is a conservative estimate of the impact of the London Environment Strategy in comparison to the ULEZ policies which are implemented earlier.

The ULEZ and LES scenarios were observed to have a larger relative impact in London compared to Lambeth. This can be explained by comparing the age profile of the two populations, London as a whole has an overall older population than Lambeth. As a result, the Londonwide population is more vulnerable to disease in the simulation, and thus more impacted by changes in air pollution in this time period. This finding can be explored by comparing the impact of LES on 'older age diseases' such as dementia, where 92 cases per 100,000 were avoided in London, compared with 63 per 100,000 in Lambeth. It is important to note that children are also particularly vulnerable to the impacts or poor air quality, however many diseases will not manifest until later in life, and so a longer simulation period would be required in order for high-levels of disease to manifest in areas with a younger population structure.

Exploring the impacts in each borough, we observe that ULEZ and LES have a larger impact on the total number of new disease cases avoided in those boroughs where populations are larger. For example, City of London has the smallest population and the least number of cases avoided.

Exploring the number of new diseases avoided per 100,000 residents (provided in the Appendix) enables comparison across a standardised population. This reveals that in central and inner London, where the central and expanded ULEZ will be in place, the reduction in new diseases per 100,000 residents is higher than for outer boroughs. This is particularly true for NO_2 related diseases, with a less pronounced difference seen between inner and outer London for $PM_{2.5}$ related disease. For example, the largest impact of ULEZ and LES per 100,000 residents is observed in inner boroughs of Kensington and Chelsea, Westminster, City of London, Camden, and Hammersmith and Fulham. The smallest impact per 100,000 residents is observed in the outer London boroughs of Havering, Bexley, Bromley, Sutton, Harrow and Hillingdon.

The lower levels of air pollution in outer London boroughs result in lower numbers of air pollution related diseases. As a result, the reductions in new cases of disease that occur as a result of the policy scenarios make up a bigger proportion of disease attributable to air pollution in outer London than central and inner London. Therefore, continued work to reduce air pollution in inner boroughs is required since exposure to pollutants is much higher and thus burden of related disease likely to rise the most.

It is important to recognise that there are health benefits in every borough, even though not every borough is included in the expanded ULEZ. After ULEZ is expanded and tighter standards for buses, coaches and lorries are introduced Londonwide, just 4 per cent of roads in outer London will be exceeding legal limits in 2021. There are equally effective, and quicker, ways of improving these areas rather than making 1.7 million extra people meet the ULEZ standards.

What are the policy implications of this report?

This report shows that the policies considered are effective in reducing air quality related disease, especially over the long-term since health benefits accrue over time. It is therefore important that these policies continue to be implemented for their full impact to take effect.

However, as highlighted above, these policies are not enough to eliminate all air-quality related disease. In particular more action is needed to reduced levels of $PM_{2.5}$. In a recent report (29) City Hall outlines the additional powers required to tackle this source in London and the importance of adopting legally binding targets for $PM_{2.5}$ in the upcoming Environment Bill.

Importantly, this report shows that a pan-London approach is required, and that reducing air pollution even in lower pollution areas has an important impact on disease cases avoided. The age makeup of the population also contributes to the policies impact. Younger groups tend to move into the outer London boroughs as they age, meaning reducing air pollution in these areas is still as important as tackling central London pollution hot spots.

How does this report complement other research?

This study focusses on long-term health impacts of air quality interventions and does not take account of the short-term health impacts such as reductions in exacerbations due to daily changes in air pollution (30–33). Short-term peaks may lead to increased hospitalisations and therefore greater NHS costs. For example, in their collation of evidence, Evangelopoulos and colleagues (5) reported that ‘the risk of out of hospital cardiac arrest in London is 2.2% higher on high air pollution days than lower air pollution days’.

Therefore, it should be reiterated that the change in hospitalisation cases and cost estimates reported may be underestimates of the true impact of the policies since they are a result of changes in the number of cases of diseases only, rather than the result of changes in rates of short-term impacts on health from air-quality-related exacerbations of pre-existing disease. For instance, NO_2 has been shown to exacerbate COPD but not cause its occurrence (10). Thus, if prevalence stayed constant, a reduction in air pollution should result in a decrease in disease exacerbations. A recent study used existing data to estimate the impact of air pollution on asthma hospitalisations in London. The study reports that air pollution resulted in approximately 1,000 childhood asthma admissions from 2014-2016, equating to around 10% of all asthma admissions in children in London (10).

However, it is unclear how short-term and long-term risk overlap. The microsimulation structure uses a modelling approach that provides annual (rather than daily) outputs.

This study complements previous work that has quantified mortality impacts attributable to air pollution for London (31), by providing estimates of morbidity due to air-pollution in each London borough. This analysis also builds on previous work using this model that was carried out in collaboration with Imperial College London and Public Health England (11,12). However, in that study hypothetical scenarios were run, rather than the real-life policy interventions which this study adds.

Comparing the PHE study with the current study for Lambeth, the PHE study projected 5,120 and 5,509 cases attributable to $PM_{2.5}$ and NO_2 respectively in Lambeth between 2017 and 2025. In comparison this study found 6,496 and 4,302 attributable to $PM_{2.5}$ and NO_2 respectively between 2016 and 2025. The larger difference in the $PM_{2.5}$ figure is because the background exposure rate (or non-anthropogenic $PM_{2.5}$) was much smaller in the present study, 0.27 µg/m^3, compared to 3.04 µg/m^3 in the previous study. The non-anthropogenic $PM_{2.5}$ in this study based on estimates from King’s College London (10). Background rates were not included for NO_2, so the figures are more comparable. The lower figure in the current study is likely due to the updates in input data, such as a lower dementia incidence data updated from the previous study (34). Costs are higher in the present study for $PM_{2.5}$ since the disease cases avoided are higher, new cost data for stroke and COPD have been included (which have a higher cost per case) and also discounting was not applied (but was in the previous PHE study). This study also included 2016 baseline exposure data, compared with 2015 baseline data in the previous study and these data are calculated this using different methods[7]. In addition, this study included population projections compared with a static population in the previous study.

What further research can be done?

While this report clearly presents a case for action, additional research could provide further evidence of policy impacts. In the present study we focussed on morbidity, however further work might add to this by quantifying the impact of ULEZ and LES policies on mortality outcomes and quality of life.

This study does not include differential impacts by social groups. The impact of poor air quality and social inequality are well documented (35,36). This will be an important addition to this work since those who live in more deprived areas are more exposed to air pollution. In a recent study of social inequality and air pollution exposure in London, it was shown that the average concentration of NO_2 in the most deprived deciles is 24% higher than the least deprived (35). Quantifying the impact of different policies across different social groups would add to this body of work.

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[7] The PHE study used air pollution concentration surfaces from land use regression (LUR) models covering England with a spatial resolution of 100m for $PM_{2.5}$ (37) and 200m for NO_2 (38). For the present study the concentrations published by the GLA as part of the London Atmospheric Emissions Inventory (LAEI) 2013 update were used, with a spatial resolution of 20m. The LAEI includes both total emissions by source type, as well as ground level concentrations based on detailed dispersion modelling of emissions for the year 2013 and 2020, which were used to interpolate 2016 concentrations.

Strengths and limitations

This study has both strengths and limitations. The microsimulation is a robust tool for modelling population level interventions in detail because it models every individual within the population many years into the future. Individuals are randomly generated (age, sex, exposure) to reproduce exposure and population statistics. However, it may underestimate the impact on diseases which take many years to accumulate.

It was not possible to include short-term effects of air pollution within the model since it focuses on long-term predictions using annual estimates. Therefore, including short-term peaks was not possible. This is largely due to short-term peaks in air pollution being unpredictable, both temporally and geospatially.

Short-term peaks may lead to increased hospitalisations and therefore greater NHS costs. However, the project would require a much longer time scale to develop ways of incorporating both short and long-term effects. Further, it is unclear how short-term and long-term risk overlap. The microsimulation structure quantifies disease incidence/prevalence on an annual basis.

Due to data availability, it was not possible to take account of other factors such as socio-economic status. Deprived sub-populations are more susceptible to the negative health effects of air pollution and at the same time are more likely to be exposed to higher air pollution levels (35). The microsimulation, however, assumes that the dose-response of exposure to disease varies only by age and sex, but not also by socioeconomic status group. Such data could be incorporated into the model in future work.

Dose-response estimates for NO_2 and morbidity outcomes were adjusted and reduced by 60% to take account of overlaps between risks based on COMEAP recommendations for mortality (6). However, while guidance from COMEAP for adjusting NO_2 on $PM_{2.5}$ dose-response metrics exists, there is still uncertainty amongst the scientific community about the most appropriate level of adjustment. COMEAP have reviewed and quantified a number of dose-response relationships, however, others are available in published literature. Some evidence is just emerging, such as that for dementia and low birthweight so results should be interpreted with this in mind.

Policy implications and future work

This project has a number of implications for policy and future work.

- Successful implementation of ULEZ and LES will have important impacts on disease burden, and related costs to the NHS and social care.
- This study provides useful data for making the case to ensure uptake and enforcement of these policies.
- However, further policy measures are needed, especially those tackling $PM_{2.5}$ specifically, if air pollution related diseases are to be eliminated and London is to meet World Health Organization limits
- This study provides important evidence for understanding the long-term effect of air pollution exposure across London, which is useful when considering additional potential policy measures into the future (e.g. population transport mode shift, significant change in vehicle type).
- This report highlights the need for further research into policies linked with short-term incidence of high levels of pollution (i.e. hospitalisation) versus long-term exposure and inequality of exposure between different social groups.

- Further work could replicate this study in other metropolitan areas or across different social groups considering some of the same policies.

Modelling is a useful tool for quantifying the long-term impact of policy change that is not possible with randomised controlled trials. Further work could explore the differential impact of ULEZ and LES on deprived sub-populations.

Conclusion

This study found that if air pollution were to remain at 2016 levels, by 2050 there would be 850,000 new cases of disease attributable to air pollution, with a cost of over £15 billion to the NHS and social care system. The report highlights the importance of the Ultra Low Emission Zone and policies included in the London Environment Strategy (LES) are effective and should continue to be implemented. The study found the policies included in the LES (including the Ultra Low Emission Zone) would avoid 295,000 of these new cases of disease, avoiding almost £5 billion in costs to the NHS and social care system. This would pay for over 16,500 nurses for 10 years.

However, the study also highlights that additional measures are required if air pollution related diseases are to be eliminated. Pan-London action is required alongside national legislation and action if larger health benefits are to be made.

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Appendix

Appendix 1. Detailed methodology

Microsimulation framework

The microsimulation model employed for this project is modular. The first module calculates the predictions of risk factor trends over time based on data from rolling cross-sectional studies. The second module performs the microsimulation of a virtual population, generated with demographic characteristics matching those of the observed data. The health trajectory of each individual from the population is simulated over time allowing them to contract, survive or die from a set of diseases or injuries related to the analysed risk factors. The detailed description of the two modules is presented below.

Module one: Predictions of NO2 and PM2.5 over time

The concentration predictions are based on modelling undertaken by TfL, King's College London and the GLA. The 2016 baseline data comes from the London Atmospheric Emission Inventory (LAEI), full details of the data and methodology can be found here: https://data.london.gov.uk/air-quality/

Concentration predictions for the impacts of the Ultra Low Emission Zone, Low Emission Zone and expanded Ultra Low Emission Zone are from modelling for the scheme consultation, more information can be found here: https://consultations.tfl.gov.uk/environment/air-quality-consultation-phase-3b/user_uploads/supporting-information-document-updated-12.12.17.pdf

Concentration predictions for the impacts of the London Environment Strategy are from the strategy, more information can be found here:

https://www.london.gov.uk/sites/default/files/london_environment_strategy_0.pdf

NO_2 and $PM_{2.5}$ are analysed within the model as risk factors (RF), as described in **Table 1**.

Table 1 Description of the categories used for the risk factors NO_2 and $PM_{2.5}$

Risk factor (RF)	**Number of categories (N)**	**Categories**
Nitrogen dioxide (NO_2)	3	NO_2 < 20.5 µg m-3 NO_2 from 20.5 to 28.5 µg m-3 NO_2 ≥ 28.5 µg m-3
Particulate matter ($PM_{2.5}$)	3	$PM_{2.5}$ < 12.3 µg m-3 $PM_{2.5}$ from 12.3 to 13.5 µg m-3 $PM_{2.5}$ ≥ 13.5 µg m-3

Note that the cases avoided for London are not the sum of each borough because as described, the concentrations in the baseline 2016 and ULEZ/LES 2016 scenarios are not identical. Microsimulation methods considers the history of each individual from birth to death/ the end of the simulation. Therefore, an individual of age a and sex s in 2016 in the baseline will follow a different trajectory than the same individual with same age a and sex s in the ULEZ/LES from 2016. The incident cases of diseases of interest are linked to the projections of:

i. air pollution exposures and associated risks to air pollution-related diseases,
ii. age and sex distributions of the population,

Therefore, the quantified disease cases will be impacted.

Module two: Microsimulation model

Microsimulation initialisation: birth, disease and death models

Simulated people are generated with the correct demographic statistics in the simulation's start-year. In this year women are stochastically allocated the number and years of birth of their children – these are generated from known fertility and mother's age at birth statistics (valid in the start-year). If a woman has children then those children are generated as members of the simulation in the appropriate birth year.

The microsimulation is provided with a list of air pollution-related diseases. These diseases used the best available incidence, mortality, survival, relative risk and prevalence statistics (by age and gender). Individuals in the model are simulated from their year of birth (which may be before the start year of the simulation). In the course of their lives, simulated people can die from one of the diseases caused by an air pollutant that they might have acquired or from some other cause(s). The probability that a person of a given age and gender dies from a cause other than the disease are calculated in terms of known death and disease statistics valid in the start-year. It is constant over the course of the simulation.

The microsimulation incorporates a sophisticated economic module. The module employs a Markov-type simulation of long-term health benefits and health care costs. It synthesises and estimates evidence on cost-utility analysis. The model is used to project the differences in quality-adjusted life years (QALYs), and direct lifetime health-care costs over a specified time scale. The direct healthcare costs are presented separately in terms of NHS costs and social care costs. Costs were not discounted for the current study since we were not running a cost-benefit analysis.

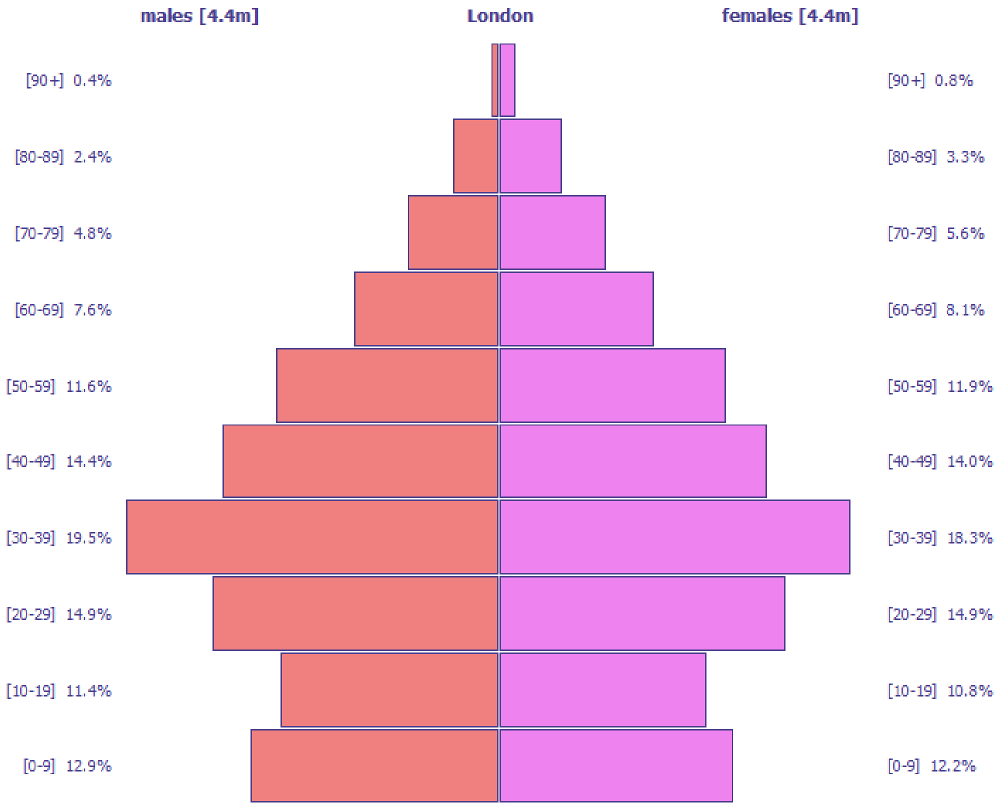
This following section provides an overview of the main assumptions of the model.

Population models

Populations are implemented as instances of the TPopulation C++ class. The TPopulation class is created from a population (*.ppl) file. Usually a simulation will use only one population but it can simultaneously process multiple populations (for example, different ethnicities within a national population).

Population Editor

The Population Editor Allows editing and testing of TPopulation objects. The population is created in the start-year and propagated forwards in time. An example population pyramid which can be used when initialising the model is shown in Figure 1 shows the population distribution for London and Lambeth respectively in 2016 which was used in the initialisation of the model.


males [4.4m]
London
females [4.4m]
[90+] 0.4%
[80-89] 2.4%
[70-79] 4.8%
[60-69] 7.6%
[50-59] 11.6%
[40-49] 14.4%
[30-39] 19.5%
[20-29] 14.9%
[10-19] 11.4%
[0-9] 12.9%
[90+] 0.8%
[80-89] 3.3%
[70-79] 5.6%
[60-69] 8.1%
[50-59] 11.9%
[40-49] 14.0%
[30-39] 18.3%
[20-29] 14.9%
[10-19] 10.8%
[0-9] 12.2%

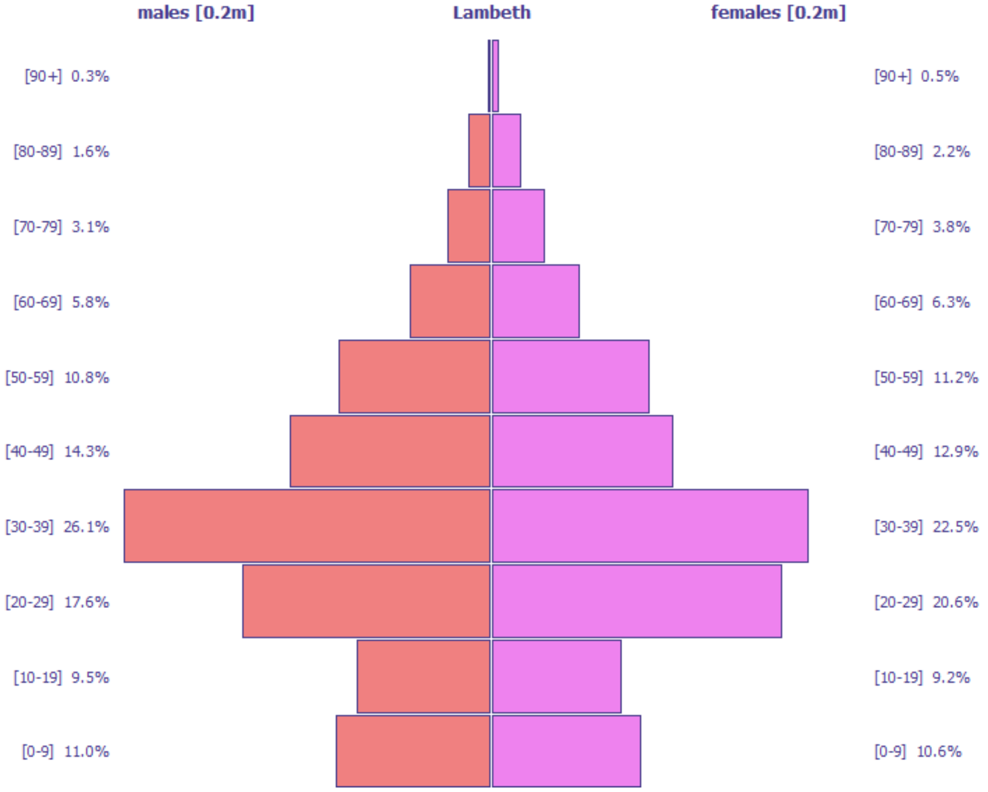

males [0.2m]
Lambeth
females [0.2m]
[90+] 0.3%
[80-89] 1.6%
[70-79] 3.1%
[60-69] 5.8%
[50-59] 10.8%
[40-49] 14.3%
[30-39] 26.1%
[20-29] 17.6%
[10-19] 9.5%
[0-9] 11.0%
[90+] 0.5%
[80-89] 2.2%
[70-79] 3.8%
[60-69] 6.3%
[50-59] 11.2%
[40-49] 12.9%
[30-39] 22.5%
[20-29] 20.6%
[10-19] 9.2%
[0-9] 10.6%

Figure 1 Population pyramid for London and Lambeth respectively in 2016

People within the model can die from specific diseases or from other causes. A disease file is created within the program to represent deaths from other causes. The following distributions are required by the population editor (**Table 2**).

Table 2 Summary of the parameters representing the distribution component

Distribution name	symbol	note
MalesByAgeByYear	$p_m(a)$	Input in year0 – probability of a male having age a
FemalesByAgeByYear	$p_f(a)$	Input in year0 – probability of a female having age a
BirthsByAgeofMother	$p_b(a)$	Input in year0 – conditional probability of a birth at age a| the mother gives birth.
NumberOfBirths	$p \quad (n)$	λ≡TFR, Poisson distribution, probability of giving birth to n children

Birth model

Any female in the child-bearing years {*AgeAtChild.lo, AgeAtChild.hi*} is deemed capable of giving birth. The number of children, n, that she has in her life is dictated by the Poisson distribution $p \quad (n)$ where the mean of the Poisson distribution is the Total Fertility Rate (TFR) parameter[8].

The probability that a mother (who does give birth) gives birth to a child at age a is determined from the BirthsByAgeOfMother distribution as $p_b(a)$. For any particular mother the births of multiple children are treated as independent events, so that the probability that a mother who produces N children produces n of them at age a is given as the Binomially distributed variable,

---

[8] This could be made to be time dependent; in the baseline model it is constant.

$$p_b\left(\text{n at a} \mid N\right) = \frac{N!}{n!\left(N-n\right)!}\left(p_b\left(a\right)\right)^n\left(1-p_{bm}\left(a\right)\right)^{N-n} \tag{9}$$

The probability that the mother gives birth to n children at age a is

$$p_b\left(n\,at\,a\right) = e^{-\lambda}\sum_{N=n}^{\infty}\frac{\lambda^N}{N!}p_b\left(\text{n at a} \mid N\right) = e^{-\lambda}\sum_{N=n}^{\infty}\frac{\lambda^N}{n!\left(N-n\right)!}\left(p_b\left(a\right)\right)^n\left(1-p_b\left(a\right)\right)^{N-n}$$

(1.12)

Performing the summation in this equation gives the simplifying result that the probability $p_b(n\ at\ a)$ is itself Poisson distributed with mean parameter $\lambda p_b(a)$,

$$p_b\left(n\,at\,a\right) = e^{-\lambda p_b(a)}\frac{\left(\lambda p_b\left(a\right)\right)^n}{n!} = p_{\lambda p_b(a)}\left(n\right) \tag{10}$$

Thus, on average, a mother at age a will produce $\lambda p_b(a)$ children in that year.

The gender of the children[9] is determined by the probability $p_{male}=1-p_{female}$. In the baseline model this is taken to be the probability $N_m/(N_m+N_f)$.

The Population editor’ menu item Population Editor\Tools\Births\show random birthList creates an instance of the TPopulation class and uses it to generate and list a (selectable) sample of mothers and the years in which they give birth.

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[9] The probability of child gender can be made time dependent.

Deaths from modelled diseases

The simulation models any number of specified diseases some of which may be fatal. In the start year the simulation's death model uses the diseases' own mortality statistics to adjust the probabilities of death by age and gender. In the start year the net effect is to maintain the same probability of death by age and gender as before; in subsequent years, however, the rates at which people die from modelled diseases will change as modelled risk factors change.

The risk factor model

The distribution of risk factors (RF) in the population is estimated using regression analysis stratified by both sex S = {male, female} and age group A = {0-4, 5-9, ..., 70-74, 75+}. The fitted trends are extrapolated to forecast the distribution of each RF category in the future. For each sex-and-age-group stratum, the set of cross-sectional, time-dependent, discrete distributions $D = \{p_k(t) | k = 1, \ldots N;\ t > 0\}$, is used to manufacture RF trends for individual members of the population. Each air pollutant (e.g. NO_2, PM2.5) is modelled as a continuous risk factor.

Continuous risk factors

In the case of a continuous RF, for each discrete distribution D there is a continuous counterpart. Let β denote the RF value in the continuous scale and let $f(\beta | A, S, t)$ be the probability density function of β for age group A and sex S at time t. Then

$$p_k(t|A,S) = \int_{\beta \in k} f(\beta | A, S, t)\, d\beta. \tag{11}$$

Equation (11) uses the definition of the probability density function to express the age-and-sex-specific percentage of individuals in RF category *k* at time *t*. The cumulative distribution function of β is

$$F(\beta|A,S,t)=\int_{0}^{\beta} f(\beta|A,S,t)\,d\beta. \tag{12}$$

At time *t*, a person with sex S belonging to the age group A is said to be on the p–th percentile of this distribution if Given the cross-sectional information from the set of distributions D, it is possible to simulate longitudinal trajectories by forming pseudo-cohorts within the population. A key requirement for these sets of longitudinal trajectories is that they reproduce the cross-sectional distribution of RF categories for any year with available data. The method adopted here and in our earlier work is based on the assumption that person's RF value changes throughout their lives in such a way that they always have the same associated percentile rank. As they age, individuals move from one age group to another and their RF value changes so that they have the same percentile rank but of a different RF distribution. Crucially it meets the important condition that the cross-sectional RF distributions obtained by simulation match the RF distributions of the observed data.

The above procedure can be explained using the example of the NO_2 distribution. The NO_2 distributions are known for the population stratified by sex and age for all years of the simulation (by extrapolation of fitted model, see equation (11). A person who is in age group A and who grows ten years older will at some time move into the next age group A' and will have an exposure that was described first by the distribution $f(\beta|A,S,t)$ and then at the later time t' by the distribution $f(\beta|A',S,t')$. If the NO_2 exposure level of that individual is on the p-th percentile of the NO_2 distribution, their NO_2 exposure level will change from β to β' so that

$$\beta = F^{-1}\left(\frac{p}{100}|A,S,t\right) \tag{13}$$

$$\beta' = F^{-1}\left(\frac{p}{100}|A',S,t'\right) \Rightarrow \beta' = F^{-1}\left(F(\beta \mid A,S,t)|A',S,t'\right) \tag{14}$$

Where F^{-1} is the inverse of the cumulative distribution function of β, which we model with a continuous uniform distribution within the RF categories. Equation (15) guarantees that the transformation taking the random variable β to β' ensures the correct cross-sectional distribution at time t'..

The microsimulation first generates individuals from the RF distributions of the set D and, once generated, grows the individual's RF in a way that is also determined by the set D. It is possible to implement equation (14) as a suitably fast algorithm.

Relative risks

Suppose that α is a risk factor state of some risk factor A and denote by p_A (d|α,a,s) the incidence probability for the disease d given the risk state, α, the person's age, a, and gender, s. The relative risk ρ_A is defined by equation (15).

$$\begin{aligned} &p_{\mathrm{A}}\left(d\,|\alpha,a,s\right) = \rho_{\mathrm{A}|d}\left(\alpha\,|a,s\right) p_{\mathrm{A}}\left(d\,|\alpha_0,a,s\right) \\ &\rho_{\mathrm{A}|d}\left(\alpha_0\,|a,s\right) \equiv 1 \end{aligned} \tag{15}$$

Where α_0 is the zero risk state.

The incidence probabilities, as reported, can be expressed in terms of the equation,

$$\begin{aligned} p\left(d \mid a,s\right) &= \sum_{\alpha} p_{\mathrm{A}}\left(d \mid \alpha,a,s\right)\pi_{A}\left(\alpha \mid a,s\right) \\ &= p_{A}\left(d \mid \alpha_{0},a,s\right)\sum_{\alpha} \rho_{\mathrm{A}|d}\left(\alpha \mid a,s\right)\pi_{A}\left(\alpha \mid a,s\right) \end{aligned} \tag{16}$$

Combining these equations allows the conditional incidence probabilities to be written in terms of known quantities

$$p\left(d \mid \alpha,a,s\right) = \rho_{A|d}\left(\alpha \mid a,s\right)\frac{p\left(d \mid a,s\right)}{\sum_{\beta} \rho_{A|d}\left(\beta \mid a,s\right)\pi_{A}\left(\alpha \mid a,s\right)} \tag{17}$$

Previous to any series of Monte Carlo trials the microsimulation program pre-processes the set of diseases and stores the *calibrated* incidence statistics p_A ($d|\alpha_0$, a, s). These incidence statistics are calibrated to national level data sets for both national level and local authority model simulations. In this project the risk factor distributions and incidence risks for England are used to calculate the calibrated risks.

Modelling diseases

Disease modelling relies heavily on the sets of incidence, mortality, survival, relative risk and prevalence statistics. In some cases where a data set is unavailable or not available is the specified form for the model, data has been approximated from the known sets of the data.

The microsimulation uses risk dependent incidence statistics and these are inferred from the relative risk statistics and the distribution of the risk factor within the population. In the simulation, individuals are assigned a risk factor trajectory giving their personal risk factor history for each year of their lives. Their probability of getting a particular risk factor related disease in a particular year will depend on their risk factor state in that year.

Once a person has a fatal disease (or diseases) their probability of survival will be controlled by a combination of the disease-survival statistics and the probabilities of dying from other causes. Disease survival statistics are modelled as age and gender dependent exponential distributions.

Mortality statistics

In any year, in some population, in a sample of N people who have the disease a subset N_ω will die from the disease.

Mortality statistics record the cross-sectional probabilities of death as a result of the disease – possibly stratifying by age

$$p_\omega = \frac{N_\omega}{N} \tag{18}$$

Within some such subset N_ω of people that die in that year from the disease, the distribution by year-of-disease is not usually recorded. This distribution would be most useful. Consider two important idealised, special cases.

Suppose the true probabilities of dying in the years after some age a_0 are $\{p_{\omega 0}, p_{\omega 1}, p_{\omega 2}, p_{\omega 3}, p_{\omega 4}\}$

The probability of being alive after N years is simply that you don't die in each year

$$p_{survive}\left(a_0 + N\right) = \left(1 - p_{\omega 0}\right)\left(1 - p_{\omega 1}\right)\left(1 - p_{\omega 2}\right)..\left(1 - p_{\omega N-1}\right) \tag{19}$$

Survival rates

It is common practice to describe survival in terms of a survival rate R, supposing an exponential death-distribution. In this formulation the probability of surviving t years from some time t_0 is given as

$$p_{\text{survival}}(t) = 1 - R\int_0^t due^{-Ru} = e^{-Rt} \tag{20}$$

For a time period of 1 year

$$\begin{aligned} p_{survival}(1) &= e^{-R} \\ &\Rightarrow \\ R &= -\ln\left(p_{survival}(1)\right) = -\ln\left(1 - p_\omega\right) \end{aligned} \tag{22}$$

For a time period of, for example, 4 years,

$$p_{\text{survival}}(t=4) = 1 - R^{-1}\int_0^4 due^{-Ru} = e^{-4R} = \left(1 - p_\omega\right)^4 \tag{23}$$

In short, the Rate is minus the natural log of the 1-year survival probability.

The survival models

For any potentially terminal disease the model can use any of the three survival models, numbered ((0, 1, 2)). The parameters describing these models are given below.

Survival model 0

A single probability of dying $\{p_{\omega 0}\}$, where $p_{\omega 0}$ is valid for all years. Given the 1-year survival probability $p_{survival}(1)$

The model uses 1 parameter ((R))

$$R = -\ln\left(p_{survival}(1)\right) \tag{24}$$

Survival model 1

Two different probabilities of dying $\{p_{\omega 0}, p_{\omega 1}\}$, where $p_{\omega 0}$ is valid for the first year; $p_{\omega 1}$ thereafter. The model uses two parameters ((p1, R)). Given the 1-year survival probability $p_{survival}(1)$ and the 5-year survival probability $p_{survival}(5)$

$$\begin{aligned} p_1 &= 1 - p_{survival}(1) \\ R &= -\frac{1}{4}\ln\left(\frac{p_{survival}(5)}{p_{survival}(1)}\right) \end{aligned} \tag{25}$$

Survival model 2

Three different probabilities of dying $\{p_{\omega 0}, p_{\omega 1}, p_{\omega 5}\}$, where $p_{\omega 0}$ is valid for the first year; $p_{\omega 1}$ for the second to the fifth year; $p_{\omega 5}$ thereafter. The model uses three parameters ((p1, R, R>5))

Given the 1-year survival probability $p_{survival}(1)$ and the 5-year survival probability $p_{survival}(5)$

$$\begin{aligned} p_1 &= 1 - p_{survival}(1) \\ R &= -\frac{1}{4}\ln\left(\frac{p_{survival}(5)}{p_{survival}(1)}\right) \\ R_{>5} &= -\frac{1}{5}\ln\left(\frac{p_{survival}(10)}{p_{survival}(5)}\right) \end{aligned} \tag{26}$$

Remember that different probabilities will apply to different age and gender groups. Typically the data might be divided into 10 year age groups.

Modelling low birth weight

The modelling method assumes that low birth weight (LBW) is a disease associated with a women who gives birth. The method also assumes that LBW is an acute disease; an incidence case in any year affects the prevalence rate in that year only. In the start year of the simulation the total of number of births associated to a woman and the year of each birth is computed. The probability of a newborn being LBW is calculated using the risk factor level (i.e., air pollution level) in the year of birth and the associated relative risk. This approach is used when modelling other diseases in the simulation.

There are two differences between modelling LBW and other diseases. Firstly, a mother can have multiple births in a given year which can result in multiple incident cases of LBW. In comparison other diseases can be contracted only once in a year. Secondly, it is possible that in some years of a mother's life she does not give birth. The probability of contracting a LBW in these years is therefore zero.

Limitations

The modelling method assumes that LBW is a disease per se. A limitation extending from this would be that we do not take account of subsequent diseases brought about by LBW, e.g., diabetes or CHD. The model therefore underestimates the long-term economic costs of LBW associated with air pollution. Another limitation is that we allow multiple births in the simulation (e.g. twins), but we do take account of the possible impact of multiple births on LBW. Multiple births are simulated as a list of independent births having the same probability of causing LBW.

Approximating missing disease statistics

A number of tools have been developed in the model in order to compute missing disease statistics data such as incidence or prevalence.

Approximating survival data from mortality and prevalence

An example is provided here with a standard life-table analysis for a disease *d*.

Consider the 4 following states:

state	**Description**
0	alive without disease *d*
1	alive with disease *d*
2	dead from disease *d*
3	dead from another disease

p_{ik} is the probability of disease *d* incidence, aged *k*

$p_{\omega k}$ is the probability of dying from the disease *d*, aged *k*

$p_{\bar{\omega} k}$ is the probability of dying other than from disease d, aged *k*

The state transition matrix is constructed as follows

$$\begin{bmatrix} p_0(k+1) \\ p_1(k+1) \\ p_2(k+1) \\ p_3(k+1) \end{bmatrix} = \begin{bmatrix} (1-p_{\bar{\omega}k})(1-p_{ik}) & (1-p_{\bar{\omega}k}-p_{\omega k})\,p_{\alpha k} & 0 & 0 \\ (1-p_{\bar{\omega}k})\,p_{ik} & (1-p_{\bar{\omega}k}-p_{\omega k})(1-p_{\alpha k}) & 0 & 0 \\ 0 & p_{\omega k} & 1 & 0 \\ p_{\bar{\omega}k} & p_{\bar{\omega}k} & 0 & 1 \end{bmatrix} \begin{bmatrix} p_0(k) \\ p_1(k) \\ p_2(k) \\ p_3(k) \end{bmatrix} \tag{27}$$

It is worth noting that the separate columns correctly sum to unity.

The disease mortality equation is that for state-2,

$$p_2(k+1) = p_{\omega k}\, p_1(k) + p_2(k) \tag{28}$$

The probability of dying from the disease in the age interval [*k*, *k*+1] is $p_{\omega k} p_1(k)$ - this is otherwise the (cross-sectional) disease mortality, $p_{mor}(k)$. $p_1(k)$ is otherwise known as the disease prevalence, $p_{pre}(k)$. Hence the relation

$$p_{\omega k} = \frac{p_{mor}(k)}{p_{pre}(k)} \tag{29}$$

For exponential survival probabilities the probability of dying from the disease in the age-interval [*k*, *k*+1] is denoted $p_{\Omega k}$ and is given by the formula

$$p_{\omega k} = 1 - e^{-R_k} \quad \Rightarrow \quad R_k = -\ln\left(1 - p_{\omega k}\right) \tag{30}$$

When, as is the case for most cancers, these survival probabilities are known the microsimulation will use them, when they are not known or are too old to be any longer of any use, the microsimulation uses survival statistics inferred from the prevalence and mortality statistics (equation). An alternative derivation equation (29) is as follows. Let N_k be the number of people in the population aged *k* and let n_k be the number of people in the population aged *k* with the disease. Then, the number of deaths from the disease of people aged *k* can be given in two ways: as $p_{\omega k} n_k$ and, equivalently, as $p_{mor}(k) N_k$. Observing that the disease prevalence is n_k/N_k leads to the equation

$$\begin{gathered} p_{\Omega k} n_k = p_{mor}(k) N_k \\ p_{pre}(k) = \frac{n_k}{N_k} \\ \Rightarrow \\ p_{\Omega k} = \frac{p_{mor}(k)}{p_{pre}(k)} \end{gathered} \tag{31}$$

Approximating disease incidence from prevalence

The algorithm estimates the probability of contracting a disease given age and sex, $\hat{p}(d\,|\,a,s)$ from prevalence rates, survival rates and mortality rates.

Step 1: State transition matrix of the algorithm

$$\begin{pmatrix} p_{\bar{d}}(a+1|s) \\ p_{d1}(a+1|s) \\ p_{d}(a+1|s) \\ p_{dead}(a+1|s) \end{pmatrix} = \begin{pmatrix} (1-p_{\bar{w}}(a\,|\,s))(1-\hat{p}(d\,|\,a,s)) & 0 & 0 & 0 \\ (1-p_{\bar{w}}(a\,|\,s))\,\hat{p}(d\,|\,a,s) & 0 & 0 & 0 \\ 0 & 1-p_{w1+\bar{w}1}(a\,|\,s) & 1-p_{w+\bar{w}}(a\,|\,s) & 0 \\ p_{\bar{w}}(a\,|\,s) & p_{w1+\bar{w}1}(a\,|\,s) & p_{w+\bar{w}}(a\,|\,s) & 1 \end{pmatrix} \begin{pmatrix} p_{\bar{d}}(a\,|\,s) \\ p_{d1}(a\,|\,s) \\ p_{d}(a\,|\,s) \\ p_{dead}(a\,|\,s) \end{pmatrix} \tag{32}$$

The probability of being in a set of states:

S_0	$p_{\bar{d}}(a\,|\,s)$	**The probability of being alive without disease at age a**
S_1	$p_{d1}(a\,|\,s)$	The probability of being alive with new disease (contracting within a year) at age a
S_2	$p_{d}(a\,|\,s)$	The probability of being alive with old disease at age a
S_3	$p_{dead}(a\,|\,s)$	The probability of being dead for any reason (from the disease or other reasons) at age a

$\hat{p}(d\,|\,a,s)$ The estimated incidence probability at age of a given sex type s .

$p_{\bar{w}}(a\,|\,s)$ The probability of dying from other causes at age of a given sex type s.

$p_{w1+\bar{w}1}(a\,|\,s)$ The probability of dying from any reason within the first years of contracting the disease at the age of a given sex type s.

$p_{w+\bar{w}}(a\,|\,s)$ The probability of dying from any reasons after the first years of contracting the disease at the age a given sex type s.

$p_{survival1st}(a \mid s)$ The probability of surviving the first year after contracting the disease at the age of a given sex type s.

$p_{survival1}(a \mid s)$ The probability of surviving the year at the age of a given sex type s.

Step 2: The prevalence for a particular age group

Estimated prevalence rate can be expressed by,

$$\hat{P}_{pre\_mean}(agegroup \mid s) = \frac{\sum_{\min\_a}^{\max\_a} \hat{P}_{pre}(a \mid s) \cdot \pi(a \mid s)}{\sum_{\min\_a}^{\max\_a} \pi(a \mid s)} \qquad (33)$$

where

$$\hat{P}_{pre}(a \mid s) = \frac{p_d(a \mid s) + p_{d1}(a \mid s)}{p_d(a \mid s) + p_{d1}(a \mid s) + p_{\bar{d}}(a \mid s)} \qquad (34)$$

where $\min\_a$ is the youngest age in that age group and $\max\_a$ the oldest. $\pi(a \mid s)$ is the population distribution stratified by age given sex.

Step 3: Regression

We have two algorithms to find the optimum value of $\hat{p}(d \mid a, s)$: simplex algorithm and cauchy algorithm. Simplex algorithm finds an optimum set of incidence rates of all age groups by minimising the distance between the estimated global prevalence rate and the actual global prevalence rate, shown in (35). We use simplex algorithm for most diseases as it is faster.

$$\underset{set(\hat{p}(d|a,s))}{\arg\min}\ S = \underset{set(\hat{p}(d|a,s))}{\arg\min}\ S\left(\sum_{age\_group}(P_{pre\_mean}(agegroup\,|\,s) - \hat{P}_{pre\_mean}(agegroup\,|\,s))\right) \tag{35}$$

Cauchy algorithm finds an optimum incidence rate for each individual age group by minimising the distance between the estimated prevalence rate and the actual prevalence rate of the age group, shown in (36). We use Cauchy algorithm for diseases which are associated to certain age groups, e.g., dementia which is only associated to people older than 60.

$$\underset{\hat{p}(d|a,s)}{\arg\min}\, S = \underset{\hat{p}(d|a,s)}{\arg\min}\, S\left(P_{pre\_mean}(agegroup\,|\,s) - \hat{P}_{pre\_mean}(agegroup\,|\,s)\right) \tag{36}$$

Model scenarios

A baseline scenario (‘no change’) and three additional scenarios were modelled. The baseline related to the current exposure data, which included background levels of air pollution. The second scenario modelled the impact of the background air pollution levels. This scenario was used to calculate the attributable diseases and costs related to air pollution. The final two scenarios were the two policies – Ultra Low Emission Zone (ULEZ) and the London Environment Strategy (LES).

Direct costs

The cost model used in the simulation is part of the economics module and, here, simply scales the aggregated individual disease costs according to the relative disease prevalence in years after the start year for which the costs are known.

In any year, the total healthcare cost for the disease D is denoted $C_D(year)$. If the prevalence of the disease is denoted $P_D(year)$ we assume a simple relationship between the two of the form

$$C_D\left(year\right) = \kappa P_D\left(year\right) \tag{37}$$

for some constant κ.

For each of the trial years, the microsimulation records the prevalence of each disease call it $P_D(year|trial)$ and the trial population size for that year, $N_{pop}(year|trial)$. Further assume that the prevalence in the whole population $N_{pop}(year)$ is a simple scaling of the trial prevalence, then

$$C_D\left(year\right) = \kappa P_D\left(year\right) = \lambda \frac{N_{pop}\left(year\right) P_D(year\,|\,trial)}{N_{pop}(year\,|\,trial)} \tag{38}$$

for some constant λ.

By comparing any trial year to some initial year, *year0*, the total disease cost in any year is given as

$$\frac{C_D\left(year\right)}{C_D\left(year0\right)} = \frac{N_{pop}\left(year\right)}{N_{pop}\left(year0\right)} \frac{N_{pop}(year0\,|\,trial)}{N_{pop}(year\,|\,trial)} \frac{P_D(year\,|\,trial)}{P_D(year0\,|\,trial)}$$

Modelling hospitalisations

The hospitalisation model calculates hospitalisations using a similar method to the economic cost module. The hospitalisation rate per 1 by disease is scaled according to the relative disease prevalence in each year after the start year for which the hospitalisations per case are known.

In any year, the total number of hospitalisations for the disease *D* is denoted $H_D(year)$. If the prevalence of the disease is denoted $P_D(year)$ we assume a simple relationship between the two of the form

$$H_D(year) = \kappa P_D(year) \tag{39}$$

for some constant κ.

For each of the trial years, the microsimulation records the prevalence of each disease call it $P_H(year|trial)$ and the trial population size for that year, $N_{pop}(year|trial)$. Further assume that the prevalence in the whole population $N_{pop}(year)$ is a simple scaling of the trial prevalence, then

$$H_D(year) = \kappa P_D(year) = \lambda \frac{N_{pop}(year) P_H(year|trial)}{N_{pop}(year|trial)} \tag{40}$$

for some constant λ.

By comparing any trial year to some initial year, *year0*, the total number of hospitalisations in any year is given as

$$\frac{H_D(year)}{H_D(year0)} = \frac{N_{pop}(year)}{N_{pop}(year0)} \frac{N_{pop}(year0|trial)}{N_{pop}(year|trial)} \frac{P_D(year|trial)}{P_D(year0|trial)}$$

Appendix 2. Data inputs

Concentration data for London can be found here: https://data.london.gov.uk/air-quality/

Appendix 3. Data references

Table 1 Population data sources by geography

Demography	Geography	Source
Total population by age and sex	London and local authorities in London	GLA population projections - 2016
Births by mothers age	London and local authorities in London	ONS. Live births (numbers): age and administrative area of usual residence of mother, England and Wales. ONS; 2016
Total fertility rate	London and local authorities in London	ONS. Live births, total fertility rates. ONS; 2016
Deaths by age and sex	London and local authorities in London	ONS. Mortality statistics - underlying cause, sex and age. ONS; 2016

Table 2. Characteristics of diseases modelled for each pollutant

	Duration	Terminal	Age category	Pollutant	
				NO_2	$PM_{2.5}$
Respiratory outcomes					
Asthma (children)	Chronic	Yes	Child	X	X
Asthma (adults)	Chronic	Yes	Adult	X	
COPD	Chronic	Yes	Adult		X
Cardiovascular outcomes					
CHD	Chronic	Yes	Adult		X
Stroke	Chronic	Yes	Adult		X
Diabetes	Chronic	No	Adult	X	X
Cancer and other outcomes					
Dementia	Chronic	Yes	Adult	X	
Low birth weight	Acute	No	Adult	X	X
Lung cancer	Chronic	Yes	Adult	X	X

All diseases except for low birth weight were lifelong, chronic diseases, so once acquired, were prevalent for the duration of an individual’s life. Individuals could develop more than one disease, but these were considered independent of one another. All diseases apart from diabetes and low birth weight were terminal. Epidemiological data on each disease’s incidence, prevalence, mortality and survival and dose-response was collected (see **Table 3**). When a parameter, e.g. Survival was not available from the literature or national statistics, this was computed.

Table 3. Summary of disease data sources

Diseases	Incidence	Prevalence	Mortality	Survival	Relative Risk
Asthma	BLF Asthma Statistics (1)	BLF Asthma Statistics (1)	ONS, Deaths Registrations Summary Statistics, England and Wales, 2017 (2)	Computed from prevalence and mortality	**NO_2:** Khreis *et al.* 2016 (3) In children =<6 years : OR 1.08 (1.04; 1.12) per 4µg/m^3→*Converted to* *OR 1.212 (1.103; 1.328)* per 10µg/m^3→*REDUCED by 60%* → **1.08 (1.01; 1.12) per 10µg/m^3** In children >6 years: OR 1.03 (1.00; 1.06) per 4µg/m^3→*Converted to OR 1.08* *(1.00; 1.16)* per 10µg/m^3→ *REDUCED by 60%* → **1.03 (1.00; 1.06) per 10µg/m^3** Jaquemin *et al.* 2015 (4) *In adults:* OR 1.10 (0.99;1.21) per 10µg/m^3 →*REDUCED by 60%* → **1.04 (0.996; 1.08) per 10µg/m^3** **$PM_{2.5}$:** Khreis et al. 2016 (3) In children >6 years: OR 1.04 (1.02; 1.07) per 1µg/m^3 →Converted OR **1.48 (1.22 ; 1.97) per 10µg/m^3**
COPD	Computed	Imperial	(ONS,	Computed	**$PM_{2.5}$:** COMEAP 2016 (5)

	from prevalence	College 2015: Dr diagnosed prevalence	Deaths Registrations Summary Statistics, England and Wales, 2017	from incidence, prevalence and mortality	COMEAP recommend using PM_{10} estimate based on Cai et al. 2014 estimate for chronic phlegm in never smokers in sensitivity analyses: OR 1.32 (1.02; 1.71) per 10µg/m^3 of PM_{10} → scale to $PM_{2.5}$ using the conversion factor of $PM_{2.5}$-> PM_{10}: 0.7 (or PM_{10} -> $PM_{2.5}$:1.42) recently used in the air quality index, COMEAP: Converted to **1.49 (1.03; 2.14) per 10µg/m^3 of $PM_{2.5}$**
CHD	Smolina et al 2012. Corrected data on incidence and mortality in 2013 (6)	BHF, Cardiovascular Disease Statistics 2014 (7)	ONS, Deaths Registrations Summary Statistics, England and Wales, 2017	Computed from incidence, prevalence and mortality	**$PM_{2.5}$:** Cesaroni et al. 2014 (8) Estimate used in CAPTOR tool from subgroup analysis of participants with additional information on CVD risk factors: HR 1.19 (1.01; 1.42) per 5µg/m^3→ Converted to **1.41 (1.00 - 2.01) per 10µg/m^3**
Diabetes	Personal communication with dr Craig Curry from Cardiff University	National Diabetes Audit 2015-2016(9)	Non-terminal	Non-terminal	**NO_2:** Eze *et al.* 2015 (10) RR 1.12 (1.05; 1.19) per 10µg/m^3→*REDUCED by 60%* → **1.05 (1.02; 1.07) per 10µg/m^3** **$PM_{2.5}$**: Eze et al. 2015 (10) RR **1.10 (1.02; 1.18) per 10µg/m^3**
Stroke	BHF, stroke statistics 2009 (11)	BHF, Cardiovascular Disease Statistics 2014 (7)	ONS, Deaths Registrations Summary Statistics, England and Wales, 2017	Computed from incidence, prevalence and mortality	**$PM_{2.5}$:** Scheers et al. 2015 (12) HR 1.064 (1.021; 1.109) per 5µg/m^3 →Converted to **1.13 (1.04; 1.23) per 10µg/m^3**
Dementia	Computed from prevalence	Dementia UK 2014 (13)	ONS, Deaths Registrations Summary Statistics, England and Wales, 2015 (2)	Computed from prevalence and mortality	**NO_2**: Oudin et al. 2016(14) HR 1.08 (1.00; 1.16) per 10µg/m^3 NOx. Scaling factor: NOx → NO2: 0.44 which was developed by Anderson et al. based on the ratio that fell midway between the average or roadside vs urban background monitoring sites in London for 2001 (see Online Supp

					2) (15) Converted from NOx to NO2:HR 1.03 (1.00; 1.07) →REDUCED by 60% → **1.01 (1.01; 1.03) per 10μg/m3 of NO2**
Low birth weight	ONS Birth Characteristics, 2015 (16)	Considered equivalent to incidence	Non-terminal	Non-terminal	**NO$_2$**: Pedersen et al. 2013 (17) OR 1.09 (1.00; 1.19) per 10$\mu g/m^3$→*REDUCED by 60%* → **1.04 (1.00; 1.07) per 10$\mu g/m^3$** **PM$_{2.5}$:** Pedersen et al. 2013 (17) OR 1.18 (1.06; 1.33) per 5$\mu g/m^3$→Converted OR **1.39 (1.12; 1.77) per 10$\mu g/m^3$:**
Lung cancer	ONS 2016	Not required in model as model uses incidence	ONS 2016	ONS 2016	**NO$_2$**: Hamra et al. 2015 (18) RR 1.04 (1.01; 1.08) per 10$\mu g/m^3$→*REDUCED by 60%* → **1.02 (1.00; 1.03) per 10$\mu g/m^3$** **PM$_{2.5}$:** Hamra et al. 2014 (19) **RR 1.09 (1.04; 1.14) per 10$\mu g/m^3$**

All NO$_2$ relative risks reduced by 60% following COMEAP recommendations

Appendix 4. Output files for each local authority

Cumulative incidence cases avoided per 100,000 by borough by 2050

Borough	ULEZ	LES
Barking	1,594	1,894
Barnet	2,145	2,495
Bexley	1,509	1,755
Brent	2,462	2,910
Bromley	1,596	1,838
Camden	2,629	3,264
City of London	2,717	3,406
Croydon	1,983	2,273
Ealing	2,182	2,614
Enfield	1,666	1,941
Greenwich	2,055	2,485
Hackney	2,198	2,753
Hammersmith and Fulham	2,570	3,155
Haringey	2,500	2,972
Harrow	1,581	1,820
Havering	1,364	1,577
Hillingdon	1,525	1,749
Hounslow	1,950	2,341
Islington	2,323	2,890
Kensington and Chelsea	3,193	3,962
Kingston upon Thames	1,718	2,006
Lambeth	2,252	2,741
Lewisham	2,582	3,037
Merton	2,539	2,915
Newham	2,122	2,614
Redbridge	1,730	2,048
Richmond upon Thames	2,093	2,461
Southwark	2,337	2,913
Sutton	1,632	1,887
Tower Hamlets	2,063	2,623
Waltham Forest	2,492	2,896
Wandsworth	2,516	2,970
Westminster	2,928	3,624
Londonwide	**2,852**	**3,348**

Please refer to online files for rates per 100,000 by borough, which can be found here: https://www.london.gov.uk/what-we-do/environment/pollution-and-air-quality/modelling-long-term-health-impacts-air-pollution-london

Note: Slight rounding errors occur when totals are disaggregated by age group.

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