Environment and Planning A 2002, volume 34, pages 695 – 716

DOI:10.1068/a34184

Modelling environmental equity: access to air quality in Birmingham, England

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Received 5 June 2001; in revised form 21 September 2001

Abstract. Many studies in the USA have noted inequities with regard to the socioeconomic status or racial character of communities and their relative exposure to environmental disamenities. In this paper the authors focus particularly on the environmental equity of air pollution in the English city of Birmingham. Using statistical methodologies they examine the pattern of exposure to two key air pollutants: carbon monoxide (CO) and nitrogen dioxide (NO_2) across certain population groups in the city. Estimated emission levels of CO and NO_2 were mapped by using modelled associations between vehicle densities and measured emissions at existing monitoring stations. These data were input to a geographical information system (GIS) for subsequent comparisons with population maps. Three types of variables were considered to distinguish possibly disadvantaged populations: age profile, ethnic make-up, and poverty indicators. From the 1991 Census, relevant statistics were derived for each enumeration district in the city. No relationship could be established on the age variable (that is, neither children nor pensioners appear to differ from the general population in their likely exposure patterns). However, there was a striking relationship between modelled emissions and poverty indicators and ethnicity. The effects are difficult to separate out but there is strong evidence to suggest that the two factors (poverty and ethnicity) operate in an independent manner. The implications of these findings, with regard to the causes of the disparities and the likely impacts of possible efforts to improve air quality in Birmingham, are discussed.

Introduction

Recent decades have seen increased recognition that biases within environmental policymaking and regulatory processes, combined with discriminatory market forces, may lead to disproportionate exposure to environmental toxins amongst certain population groups. In the context of examining such discrepancies, the terms *environmental equity* and *environmental justice* are sometimes used synonymously (Harding and Holdren, 1993), but often a distinction is made. Lavelle (1994) suggests that environmental equity implies an equal sharing of risk burdens, but not necessarily a reduction in the total burden of pollution. Cutter (1995) argues that environmental justice implies much more, including remedial action to correct an injustice imposed upon a specific subgroup society. Perlin et al (1995) further advocate that environmental justice should achieve adequate protection from harmful hazardous agents for everyone, regardless of ethnicity, age, or socioeconomic status.

In the current political context the above terms refer more specifically to the distribution of health risks resulting from exposure to toxic substances in the residential or occupational environments of different racial, ethnic, or socioeconomic groups.

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The hazardous environmental exposure often associated with environmental inequities include multiple sources of air pollution, waste treatment and disposal facilities, water-quality concerns, and the cumulative impacts associated with living in urban or rural areas.

Studies to document the relationship between the geographic distribution of environmental pollution and minority populations were published in the USA during the 1970s (for example, CEQ, 1971). Environmental equity became a national issue in 1982 when attention was focused on the proposed siting of a landfill for polychlorinated biphenyls (PCBs) in a predominantly black county in North Carolina (USGA, 1983). More recently, a plethora of US-based empirical studies (including Brajer and Hall, 1992; Breen, 1993; Brooks and Sethi, 1997; Burke, 1993; Morello-Frosch et al, 2001; Perlin et al, 1995; Zimmerman, 1993) have confirmed that minority racial groups are more likely than are white people to live in areas close to toxic waste facilities or with higher than average pollutant emissions.

To understand the processes by which environmental inequalities may be operating, there is a need to separate ethnic from poverty effects. Although the assumption may be made that more impoverished populations live in areas with higher levels of contamination, empirical studies have found the relationship to be inconsistent. Perlin et al (1995) in the USA and Jerrett et al (1996) in Canada reported positive relationships between income and pollutant emissions. Similarly, McLeod et al (2000) observed that densely populated urban areas in the United Kingdom with the highest air pollutant levels also tended to contain predominantly wealthy populations.

Morello-Frosch et al (2001) undertook a multivariate analysis that verified the joint importance of both income *and* racial factors in calculated cancer risks. Zimmerman (1993) noted that a disproportionate number of inactive hazardous waste disposal sites were located in predominantly black and Hispanic neighbourhoods in the USA, but they also observed that the percentage of persons below the poverty line in these communities largely matched that of the nation as a whole. This finding suggests that racial character rather than poverty may have biased the location of the disposal sites in those communities. However, Graham et al (1999) note that there may also be historical factors to consider. They examined the population surrounding 82 coke plants or oil refineries in the USA and found a disproportionate number of poor and nonwhite residents in the most recent census. Nevertheless, Graham et al noted that the plants and refineries were built near the year 1900, when the populations in the areas were largely white, suggesting that changes in the racial character of the communities had taken place since the construction of the refineries.

Relatively little research has been undertaken to examine the relationship between air quality, ethnicity, and poverty outside the USA. The US lead is, in some part, a result of long-established and lengthy legislation relevant to air pollution in that country. In the United Kingdom, since December 1997, each local authority has been charged with the task of reviewing and assessing air quality in its area. This involves measuring air pollution and trying to predict how it will change in the future. The aim of the review is to ensure that the national air quality objectives, laid out in the Air Quality Strategy published by the government in January 2000 (DETR, 2000), will be achieved. If a local authority finds any places where the objectives are not likely to be achieved, it must declare an Air Quality Management Area (AQM) there. An AQM may range in size from a few streets to an entire urban zone.

The requirements for the development of AQMs set out in the Air Quality Strategy has meant that a considerable amount of work is ongoing within UK local authorities to model spatial variations in air quality across small geographical areas. By combining the output of this work with information on population demographic characteristics and measures of exposure in a geographical information system (GIS) there is, for the first time, the potential to assess whether the associations between ethnicity, poverty, and air quality observed in the USA are also present in the United Kingdom.

Using the city of Birmingham as a case-study area, we examine environmental inequities in exposure to two key pollutants: carbon monoxide (CO) and nitrogen dioxide (NO_2). A model is developed to map concentrations of the two pollutants across the city. Using statistical methodologies we then compare these concentrations with the geographical distribution of communities of different ethnicity, age, and deprivation (poverty) related characteristics. Finally, the policy implications of the funding of these comparisons are discussed.

Methodology

The study area

The boundaries of the city of Birmingham were used to define the study region area (see inset on figure 1 below). Birmingham is one of the seven metropolitan local authorities that form the West Midlands region. There were just under one million residents in the city of Birmingham recorded in the 1991 UK Census of Population. Birmingham is fortunate in benefiting from an extensive monitoring network providing automatic air pollution measurements and NO_2 diffusion tube measurements. Thus the city possesses a robust set of data for the assessment of spatial variations in emissions of key pollutants.

Data sources

Information on the demographic structure of the study-area population was extracted from the UK census records from the archive available at Manchester Information and Associated Services (MIMAS), Manchester Computing, University of Manchester, Manchester. This was combined with modelled concentrations of airborne concentrations of two key air pollutants—CO and NO_2—so that measures of equity of exposure to pollution could be calculated.

Population socioeconomic characteristics

Measures of spatial variations in the socioeconomic characteristics of neighbourhood populations in Birmingham were extracted from the 1991 Census. Indicators were obtained at the enumeration district (ED) level, the smallest spatial unit for which census data are routinely available in the United Kingdom. In total there were 1950 EDs within the study area. However, owing to national confidentiality requirements, complete information was not available on the population of ten EDs. Hence, 1940 EDs, with a medium population of 496 residents and typical area of about 8.5 ha, were included in the final analysis.

A variety of socioeconomic indicators were directly extracted or derived from the census (table 1, over). As there is no explicit income question in the census, a number of variables were interpreted as proxies of poverty and affluence. In particular, home-ownership, car ownership, and social class have proven to be useful indicators in the past. There is a social class designator in the census, based upon the occupation of each head of household. Social class 5 includes individuals employed in unskilled profession; social class 4 includes partly skilled workers. Social class 1 refers to professional people, and social class 2 refers to people in managerial or technical positions. These groups were combined into two variables, SC12 and SC45, measuring the percentage of households with a head in classes 1 and 2 (an indicator of affluence), or in classes 4 and 5 (an indicator of poverty) in each ED.

Table 1. Variables extracted or derived from the 1991 Census, for each enumeration district; unless otherwise noted, all variables are expressed as percentages of population.

Variable name	Description	Range of observed values		
		min.	med.	max.
Ethnicity				
BANG	Bangladeshi population	0	0	35.96
INDN	Indian populations	0	1.54	67.38
PAK	Pakistani population	0	0.40	85.11
TASIAN	Total Asians (including the three preceding and other groups)	0	3.09	87.82
BLACK	Black (African and Caribbean population)	0	3.32	43.43
WHITE	White population	4.95	92.10	100.0
Social characteristics				
MUNEM	Male unemployment	0	15.98	65.63
NOCAR	Households without a car	0	47.87	93.75
OWNHO	Homeowners	0	60.95	100
RET	Pensioners (women $\geqslant 60$ years and men $\geqslant 65$ years old)	0.92	17.71	84.51
SC12	Social classes 1 or 2	0	23.08	100
SC45	Social classes 4 or 5	0	21.43	100
U5	Under 5 years	0	7.16	22.97
U15	Aged 5–14 years	0	21.80	60.17
Deprivation				
CARST	Carstairs deprivation index	−5.50	−0.29	9.66
JARM	Jarman underprivileged area index	−20.22	−0.40	43.15
TOWNS	Townsend deprivation index	−7.79	0.48	7.28

Note: min., minimum; med., median; max., maximum.

In addition to individual census variables, several deprivation indices were also calculated for each ED. The Townsend deprivation score (Townsend et al, 1988), the Jarman underprivileged areas index (Jarman, 1984), and the Carstairs index (Carstairs and Morris, 1989) were all employed. The three measures were standardised onto the same scale by using Z-scores, such that the scores centre around zero: negative scores indicate less deprived (and hence more affluent) areas, whereas positive scores indicate neighbourhoods with higher levels of deprivation. The Carstairs measure proved particularly significant in subsequent analysis and merits further description. Each value in the Carstairs index is a composite score based on four variables (unemployed male residents aged over 16 years as a proportion of all economically active male residents aged over 16 years; persons in households with one or more persons per room as a proportion of all residents in the households; residents in households with no car as a proportion of all residents in households; and residents in households with an economically active head of household in social class 4 or 5 as a proportion of all residents in households).

Ethnicity

The use of secondary data sources, such as the UK census, to determine the ethnic character of populations is not simple, as the dominant approach to the study of ethnic minority populations in the United Kingdom focuses on the relations between individuals within groups. Whereas the term 'race' may be treated as a distinct phenomenon linked to colour or racial categorisation (Rex, 1970), the analytical validity of the categorisation has been questioned (Miles, 1980). Ethnicity, in contrast, is associated with a sense of belonging to a particular group (Anthias, 1992). As the categorisations in the UK census are based on self-reported characteristics, we have chosen to use the term 'ethnicity' rather than 'race' here. White, Asian (including persons of Indian, Pakistani, or Bangladeshi origin), and black (predominantly Caribbean but also African ancestry) ethnic groups are particularly represented in Birmingham, and information on the population of each ethnic group was extracted for every ED from the census.

Age

Age-groups extracted from the census included the population of children under 5 years old, children under 15 years old, and retired persons (aged 60 or more years for women, and 65 or more years for men).

Air pollution

Information on modelled concentrations of two pollutants—average hourly CO and annual (hourly) NO_2 (both expressed in $\mu g\ m^{-3}$)—were supplied by Birmingham City Council. In urban environments, both CO and NO_2 are emitted primarily from vehicle exhausts. CO is a gas formed by the incomplete combustion of carbon-containing fuels. Chronic exposure to elevated levels of CO may increase the risk of heart problems in predisposed individuals (Peters et al, 2000). As the main source of CO in the United Kingdom is motor traffic (almost 89% of annual emissions), levels are highest near to heavily trafficked roads (DETR, 2000). Concentrations fall fairly rapidly with distance from roads, such that CO is very much a localised pollutant. NO_2, as with CO, is largely associated with vehicle transport, although the pollutant is less localised. Within the United Kingdom, road transport accounts for around 50% of emissions of nitrogen oxides. Exposure to NO_2 can bring about reversible effects on lung function and airway responsiveness. It can also increase reactivity to natural allergens. NO_2 exposure may also put children at risk of respiratory infections and may lead to poorer lung function in later life.

Although data on actual concentrations of air pollutants were available for monitoring stations within the city, these provided information only on conditions in the immediate vicinity of each station. The requirement for this study was a map depicting the manner in which air quality varied across the whole of the city. In order to produce this, a model was developed using a proprietary software package (Airviro, from the Swedish Meteorological and Hydrological Institute, Norrköping), which incorporated information about land use and pollution sources. The model assumes a Gaussian dispersion of pollutants to estimate concentrations at 2 m above ground level. The implication of this is that it is assumed that pollutants will disperse evenly from their sources.

Owing to the importance of road transport in determining emissions of CO and NO_2, traffic flow information was the key data source used to model their concentrations in Airviro. Hence the model worked by first estimating the amount of each pollutant emitted from every road section in the city, and second by predicting the manner in which that pollutant would disperse into the atmosphere surrounding the road. Data on traffic flows on road links within the study area were supplied to Birmingham City Council by the West Midlands Joint Data Team, Solihull, Birmingham. The road data were received in spreadsheets, with each record containing information on grid reference, link length, peak hours flows, vehicle types, and traffic speed. The average daily traffic flow was calculated by multiplying the peak hourly flows by a factor of twelve. Revised pollutant-specific guidance [LAQM.TG4(00)] from the Department of the Environment, Transport and the Regions (DETR) provided help on how to calculate the traffic volume thresholds above which the emission of a particular pollutant is considered to be a significant health risk in public health terms. For Birmingham the calculations indicate that the thresholds are: 15 000 vehicles per day for NO_2, 15 000 vehicles per day for PM10 particles (particles with a diameter less than 10 μm), and 80 000 vehicles per day for CO. All the links that met these criteria were plotted on an Arcview (ESRI Inc, Redlands, CA) GIS system and overlain on a digital Ordnance Survey street map of the area. Each link was then defined with its road name and/or road number and a description of its starting and finishing points. From this, scaling factors were used to estimate the emissions of CO and NO_2 from each link, based on the link's traffic flow. The output from the model was then calibrated by using actual data on pollutant concentrations from the monitoring stations. The resulting modelled distributions are shown in figure 1 for both CO and NO_2.

It is important to emphasise that the pollutant information used in this analysis reflects modelled emissions rather than known individual exposure to air pollution. Sexton et al (1993) consider emissions and exposure data to tend to correlate very well, but it is known that the two will differ from person to person depending on personal mobility, time spent outdoors, and the level of activity. A superior approach would be an internal dose – response model, but suitable data were not available. Moreover, given that this analysis was undertaken with population-based rather than individual-based datasets the use of aggregate measures is acceptable.

Population-weighted average emissions for each ED

Figure 1 shows the mapped distribution of estimated CO and NO_2 emissions in the study area. In order to convert these ambient air quality indicators to estimates of population dose, a surface of population derived from the 1991 Census of Population, providing estimates of the number of persons residing in 200 m × 200 m grid cells across the study area, was used (Martin, 1996). These data were subsequently resampled to a resolution of 20 m × 20 m cells to allow for the irregular shape and small size of many of the Birmingham EDs to be incorporated into the analysis. The pollution concentrations mapped in figure 1 were converted to area averages by first finding the value for each 20 m × 20 m cell in every ED. The modelled emission value was multiplied by the population in that same cell. Summing these values for the entire ED, and dividing by the total population of the ED, gave a population-weighted average for each pollutant across the entire ED.

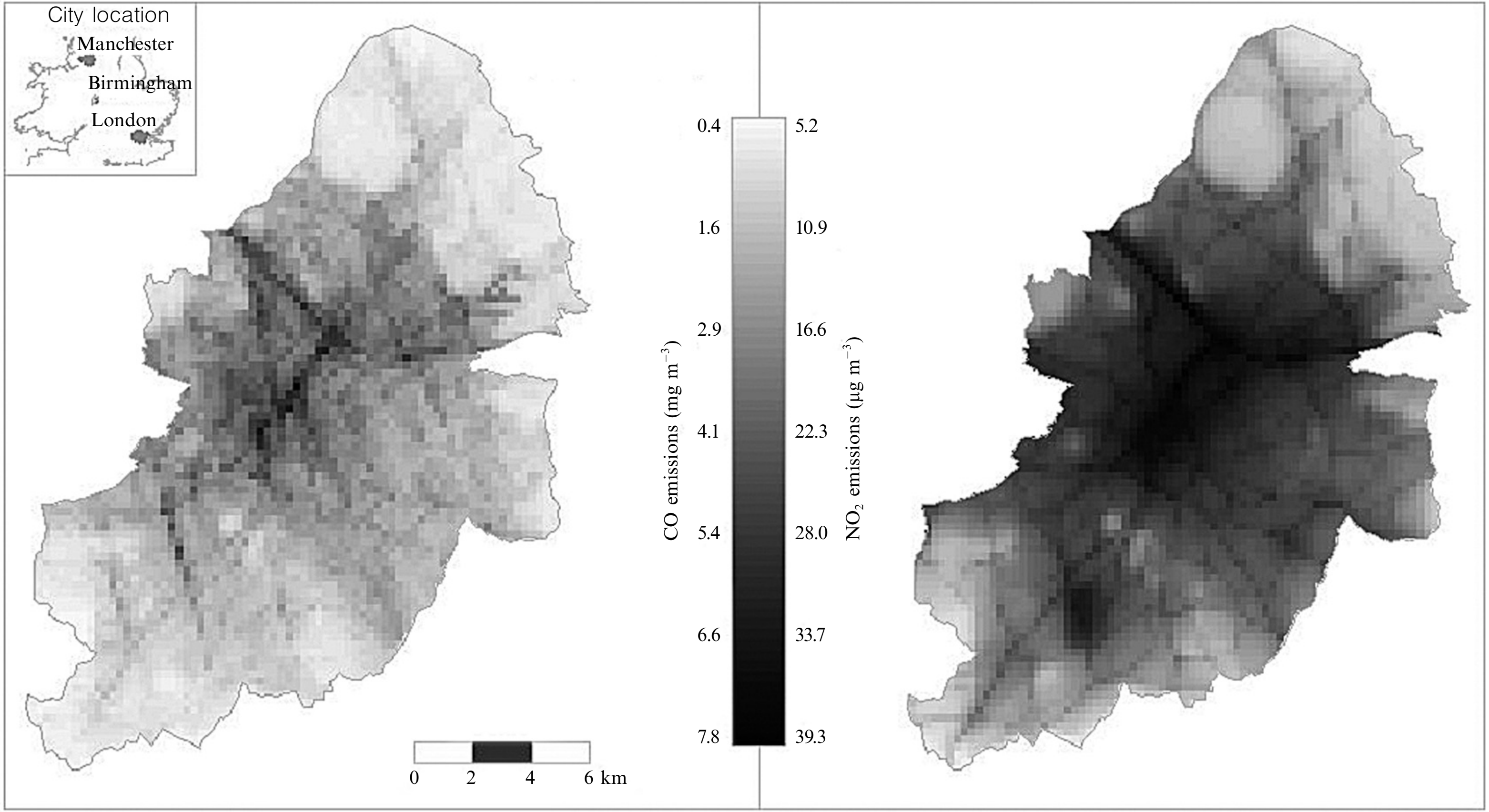
Statistical analysis

The aim of this research was to examine differences in air quality related to variations in population ethnicity, poverty, and age within Birmingham. The statistical analysis was undertaken using S-Plan (version 5; MathSoft, Cambridge, MA) and SPSS (version 9; SPSS Inc., Chicago, IL). The relationship between the measures of air quality and the variables of interest were assessed by the calculation of averages, correlation coefficients, and the fitting of analyses of variance and regression models. To examine the relationship between population composition and various levels of pollution exposure, Kolmogorov – Smirnov (KS) tests were also undertaken.

Results

Average estimated exposures

Table 2 (see over) shows the relationship between the mean values of CO and NO_2 emissions and the demographic indicators studied. Across all population groups, the mean hourly emission of CO was 2250 $\mu g\ m^{-3}$. For NO_2 the mean level was 23.15 $\mu g\ m^{-3}$. The mean emission estimates for both pollutants are slightly elevated, yet comparable, amongst the populations in social classes 4 and 5, or ages under 15 years. Average values for populations of retired populations are somewhat lower



(a) (b)

Figure 1. Modelled emissions in Birmingham for (a) carbon monoxide (CO) and (b) nitrogen dioxide (NO_2). Please note that the units of measurement for the two parts of this figure differ.

Table 2. Average carbon monoxide (CO) and nitrogen dioxide (NO_2) emissions for populations, by ethnic group, age-group, and class group, based on residential location. Variable names are as defined in table 1.

Pollutant	Mean ($\mu g\ m^{-3}$)								
	city	WHITE	TASIAN	BLACK	U5	U15	RET	SC12	SC45
CO	2276	2091	2824	2919	2340	2355	2155	2112	2331
NO_2	23.32	22.10	27.16	27.05	23.73	23.82	22.54	22.29	23.71

than the group mean, lying on the 47th percentile for hourly CO, and the 37th percentile for NO_2 emissions. Populations with a high proportion of individuals in social classes 1 and 2 exhibit lower exposure to emissions than average. For example, the mean CO emission is 2112 $\mu g\ m^{-3}$ for populations of social classes 1 and 2, lying on the 37th and 45th percentiles for CO and NO_2, respectively. Conversely, the social classes 4 and 5 experience pollutant levels somewhat higher than the citywide average.

The relationship between mean pollutant emissions and ethnicity is more striking than that observed for age and deprivation. The average black population in Birmingham lives in an area with estimated average CO concentrations of 2919 $\mu g\ m^{-3}$. This is compared with the citywide average of 2276 $\mu g\ m^{-3}$. The value for black residents and NO_2 is 27.05 $\mu g\ m^{-3}$. The measures of mean emissions for Asians are similar, with CO levels of 2824 $\mu g\ m^{-3}$, and 27.16 $\mu g\ m^{-3}$ of NO_2. Meanwhile, the average white Birmingham population lives in an area with average hourly concentrations of 2091 $\mu g\ m^{-3}$ of CO, and 22.10 $\mu g\ m^{-3}$ of NO_2. On average, mean hourly CO emissions are effectively 35% – 40% higher for ethnic minorities compared with the white population, and levels of NO_2 are around 22% higher for the typical nonwhite population.

Population distributions of pollutant emissions

Population averages provide a useful insight into overall discrepancies in pollution exposure. However, they may be deceptive if the underlying distributions of pollutant exposures are inconsistent between groups. To examine the relationship between the chosen indicators in more detail, a further analysis was undertaken based not simply on means but rather on the distribution of exposure patterns between the different groups.

The distribution of exposures based upon age profile

The statistics that were extracted on the number of persons in Birmingham below the age of 5 years, between 5 and 14 years old, and at pensionable age were taken to represent particularly vulnerable populations. Of course, although the census still provides the most up-to-date source of information on population demographics in the United Kingdom it is some time since 1991 Census data were collected. It may be that the effects of migration, coupled with an ageing population cohort, will mean that the geographical distribution of some age-groups for the period for which the air quality measurements were made will not match that present in the census. However, it is likely that the nature of certain neighbourhoods will tend to attract either pensioners or families with children, and that these characteristics will not have changed strongly over the period since the census was undertaken. Thus the indicators used are most likely still robust.

To compare levels of pollutant emissions across these populations, the percentage of the total Birmingham population in each age-group was determined for each ED.

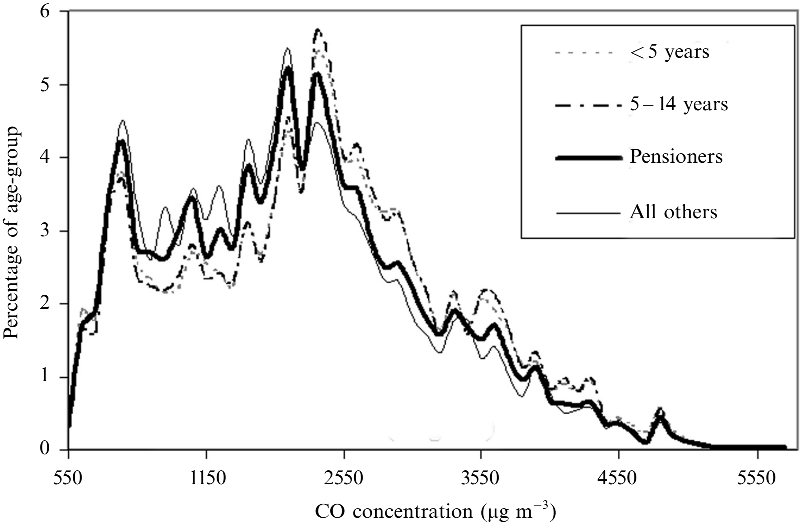


Figure 2. Percentage of specified age-groups exposed to given carbon monoxide (CO) emission levels.

For example, the ED labelled CNFA10 had 56 children aged between 5 and 14 years. This equates to 0.012% of the total 45 140 persons within this age range residing in Birmingham in 1991. The calculation of a percentage value for each ED allowed the proportion of each age-group exposed to various pollutant levels to be determined. Figure 2 displays the percentage of persons in each age-group against estimated CO values. The '< 5 years', '5 – 14 years', and 'pensioners' lines are largely coincident. The equivalent plot of age against NO_2 values was extremely similar, and has been omitted for the sake of brevity. There is some evidence that younger populations are somewhat overrepresented at higher CO and NO_2 emission levels (for example, at around 3600 μg m^{-3} CO), but these disparities are statistically insignificant.

The distribution of exposures based upon ethnic profile

The population of Birmingham was reported as being 78.49% white, 14.13% Asian, and 5.85% black in the 1991 Census. As with the analysis of age, the percentage of each ethnic group in each ED was determined so that comparisons between these groups could be made. Table 3 shows the median estimated emission levels of CO and NO_2 for each ethnic group. The table shows clear disparities between ethnic groups in median emissions for both pollutants, with white populations consistently in the lowest category for each, and Bangladeshi populations in the highest.

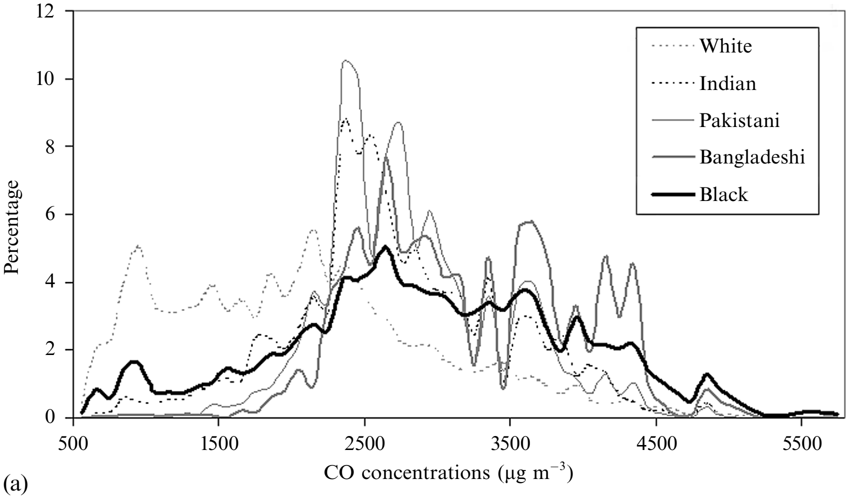
To examine the detailed relationship between levels of exposure and variations in population ethnicity, figures 3(a) and 3(b) (see over) were produced. In figure 3(a) we plot for each ethnic group the proportion of the population living in an area

Table 3. Median estimated emission levels of carbon monoxide (CO) and nitrogen dioxide (NO_2), based on residential location, for residents in Birmingham, by ethnicity.

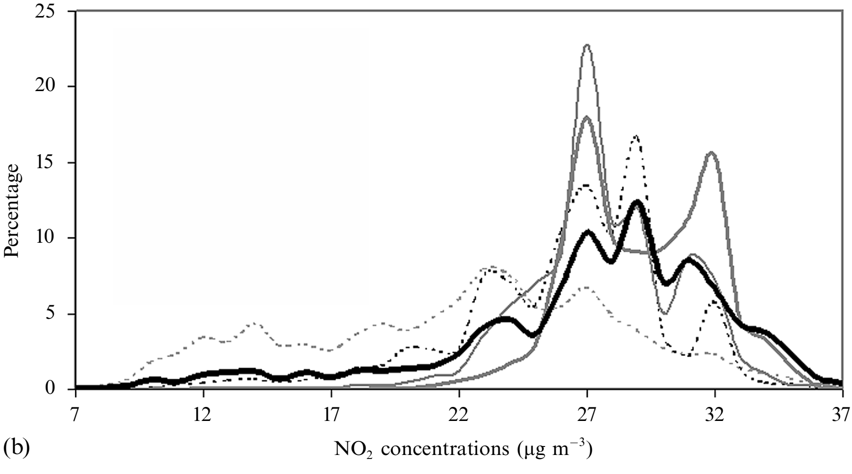
Pollutant	Median (μg m^{-3})				
	white	Indian	Pakistani	black	Bangladeshi
CO	1989	2579	2680	3047	3050
NO_2	22.36	26.32	26.92	27.58	28.56

receiving the corresponding absolute CO emissions. In figure 3(b) we show the equivalent information for NO_2. These graphs show a very different pattern for white people compared with other ethnic groups. Most of the nonwhite groups live in EDs with emission peaks around 2500 μg m^{-3} for CO and 27 – 28 μg m^{-3} for NO_2. Meanwhile, only 30% of the white population resides in areas with CO levels over 2500 μg m^{-3}, and only 20% of white people live in EDs with estimated NO_2 emissions above 28 μg m^{-3}. The pattern is noticeably asymmetrical for CO, with white residents, particularly tending to dwell in areas with relatively low emissions. Both graphs show that for black populations pollutant emissions span the full spectrum of values for the whole of Birmingham; there are no dramatic peaks in concentration levels. This suggests that, although mean emission values are higher for black communities compared with white communities, black communities are also located in a wider variety of neighbourhoods, with associated variations in emission levels.

In contrast to the findings for white and black people, the effect of enclaves amongst the Asian communities is quite striking. On both plots, there are distinct and separate peaks for each of the main Indian subcontinent nationalities—Pakistani,



(a)



(b)

Figure 3. Percentage of specified ethnic groups exposed to (a) given carbon monoxide (CO) emission levels; (b) given nitrogen dioxide (NO_2) emission levels.

Indian, and Bangladeshi. The apparent tendency of these communities to form ethnic neighbourhoods has important implications for environmental equity. When a group is geographically concentrated in localised neighbourhoods then any small-scale improvement in air quality is likely to have a substantial impact on the community as a whole. However, the nature of the primary source (vehicle exhausts) for the pollutants investigated here is a concern, as roads are not easily moved, and bypass schemes in an urban setting are expensive and highly disruptive.

The differences between ethnic groups were more formally quantified using a nonparametric test to compare the distribution of values in figures 3(a) and 3(b). Two-sample KS tests (see Connover, 1999; Ebdon, 1985) were run between each of the ethnic subgroups. This statistical measure requires only that the data belong to a continuous distribution. The KS test was used to determine the degree of difference in the shape of the exposure lines in the figures. For example, in figure 3(a) the size of the KS statistic makes it possible to determine how strongly the pattern of exposure to CO differs between the various ethnic groups considered in this analysis, whereby larger KS scores represent more strongly divergent exposure lines. Table 4 shows the resulting KS scores, along with the critical values of the KS statistic. Critical values for the KS statistic vary with sample intervals; in this case, frequencies for CO emissions were broken down into 53 categories in 100 μg intervals, from 550 μg m^{-3} to 5750 μg m^{-3}. Frequencies for NO_2 were calculated in intervals of 1 μg, from 7 μg m^{-3} to 37 μg m^{-3}. These breakdowns are inevitably somewhat arbitrary. However, a range of different categorisations were tested and none was found significantly to alter the results.

Compared with black and Asian populations, table 4 illustrates that white communities have a substantially different pattern of estimated emission levels at a 99% level of confidence for both CO and NO_2. At a 95% level of confidence, the Indian

Table 4. Kolmogorov – Smirnov statistics for two-sample tests comparing cumulative probability distributions for ethnic groups shown in figure 3.

	Ethnic group			
	Indian	Pakistani	black	Bangladeshi
Carbon monoxide				
white	0.3891*	0.4791*	0.3800*	0.5420*
Indian	–	0.0940	0.1504	0.2535*
Pakistani	–	–	0.1507	0.2190*
black	–	–	–	0.1732
Critical value				
$p = 0.1$	0.15			
$p = 0.05$	0.19			
$p = 0.01$	0.22			
Nitrogen dioxide				
white	0.3300*	0.4957*	0.4355*	0.6103*
Indian	–	0.1671	0.2009	0.3209*
Pakistani	–	–	0.1209	0.2078*
black	–	–	–	0.2082
Critical value				
$p = 0.1$	0.19			
$p = 0.05$	0.24			
$p = 0.01$	0.29			

* Significant at the $p = 0.05$ level.

population also seems to experience significantly different emissions levels of CO and NO_2 compared with Bangladeshi, but not Pakistani, residents. The Pakistani and Bangladeshi emission patterns also appear to be somewhat divergent, with KS statistics that are significant at a level of confidence of at least 90% for each pollutant. Emission levels of NO_2, but not of CO, are also divergent for black compared with Bangladeshi populations at a 99% level of confidence.

Overall, the results highlight that there appears to be a clear ranking between estimated emission levels across the different ethnic groups. White populations experience the lowest level of emissions, followed by, in ascending order, Indian, Pakistani, black, and Bangladeshi populations.

The distribution of exposures based upon measures of poverty

Of the three chosen deprivation indices derived from the census, the Carstairs index proved to be the most sensitive indicator of variations in pollutant emissions associated with deprivation. It was therefore selected for the more detailed analysis presented here. It should be noted that ethnicity is closely associated with the Carstairs measure. For instance, the percentage of people in each ED population who are classified as black has a correlation coefficient of 0.541 with the Carstairs index. The equivalent correlation with the Asian community is 0.528 (p-values greater than 0.001 for each correlation). Table 5 confirms the close link between ethnicity and deprivation by showing the proportion of each ethnic group population in each Carstairs quartile. A large percentage of several of the ethnic minority groups are further concentrated in the most deprived 10% of areas, as indicated by the final column in table 5.

To compare the measures of pollutant emissions for different levels of deprivation, EDs were categorised into quartile groups based on their Carstairs score. The lowest (first) group refers to the least deprived 25% of areas according to the Carstairs measure. The fourth quartile is the most deprived 25% of EDs. There is a clear trend towards higher emission levels with increasing deprivation. Table 6 gives median CO and NO_2 values for each Carstairs quartile.

Table 5. Percentage of each ethnic group in each Carstairs deprivation index quartile. The top decile is also included.

Population	Quartile				Top decile
	1st	2nd	3rd	4th	
White	30.23	27.53	25.99	16.24	4.80
Asian					
Bangladeshi	1.89	2.73	7.55	87.83	55.36
Indian	17.18	19.61	22.31	40.90	16.95
Pakistani	2.70	5.29	13.75	78.26	44.08
all	8.63	10.73	16.67	63.97	34.18
Black	7.21	15.37	25.77	51.65	22.95

Table 6. Median estimated emissions of carbon monoxide (CO) and nitrogen dioxide (NO_2) ($\mu g\ m^{-3}$) for each Carstairs quartile. Recall that deprivation increases with quartile rank.

Pollutant	Quartile			
	1st	2nd	3rd	4th
CO	1840	2010	2150	2840
NO_2	21	23	24	28

The distribution of exposure based upon both poverty and ethnicity

The analysis presented above has shown that both ethnicity and poverty are associated with pollutant emissions in Birmingham, with the highest emissions being recorded for populations with the highest proportions of minority ethnic groups and impoverished residents. However, a crucial issue is whether these observations are independent. This issue is important as it has also been shown that ethnic groups tend to live in more impoverished areas. Thus the question arises as to whether the apparent relationship between emissions and ethnicity is in fact a result of poverty, or whether the two effects can be distinguished.

To investigate the relative importance of ethnicity and poverty, the Carstairs score and percentage of nonwhite statistics were submitted to an analysis of variance. It would have been preferable to use all ethnic groups, and all Carstairs index quartiles. Unfortunately, this was not possible as there were unequal variances (in CO and NO_2 estimates) between Carstairs quartiles and quartiles for any ethnic measure. The presence of large variances also made it difficult to assume group means for CO and NO_2 emissions. The solution adopted was to focus on only the most deprived 25% of EDs according to the Carstairs measure. Some 483 EDs fell into this category. They were categorised by ethnic character as follows: $>90\%$ white (101 EDs), 50%–90% white (102 EDs), $>50\%$ Asian (158 Eds), $>25\%$ black (66 EDs), and mixed (the remaining 56 EDs). One ED was $>25\%$ black and $>50\%$ Asian; this area was assigned as black. Given our previous findings it would have been interesting to differentiate Bangladeshi and Indian areas from the other ethnic groups. This was not feasible, however, as neither community shows a particularly distinct geographical distribution. Although the ethnic characterisations used here are somewhat arbitrary, they do have the advantage of identifying areas that are entirely distinct from each other.

Table 7 shows the mean distribution of CO and NO_2 values for EDs by specified ethnic character. Differences between the groups were tested using the Kruskal–Wallis rank sum test. The Kruskal–Wallace test, described in Goldman and Weinberg (1985), is used when, as was the case here, the data being analysed do not conform to a normal, or Gaussian, distribution. The test gives an indication of the degree of similarity in a specified characteristic between different groups. Here it was used to determine how strongly each of the two pollutant concentrations differed between the chosen categories of ethnicity. For CO the output χ^2-statistic was 179.88; for NO_2 it was 159.88. There were four degrees of freedom, allowing for a critical value of 13.28 when $p = 0.01$, thus making these χ^2-statistics extremely significant and highlighting the apparently strong disparities in exposure depicted in table 7.

As noted earlier, large discrepancies in variance and distributions made it impossible to run a parametric analysis of variance for all EDs by both ethnic character and Carstairs index scores. However, upon excluding the predominantly white areas (that is, $>90\%$ white and 50%–90% white), and combining the first three quartiles for Carstairs values, variances for CO and NO_2 in each group were sufficiently similar

Table 7. Median carbon monoxide (CO) and nitrogen dioxide (NO_2) ($\mu g\ m^{-3}$) in the 25% most deprived enumeration districts (EDs), by ethnic character.

Pollutant	ED character				
	>90% white	50%–90% white	mixed	>50% Asian	25% black
CO	1700	2925	2960	2750	3740
NO_2	19.8	29.3	28.2	27.5	30.3

to enable a conventional two-way analysis of variance to be performed, although the results relate only to the mixed, Asian, and black categorised areas and distinguish only between two Carstairs divisions: the top quartile and bottom 75%. Because of the exclusion of predominantly white areas, only 351 EDs were available for the analysis of variance. Table 8 shows the results.

Both the measure of ethnicity and that of deprivation were statistically significant when included in the model together. This suggests that the two effects are independent of each other. However, the need to omit two types of area (> 90% white and 50% – 90% white) from the analysis of variance is unfortunate.

Table 8. Analyses of variance for carbon monoxide (CO) and nitrogen dioxide (NO_2) emissions, for ethnicity and deprivation.

	Degrees of freedom	Sum of squares	Mean square	*F*-statistic	Pr(*F*)
Carbon monoxide					
Carstairs index	1	4 120 349	4 120 349	11.87	0.00647
ethnic character	2	26 473 612	13 236 806	38.06	≈ 0
residuals	347	120 681 071	347 784	na	na
Nitrogen dioxide					
Carstairs index	1	180.77	180.77	29.17	1.23×10^{-7}
ethnic character	2	308.54	190.27	30.70	5.00×10^{-13}
residuals	347	2 150.32	6.20	na	na

Note: na, not applicable

Table 9. Kolmogorov – Smirnov statistics for enumeration districts (EDs) of specified ethnic character in the 25% most deprived areas in Birmingham.

	ED character			
	50% – 90% white	Asian	Mixed	black
Carbon monoxide				
> 90% white	0.485*	0.653*	0.701*	0.826*
50% – 90% white	–	0.203*	0.203*	0.406*
Asian	–	–	0.226*	0.446*
mixed	–	–	–	0.588*
Critical value				
$p = 0.1$ 0.15				
$p = 0.05$ 0.19				
$p = 0.01$ 0.22				
Nitrogen dioxide				
> 90% white	0.629*	0.837*	0.723*	0.761*
50% – 90% white	–	0.313*	0.311*	0.306*
Asian	–	–	0.434*	0.387*
mixed	–	–	–	0.144
Critical value				
$p = 0.1$ 0.19				
$p = 0.05$ 0.24				
$p = 0.01$ 0.29				

* Significant at the $p = 0.05$ level.

Two-sample KS tests were undertaken to examine further the differences between EDs of specified ethnic characters, this time including the predominantly white areas. The focus was narrowed to the 25% most deprived areas (483 EDs); the results are shown in table 9. The KS statistic is almost universally significant at a 99% level of confidence. The exception is the 50%–90% white or Asian comparison for CO, which is still significant at $p = 0.05$, and the mixed or black comparison for NO_2.

These findings are not as definitive as the earlier assessment of exposure by ethnicity alone (table 4). The KS statistics suggest the distributions are different, but this observation is at odds with visual examination of the data. Reviewing the median values in table 7 and the plots in figures 4(a) and 4(b) it is difficult to determine if typical emissions for either pollutant are really distinct for the 50%–90% white, mixed, and Asian EDs. However, the EDs classified as >90% white or >25% black residents do clearly appear to belong to different populations in terms of their CO and NO_2 emissions.

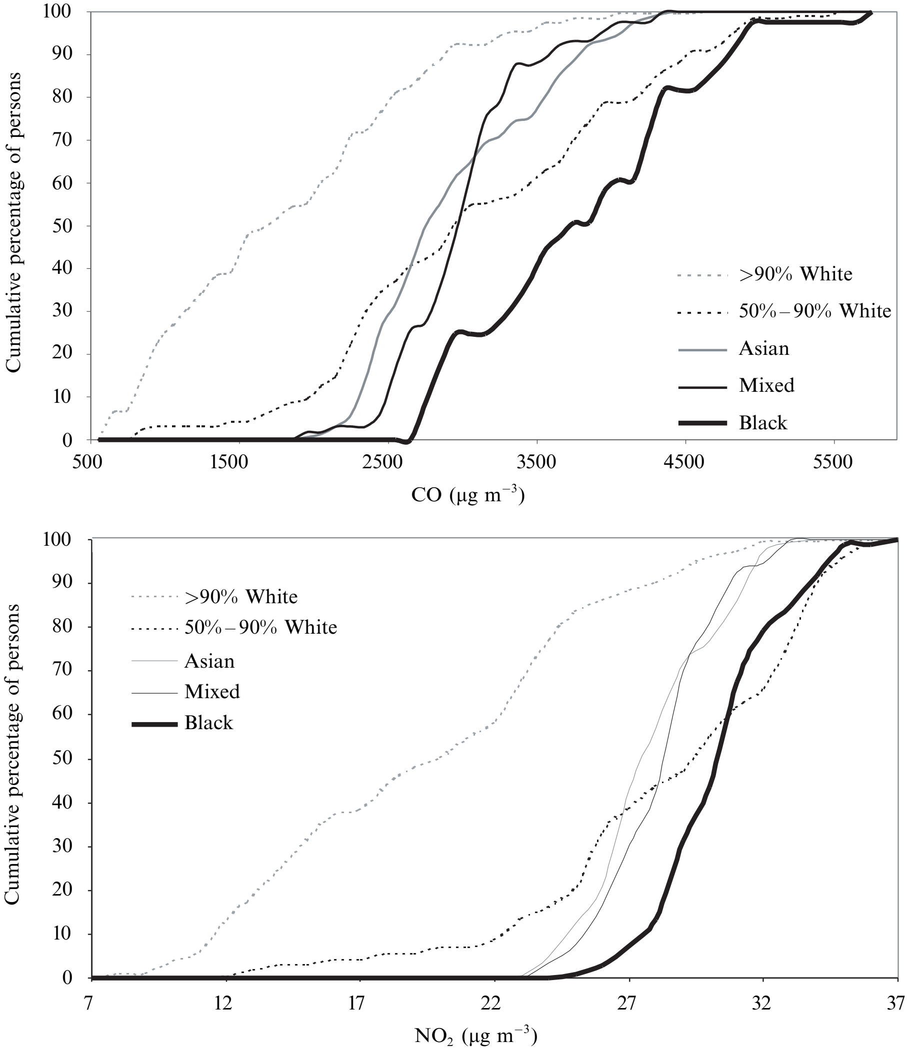


Figure 4. Cumulative proportion of ethnic groups exposed to (a) different carbon monoxide (CO) and (b) different nitrogen dioxide (NO_2) values in enumeration districts falling in the highest Carstairs deprivation quartiles.

Table 5 shows us that ethnic minorities in Birmingham are disproportionately concentrated in the most deprived 10% of areas. Hence it is important to consider whether the findings presented here are unduly biased by the choice of only the 25% most deprived areas. Table 10 shows KS statistics for these most deprived 10% of EDs. Again, the KS values suggest significant differences in the apparent relationships with emissions for EDs in each category. However, only 13 EDs in this most deprived group fall within the '> 90% white' category. Furthermore, only 16 of EDs lie in the 'mixed' category. Compared with the 50%–90% white category (40 EDs), Asian category (97 EDs) and black category (28 EDs), these numbers may not be sufficient to ensure adequate continuity in the distributions for reliable KS statistics to be generated.

Regression analysis

The analysis presented above has illustrated that independent relationships exist between air pollution, ethnicity, and deprivation in Birmingham. However, the question arises regarding the joint effect of these factors. In order to investigate these issues it is normal to employ regression modelling approaches whereby the joint relationship between various independent variables (in this case indicators of ethnicity and poverty) are modelled against dependent variables (here, measures of air quality). However, a problem with this analysis was that our measures of poverty and ethnicity were strongly correlated with each other, and hence it was difficult to determine their independent effects by using traditional regression modelling approaches. Hence, ridge regression, a nonparametric regression modelling technique which is specifically designed for the analysis of variables exhibiting high collinearity, was employed. For more details on ridge regression, see Hoerl and Kennard (1970) or Ryan (1997).

Table 10. Kolmogorov–Smirnov statistics for enumeration districts (EDs) of specified ethnic character in the 10% most deprived areas in Birmingham.

	ED character			
	50%–90% white	Asian	mixed	black
Carbon monoxide				
> 90% white	0.761*	0.762*	0.701*	0.826*
50%–90% white	–	0.433*	0.571*	0.192*
Asian	–	–	0.403*	0.403*
mixed	–	–	–	0.588*
Critical value				
$p = 0.1$ 0.15				
$p = 0.05$ 0.19				
$p = 0.01$ 0.22				
Nitrogen dioxide				
> 90 white	0.852*	0.918*	0.809*	0.915*
50%–90% white	–	0.232	0.528*	0.607*
Asian	–	–	0.526*	0.500*
mixed	–	–	–	0.370*
Critical value				
$p = 0.1$ 0.19				
$p = 0.05$ 0.24				
$p = 0.01$ 0.29				

* Significant at the $p = 0.05$ level.

When multicollinearity occurs, least squares estimates, such as those obtained from traditional regression models, are unbiased, but their variances are large so they may be far from the true value. By adding a degree of bias to the regression estimates, as is done in ridge regression, it is hoped that the net effect will be to give more reliable estimates. Hence, ridge regression deflates correlation values, reducing the effects of collinearity. Unfortunately, ridge regression suffers from the criticism that it relies on the somewhat arbitrary specification of a regularisation parameter (k) needed to balance the variance matrix in the regression. However, in the absence of superior regression techniques for dealing with highly collinear data, the technique was used here to determine if the output might conform with conclusions made thus far.

The choice of k-value is the most arbitrary element in ridge regression model specification. In this case, systematic and repeated model simulations were employed to determine the effect of using values of k between 0 and 1000. The results of this procedure suggested that the model strength, as indicated by the adjusted R^2-value, had a tendency to increase as k decreased, but improvements became marginally smaller as k approached zero. Hence, a k-value of 0.001 was selected as appropriate for this analysis. Table 11 shows the results of applying ridge regression with a k-value of 0.001. The models are formulated identically for both of the pollutants analysed. The dependent variables in these models were set to be the respective CO and NO_2 values, and were compared with independent variables measuring ethnicity. Jarman index scores (JARM) were included as a measure of deprivation. The Jarman index was chosen in preference to the others on this occasion as it proved to give a better fit in the ridge models. The t-values on all variables in both models in table 11 are highly significant, with signs that follow a priori expectations; pollutant emissions increase

Table 11. Ridge regression for carbon monoxide (CO) and nitrogen dioxide (NO_2), predicted as a linear function of percentage black, white, and Bangladeshi population, and the Jarman underprivileged areas index (BLACK, WHITE, BANG, and JARM, respectively).

		B	SE(B)	β	t-value	$B/\mathrm{SE}(B)$
Carbon monoxide						
BLACK		56.09		3.13	0.42	17.93
WHITE		−8.70		1.20	−0.22	7.25
BANG		24.73		6.24	0.09	3.96
JARM		21.72		3.07	0.15	7.09
constant		2602.04		112.83	0.00	23.06
Multiple R	0.60					
Adjusted R^2	0.35					
R^2	0.36					
SE	790.14					
Nitrogen dioxide						
BLACK		0.270		0.0203	0.319	13.27
WHITE		−0.081		0.0078	−0.327	10.48
BANG		0.951		0.0406	0.055	2.34
JARM		0.147		0.0199	0.156	7.40
constant		28.08		0.7328	0.000	38.32
Multiple R	0.57					
Adjusted R^2	0.32					
R^2	0.33					
SE	5.132					

Note: B, ridge regression coefficient; SE, standard error.

with percentage black and percentage Bangladeshi population (BLACK and BANG, respectively), as well as increasing values of the Jarman deprivation index. There is a separate and negative effect for increasing white population (WHITE). The percentages of Pakistani and Indian populations were not statistically significant in the model. These findings provide evidence that the effects of ethnicity and poverty are indeed independent.

Conclusions

Much previous environmental research has failed to address effectively the question of the differential impact of air pollutants upon the diverse communities residing in urban areas (Morello-Frosch et al, 2001). In particular, the United Kingdom has suffered from a lack of investigation in this field. In this study we have sought to go some way to rectify this by assessing the distributional pattern of exposures to two key pollutants—CO and NO_2—in the city of Birmingham. Our findings suggest a disproportionate burden of pollutant exposure may be being borne by nonwhite communities and populations exhibiting higher levels of deprivation. Although a strong association was detected between ethnicity and poverty it can be difficult to distinguish between the two effects. However, the results of this analysis provide evidence that, at least with regard to air pollution in the city, the effects are independent rather than additive.

There are some caveats to note regarding the data underlying our analysis. First, it is important to recognise that our measures of air pollutants were based on emissions, not ambient concentrations. Although these two pollution indicators have been shown to be strongly associated (Peterson and Williams, 1999), differing microclimates and their associated influences on dispersion can lead to discrepancies. In the case of this analysis, the data and computational demands required to model localised variations in ambient concentrations from emissions were not justified. However, such an undertaking would provide a useful future extension to the work.

We chose to study emissions of only two pollutants—CO and NO_2—as key indicators of air quality in Birmingham. In reality, the urban pollution profile comprises a number of major pollutants, with sulphur dioxide (SO_2), particulates (PM10), ozone (O_3), benzene, and 1,3-butadiene all being important. Although it would have been possible to incorporate a wider number of contaminants in this analysis, such an extension was felt to be unnecessary as both of the indicators chosen are strongly associated with traffic emissions. Traffic emissions are a key moderator of spatial variations in pollutant concentrations in urban areas (Festy, 1997). The only pollutant that carries a different concentration profile from CO and NO_2 is O_3. This is because of the fact that the complex chemical reactions required to generate O_3 take some time, and hence concentrations can be highest some distance from sources (Sandoval et al, 2001). However, it is problematic to map the precursors of O_3 (Kim and Kim, 2000), and concentrations of the pollutant would show little geographical variations at the small spatial scale of our study area (DETR, 2000). Hence it would have been difficult in this work to detect population gradients associated with exposure to O_3.

It is also important to place the modelled emissions of CO and NO_2 used here in Birmingham within the wider context of pollution exposure across the whole of the United Kingdom. The data employed in this research relate to hourly emissions, averaged over the entire year. These average values suggest that, despite the presence of strong geographical disparities in modelled levels, government standards may not be being generally exceeded in Birmingham over the time period under consideration. A definitive assessment of this issue would require local estimates of actual CO and NO_2 concentrations, but that informations was not available.

One further caveat to be put on our findings is that they are based upon population, and not individual, characteristics. As with any aggregate analysis, our results are therefore derived from ecological associations. This leads to the potential problem of the ecological fallacy whereby relationships detected at the population level may not be operating at the level of individuals (Guthrie and Sheppard, 2001). However, we have no a priori reason to believe that the use of ecological associations in this work have led to the wrong conclusions being made. Indeed, Seiler and Alvarez (2000) have recently argued empirically that it is the prediction of the health effects in an exposed population, the type of which is provided by ecological associations, that is of primary importance, not the shape of the 'true' exposure relationship produced from other study designs.

A further limitation of the use of a geographical study design is that our results may be influenced by the modifiable areal unit problem (MAUP) (Openshaw, 1984). The MAUP refers to the likelihood that the strength of correlations between the attributes of areas (in our case, EDs) will to some extent be associated with the size and shape of those areas. However, because of the small size of EDs, it is unlikely that the MAUP has had a significant effect here.

In our analysis we assumed that air quality across the place of residence of populations was the sole contributor to the pollution dose they received. This is, of course, a simplification of reality, as individual daily commuting patterns may mean that work, recreational, and domestic activities take place in different areas. Hence, the daytime and nighttime populations of central Birmingham may be rather different. Unfortunately, data on commuting patterns were not available at a high enough spatial resolution to allow us to assess daytime exposures here; in the statistics on employment commuting from the 1991 Census all of the Birmingham city boundary is subsumed within a travel-to-work area that measures 61 km × 22 km in size. Furthermore we have no information on the locations of the schools attended by the children included in our analysis, although the work of Rex and Tomlinson (1979) suggests that the majority of individuals within the city attend a school that is close to their residential location. As part of a separate analysis, we are examining equity of access to parks and other green spaces within Birmingham. However, individual-level activity-pattern data would be required to generate detailed exposure assessments, and these were not available here. Nevertheless, an assessment of equity based upon more detailed daytime and nighttime exposures would be an innovation in the environmental equity literature and a worthy future extension to this analysis.

It was not our aim to develop a policy framework of remediation measures of environmental inequities. However, it is useful briefly to consider the policy implications of our findings. Despite that fact that our study area is not large, our research has shown strong variations in equity of exposure to two key air pollutants—CO and NO_2. Research, regulatory, and public attention has generally focused on exposure to the type of pollutants that arise from concentrations of large manufacturing facilities in highly industrialised regions. However, decades of economic restructuring in the United Kingdom are shifting a significant proportion of economic activity, along with associated pollutant emissions, to small service industries and transportation sources. The sources of the pollutants that we have considered in Birmingham are likely to be small, mobile, and diverse in character. This diversity means that emissions will be much more difficult to control in a regulatory framework, particularly as increasing levels of vehicle ownership can easily act to erode gains made from the introduction of stricter emissions standards. Hence we suggest that, at a local scale at least, future policies to reduce inequities in exposure to these pollutants should place a particular emphasis on the mechanisms driving changes in land-use patterns, urbanisation, and the development of transportation corridors.

From a policy standpoint, consideration also needs to be taken of the social factors that have led to concentration of more deprived populations and ethnic groups in areas with poor environmental quality. Recent research elsewhere has suggested that the process may be linked with lower housing costs in polluted areas (Oakes et al, 1996). However, other findings propose that disproportionate siting of pollution sources matters far more than post-siting minority move-in (Pastor et al, 2001). At the heart of this, factors such as economic restructuring across cities undoubtedly hold important social consequences for immigrant and impoverished populations. Such people, induced to migrate by changing economic circumstances, find growing ghettoisation, isolation, cultural antipathies, and environmental degradation in their new settings (Laws, 1997).

In Birmingham the situation is complex, and the present-day distribution of ethnic, deprived groups within the city is a result of the interplay between personal preferences and forces operating in the public and private housing markets. Undoubtedly, discriminatory housing practices have been important. A significant proportion of ethnic groups in Birmingham live in the rented sector (Henderson and Karn, 1987). There is historical evidence of widespread practices within the city whereby landlords and housing agencies have discriminated by telling individuals from ethnic groups that housing was not available in certain 'white' areas (Smith, 1977). Hence a racial steering process operated whereby families were forced to live in poor-quality housing, often rented from landlords from the same ethnic background, in concentrated localities. The preference of white members of Birmingham's population for suburban dwellings away from the city centre has also accentuated this process of ghettoisation, with a gradual outward migration of relatively prosperous white families to the periphery of the city. Meanwhile, the generally weaker financial and political voice of ethnic families meant that they were forced to remain in less desirable central areas (Rex and Tomlinson, 1979).

The previous housing policies of Birmingham City Council have also contributed to the observed inequalities in exposure to air pollutants within the city. It is important to note that many ethnic and poor families are housed within the public (council) rented sector. A significant proportion entered as a result of compulsory purchase from Birmingham's postwar slum clearance programme, which was at its peak in the late 1960s and early 1970s (Henderson and Karn, 1987). During this period the pattern of housing allocations in the city was dominated by the need to rehouse people from demolished stock. One result of this policy was that families from ethnic minority groups tended to be allocated older housing, and this type of housing stock is located towards the city centre in Birmingham.

By the late 1960s the concentration of West Indians and Asians in the inner and middle rings of Birmingham had become an issue of considerable concern to the City Council, particularly in terms of service provision in those areas (BCC, 1968). As a consequence, a policy of dispersing council tenants was adopted, with the aim of avoiding high concentrations of families from a single ethnic background in particular areas. However, the policy faced implementation problems, particularly associated with the unwillingness of West Indian, Asian, and white families to cohabit in neighbourhoods. Consequently, it resulted in a pepper-pot distribution of allocations that tended only to accentuate the development of predominantly ethnic neighbourhoods. The Birmingham dispersal policy was eventually abandoned in 1975.

As a result of all the forces outlined above, there has been a distinct pattern to the redistribution of ethnic populations in Birmingham in the years leading up to this study.

In particular, there has been a picture of white movement from the middle to the outer rings of the city, West Indian movement from the middle to the inner rings, and Asian movement within the middle ring. These trends, coupled with the fact that many ethnic families in Birmingham live in much higher levels of poverty than do their white counterparts (Rex and Tomlinson, 1979), have contributed much to the disparities in exposure to air pollution revealed here. It will be a challenge for legislators to address many of these fundamental issues.

The aim in this paper was to investigate environmental equity in the distribution of two common air pollutants in the city of Birmingham, England. We found that the pollutants show strong gradients in exposure between populations of different levels of deprivation and ethnic background. Although many of the indicators we analysed were collinear, we used the technique of ridge regression to determine that the gradients for ethnicity and poverty were independent. This is an important finding, as it implies that more than one underlying process may be operating to produce these associations. Our results hence suggest that a problem of multiple inequity does exist, and we propose that policymakers need to give careful thought to the development of innovative solutions to address these disparities in exposure to air pollutants, with their associated health risks.

Acknowledgements. The pollution emission layers were originally modelled by Adrienne Dunn at Birmingham City Council. Relevant data were also supplied by Dr Iain Lake of the University of East Anglia, as part of related research funded by the Department of the Environment, Transport and the Regions. The 1991 Census data are crown copyright, purchased by the Economic and Social Research Council.

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