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Legal but lethal: Lessons from NO_2 related mortality in a city compliant with EU limit value

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ABSTRACT

Research has indicated that the legal maximum annual-average concentration of nitrogen dioxide (NO_2) for safe long-term exposure in the European Union and United Kingdom (40 μg/m^3) may not offer adequate protection and that a lower value may be needed. At the same time concerns have been raised in the UK about government methods to assess NO_2 for the purposes of compliance with the legal limit. It is suggested that the national assessment underestimates levels of the pollutant and that local authority assessments, which in several cases find higher NO_2 levels, are a more accurate reflection of pollution. This research used Brighton and Hove – which is deemed compliant with NO_2 limits by the national assessment – as a case study to inform these debates. Using local authority pollution data, the research found that: up to 15.9% (95% CI 9.4% – 21.9%) of mortality in the examined area, which approximately corresponds to central Brighton, can be attributed to long-term exposure to 2016 levels of NO_2; up to 13.9% (95% CI 8.2% –19.2%) of mortality in this area can be attributed to legal concentrations of the annual-average limit; and up to 3% of mortality in the area examined can be attributed to the portion of 2016 concentrations above the 40 μgNO_2/m^3 annual average limit. These results suggest the current EU and UK limit value for long-term exposure to NO_2 may not be adequate to protect public health. The findings also indicate the UK government assessment does not identify all the local NO_2 hotspots that are contributing to premature deaths.

Keywords: air quality policy, air quality assessment, NO_2, health burden, mortality

1. Introduction

Outdoor air pollution poses the biggest environmental risk to public health (WHO, 2016), with particulate matter (PM) responsible for 412,000 deaths a year in the European Union (EU) and Nitrogen Dioxide (NO_2) 71,000 deaths (EEA, 2019). In the UK, PM is thought to cause 29,000 deaths a year and NO_2, 11,000 deaths (RCP, 2016). Despite the larger health burden associated with PM however, NO_2 has assumed more significance from the point of view of UK policy makers and campaigners (COMEAP, 2014). This is because the UK is compliant with the legal concentrations for PM but in breach of the legal limit for long-term exposure to NO_2 (COMEAP, 2014; Defra, 2017).

Long-term exposure to NO_2 has been associated with increased rates of morbidity and with increased rates of mortality (COMEAP, 2014, 2015a; WHO, 2013b). This increased morbidity and mortality principally relates to the exacerbation of chronic respiratory and cardiovascular disease (Beelen et al., 2008; Cesaroni et al., 2013; COMEAP, 2014; Hoek et al., 2013; Lipsett et al., 2011; Schultz et al., 2012; US EPA, 2016; Zhang et al., 2011).

Under both European Union (EU) and UK law the maximum permissible annual-average concentration for NO_2 is 40 $\mu g/m^3$. This limit reflects the World Health Organisation's (WHO) estimation of the maximum annual-average NO_2 concentration for safe long-term exposure (WHO, 2018). However, doubt exists about whether this limit does protect the public as research has failed to establish a clear threshold below which exposure does not have negative health effects (COMEAP, 2015a). The 40 $\mu gNO_2/m^3$ guideline maximum level for long-term outdoor exposure was put forward by WHO in 1997 on the basis that children had exhibited respiratory illness when exposed to annual-average indoor concentrations of 38-56 $\mu gNO_2/m^3$ (Graham et al., 1997). It was noted that the limit would not provide a margin of safety, but would protect children from the most severe outdoor concentrations (Graham et al., 1997). Since the guideline was issued, adverse health effects at concentrations below 40 $\mu gNO_2/m^3$ have been demonstrated and a 2013 WHO review of the evidence said recent research may result in lower guideline values (WHO, 2013a).

For the purpose of compliance with the 40NO_2 $\mu g/m^3$ limit value in the UK, annual nationwide assessments of NO_2 concentrations are undertaken by the Department for Environment, Food and Rural Affairs (Defra). Monitoring is performed using a network of Automatic Urban and Rural Network (AURN) measurement stations which record direct measurements of NO_2 concentrations across the UK. This is supplemented with modelling to estimate background concentrations at $1km^2$ resolution and concentrations at the sides of major urban roads, defined as motorways and major A-roads (Defra, 2017).

Because of the scale at which the monitoring and modelling are undertaken, Defra has been criticised for not adequately identifying local pollution hotspots. The number of AURN monitors in the national monitoring network – 157 – has been described as "insufficient" for flagging up all exceedances of the limit value (Barnes et al., 2018). Similarly, the modelling is performed at too coarse a scale to accurately capture concentrations in urban areas or at the sides of locally-managed roads where people live (Barnes et al., 2018).

Separate to the national assessment, local authorities are legally required to conduct their own air quality assessments (Defra, 2018a; Environment Food and Rural Affairs Committee et al., 2018). It has been argued that these assessments, using direct measurements from a relatively dense network of monitoring sites, provide a more accurate reflection of exceedances in areas of exposure (Barnes et al., 2018). A joint report on air quality by four House of Commons' select committees concluded that "direct measurement of air pollution [by local authorities] is much more accurate than estimation and modelling is likely to be", (Environment Food and Rural Affairs Committee et al., 2018). Local authorities themselves have criticised the disparity between local data and Defra's assessment, saying that, as a result, action to tackle NO_2 will not be "effective or proportionate" (Environment Food and Rural Affairs Committee et al., 2018).

The difference in the methodology used by the Defra assessments and the local authorities' own assessment means that Defra has declared some local authority areas compliant whereas the council itself has found significant exceedances of the limit value (Defra, 2019, 2018b; Preston City Council, 2018). Brighton and Hove, a local authority in the south east of England, is one such authority.

Brighton and Hove is one of six "reporting zones" set up for the purposes of assessing compliance, that has been declared by Defra to be within the annual mean limit (Defra, 2017). However, the council's own monitoring – consisting of 65 roadside monitors – has recorded significant exceedances of the annual-mean limit, with 10 monitors averaging over 50 $\mu g NO_2/m^3$ a year and one recording an average above 100 μg NO_2/m^3 a year (Brighton and Hove City Council, 2017).

Local politicians and civil servants reject the Defra assessment and point to the fact that only two AURN monitoring stations are within the Brighton and Hove reporting zone (personal communication, April 4th, 2018). Of these, one is in Worthing, outside the local authority area, and the other is situated in a public park 190 metres from the nearest road (Defra, 2019). There is therefore no input into the Defra assessment of Brighton and Hove from roadsides in the city where NO_2 concentrations are likely to be highest. The consequence of being found compliant with the annual mean limit by Defra is that Brighton and Hove is unable to access funding to deal with the air pollution exceedances found by their own assessments.

In view of these considerations, the research set out to quantify the health burden of long-term exposure to levels of NO_2 pollution in Brighton and Hove as reported in local data. If it could be demonstrated there is a significant health burden from NO_2 exposure, it would add weight to arguments that the national assessment methodology needs to be altered to properly reflect NO_2 pollution in Brighton and Hove, and elsewhere in the UK. Furthermore, the research attempted establish the health burden of long-term exposure to legal annual-average NO_2 concentrations in Brighton and Hove. This allowed the research to inform the on-going debate about the adequacy of the current maximum limit value. Lastly the research assessed the health burden of the portion of NO_2 concentrations above the legal limit (exceedances). This can be considered the human cost of the status quo in which efforts are not being made at the national level to make Brighton compliant with the legal limit.

2. Materials and methods

The methodological approach broadly followed a cross-sectional technique established by the Committee on the Medical Effects of Air Pollutants (COMEAP) (COMEAP, 2010; COMEAP, 2012), which uses Concentration Response Functions (CRFs) and existing population, pollution and mortality data.

2.1 Population-weighted annual-average concentration

The COMEAP method requires a population-weighted annual-average concentration to be calculated for the area being studied. This is a metric that reflects the proportions of people within the studied population that are exposed to the different levels of pollution present (COMEAP, 2012; Gowers et al., 2014).

To do this it was necessary to map population and pollution data in a grid over the area of interest, such that each square in the grid had a discrete value for population and annual-average NO_2 concentration. Gridded population data, at $10m^2$ resolution, was taken from a data set in which Office of National Statistics 2011 census headcounts were redistributed to residential buildings across the UK (Murdock et al., 2015).

Gridded pollution data was generated by taking local authority reports of the 2016 NO_2 annual-average concentrations at 65 monitoring sites and using the GIS software QGIS to make a spatial interpolation calculation. The method of spatial interpolation used was Inverse Distance Weighting (IDW). This method uses a formula to estimate the values of unknown data points by averaging the values of the surrounding known data points after weighting them according to their distance from the unknown point (Ramos et al., 2016). It has been used widely in studies examining air quality and the health burden of pollution (Beelen et al., 2007; Bell, 2006; Hoek et al., 2002; Hubbell et al., 2005; Jerrett et al., 2013; Kim et al., 2014; Lipsett et al., 2011; Marshall et al., 2008; Pereira et al., 2016; Ramos et al., 2016; Salam et al., 2005; Shukla et al., 2020; Wong et al., 2004; Wu et al., 2006).

The location of the council's NO_2 pollution monitors were overlaid on Ordnance Survey (OS) maps in the GIS software using OS coordinates. Gridded interpolated pollution data was then generated for the whole of the local authority area at $100m^2$ resolution. Gridded pollution data has been estimated at various different spatial resolutions for the purposes of calculating health burdens – from $20m^2$ (Walton et al., 2015) to $10km^2$ (Al-Hamdan et al., 2009). It was considered that pollution data at $100m^2$ resolution would capture some of the spatial variation of NO_2 concentrations, which is known to vary at small spatial scales (Jerrett et al., 2005), while still having a manageable number of pollution values. A basic cross-validation of the interpolated data was carried out using the leave one out method. A subset of five monitors was taken from the centre of the data map and the IDW interpolation performed five times, excluding one monitor each time. A comparison of the known and predicted values at the monitor sites showed the root mean squared error of the predicted values to be 3.5. The range of the pollution values generated by the IDW interpolation was 18.1 $\mu gNO_2/m^3$ to 63.3 $\mu gNO_2/m^3$.

After generating gridded pollution data, the boundary of the area being examined was determined by considering the data quality. Robust modelling of pollution using spatial interpolation requires a reasonably dense network of sampling sites (Jerrett et al., 2005; Wong et al., 2004). In Brighton and Hove, the monitoring stations are largely clustered in the city centre, while much of the rest of the local authority area is several kilometres from a monitoring station. Because of concerns about the reliability of interpolated data based on relatively distant monitoring values, it was decided to only assess the health burden of NO_2 exposure within the city centre.

The area studied was determined precisely by establishing radii of 500m around each of the central cluster of monitoring stations and including interpolated data squares which were wholly or partly within these radii. Previous efforts to map urban pollution have established radii around known data points (recorded by monitoring stations) and only attempted to map pollution within these radii, which range from as little as 100m (Brauer et al., 2008) to as much as 100km (Pereira et al., 2016). Given that NO_2 varies over small spatial scales, it was considered that 500m radii struck a balance between accuracy (i.e. only including interpolated data based on relatively close monitoring stations) and ensuring a meaningful proportion of the city's population fell within the examined area.

The **examined area** (**Fig. 1**) – which can be loosely described as central Brighton – was 3.87 km^2 and the **examined population** within this area was 44,553.

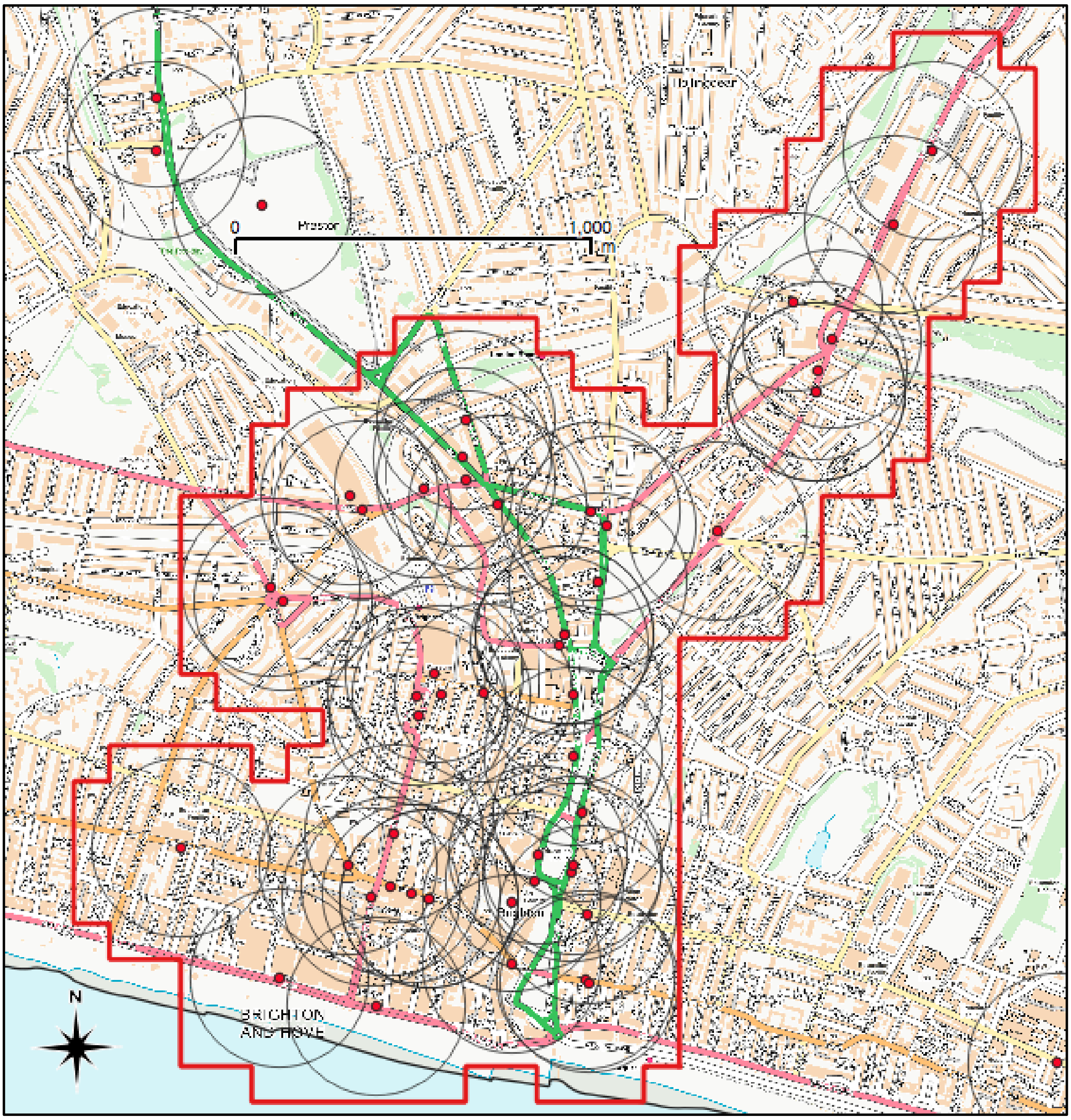

Fig. 1. The examined area, showing central cluster of local authority monitors (red dots), with 500m radii around them. The red line encompasses all 100m2 pollution value squares partly or wholly within the radii.

The population-weighted annual-average concentration was calculated for this area by first aligning the gridded population and pollution data in the GIS software using OS coordinates. The population and pollution values in each 100m2 square were then multiplied and the resulting values added together and divided by the total population in the examined area.

2.2 Cut-offs

Cut-offs refer to a threshold in a NO_2 concentration. They are used to ensure that only concentrations considered to have negative health effects are included in health burden calculations, with values below the cut-off discounted. However, because it is unclear whether there is a threshold below which exposure to NO_2 does not have negative health effects (COMEAP, 2015a), COMEAP's and WHO's advice regarding cut-offs differs.

WHO recommends using 20 $\mu gNO_2/m^3$ as the cut off (WHO, 2013b), while COMEAP recommends using no cut-off, and also using the lowest concentration reported in the studies analysed to derive the coefficient as the cut off (1.5 $\mu gNO_2/m^3$) (COMEAP, 2015b).

It was decided to use all three approaches, which meant calculating three different population-weighted annual-average concentrations:

1. No cut-off. The population-weighted annual-average concentration was calculated as above, using all of each $100m^2$ pollution value.
2. 1.5 $\mu gNO_2/m^3$ cut-off. This amount was subtracted from each $100m^2$ pollution value before calculating the population-weighted concentration.
3. 20 $\mu gNO_2/m^3$ cut-off. This amount was subtracted from each $100m^2$ pollution value before calculating the population-weighted concentration.

2.3 Concentration-response functions (CRFs)

The CRFs used describe the quantitative relationship between additional mortality risk and long-term exposure to every 10 $\mu g/m^3$ annual-average of NO_2 pollution (Gowers et al., 2014). They were:

- **1.025 (2.5% additional mortality risk) per 10 $\mu g/m^3$ annual-average NO_2** – put forward by COMEAP (2015a) and derived from meta-analyses of cohort studies by Hoek et al. (2013) and Faustini et al. (2014).
- **1.055 (5.5% additional mortality risk) per 10 $\mu g/m^3$ annual-average NO_2** – put forward by WHO (2013a) and derived from the meta-analysis by Hoek et al. (2013).
- **1.039 (3.9% additional mortality risk) per 10 $\mu g/m^3$ annual-average NO_2** – put forward by Walton et al. (2015) in their study of pollution in London.

Walton et al. calculate that the WHO CRF overestimates the health burden of long-term NO_2 exposure by up to 30% because of the overlap with the effects of $PM_{2.5}$. They therefore reduced it by this amount to 1.039. Using this CRF meant a meaningful comparison could be made between the results of this study and those of Walton et al. (2015).

As the CRFs provide additional mortality risk per 10 μg/m^3 annual-average NO_2, it is necessary to scale them according to the actual NO_2 concentration that the examined population is exposed to. This value is provided by the population-weighted annual-average concentration(s).

When scaling the different CRFs, only cut-offs used by the researchers who put forward the CRF were used. The following calculations were thus made: WHO's CRF scaled with population-weighted annual-average concentration calculated with a 20 μg/m^3 cut off; COMEAP's CRF scaled with population-weighted annual-average concentrations calculated with no cut-off and a 1.5 μg/m^3 cut-off; WHO's CRF reduced by 30% and scaled with population-weighted annual-average concentration calculated with no cut-off, as per Walton et al. (2015). The method of scaling used was multiplicative scaling according to the following formula (COMEAP, 2010): **Scaled CRFs (sCRFs) =** $x^{(y/10)}$, where x = the concentration-response function and y = population-weighted annual-average concentration.

2.4 Calculating the health burden

The sCRFs were used to calculate different metrics of the health burden using mortality data for the examined area. COMEAP note that for the purposes of calculating the health burden of long-term pollution exposure, mortality data for a specific year is typically used (COMEAP, 2010). However, it is recommended that the average of the last three to five years of available data is used owing to the variability in small datasets (Gowers et al., 2014). The mortality data used were an average of all-cause mortality, among all ages and both sexes, within the local authority area over the last three years available: 2014, 2015, 2016 (ONS, 2017).

As only a proportion of the local authority population was being examined, it was necessary to refer to the same proportion of the mortality data. The examined population is 16.3% of the local authority population at the 2011 census so this percentage of the mortality data was used (339 deaths).

Three different metrics of the health burden were calculated:

i) **The proportion of annual deaths attributable to exposure to NO_2 in the examined population.** This was calculated using the formula: proportion of attributable deaths = (sCRF – 1)/sCRF (COMEAP, 2012).

ii) **The number of deaths attributable to long-term exposure to NO_2 in the examined population**. This was calculated by multiplying the proportion of attributable deaths by the total number of deaths (339) (COMEAP, 2012).

iii) **The number of years of life lost to the population in the examined area as a result of exposure to NO_2**. This was calculated by assuming that an average of 11 years of life is lost per attributable death (see below).

2.5 Years of life lost metric

The years of life lost health burden metric is calculated by multiplying the number of deaths attributable to pollution for each age group by the relevant age-specific life expectancies (Gowers et al., 2014). However, it has been suggested that a reasonable estimate can be made by multiplying the total calculated figure for attributable deaths by an average per-person loss of life (COMEAP, 2012). The average per-person loss of life used was 11 years. It was arrived at by dividing the total years of life lost as a result of long-term NO_2 exposure in the UK in 2013 by the total number of UK annual deaths attributed to long-term NO_2 exposure in the same year. This data was taken from the European Environment Agency's *Air Quality Europe – 2016 report* (EEA, 2016).

2.6 Baseline scenario, alternative scenario and exceedances

The method described calculates the health burden of long-term exposure to the current level of NO_2 pollution in the examined area. This can be seen as the **baseline scenario** and provides an answer to the first research question.

To quantify the health burden of legal annual average NO_2 concentrations in the examined area – and answer the second research question – it was necessary to reduce annual-average concentrations reported by monitoring stations in the examined area to 40 $\mu gNO_2/m^3$ if a value over 40 $\mu gNO_2/m^3$ had been reported, then repeat the method on this basis. This is described as the **alternative scenario**. There were 47 monitors in the examined area and 33 reported annual-average values over 40 $\mu gNO_2/m^3$.

The health burden of the alternative scenario can be regarded as both hypothetical and real. It is hypothetical in the sense that it represents the health burden of long-term exposure if NO_2 concentrations were reduced to legal limits. It is real in the sense that it is the health burden of the portion of current concentrations that are within 40 $\mu gNO_2/m^3$.

The health burden of the exceedances, which relate to the third research question, were regarded as the difference in health burdens between the baseline and alternative scenarios.

This was calculated by subtracting the alternative scenario results from the baseline scenario results.

2.7 Definition of 'health burden' and 'long-term'

As the CRFs used describe the additional likelihood of death from all-causes, the health burden assessed was the effect of long-term NO_2 exposure on mortality in general. Long-term in this context refers to exposure to NO_2 for a year or more (Gowers et al., 2014; Hoek et al., 2013).

Although the burden of long-term exposure to NO_2 was examined, the pollution and population data used reflected levels in the last single year for which data was available. Regarding pollution data, it has been noted that "historical exposure is likely to be correlated with current levels and current concentrations can, therefore, also be viewed as a proxy for long-term exposure history" (Gowers et al., 2014). This approach has been used to calculate the health burden of long-term pollution exposure in several studies (for eg COMEAP, 2010; Gowers et al., 2014; Walton et al., 2015). Nevertheless, the use of concentrations from a single year allows only for "approximate snapshot" calculations of the health burden in a particular year (Walton et al., 2015). As 2016 pollution data is used, the results presented here indicate the health burden of long-term exposure to the concentrations present in that year.

2.8 Analysis and quantification of uncertainty

By calculating the health burden using different CRFs and cut-offs, some of the uncertainty about the precise causal relationship between of NO_2 and all-cause mortality is reflected in the results.

This was further quantified by performing the health burden calculations at the upper and lower boundary of the 95% confidence intervals reported by COMEAP (2015a) (1.01–1.04 per 10 $\mu gNO_2/m^3$), WHO (2013a) (1.031–1.080 per 10 $\mu gNO_2/m^3$) and Walton et al. (2015) (1.022–1.056 per 10 $\mu gNO_2/m^3$) for their proposed CRFs.

3. Results and discussion

3.1 Health burden of NO_2 concentrations (baseline scenario)

As much as 15.9% of annual deaths in the examined population can be attributed to long-term exposure to 2016 concentrations of NO_2 pollution (Table 1). The proportion of deaths attributable to long-term exposure to the 2016 level of NO_2 in the examined population ranges from 10.2%, using the COMEAP CRF and a 1.5 µg/m3 cut-off, to 15.9% using the Walton et al. CRF and no cut-off.

The upper limit of the range of proportion of attributable deaths, 15.9%, means up to 54 deaths a year in the examined population can be attributed to long-term exposure to 2016 concentrations of NO_2 (Table 1). The range of annual deaths in the examined population attributable to long-term exposure to 2016 NO_2 concentrations is from 35 to 54. Expressed as life years lost, the health burden in the examined population of long-term exposure to 2016 levels of NO_2 is as much as 593 (Table 1).

Table 1

The health burden among examined population attributable to long-term exposure to 2016 concentrations of NO_2 (baseline scenario)

	Proportion of deaths	Attributable deaths	Years of life lost
Walton et al.	15.9% (95% CI 9.4% – 21.9%)	54 (95% CI 32 – 74)	593 (95% CI 350 – 816)
WHO	12.7% (95% CI 7.4% – 17.7%)	43 (95% CI 25 – 60)	472 (95% CI 277 – 660)
COMEAP no cut-off	10.6% (95% CI 4.4% – 16.3%)	36 (95% CI 15 – 55)	395 (95% CI 164 – 607)
COMEAP 1.5 cut-off	10.2% (95% CI 4.3% – 15.8%)	35 (95% CI 14 – 54)	382 (95% CI 159 – 589)
Average	12.3%	42	461

These results indicate that long-term NO_2 exposure has a significant health burden in the examined area, with the proportion of deaths attributable to NO_2 similar to that found in Inner London in 2010 (Table 2).

Table 2

Health burden from long-term NO_2 exposure in examined area and 10 most polluted London boroughs 2010

	Examined area versus London boroughs	Proportion of attributable deaths	Population-weighted NO_2 concentration (µg/m^3)

1	City of London	20%	58.2
2	Westminster	17.2%	49.5
3	Tower Hamlets	16.3%	46.5
4	Kensington & Chelsea	16.6%	47.5
5	Camden	16%	45.7
6	**Baseline scenario**	15.9%	45.3
7	Islington	15.9%	45.2
8	Southwark	15.5%	44.1
9	Hammersmith & Fulham	15%	42.6
10	Lambeth	14.7%	41.6
11	Hackney	14.7%	41.4

(Adapted from Walton et al., 2015)

3.2 Health burden of legally compliant NO_2 concentrations (alternative scenario)

As much as 13.9% of deaths in the examined population can be attributed to long-term exposure to legally compliant concentrations of NO_2 (Table 3). The proportion of deaths attributable to legally compliant NO_2 concentrations ranges from 8.9% using the COMEAP CRF and a 1.5 μg/m^3 cut-off to 13.7% using the Walton et al. CRF and no cut-off.

The top of this range, 13.9%, represents 47 deaths a year (Table 3). The range of deaths a year that can be attributed to long-term exposure to legally compliant concentrations of NO_2 is 30 to 47 and the range of attributable years of life lost is 331 to 518 (Table 3).

The results show that an overwhelming majority of the health burden of long-term NO_2 exposure in the examined area is attributable to legal concentrations. This was also the case in the study of the health burden of pollution in London by Walton et al. (2015). Other studies have also found that long-term NO_2 exposure increased mortality risk when the majority or all of the populations studied were exposed to NO_2 levels below 40 μg/m^3 (Cesaroni et al., 2013; Gan et al., 2011; Hart et al., 2011; Jerrett et al., 2011).

Table 3

The health burden among examined population attributable to long-term exposure to legally compliant NO_2 concentrations (alternative scenario)

	Proportion of deaths	Attributable deaths	Years of life lost
Walton et al.	13.9% (95% CI 8.2% –19.2%)	47 (95% CI 28 – 65)	518 (95% CI 304 – 715)
WHO	9.7% (95% CI 5.7% – 13.6%)	33 (95% CI 19 – 46)	362 (95% CI 211 – 509)

COMEAP no cut-off	9.2% (95% CI 3.8% – 14.2%)	31 (95% CI 13 – 48)	343 (95% CI 142 – 530)
COMEAP 1.5 cut-off	8.9% (95% CI 3.7% – 13.7%)	30 (95% CI 12 – 46)	680 (95% CI 404 – 937)
Average	10.4%	35	476

3.3 Health burden of the exceedances legal NO_2 limit

As discussed (section 2.6), the health burden of the exceedances was arrived at by subtracting the results of the alternative scenario from those of the baseline scenario. Doing this, we see that proportion of annual deaths attributable to long-term exposure to the 2016 exceedances of the legal limit ranges from 1.4%, using the COMEAP CRF, to 3%, using the WHO CRF and a 20 $\mu gNO_2/m^3$ cut-off.

The proportion of deaths arrived at with the WHO CRF, 3%, means the 2016 exceedances of the legal limit are responsible for up to 10 deaths and 110 life years lost (Table 4). These figures can also be seen as the potential health *impact* (COMEAP, 2010) of policy interventions that would reduce NO_2 concentrations to the legal limit. In other words, the results show that measures to reduce NO_2 concentrations to within the legal limit may prevent up to 10 deaths a year and extend lives by up to 110 years.

Table 4

The health burden among examined population attributable to long-term exposure to 2016 exceedances of NO_2 legal limit

	Proportion of deaths	Number of deaths	Years of life lost
Walton et al.	2.0%	7	75
WHO	3.0%	10	110
COMEAP no cut-off	1.4%	5	52
COMEAP 1.5 cut-off	1.4%	5	52
Average	1.9%	7	72

3.4 Interpreting the results

The greatest health burden from long-term NO_2 exposure in the examined area is found when using Walton et al.'s method. This method finds a larger health burden than that recommended by WHO even though the relative risk of NO_2 exposure under the WHO method is greater.

This is because, under the WHO method, 20 $\mu gNO_2/m^3$ is subtracted from the population-weighted average pollution value when making the calculations.

However, it should be noted that a larger health burden is attributable to the exceedances using the WHO method. This is because the exceedances represent a bigger proportion of the baseline population-weighted annual-average concentrations when a cut-off is used. When multiplicative scaling of the CRFs takes place, it results greater difference between the relative risk of the baseline and alternative scenarios than if no cut off were used.

3.5 Internal validity issues

There are a number of uncertainties about the results which stem from the methods used. Although it is agreed that NO_2 has a causal relationship on mortality (WHO, 2013b; COMEAP, 2014; US EPA; 2016), the exact quantitative nature of the relationship remains uncertain. COMEAP describes their CRF as "interim" (COMEAP, 2015b) and after an attempt to put forward a definitive CRF, COMEAP said it was unable to establish the relationship between NO_2 and mortality independent of other pollutants, particularly PM (COMEAP, 2018). For the same reason, the WHO acknowledge that estimates of the effects of NO_2 based on their CRF may overestimate the effect from 0% to 33% (WHO, 2013b).

Another source of uncertainty is the mapped pollution data. Firstly, 62 of the 65 monitors used to produce the pollution data are diffusion tubes, which are described as an "indicative" monitoring technology with levels of uncertainty up to ± 25% (Targa and Loader, 2008). Secondly, the pollution data may not have been mapped at a sufficiently fine resolution to accurately reflect the distribution of pollution concentrations and consequently people's pollution exposure. The resolution used, $100m^2$, is finer than that used in several studies of the effect of NO_2 (Al-Hamdan et al., 2009; Lipsett et al., 2011; Gowers et al., 2014). However, because NO_2 concentrations are known to vary at small spatial scales, it remains possible that levels in hot spots were smoothed, or rounded down, so that exposure was underestimated.

Thirdly, although IDW is commonly used to map pollution values in epidemiological studies of NO_2, other more techniques may map pollution values more accurately (Jerrett et al., 2005). In this case, atmospheric dispersion modelling, which is more complex and, for the best results, requires proprietary software (Yudego et al., 2018), was not possible within the budget and time period of this research. Similarly, land use regression modelling requires other data relating to emission sources and their dispersion in order to develop a multi-variable model in GIS software (Beelen et al., 2013; Jerrett et al., 2005). Consequently, it was not possible with the resources available. It should be noted however, that, of the other interpolation techniques available, kriging provides limited advantages over IDW (Qiao et al., 2018; Shukla et al., 2020; Vorapracha et al., 2015).

The final source of uncertainty is the mortality data. As the examined area is idiosyncratic in the sense that it has only been defined for the purpose of this research, there was no corresponding mortality data for just this area. It was necessary to assume that, as the examined population was 16.3% of the whole local authority area population, the examined population also experienced 16.3% of the mortality. However, the distribution of the mortality across the local authority may not match the distribution of the population so that the mortality assumed for the examined area was over or under-estimated. As a consequence, the health burden may also have been over or under-estimated.

4. Conclusions

By providing a quantitative description of the health burden of NO_2 pollution in central Brighton, it is hoped the research will inform on-going policy debates about NO_2 pollution.

In Brighton and Hove, air quality is already a concern among residents, local environmental activists and politicians (Vowles, 2017). Quantifying the health burden of NO_2 levels in central Brighton (baseline scenario) helps increase understanding of the public health risk local people are exposed to and enables concerned stakeholders to increase pressure on policy makers to reduce pollution.

In the context of UK policy, the findings of the research raise questions about the adequacy of the national assessment. The select committee report discussed above (section 1) recommends Defra adjust its NO_2 assessment methodology to include more accurate local data so that the true extent of NO_2 pollution is recognised. By demonstrating that, with local data, up to 54 lives a year are attributable to NO_2 pollution in a sub-section of a city deemed compliant by the national assessment, the research supports this recommendation.

Efforts to get Defra to improve its assessment methods are bolstered further by the quantification of the health burden of just the exceedances of 40 $\mu gNO_2/m^3$. The results show that, in a sub-section of one city, the consequence of the government not acknowledging or eliminating NO_2 exceedances could be as many as 10 deaths a year. This finding strengthens calls by local MPs and councillors for Defra to recognise the exceedances by including councilrun automatic monitors in two of the city's most polluted roads in the AURN network used to calibrate the modelling (personal correspondence, April 4th and 12th, 2018).

At the same time, putting a figure on the health burden of legally compliant NO_2 concentrations in central Brighton (alternative scenario) informs the on-going debate about the adequacy of the guideline maximum limit for safe long-term exposure. In its 2013 review of the evidence of the effect of long-term NO_2 exposure, the WHO concluded that "it would be wise to consider whether the guideline [40 µg NO_2/m^3] should be lowered at the next revision of the guidelines" expected in 2020 (WHO, 2013b). This study, and that of Walton et al. (2015), does not contradict that conclusion. Rather the finding that there is a significant health risk associated with NO_2 concentrations currently deemed safe supports moves to lower the WHO guidelines and the EU annual mean limit to protect public health.

It would be useful to calculate the health burden of long-term NO_2 exposure for the whole of the local authority area, rather than for a sub-section as has been done here. Providing a health burden metric for the whole governance area may strengthen impetus for policy measures to tackle the problem. Such a calculation could be performed by determining pollution levels across the authority using atmospheric dispersion modelling.

Looking beyond Brighton and Hove, it would be interesting to conduct a similar study to this one in another city deemed compliant with NO_2 concentrations by the national assessment. If it can be shown that there is a pattern of Defra's modelling underestimating NO_2 pollution and the associated health burden vis à vis local assessments, it would further illuminate whether Defra's approach needs revising. Similarly, further studies quantifying the health burden of long-term exposure to legal NO_2 concentrations would also inform whether the current legal limit value is adequate.

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