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Emissions vs exposure: Increasing injustice from road traffic-related air pollution in the United Kingdom

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ABSTRACT

This paper presents unique spatial analyses identifying substantial discrepancies in traffic-related emissions generation and exposure by socioeconomic and demographic groups. It demonstrates a compelling environmental and social injustice narrative with strong policy implications for the UK and beyond.

In the first instance, this research presents a decadal update for England and Wales to Mitchell and Dorling's 2003 analysis of environmental justice in the UK. Using 2011 UK Government pollution and emissions data with 2011 UK Census socioeconomic and demographic data based on small area census geographies, this paper demonstrates a stronger relationship between age, poverty, road NO_x emissions and exposure to NO_2 concentrations. Areas with the highest proportions of under-fives and young adults, and poorer households, have the highest concentrations of traffic-related pollution.

In addition, exclusive access to UK annual vehicle safety inspection records ('MOT' tests) allowed annual private vehicle NO_x emissions to be spatially attributed to registered keepers. Areal analysis against Census-based socioeconomic characteristics identified that households in the poorest areas emit the least NO_x and PM, whilst the least poor areas emitted the highest, per km, vehicle emissions per household through having higher vehicle ownership, owning more diesel vehicles and driving further.

In conclusion, the analysis indicates that, despite more than a decade of air quality policy, environmental injustice of air pollution exposure has worsened. New evidence regarding the responsibility for generation of road traffic emissions provides a clear focus for policy development and targeted implementation.

1. Introduction

Air pollution has been recognised by the World Health Organization (WHO, 2014) as the world's "largest single environmental health risk", with 4.2 million premature deaths in 2016 resulting from exposure to ambient (outdoor) air pollution (WHO, 2018). In highly-populated urban areas, road transport is often a major local source of ambient air pollution, in particular contributing significantly to nitrogen dioxide (NO_2) concentrations. In the UK, almost a third of total NO_x was generated by road vehicles, with 23% from cars and light duty vehicles (LDVs) (Wakeling et al., 2016). Across European Member States, there are widespread exceedences of the 40 µg/m^3 NO_2 annual mean limit value set by Directive 2008/50/EC on ambient air quality and cleaner air for Europe (the

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Ambient Air Quality Directive (AAQD)). On 1st January 2010, the date for achievement of this limit value, 93% of the UK's zones and agglomerations exceeded the threshold, despite the deadline for parallel national NO_2 objectives having been passed five years earlier (Defra, 2011). In their 2017 air quality plan, the Joint Air Quality Unit (JAQU) (comprising the Department for Transport (DfT) and the Department for the Environment, Food and Rural Affairs (Defra)), estimated that some urban areas would still exceed the NO_2 limit value by 2025 (JAQU, 2017). The most recent modelling, however, indicates that exceedences will continue beyond this date in four local municipalities (JAQU, 2018). This failure to bring air pollution under control now risks substantial fines being levied against the UK Government by the European Commission, due to infraction proceedings initiated in February 2014 (European Commission, 2014), although at this stage, it is unclear how the UK's intention to exit from the EU will affect this risk.

EU and UK air quality limit values and objectives are derived from WHO health-based standards, and, whilst it is difficult to unpick the synergistic effects of multi-pollutant exposure, research indicates that NO_2 may directly contribute to poor health, in addition to being a proxy for other traffic-related pollutants (COMEAP, 2015). Based on the most recent epidemiological and mechanistic evidence, the number of premature deaths attributable to both $PM_{2.5}$ and NO_2 in the UK are estimated to be equivalent to 28,000–36,000 per annum (COMEAP, 2018). Furthermore, Jarvis et al. (2010) suggest that, similarly to $PM_{2.5}$, NO_2 may be a non-threshold pollutant with health effects experienced at concentrations below the thresholds set in EU and UK legislation. The WHO (2015) estimated the UK economic cost of early deaths due to ambient particulate pollution in 2010 as approximately US$83bn (equivalent to ~£54bn). In addition, exposure to $PM_{2.5}$ and NO_2 is estimated to cost the UK National Health Service in the range £5.37bn - £18.57bn in health and social care, with ~2.5 million incidences of non-communicable diseases due to air pollution by 2035 if these pollutants remain at current levels (Pimpin et al., 2018). Given > 80% of the population of England and Wales live in urban areas (ONS, 2013), there is significant risk of chronic and acute effects due to exposure to traffic-related pollutants, including $PM_{2.5}$ and NO_2.

Whilst concentrations of traffic-related pollution are highest in cities and towns, there is also considerable variation within urban areas leading to spatial variability in exposure patterns and associated health impacts (Dietz and Atkinson, 2005; Gegisian et al., 2006; Pye et al., 2006; Briggs et al., 2008; Namdeo and Stringer, 2008; Jephcote et al., 2016). Demographic and socioeconomic analysis has indicated that, in Britain, young families and poorer households may be disproportionately represented in areas with the highest concentrations of NO_2, suggesting the presence of social inequality and environmental injustice (Mitchell and Dorling, 2003). This is of particular significance as infants are especially susceptible to the health effects of exposure to air pollution (Knox, 2005), including the longer-term effects relating to early-life exposure. Consequently, pregnant women, the aging population, people with health conditions and poorer households may also be considered vulnerable groups, with poor ill-health resulting from living in deprived socioeconomic circumstances, exacerbated by exposure to higher concentrations of air pollution (Jerrett et al., 2001). Mitchell and Dorling (2003) also found an inverse relationship between NO_2 concentrations and car ownership, compounding the injustice. However, based on their assumption that poorer areas were likely to have households that drove older, dirtier vehicles, they concluded that the poorest were still significant contributors to the problem. The strength of this conclusion was limited by their methodology and by data which could not take into account any differential in distances driven by people in poorer and less poor areas.

This paper contributes and furthers social inequality studies relating to air pollution, by updating and developing Mitchell and Dorling's 2003 research in the following respects:

- Firstly, updated (2011) NO_2 concentrations and road NO_x emissions data explore whether, following 15 years of air quality policy and management, traffic impacts on air quality are still an environmental justice issue.
- Secondly, socioeconomic and age-profile data from the UK 2011 Census, contemporaneous with the NO_2 and NO_x data, are used to analyse patterns of exposure, whereas the previous study used non-contemporaneous data from the 1991 Census.
- Thirdly, Lower-layer Super Output Areas (LSOAs) (~700 households), rather than wards (~6600 households), are used to reduce variability in the data and allow for significantly more focused spatial analyses.
- Fourthly, privileged access to DfT's annual vehicle safety inspection ('MOT' test) digital dataset, provided under the EPSRC-funded MOT Project, allows average household NO_x emissions for each LSOA to be estimated based on actual mileages from every private vehicle, up to 3.5 tonnes, in the UK ($n \approx 27$ million). The ability to calculate actual mileages for each vehicle enables a considerably more robust emissions calculation than in the previous study, which used a Weibull function fitted to MEET (Methodology for Estimating Emissions from Transport) observations (TRL, 1999) to estimate distance driven by age of vehicle.

By using the actual mileages driven by each vehicle, it is possible to explore whether differences in emissions between poor and less poor areas are due to differences in the 'absolute cleanliness' of vehicles (in terms of per km emission factors) or due to differences in actual emissions resulting from how far the vehicles are driven. Linking robust emission estimates to the LSOA of the registered keeper, together with car-ownership and socioeconomic data, enables identification of who (on an areal basis, if not in terms of actual individuals) generate the most traffic emissions, and whether this leads to new patterns of environmental injustices.

In addition to using ambient NO_2 concentrations as the measure of environmental harm, the analysis presented here also uses NO_x emissions within an area as a more direct measure of transport impact for the following reasons. Firstly, due to the methods by which the Defra concentration data are modelled, this only provides an indication of 'background' concentrations and is not able to represent where concentrations may be higher due to localised road sources and poor dispersion related to small-scale geographic features (e.g. buildings). Secondly, and more importantly, air pollution is not the only health risk associated with heavily trafficked areas. Increased volumes of traffic are associated with greater levels of noise (Babisch et al, 2005), diminished social integration (Appleyard and Lintell, 1972; Hart and Parkhurst, 2011), lower quality public (especially green) spaces (Woolley, 2004), reduced physical activity (Pikora et al, 2003) and greater risk of road traffic accidents (Dickerson et al., 2000). These risks all increase as levels of traffic increase, irrespective of local pollution dispersion characteristics. The use of NO_x emissions from road transport therefore may provide a much better indicator of health risks caused by motor traffic than NO_2 concentrations.

2. Data and methodology

2.1. Study area and scale of analysis

This research utilises LSOAs for England and Wales from the 2011 Census (ONS, 2016a). With 34,753 LSOAs (~700 households (range 400–1200), ~1600 residents (range 1000–3000) in each), this analysis presents a much finer spatial resolution than the ward analysis (~8500 in England and Wales) used by Mitchell and Dorling (2003). LSOAs also have a much more consistent population size and, importantly, a greater degree of uniformity in terms of socioeconomic characteristics, thereby limiting the ecological fallacy inherent in area census data analysis (Openshaw, 1984), i.e. the risk of misrepresenting the socioeconomic characteristics of individuals, based on analyses undertaken on the LSOAs in which they reside, is reduced.

2.2. Census data

Socioeconomic and demographic data (covering every household in England and Wales) for all LSOAs (ONS, 2016b) were analysed against air pollution data following the methodology set out by Mitchell and Dorling (2003). Quantile plots were constructed using R (v. 3.2.3) (R Core Team, 2015).

2.2.1. Demographic analysis

Using the 2011 Census data, the population of each LSOA was calculated using the following year age categories: < 1, 1–4, 5–9, 10–14, 15–19, 20–24, 25–34, 35–44, 45–54, 55–64, 65–74, 75–84, 85+. The bands were split into deciles using R, lower deciles signifying the lowest populations in a specific age category and vice versa.

2.2.2. Socioeconomic data and analysis

There are many different ways of assessing poverty (e.g. income, deprivation), however their temporal and spatial inconsistencies can prove problematic in undertaking socioeconomic analyses. A number of social equity and air pollution studies and datasets were reviewed to determine the most suitable poverty metric for this study (Hick, 2013; Treanor, 2013; Mitchell and Norman, 2012; Berthoud and Bryan, 2010; Nolan and Whelan, 2010; Gordon, 2006; Walker et al., 2005; Samet and White, 2004; Hillyard et al., 2003; Mack and Lansley, 1985). Initial investigation tested the utility of deprivation and income proxies: the 2010 English Indices of Deprivation (IMD) (Department for Communities and Local Government, 2010) and estimated median household income (Experian, 2011). Although the pattern of the results of these datasets are comparable, the variability (large error margins on the Experian data) and spatial coverage (independent deprivation indices for England and Wales) were not appropriate for this study. Instead the 'percentage of households in poverty' metric was adopted, based on the University of Bristol's Poverty and Social Exclusion (PSE) Unit (http://www.poverty.ac.uk) Breadline Britain Index (BBI), and following Mitchell and Dorling (2003).

The BBI was originally based on analysis of the 1990 Breadline Britain survey data (Gordon and Pantazis, 1997). The percentage of households 'Below the Breadline' (i.e. in poverty) are determined based on census data e.g. housing tenure, employment, health, household composition. The Breadline Britain survey was repeated by PSE in 1999, to reflect changing patterns of poverty, and updated to include new 2001 Census variables. A revised BBI was created for each LSOA by totaling the variables (Dorling et al., 2007).

For this updated analysis, advice was sought from academics involved in the creation of the PSE index[1] on the suitability of applying the 1999 variable coefficients to the 2011 Census data. Although data on 'households without sole use of amenities' was absent from the 2011 Census, and other determinants and symptoms of poverty may have changed, it was judged that this was the best available methodological approach. It is important to note that, as with measures like the IMD, a lower level of poverty (or deprivation) does not necessarily correlate directly with greater affluence or wealth. For example, the fact that an area only has a small number of households that are below the breadline, does not indicate anything about the wealth of the remaining houses (DCLG, 2015).

2.2.3. Car availability analysis

Using R, LSOAs showing 2011 UK Census data on availability of cars and vans were sorted into deciles by car/van availability within the following categories: proportion of households with availability of 0, 1, 2, 3, and 3+ cars/vans.

2.3. Pollution data and analysis

Air pollution data were acquired from two sources. Firstly, modelled annual mean UK ambient background data for NO_x as NO_2 and PM_{10} for 2011 (Defra, 2018), split into attributions to 20 and 23 different source sectors respectively, allowing just the road

[1] Dorling, D., 2015. Pers. comm., Halford Mackinder Professor of Geography, University of Oxford, 9th January.

transport components to be extracted. Secondly, UK National Atmospheric Emissions Inventory (NAEI) (2017) ASCII files of 2011 UK NO_x emissions, split into 13 different source categories, from which the road transport component was extracted. Where the term 'total' concentrations/emissions is used this refers to the sum of concentrations/emissions from all sources; 'road NO_x/NO_2/PM' relates to only that portion attributable in the datasets to road transport sources.

The ASCII files of NO_x emissions data were converted to point vector data (via raster) using ArcGIS (10.3). Both the NO_2 and NO_x datasets, used by Defra to report against the AAQD (2008/50/EC), are available at a 1 km^2 grid resolution. LSOAs vary in spatial area dependent on population density, with more rural LSOAs comprising > 1 km^2 grid cell while more densely-populated LSOAs may cover < 1 km^2 grid cell. Annual mean NO_2 was proportionally averaged across each LSOA, weighted by area, against the LSOA fraction intersecting with each 1 km^2 grid cell, e.g. if quarter of a LSOA fell within a grid cell with 40 $\mu g/m^3$ and the other three-quarters fell within another with 60 $\mu g/m^3$ the NO_2 concentration attributed to the LSOA would be $(25\% \times 40\,\mu g/m^3) + (75\% \times 60\,\mu g/m^3) = 55\,\mu g/m^3$. Conversely, NO_x emissions were area-weighted based on the fraction of grid cells covered by each LSOA, e.g. if a LSOA fell across half of a grid cell with 10 t/km^2 and the whole of another with 15 t/km^2 the NO_x emission attributed to the LSOA would be $(50\% \times 10\,t/km^2) + (100\% \times 15\,t/km^2) = 20\,t/km^2$. Without finer resolution data, with which to reveal the degree of variability within these areas, this approach assumes uniformity of average NO_2 concentrations across each LSOA and NO_x emissions over each individual grid cell.

2.4. Private vehicle emissions data and analysis

UK vehicles > 3 years old are required to have annual assessments, historically 'MOT' (Ministry Of Transport) tests. In 2010, the DfT started publishing the electronic records from these tests for every vehicle, including make and model, size of engine, type of fuel, registration date and recorded mileage. Date of first registration was used to estimate specific emission factors for each and every vehicle, which were multiplied by the annual distance driven by that vehicle (recorded mileage) to estimate a specific quantity of emissions attributable to every private vehicle (< 3.5 t) in Great Britain. These data were used to generate a profile for an average car within each LSOA and then, using Census data on household car ownership, NO_x and PM_{10} emissions (total and average) were calculated for all privately-owned vehicles in each LSOA. For a more detailed approach see Chatterton et al. (2015), however, note that subsequent to that account, two significant improvements in the dataset have been made which improve the accuracy of the results. Firstly, vehicles are now located by the LSOA of the registered keeper as opposed to the Postcode Area containing the Vehicle Testing Station. Secondly, it has become possible to account for vehicles < 3 years old (7.8% of private vehicles) in terms of their location and by calculating their annual mileage for 2011, by interpolating from the distance driven between their date of first registration and their recorded mileage at their first inspection test.

It is important to note that, contrary to most air pollution research, the analyses presented in this paper regarding emissions from private vehicles do not consider *where* these emissions happen. The novelty of this is specifically in the attribution of vehicle emissions to the location of the driver (or more precisely the registered vehicle keeper). A clear distinction is made regarding a) road transport NO_x emissions (derived from the NAEI data), which reflect emissions occurring within an LSOA (that pollution to which residents are *exposed*) and b) NO_x emissions from private vehicles registered within an LSOA, but not necessarily occurring within that LSOA (that pollution for which households are *responsible*).

3. Results

3.1. Pollution exposure and age

Fig. 1 shows the LSOA analysis of average annual mean NO_2 concentrations by age profile, using 2011 census and pollution data. The x-axis represents age deciles from low to high, i.e. age decile 1 denotes 10% LSOAs with the lowest proportion of an age group, whilst age decile 10 corresponds to 10% LSOAs with the highest proportion of an age group. Fig. 1 is comparable with the earlier Mitchell and Dorling plot, however concentrations of NO_2 have apparently reduced (by ~10 $\mu g/m^3$), using the Defra data. (N.B. inaccuracies in these data are argued in the Discussion.) The comparative exposure between age-groupings, however, does not appear to have changed over the last 10 years, with areas with more under-fives and adults aged 20–44 having elevated NO_2 concentrations. On the other hand, areas with more over-45 s tend to have better air quality. Maximum variances between upper and lower age deciles are between ages 25–34 and 55–64 (Fig. 2).

Fig. 2 examines the differential between the highest and lowest deciles in each age band in relation to both NO_2 and road NO_x in each LSOA. The plots show a strong discrepancy between younger children (< 5 years) and adults (in their 20 s and 30 s) (higher NO_2 and NO_x) compared with older children (10–20) and adults (> 50) (lower NO_2 and NO_x). This pattern may reflect the tendency for income and wealth to increase with age, and the consequent ability of older (more affluent) families to choose areas with better air quality (Mitchell and Dorling, 2003). This new analysis reveals that this discrepancy is increased: NO_2 concentrations in areas with more young adults are two times the average (cf. ~1.6–1.8 times (Mitchell and Dorling, 2003)) and there is a five-fold difference in NO_x emissions (not previously analysed). This is a significant finding, particularly given the argument made above, that NO_x emissions may be a better proxy for the range of health risks caused by motor traffic.

3.2. Pollution and poverty

Fig. 3 displays NO_2 concentrations (left) and PM_{10} concentrations (right) against households in poverty. Fig. 4 shows total NO_x

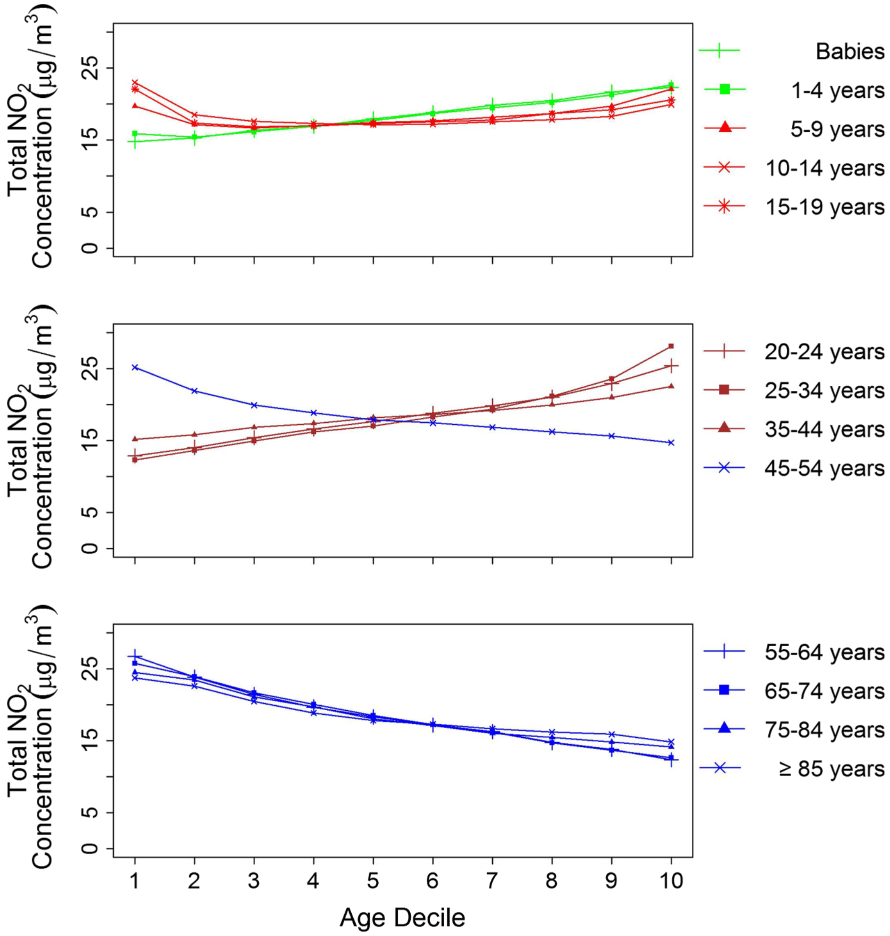

Fig. 1. NO_2 concentration by age decile (England and Wales).

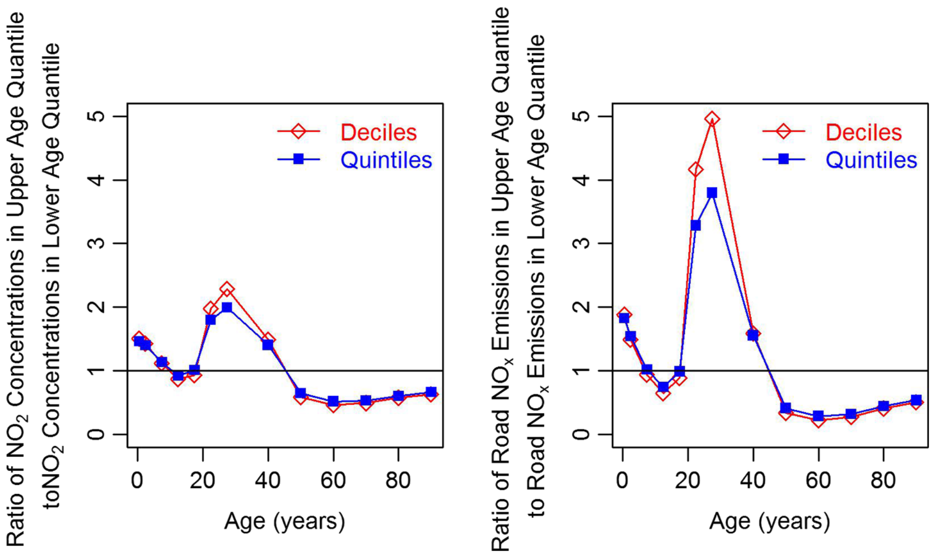

Fig. 2. NO_2 concentrations (left) and road NO_x emissions (right) ratio between highest and lowest deciles in each age band.

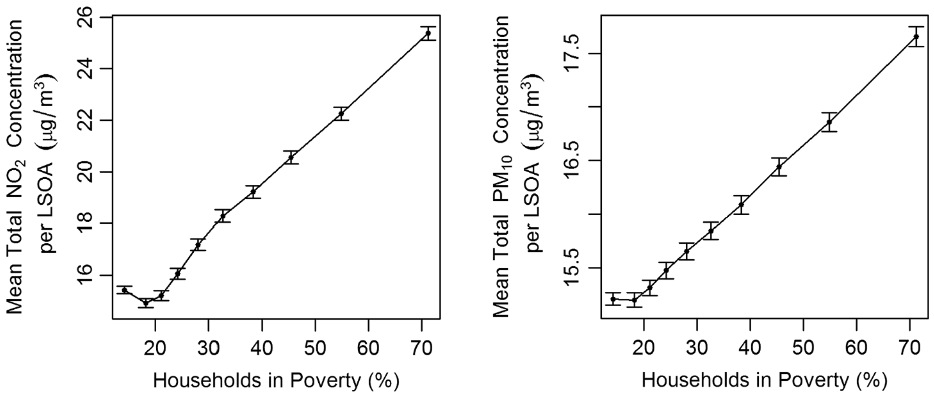

Fig. 3. Households in poverty against NO_2 (left) and PM_{10} concentrations (right). Error bars = 95% confidence intervals (CIs).

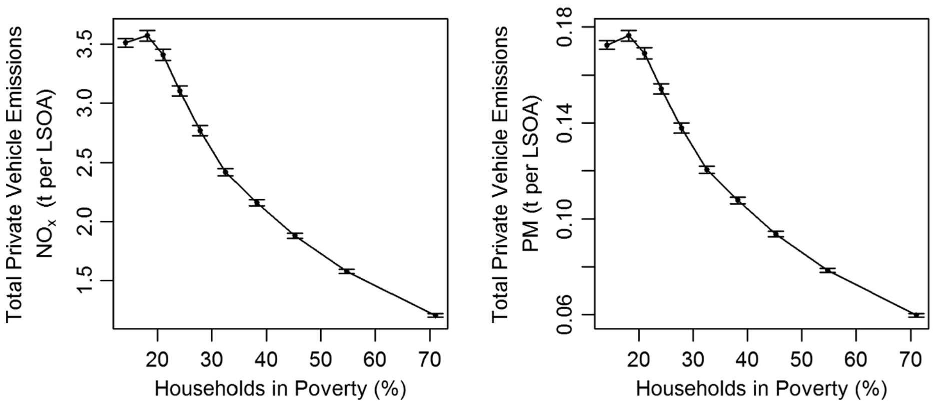

Fig. 4. Households in poverty against NO_x (left) and PM emissions (right). Error bars = 95% CIs.

emissions from private vehicles (left) and, similarly, PM emissions (right) also against households in poverty. Fig. 3 shows exposure of households to air pollution within an LSOA, regardless of the emitter (i.e. whether it is emitted by local residents, or by 'through traffic'). Fig. 4 utilises the MOT dataset and represents total private vehicle emissions per household within an LSOA, regardless of where the emissions are generated (i.e. in that locality, or on longer journeys).

The relationship between areas with poorer households and NO_2 concentrations signifies that the more households in poverty in a LSOA, the greater their chances of being exposed to poorer air quality (Fig. 3, left). Indeed, LSOAs with the highest percentage of households in poverty have NO_2 concentrations greater than 50% higher than LSOAs with the least households in poverty. The trend also holds true for PM_{10} (Fig. 3, right), although the differential between highest and lowest concentrations is less pronounced than for NO_2, probably due to the relatively higher levels of regional background PM_{10}.

There is a slight upturn in the poorest decile in the left-hand Fig. 3 plot indicating that areas with the fewest households in poverty have slightly increased NO_2 concentrations compared to the next decile. However this upturn only represents $< 1\ \mu g/m^3$, much less than earlier analysis (Mitchell and Dorling, 2003), and may reflect variation in pollutant concentrations, changes in the determinants of poverty, or differences in the areal resolution and data sources.

Conversely to Fig. 3, Fig. 4 shows a strong negative correlation between emissions generation and poverty, signifying that households in the poorest areas emit the least NO_x and PM, whilst the least poor areas emitted the most. The correlation presented in Fig. 3 indicates significant social inequality concerning exposure, however, Fig. 4 indicates that traffic pollution within those poorer areas is likely to be caused by those living in relatively more affluent areas, further compounding this environmental injustice. Furthermore, the new evidence presented in Fig. 4 contradicts the findings of Mitchell and Dorling (2003) who concluded that the poor were substantially contributing to the emissions to which they were exposed through owning older, more polluting vehicles.

3.3. Pollution and car ownership

The plots in Fig. 5 explore the relationship between household access to a vehicle and concentrations of NO_2 and confirm that those areas with households least able to access a vehicle also have the highest pollution concentrations, and conversely those areas with the highest household vehicle access have the lowest concentrations. Furthermore, as illustrated in Fig. 6, households in poverty are much less likely to have any car (left) let alone multiple cars (right). Some caution should be applied here as the PSE poverty calculation uses a proportion (18.4%) of 'households with no car' in its composition, therefore there may be some inherent correlation

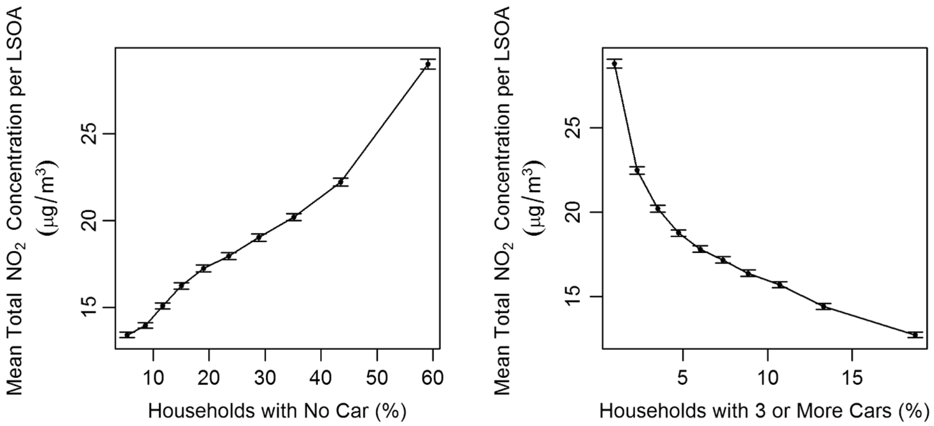

Fig. 5. NO_2 concentrations against households without access to a car (left) and with access to 3+ cars (right). Error bars = 95% CIs.

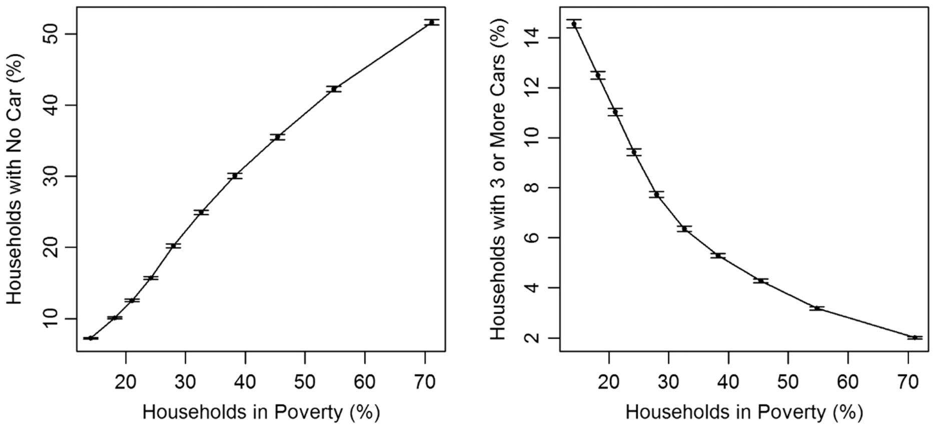

Fig. 6. Households in poverty against households without access to a car (left) and with access to 3+ cars (right). Error bars = 95% CIs.

of this poverty metric with vehicle accessibility, however the weight applied to car ownership is less than in other deprivation indicators.

3.4. Poverty and emissions

Using the 'MOT' dataset, further analysis of household poverty was undertaken against the mean NO_x emission factor for vehicles within each LSOA (Fig. 7). Similar analysis was also undertaken for PM and CO_2 (Fig. 8). Apart from a lower mean emission factor in the decile representing the fewest households in poverty, there is a strong negative correlation between poverty status and NO_x

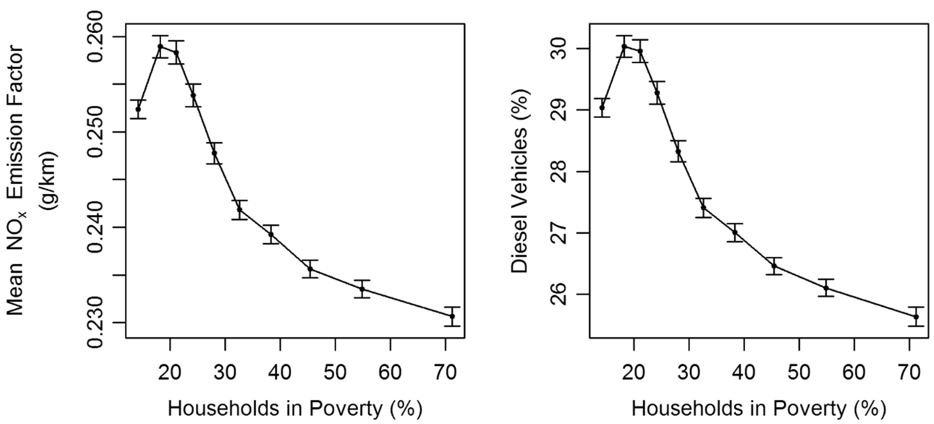

Fig. 7. Households in poverty against mean NO_x emission factor (left) and percentage of private diesel vehicles (right). Error bars = 95% CIs.

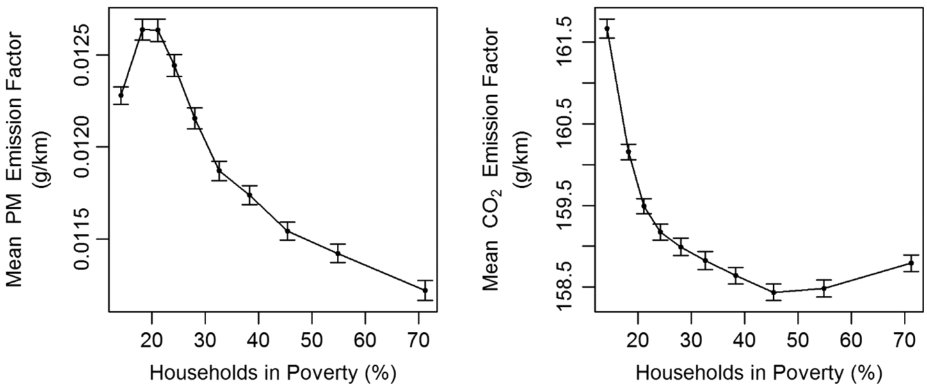

Fig. 8. Households in poverty against mean PM emission factor (left) and mean CO_2 emission factor (right). Error bars = 95% CIs.

emission factor (Fig. 7, left), indicating that, not only are households in poorer areas likely to own fewer vehicles, but that those vehicles also tend to produce lower, per km, NO_x emissions than the average vehicle owned in less poor areas. This is consistent with the pattern seen in an analysis of PM emission factors (Fig. 8, left) and, to a lesser degree, CO_2 emission factors (Fig. 8, right). For NO_x and PM, this relationship appears to be closely related to ownership of diesel vehicles, which have higher NO_x and PM emissions factors than petrol vehicles, and which are less likely to be owned in poorer areas (Fig. 7, right). This finding contradicts Mitchell and Dorling's assumption (and perhaps perceived wisdom) that households in poorer areas drive more polluting vehicles. Also, while Fig. 9 (left) shows that households in poorer areas are more likely to have older vehicles, the differential in average vehicle age between the poorest and least poor areas is only 1.2 years. Furthermore, Fig. 9 (right) reveals, perhaps more intuitively, that poorer households tend to drive less far, which, together with the lower mean NO_x emission factors (Fig. 7, left) results in lower total vehicle emissions from poorer households (Fig. 4, left). A statistical assessment of the relative importance of emission factor and distance driven on total NO_x emissions (using the R package relaimpo (Grömping, 2015)) suggests that variation in distance driven accounts for 84% of variation in overall emissions compared to only 16% for the 'cleanliness' of the vehicle (as indicated by the emission factor).

4. Discussion

Some 16 years after Mitchell and Dorling's initial work (2003) this study presents a decadal review of progress in equalizing air quality injustices in England and Wales. It has used more recent census and pollution data to investigate the contemporary relevance of the findings of the original study. These new analyses contribute to the current public debate on air quality health and environmental impacts and in so doing challenge previous assertions and assumptions.

The data presented here have identified relationships between car ownership, poverty, age and NO_2 exposure in Wales and England. By utilising emissions of NO_x derived from both the NAEI and the MOT dataset, new data have been created that serve to illustrate the relationship between the area of domicile and pollutant emissions generated by residents' vehicle use. In addition, the quality of data presented here at LSOA level is at least four times finer than that available from ward level analysis.

The spatial, demographic and socioeconomic heterogeneity of population exposure to air pollution is well established (Mitchell and Dorling, 2003; Dietz and Atkinson, 2005; Gegisian et al., 2006; Pye et al., 2006; Briggs et al., 2008; Namdeo and Stringer, 2008).

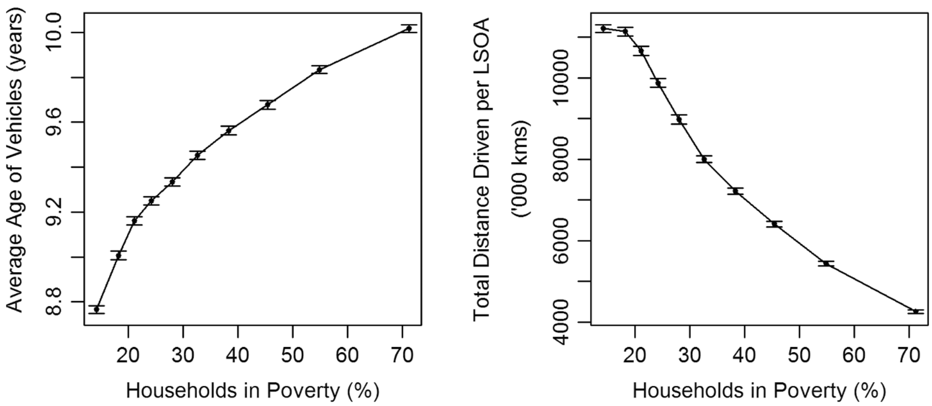

Fig. 9. Households in poverty against the average age of private vehicles per LSOA (left) and total distance driven per LSOA (right). Error bars = 95% CIs.

However, the environmental justice argument has been less clear given the difficulties with identifying responsibility for the creation of pollution. An important outcome of this work is the confirmation of the relationship of LSOAs with higher proportions of young families and households in poverty (those least able to move to cleaner areas) and both high NO_x emissions and elevated concentrations of NO_2. These areas also have a higher prevalence of non-car ownership and a lower prevalence of multiple-car households.

Although absolute concentrations of pollution may have reduced slightly over the decade between studies, the relationship appears to have strengthened with a much clearer correlation between poverty and NO_2 concentrations than previously seen. A more rounded representation of social and health impacts of road transport has been established through using the relationship between road NO_x emissions and LSOAs. It is apparent that this relationship is stronger than that established using only NO_2 concentrations. This suggests that inequalities between the poorest and least poor areas may be even greater than first appreciated.

The new 'MOT' data analysis presented here adds a unique dimension to this understanding of environmental justice. By calculating emissions based on actual mileage and emission factors for all of the vehicles in England and Wales individually, this more robust analysis has also found that those LSOAs with more households defined as in poverty also have lower total private vehicle emissions per household (in addition to lower numbers of vehicles per household). This is due to households in poorer areas driving less far overall, as well as having vehicles with lower, per km, mean emission factors. Although households in poorer areas do tend to drive older vehicles, they are, on average, only just over a year older than those in the least poor areas. This may indicate that the least poor, multicar-owning households' second, third or fourth cars are likely to be even older. Furthermore, the greater proportion of diesel vehicles (which emit higher levels of NO_x and PM per km) together with the greater mileages driven by vehicles, make households in the least poor areas the greatest contributors to road traffic emissions.

This work has confirmed that environmental injustice is occurring in England and Wales due to air pollution (emissions and concentrations) from road traffic. The research has shown that the most elevated levels of NO_2 and other pollutants occur in LSOAs containing the poorest households. These households contribute significantly less to air pollution than the least poor households. Furthermore, the economic circumstances of those living in the poorest households means that they are less capable of altering their situation, i.e. by moving to a less polluted area or purchasing newer, less polluting vehicles.

One of the limitations of the analytical approach presented here is that differentiation at scales below that of each broadly homogeneous LSOA is not possible and thus variability in the characteristics of a population, or their exposure to pollutants, cannot be represented. Another limitation of the method relates to the time household residents spend within the LSOA. Considerable amounts of time may be spent away from the LSOA attending, for example, work, school or leisure activities yet it is assumed that the concentration within the LSOA represents a good proxy for population exposure. Whilst UK policy (Defra, 2016) acknowledges residential location as a proxy for annual mean exposure it is clear that further work is needed to refine and improve the fraction of exposure associated with different activities. It is also important to note that those most vulnerable (i.e. young children, the elderly and the infirm) are more likely to spend longer at home than other sectors of the population.

The pollutant data utilised in this study are taken from UK national datasets used for compliance monitoring and other purposes. These are the best available datasets within the UK but there are, of course, questions relating to precision and accuracy amongst other features. Ongoing national action seeks to address these deficiencies. One final uncertainty relates to the emission factors used in the calculations where studies (e.g. Hooftman et al. 2018; O'Driscoll et al., 2018; DfT, 2016; Williams et al., 2016) have shown that real world emissions differ considerably from type approval data. These uncertainties and assumptions do not undermine the findings of this paper, although it is acknowledged that further methodological improvements will enhance the quality of outcomes. The spatial analysis of pollutant emissions and concentrations as NO_x and NO_2 may well underestimate the actual emissions and concentration data for the most polluted LSOAs as monitoring data do not suggest the same degree of concentration reduction as the modelled data used here. The inaccuracies in emission factors at the scale of individual vehicles are also likely to mask a greater level of inequality, especially with regard to the underperformance of emission control technologies in newer vehicles that are more likely to be owned by households in the least poor areas.

5. Conclusion

Inequalities in exposure to air pollution across England and Wales have been identified in this work. These variations in exposure are stronger than those identified in 2003 and it can further be concluded that there are significant environmental justice issues with regard to generation of traffic pollution. This inequality in exposure has a further dimension of concern in that the young, who experience the most susceptibility to air pollution, have the least agency in their place of residence. Over the last decade, knowledge and understanding about the health risks from road traffic, particularly for nitrogen dioxide and noise, mean that the known consequences of these inequalities is even greater than when the initial study was undertaken.

This work helps to reinforce the arguments proposed by others (Hull, 2008; Docherty and Mackie, 2010), but not adequately accounted for in the delivery of UK air quality policy. That is, that the underlying air quality problems experienced by the population result from decisions made in land use, economic development and transport planning, that collectively result in very unequal risks of exposure, exacerbated by the poverty status of those in the poorest LSOAs. This inequality has two dimensions, relating firstly to the responsibility for emissions, and secondly to the exposure and vulnerability of citizens (Chatterton and Barnes, 2016); essentially in respect of traffic emissions the poor pollute the least and are polluted the most. We recommend that governments should take a more social approach to efforts to reduce air pollution as opposed to current approaches that rely predominantly on technological improvements and individual choices.

Future work to further develop the findings of this paper consists of two key streams of research. Firstly, it is intended to extend this analysis to incorporate household emissions from domestic energy consumption. The second, much more challenging stream, is to make links between the attribution of emissions to households presented in this paper, with the locations where these emissions are actually occurring on the road network. This is being done with a range of tools including transport models, Automatic Number Plate Recognition (ANPR) systems and on-board vehicle telematics.

However, despite the ongoing research programme, the evidence presented in this paper with regard to the disparities between exposure to and generation of traffic-related pollution, serves to strengthen the environmental justice argument and more clearly lay the problem at the door of households in more affluent areas, who have access to more vehicles with higher average emissions and which are driven further, thereby generating an inequitable contribution to traffic-related pollution. This research has highlighted the environmental justice and social inequality issues of air pollution and it is clear that policies to remediate pollution would benefit by taking greater account of the differences between those who cause the problems and those who bear the costs. It is clear that Governments in the UK and elsewhere are struggling with devising and implementing effective air quality management policies and this work has highlighted an urgent area for policy attention and integration.

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Declaration of Competing Interest

None.

References

Appleyard, D., Lintell, M., 1972. The environmental quality of city streets: the residents' viewpoint. J. Am. Inst. Plann. 38, 84–101.

Babisch, W., Beule, B., Schust, M., Kersten, N., Ising, H., 2005. Traffic noise and risk of myocardial infarction. Epidemiology 16, 33–40.

Berthoud, R., Bryan, M., 2010. Income, deprivation and poverty: a longitudinal analysis. J. Soc. Policy 40 (01), 135–156. http://www.journals.cambridge.org/abstract_S0047279410000504.

Briggs, D., Abellan, J.J., Fecht, D., 2008. Environmental inequity in England: Small area associations between socio-economic status and environmental pollution. Soc. Sci. Med. 67, 1612–1629.

Chatterton, T., Barnes, J., Wilson, R.E., Anable, J., Cairns, S., 2015. Use of a novel dataset to explore spatial and social variations in car type, size, usage and emissions. Trans. Res. D-Tr. E. 39, 151–164. http://eprints.uwe.ac.uk/26329 (accessed 25 August 2015).

Chatterton, T., Barnes, J., 2016. A social and spatial analysis of emissions from private vehicle use in Great Britain. In: In: Longhurst, J.W.S., Brebbia, C.A., Barnes, J.H. (Eds.), Air Pollution XXIV, WIT Transactions on Ecology and the Environment, vol. 207. pp. 99–110.

COMEAP (Committee on the Medical Effects of Air Pollutants), 2015. Statement on the Evidence for the Effects of Nitrogen Dioxide on Health. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/411756/COMEAP_The_evidence_for_the_effects_of_nitrogen_dioxide.pdf (accessed 12 March 2015).

COMEAP (Committee on the Medical Effects of Air Pollutants), 2018. Associations of Long-Term Average Concentrations of Nitrogen Dioxide with Mortality. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/734799/COMEAP_NO2_Report.pdf (accessed 2 November 2018).

Defra, 2011. Air Pollution in the UK 2010. https://uk-air.defra.gov.uk/library/annualreport/viewonline?year=2010_issue_3#report_pdf (accessed 16 November 2018).

Defra, 2016. LAQM Technical Guidance, TG(16). Box 1.1, pp. 1–8.

Defra, 2018. LAQM Support, Background Maps. https://laqm.defra.gov.uk/review-and-assessment/tools/background-maps.html.

Department for Communities and Local Government, 2010. English Indices of Deprivation 2010. https://data.gov.uk/dataset/index-of-multiple-deprivation (accessed 10 June 2014).

Department for Communities and Local Government, 2015. The English Index of Multiple Deprivation (IMD) 2015 – Guidance. Department for Communities and Local Government, London. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/464430/English_Index_of_Multiple_Deprivation_2015_-_Guidance.pdf (accessed: 22/09/16).

Department for Transport, 2016. Vehicle Emissions Testing Programme, Ref: ISBN 9781474131292, P002803657 04/16, Cm 9259. https://www.gov.uk/government/publications/vehicle-emissions-testing-programme-conclusions (accessed 21 April 2016).

Dickerson, A., Peirson, J., Vickerman, R., 2000. Road accidents and traffic flows: an econometric investigation. Economica 67, 101–121.

Dietz, S., Atkinson, G., 2005. Public perceptions of equity in environmental policy: traffic emissions policy in an English urban area. Local Environ. Int. J. Justice Sustain. 10, 445–459.

Docherty, I., Mackie, P., 2010. Planning for transport in the wake of Stern and Eddington. Region. Stud. 44 (8), 1085–1096. https://doi.org/10.1080/00343400902736550.

Dorling, D., Rigby, J., Wheeler, B., Ballas, D., Thomas, B., Fahmy, E., Gordon, D., Lupton, R., 2007. Poverty, wealth and place in Britain, 1968 to 2005. The Policy Press for the Joseph Rowntree Foundation. https://www.jrf.org.uk/sites/default/files/jrf/migrated/files/2019-poverty-wealth-place.pdf (accessed 24 October 2016).

European Commission, 2014. Press Release Database, Brussels, 20 February. http://europa.eu/rapid/press-release_IP-14-154_en.htm (accessed 20 February 2014).
Experian, 2011. Household Income 2011, Data Profile, UK Data Archive Study Number 5738 - Experian Demographic Data, 2004–2011. http://doc.ukdataservice.ac.uk/doc/5738/mrdoc/pdf/5738_household-income_2011.pdf (accessed 6 December 2015).
Gegisian, I., Grey, M., Irwin, J., Longhurst, J.W.S., 2006. Environmental justice consequences of the UK's local air quality management (LAQM) system. In: Longhurst, J.W.S., Brebbia, C.A. (Eds.), Air Pollution XIV. WIT Press, Southampton and Boston, pp. 175–183.
Grömping, U., 2015. 'relaimpo' Package to Calculate Relative Importance Metrics for Linear Models. https://cran.r-project.org/web/packages/relaimpo/relaimpo.pdf.
Gordon, D., 2006. The concept and measurement of poverty. In: Pantazis, C., Gordon, D., Levitas, R. (Eds.), Poverty and Social Exclusion in Britain. The Policy Press, pp. 29–69.
Gordon, D., Pantazis, C., 1997. Breadline Britain in the 1990s. Ashgate, Aldershot.
Hart, J., Parkhurst, G., 2011. Driven to excess: Impacts of motor vehicles on the quality of life of residents of three streets in Bristol UK. WTPP 17, 12–30.
Hick, R., 2013. On 'Consistent' poverty. Soc. Indicat. Res. 118 (3), 1087–1102. https://doi.org/10.1007/s11205-013-0456-y.
Hillyard, P., Kelly, G., McLaughlin, E., Patsios, D., Tomlinson, M., 2003. Bare necessities - Poverty and Social Exclusion in Northern Ireland (Democratic Dialogue).
Hooftman, N., Messagie, M., Van Mierlo, J., Coosemans, T., 2018. A review of the European passenger car regulations – real driving emissions vs local air quality. Renew. Sustain. Energy Rev. 86, 1–21.
Hull, A., 2008. Policy integration: what will it take to achieve more sustainable transport solutions in cities? Transp. Policy 15 (2), 94–103.
JAQU, 2017. UK plan for tackling roadside nitrogen dioxide concentrations, detailed plan. Joint Air Quality Unit – Department for the Environment, Farming and Rural Affairs and Department for Transport, London, UK. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/633270/air-quality-plan-detail.pdf (accessed 9 August 2017).
JAQU, 2018. Supplement to the UK plan for tackling roadside nitrogen dioxide concentrations. Joint Air Quality Unit – Department for the Environment, Farming and Rural Affairs and Department for Transport, London, UK. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/746100/air-quality-no2-plan-supplement.pdf (accessed 2 November 2018).
Jarvis, D.J., Adamkiewicz, G., Heroux, M.E., Rapp, R., Kelly, F.J., 2010. Nitrogen dioxide. In: WHO Guidelines for Indoor Air Quality: Selected Pollutants. World Health Organization, Geneva. http://www.ncbi.nlm.nih.gov/books/NBK138707/ (accessed 21 February 2016).
Jephcote, C., Chen, H., Ropkins, K., 2016. Implementation of the Polluter-Pays Principle (PPP) in local transport policy. J. Transp. Geogr. 55, 58–71.
Jerrett, M., Burnett, R.T., Kanaroglou, P., Eyles, J., Finkelstein, N., Giovis, C., Brook, J.R., 2001. A GIS – environmental justice analysis of particulate air pollution in Hamilton, Canada. Environ. Plan. A 33, 955–973.
Knox, E.G., 2005. Oil combustion and childhood cancers. J. Epidemiol. Commun. Health 59, 755–760.
Mack, J., Lansley, S., 1985. Poor Britain. George Allen & Unwin.
Mitchell, G., Dorling, D., 2003. An environmental justice analysis of British air quality. Environ. Plan. A 35, 909–929.
Mitchell, G., Norman, P., 2012. Longitudinal environmental justice analysis: co-evolution of environmental quality and deprivation in England, 1960–2007. Geoforum 43 (1), 44–57. http://linkinghub.elsevier.com/retrieve/pii/S0016718511001485.
Namdeo, A., Stringer, C., 2008. Investigating the relationship between air pollution, health and social deprivation in Leeds, UK. Environ. Int. 34, 585–591.
National Atmospheric Emissions Inventory (NAEI), 2017. Emission maps 2011. http://naei.beis.gov.uk/data/map-uk-das.
Nolan, B., Whelan, C.T., 2010. Using non-monetary deprivation indicators to analyze poverty and social exclusion: lessons from Europe? J. Policy Anal. Manage. 29 (2), 305–325. https://doi.org/10.1002/pam.20493.
O'Driscoll, R., Stettler, M., Molden, N., Oxley, T., ApSimon, H., 2018. Real world CO2 and NO_x emissions from 149 Euro 5 and 6 diesel, gasoline and hybrid passenger cars. Sci. Total Environ. 621, 282–290.
Office for National Statistics, 2013. 2011 Census Analysis - Comparing Rural and Urban Areas of England and Wales. http://www.ons.gov.uk/ons/dcp171776_337939.pdf (accessed 22 November 2013).
Office for National Statistics, 2016. Beginners Guide to the Census. http://www.ons.gov.uk/ons/guide-method/geography/beginner-s-guide/census/super-output-areas–soas-/index.html (accessed 21/09/16).
Office for National Statistics, 2016. 2011 Census: Aggregate data (England and Wales). UK Data Service Census Support. http://infuse.mimas.ac.uk (accessed 19 February 2016).
Openshaw, S., 1984. Ecological fallacies and the analysis of areal census data. Environ. Plan. A 16, 17–31.
Pikora, T., Giles-Corti, B., Bull, F., Jamrozik, K., Donovan, R., 2003. Developing a framework for assessment of the environmental determinants of walking and cycling. Soc. Sci. Med. 56, 1693–1703.
Pimpin, L., Retat, L., Fecht, D., de Preux, L., Sassi, F., Gulliver, J., et al., 2018. Estimating the costs of air pollution to the National Health Service and social care: an assessment and forecast up to 2035. PLoS Med 15 (7), e1002602. https://doi.org/10.1371/journal.pmed.1002602.
Pye, S., King, K., Sturman, J., 2006. Air Quality and Social Deprivation in the UK: An Environmental Inequalities Analysis. Final Report to Department of Environment, Food and Rural Affairs, Didcot.
R Core Team, 2015. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. Vienna, Austria. https://www.R-project.org (accessed 10 December 2015).
Samet, J.M., White, R.H., 2004. Urban air pollution, health, and equity. J. Epidemiol. Commun. health 58 (1), 3–5.
Treanor, M.C., 2013. Deprived or not deprived? Comparing the measured extent of material deprivation using the UK government's and the Poverty and Social Exclusion surveys' method of calculating material deprivation. Qual. Quant. 48 (3), 1337–1346. https://doi.org/10.1007/s11135-013-9838-0.
Wakeling, D., Passant, N.R., Murrells, T.P., Pang, Y., Thistlethwaite, G., Walker, C., Garcia, J.M.R., Webb, J., Brown, P., Del Vento, S., Misra, A., Hobson, M., Pridmore, A., Dore, C., Misselbrook, T., 2016. UK Informative Inventory Report (1990 to 2014), 13 March. Ricardo Energy and Environment. http://naei.defra.gov.uk/reports/reports?report_id=896 (accessed 15 March 2016).
Walker, G., Mitchell, G., Fairburn, J., Smith, G., 2005. Industrial pollution and social deprivation: evidence and complexity in evaluating and responding to environmental inequality. Loc. Environ. 10 (4), 361–377. https://doi.org/10.1080/13549830500160842.
WHO, 2014. 7 Million Premature Deaths Annually Linked to Air Pollution, News Release. http://www.who.int/mediacentre/news/releases/2014/air-pollution/en/ (accessed 25 March 2014).
WHO, 2018. 9 out of 10 People Worldwide Breathe Polluted Air, But more Countries are Taking Action, News release. https://www.who.int/news-room/detail/02-05-2018-9-out-of-10-people-worldwide-breathe-polluted-air-but-more-countries-are-taking-action (accessed 2 May 2018).
WHO Regional Office for Europe, OECD, 2015. Economic Cost of the Health Impact of Air Pollution in Europe: Clean Air, Health and Wealth. WHO Regional Office for Europe, Copenhagen. http://www.euro.who.int/__data/assets/pdf_file/0004/276772/Economic-cost-health-impact-air-pollution-en.pdf (accessed 2 November 2018).
Williams, B., Barnes, J.H., Chatterton, T.J., Hayes, E.T., Longhurst, J.W.S., 2016. A critical review of the robustness of the UK government's air quality plan and expected compliance dates. In: In: Longhurst, J.W.S., Brebbia, C.A., Barnes, J.H. (Eds.), Air Pollution XXIV, WIT Transactions on Ecology and the Environment, vol. 207. WIT Press, Southampton and Boston, pp. 1–9.
Woolley, H., 2004. The Value of Public Space: How High Quality Parks and Public Spaces Create Economic, Social and Environmental Value. CABE Space, London.