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Socioeconomic inequalities in urban and transport planning related exposures and mortality: A health impact assessment study for Bradford, UK

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ARTICLE INFO	A B S T R A C T
Handling Editor: Yong-Guan Zhu Keywords: Active transport Deprivation Ethnicity Green space Physical activity	<i>Background:</i> Cities have unique geographic, environmental and sociocultural characteristics that influence the health status of their citizens. Identification and modification of these characteristics may help to promote healthier cities. <i>Objective:</i> We estimated premature mortality impacts of breaching international exposure guidelines for physical activity (PA), air pollution, noise and access to green space for Bradford (UK) adult residents (<i>n</i> = 393,091). <i>Methods:</i> We applied the Urban and TranspOrt Planning Health Impact Assessment (UTOPHIA) methodology and estimated mortality, life expectancy (LE) and economic impacts of non-compliance with recommended exposure levels. We also investigated the distribution of the mortality burden among the population, focusing on socioeconomic opsition (SEP) as defined by deprivation status and ethnicity. <i>Results:</i> We estimated that annually almost 10% of premature mortality (i.e. 375 deaths, 95% CI: 276–474) in Bradford is attributable to non-compliance with recommended exposure levels. Non-compliance was also estimated to result in over 300 days of LE lost (95% CI: 238–432), which translated in economic losses of over £50,000 per person (95% CI: 38,518–69,991). 90% of the premature mortality impact resulted from insufficient PA performance. Air and noise pollution and the lack of green space had smaller impacts (i.e. 48 deaths). Residents of lower SEP neighborhoods had the highest risks for adverse exposure and premature death. A larger number of deaths (i.e. 253 and 145, respectively) could be prevented by reducing air and noise pollution levels well below the guidelines.

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Abbreviations: BiB, Born in Bradford cohort study; ERF, Exposure response function; ESCAPE, European Study of Cohorts for Air Pollution Effects; IMD, Index of Multiple Deprivation; LE, Life expectancy; LUR, Land use regression; LSOA, Lower Super Output Area; L_{den} , EU noise indicator with 5 and 10 dB penalties for the evening and night time, respectively; METs, Metabolic equivalents of tasks; NDVI, Normalized Difference Vegetation Index; NPPF, National Planning Policy Framework; NO₂, Nitrogen dioxide; PA, Physical activity; PAF, Population attributable fraction; PM_{2.5}, Particular matter with diameter $\leq 2.5 \,\mu$ m; RR, Relative risk; SEP, Socioeconomic position; UK, United Kingdom; UTOPHIA, Urban and TranspOrt Planning Health Impact Assessment methodology; VSLY, Value of a statistical life year; WHO, World Health Organization; %GS, Percentage green space



A=Major road network of the Bradford district. B=PM_{2.5} concentrations (2009/ 2010) at LSOA level. C=Noise levels L_{den} (2006) at LSOA level. D=% green space (2012) at LSOA level.

Fig. 1. Major road network and environmental exposures at LSOA level.

- A = Major road network of the Bradford district.
- $B = PM_{2.5}$ concentrations (2009/2010) at LSOA level.
- C = Noise levels L_{den} (2006) at LSOA level.
- D = % green space (2012) at LSOA level.

1. Introduction

By 2050, it is estimated that 70% of the global population will be living in cities (United Nations, 2014). Cities have unique geographic, environmental and sociocultural characteristics that influence the health and well-being of their citizens. Therefore, identification and modification of these characteristics may help to promote healthier cities. Urban and transport planning is known to have a particularly important impact on health (Mueller et al., 2017a; Nieuwenhuijsen, 2016).

Air pollution from traffic has become a major focus of policy discussion (Héroux et al., 2015; WHO, 2014). Chronic noise exposure is increasingly linked to adverse health effects (Guski et al., 2017;

Nieuwenhuijsen et al., 2017c; Van Kempen et al., 2018). Continuing urbanization and convenience lifestyles are associated with decreasing physical activity (PA) levels and widespread sedentarism (Sallis et al., 2015). Space scarcity and competing land-use interest have resulted in the disappearance of natural outdoor environments in urban settings (Boyko and Cooper, 2011; Dallimer et al., 2011), despite emerging evidence on the physical and mental health benefits of green space in direct residential proximity (Eakin et al., 2017; Gascon et al., 2018; Nieuwenhuijsen et al., 2017a).

Incompliant exposure levels of these multiple urban and transport planning related risk factors are known to contribute to a substantial burden of disease and constrain national healthcare systems (Forouzanfar et al., 2015; Gascon et al., 2016; Héroux et al., 2015;

Table 1

Bradford population characteristics.

Bradford	Males ≥ 18 years (n)	Females ≥ 18 years (n)	Total ≥ 18 years (n)	Mortality rate	Expected annual deaths (n)
Population	192,039	201,052	393,091	1,114/ 100,000 persons	4,379

Mueller et al., 2017a, 2017b; WHO Regional Office for Europe, 2011). In addition, exposure levels are often socially patterned with more socioeconomically deprived or ethnically diverse communities being more adversely exposed (Casey et al., 2017; Clark et al., 2017; Eime et al., 2015; Hajat et al., 2015; Pan et al., 2009; Schüle et al., 2017). Numerous studies showed that residential traffic-related air pollution and noise levels are higher among low-income groups and visible minorities, as their residences are often located in high traffic areas (Brainard et al., 2004; Carrier et al., 2016; Clark et al., 2017; Grineski and Collins, 2018). Inequalities in green space access also exist: those with greater resources tend to move to greener areas (Maas, 2008). The health burden associated with the imbalance of these urban and transport planning related exposures is therefore likely to be higher among the most disadvantaged populations as the unequal access to high quality environments accounts to large extend for this 'triple jeopardy' of environmental, social and health inequalities (Pearce et al., 2010). Moreover, these groups may already exhibit a variety of other risk factors (e.g. suboptimal health care access, poor diet, stress, and violence (Khreis et al., 2016)), which makes them more susceptible to adverse health outcomes.

In this study, we aimed to estimate the mortality burden associated with current exposure levels of the multiple urban and transport planning related exposures (i.e. PA, air pollution, noise, green space) in Bradford, United Kingdom (UK). We also investigated the distribution of the mortality burden among the population, focusing on socioeconomic position (SEP) as defined by deprivation status and ethnicity.

2. Methods

2.1. Study setting

The Bradford district, located in the North of England in the West Yorkshire conurbation, as of 2016 had 534,279 residents living on 370 km² (Office for National Statistics, 2017a; The City of Bradford Metropolitan District Council, 2017). Bradford has a temperate maritime climate with an annual mean temperature of 12 °C and significant amounts of rainfall throughout the year (Met Office, 2018). A large proportion of air and noise pollution in Bradford is estimated to result

Table 2

Recommended and actual exosure levels in Bradford.

from road traffic (in European cities the traffic contribution to urban particulate matter (PM) can be as high as 66% and to nitrogen dioxide (NO₂) over 80% (Nieuwenhuijsen and Khreis, 2016; Sundvor et al., 2012) and road traffic is by far the biggest contributor to urban noise pollution (European Environment Agency, 2014)), with the highest levels in Bradford to be found within the inner ring road and along the M606 motorway corridor in the south and the adjacent towns of Shipley and Keighley in the north and north-west (Fig. 1) (Cooper et al., 2014; Khreis et al., 2018b). Bradford is located within a designated green belt region as part of the National Planning Policy Framework (NPPF) that extends into the district and surrounding counties and restricts the West Yorkshire conurbation from further convergence by limiting the sprawl of built-up areas (City of Bradford Metropolitan City Council, 2017: Ministry of Housing Communities and Local Government, 2012). Bradford has a younger demographic structure than most other British cities, with over a quarter of residents being in the age group < 18years (Fielding, 2012; Khreis et al., 2018b). The district is among the 10% most deprived authorities in the UK (Fielding, 2012), with over 35% of the current working-age population being unemployed (The City of Bradford Metropolitan District Council, 2017). In addition, Bradford residents are highly ethnically-diverse with the main ethnic groups being of South Asian origin (i.e. 30% of residents, mainly of Pakistani origin) and white British origin (i.e. 60% of residents) (The City of Bradford Metropolitan District Council, 2017; Wright et al., 2016).

2.2. UTOPHIA methodology

We conducted a health impact assessment (HIA) at the Bradford Lower Super Output Area level (LSOA; n = 310, mean population 1,724 residents, mean area 118 ha). The analysis estimated the impact of multiple exposures on all-cause mortality for Bradford residents \geq 18 years (n = 393,091) (Table 1) under compliance with international exposure level recommendations. We followed the Urban and TranspOrt Planning Health Impact Assessment (UTOPHIA) methodology that was developed and applied to Barcelona, Spain previously (Mueller et al., 2017a, 2017b). UTOPHIA follows a comparative risk assessment approach assessing health impacts related to 'unhealthy' exposure levels of the multiple urban and transport planning related exposures.

We estimated for Bradford the number of premature deaths attributable to incompliance of recommended exposure levels for PA, air and noise pollution and access to green space. Unlike for Barcelona, for Bradford we ignored temperature effects (i.e. heat) because temperature data was not available and Bradford is less of a hotspot than Barcelona for climate change vulnerability in terms of hot temperatures (Guo et al., 2014). The applied all-cause mortality rate for Bradford residents was 1,114 deaths/100,000 persons (Office for National

Counterfactual scenario	Baseline		
WHO recommendations	Year	Bradford LSOA range	Bradford district mean
600 MET min/week	2014	-	124 MET min/week ^a Insufficiently active: 49.4% of population (194.187 persons)
$10\mu g/m^3$ annual mean	2009/ 2010	$7.66 - 13.44 \mu g/m^3$	$10.12 \mu g/m^3$
40 μg/m ³ annual mean	2010	$12.82-30.08 \mu g/m^3$	$21.18 \mu g/m^3$
55 dB L _{den} annual mean	2006	30–65.1 dB L _{den}	44.41 dB L _{den}
Access to green space ≥ 0.5 ha within 300 m linear distance	2012	1–54% of population (quintiles) without access to green space \geq 0.5 ha within 300 m linear distance	17.84% of population without access to green space ≥ 0.5 ha within 300 m linear distance
	Counterfactual scenario WHO recommendations 600 MET min/week 10 µg/m³ annual mean 40 µg/m³ annual mean 55 dB L _{den} annual mean Access to green space ≥ 0.5 ha within 300 m linear distance	Counterfactual scenario Baseline WHO recommendations Year 600 MET min/week 2014 $10 \ \mu\text{g/m}^3$ annual mean 2009/ 2010 $40 \ \mu\text{g/m}^3$ annual mean 2010 $55 \ dB \ L_{den}$ annual mean 2006 Access to green space ≥ 0.5 ha within 2012 $300 \ m$ linear distance 2012	Counterfactual scenarioBaselineWHO recommendationsYearBradford LSOA range 600 MET min/week 2014 - $10 \ \mu\text{g/m}^3$ annual mean $2009/$ $7.66-13.44 \ \mu\text{g/m}^3$ 2010 2010 $40 \ \mu\text{g/m}^3$ annual mean 2000 2010 $12.82-30.08 \ \mu\text{g/m}^3$ $55 \ dB \ L_{den}$ annual mean 2006 $30-65.1 \ dB \ L_{den}$ Access to green space $\ge 0.5 \ ha \ within$ 2012 $1-54\%$ of population (quintiles) without access to green space $\ge 0.5 \ ha \ within$

dB = decibel; LSOA = Lower Super Output Area; $L_{den} = EU$ noise indicator with 5 dB penalties for the evening time and 10 dB penalties for the night time; MET = metabolic equivalents of task.

^a Mean weekly physical activity level of the insufficiently active population.

 Table 3

 Risk estimates for mortality by exposure domain.

Exposure domain	Risk estimate	Exposure	Health effect	Study design	Reference
Physical ac- tivity	RR = 0.81 (95% CI: 0.76-0.85)	660 versus 0 MET min/ week	All-cause mortality	Meta- analysis	Woodcock et al. (2011)
PM _{2.5}	RR = 1.07 (95% CI: 1.04–1.09)	per 10 µg/m ³	All-cause mortality	Meta- analysis	WHO (2014)
Noise	HR = 1.038 (95% CI: 1.019–1.0.58)	per 10 dB L _{den} (Road)	CVD mortality	Cohort study	Héritier et al. (2017)
Green space	RR = 0.99 (95% CI: 0.98–1.01)	per 10% increase in greenness	All-cause mortality	Meta- analysis	Gascon et al. (2016)

CVD = cardiovascular disease; HR = hazard rate; L_{den} = EU noise indicator with 5 dB penalties for the evening time and 10 dB penalties for the night time; MET = metabolic equivalents of task; RR = relative risk; 95% CI = 95% confidence interval.

Statistics, 2017b) (Table 1). The steps were as follows: (1) We obtained recommended exposure levels ('counterfactual scenario' – WHO exposure level recommendations) and (2) baseline exposure levels (Table 2); (3) we obtained exposure response functions (ERFs) that quantify the association between the exposures and mortality from the literature (Table 3); (4) we scaled the relative risk (RR) to the estimated difference in exposure level between baseline and recommended exposure levels; and (5) calculated the population attributable fraction (PAF) for each exposure level difference. Analyses were conducted in R (v 3.3.1) and PostgreSQL/PostGIS (v 2.3.2).

2.2.1. International exposure level recommendations

- Physical activity (PA): Adults ≥18 years are advised to achieve 150 min of moderate-intensity or 75 min of vigorous-intensity aerobic PA throughout the week (Table 2) (WHO, 2010).
- Air pollution: Annual mean particular matter with diameter $\leq 2.5 \,\mu m \,(PM_{2.5})$ should not exceed $10 \,\mu g/m^3$ and annual mean nitrogen dioxide (NO₂) levels should not exceed $40 \,\mu g/m^3$ (WHO, 2006).
- Noise: Day time (7:00–23:00 h) outdoor activity noise levels should not exceed 55 A-weighted decibels [dB(A)] and night time (23:00–7:00 h) outdoor activity noise levels should not exceed 40 dB (A) (WHO, 2009, 1999).
- Green space: Universal access to a green space defined as living within a 300 m linear distance of a green space ≥0.5 ha is recommended (European Commission, 2001; WHO, 2016a).

2.2.2. Exposure level data

2.2.2.1. Physical activity. PA data were available for Bradford residents $(\geq 16 \text{ years})$ through the population-based randomly-sampled Active People Survey (2014) that tracks the number of people participating in sports and wider PA in England (Sport Sport England, 2014) (Table S1). Proportionally reported mean PA levels of moderate to vigorous intensity PA of all PA domains were extrapolated to all Bradford residents ≥18 years (Table S1 and Table 2). WHO recommended PA levels were translated into 600 metabolic equivalents of task (MET) minutes per week (IPAQ Webpage, 2005). The association between PA and mortality was quantified using a curvilinear ERF, applying a 0.25 power transformation to the PA exposure (Table 3) (Woodcock et al., 2011). Because health benefits occur even at low levels of PA, the RR and the PAF were calculated for both the current and the recommended MET minutes per week. Estimated preventable deaths for current PA levels were subtracted from estimated preventable deaths for recommended PA levels to obtain the net gain of compliance.

2.2.2.2. Air pollution. Annual mean $PM_{2.5}$ and NO_2 levels (2009/2010) were calculated for Bradford at the LSOA level using the European Study of Cohorts for Air Pollution Effects Land Use Regression (ESCAPE LUR) model (i.e. spatial scale: point level; LUR Oxford for $PM_{2.5}$ and LUR Bradford for NO_2) (Beelen et al., 2013; Eeftens et al., 2012a, 2012b) (Fig. 1 and Table 2). For each LSOA, the exposure difference in annual mean $PM_{2.5}$ and NO_2 and the recommended $10 \,\mu g/m^3$ and $40 \,\mu g/m^3$ was estimated, respectively. Since no LSOA exceeded the recommended NO_2 annual mean of $40 \,\mu g/m^3$ (i.e. LSOA range: $12.82-30.08 \,\mu g/m^3$ annual mean), NO_2 was not included in the analysis. The association between $PM_{2.5}$ and mortality was quantified using a linear ERF (Table 3) (WHO, 2014). The RR and PAF corresponding to the exposure difference were calculated at the LSOA level.

2.2.2.3. Noise. Annual mean EU 24-h noise indicator Lden (in dB) for road traffic with 5 and 10 dB penalties for the evening and night time, respectively, was available through Bradford's strategic noise map (2006) imposed by Directive 2002/49/EC (The European Parliament and the Council of the European Union, 2002) and was assigned areaweighted at LSOA level (Fig. 1 and Table 2). LSOAs that are not or only partially part of the Bradford agglomeration (i.e. rural areas that extend into the district) and therefore had unavailable or implausible noise values (i.e. $<30\,dB~L_{den})$ were assigned 30 dB L_{den} which is defined as the threshold for 'quite rural area' ambient noise levels. Until now, most evidence exists for the association between $L_{\mbox{\scriptsize den}}$ and cardiovascular mortality (Van Kempen et al., 2018), reinforced by a recent cohort study (Héritier et al., 2017). Given that the recommended day time noise threshold for health protection is 55 dB and accounting for night time noise exposure, where the WHO in 2009 recommended a threshold of 55 dB $L_{\rm night}$ for protection against cardiovascular effects (WHO, 2009), an overall exposure threshold of 55 dB $L_{\rm den}$ was chosen as our counterfactual scenario. The difference in exposure level was determined for each LSOA exceeding $55\,dB$ L_{den} . The association between L_{den} and cardiovascular mortality was quantified using a linear ERF (Table 3) (Héritier et al., 2017). The hazard ratio and PAF corresponding to the exposure level difference between recommended and actual level were calculated at the LSOA level.

2.2.2.4. Green space. We estimated the percentage of green space surface (%GS) each LSOA needed to have, to provide universal access to a green space \geq 0.5 ha within a 300 m linear distance. Green space data were available through Urban Atlas (2012; resolution 1:10,000) (European Environment Agency, 2007) and the Born in Bradford (BiB) cohort study (2007–2010) (Fig. 1 and Table 2). The BiB study, a largely bi-ethnic cohort of families of White British and Pakistani origin representing well the Bradford general population, tracks the health and wellbeing of over 13,500 children (and their parents) born in Bradford between March 2007 and December 2010 (Wright et al., 2013).

Using PostgreSQL/PostGIS, the current %GS was calculated for each LSOA. Quintiles of the LSOA %GS distribution were calculated. Using GIS-derived green space data for 19,720 home addresses of the BiB mothers recorded from 2007 to 2010 and distributed over the 310 LSOAs, the proportion of BiB mothers living within 300 m of a green space ≥ 0.5 ha was determined for each %GS quintile (Table S2). The distribution of the BiB mothers having access to a green space across the %GS quintiles was extrapolated to the entire Bradford adult population \geq 18 years. Using the same BiB data, a binominal generalized linear model was fitted to predict the %GS needed to provide universal access to a green space ≥ 0.5 ha within a 300 m linear distance at the LSOA level (Fig. S1). It was predicted that each LSOA needed to have 25%GS to provide universal access (i.e. 96.5% of population) to a green space \geq 0.5 ha within a 300 m linear distance. The exposure level difference between the current %GS of each quintile and the necessary 25% was determined. A linear ERF was used to quantify the association between

green space and mortality (Table 3) (Gascon et al., 2016). For each %GS quintile, the RR and the PAF corresponding to the exposure level difference were calculated.

2.3. Socioeconomic position (deprivation status and ethnicity)

We estimated how mortality impacts might vary by SEP as defined by deprivation status and ethnicity. First, at the LSOA level, analyses were stratified by using the English residential area Index of Multiple Deprivation (IMD). We assigned each of Bradford's 310 LSOAs their corresponding IMD rank (Table S3). The IMD ranks each of the 32,844 LSOAs in England from 1st (most deprived) to 32.844th (least deprived) according to their level of deprivation based on seven domains (income, employment, education, health, crime, barriers to housing and services, and living environment) (Department for Communities and Local Government, 2015). Bradford LSOA's were assigned national IMD rank quintiles (each quintile representing 20% of the English population). More than 60% of Bradford's residents fall into the 40% most deprived of the country. Second, we stratified our analyses by the proportion of non-White residents at the LSOA level (Table S4). We created five categories (80-100%, 60-80%, 40-60%, 20-40%, 0-20%) of the non-White resident distribution and assigned each LSOA the corresponding category. District-wide > 30% of residents were of non-White ethnicity.

To have an idea where premature mortality impacts will most likely occur, we built a multiple environmental burdens by SEP index at LSOA level by using the quintile distribution of the environmental exposures (i.e. PM_{2.5}, noise, green space) (Fig. 2). The sum of the environmental exposure quintiles (i.e. 1–3, 4–6, 7–9, 10–12, 13–15) represent the multiple environmental burdens cutoffs. For green space, inverse quintile numbering was used. IMD rank quintiles (1–5) were used to define the cutoffs for the socioeconomic index. Fig. 2 idea is adapted from Flacke et al. (2016).

2.4. Life table and economic analyses

We estimated average changes in life expectancy (LE) following standard life table methods (Miller and Hurley, 2003) and based on published life tables for the UK (based on data for 2014–2016) (Office for National Statistics, 2017c). We assumed that British age and sexspecific LE was representative for Bradford's population and estimated losses in LE due to incompliance with recommended exposure levels. The estimated losses in LE correspond to losses in LE expected for males and females born in Bradford today and living in incompliant areas (Table 4).

We also estimated economic impacts of the estimated average changes in LE by applying a value of a statistical life year (VSLY) of £60,000 with future benefits discounted at 1.5% (Department for Transport, 2017; Glover and Henderson, 2010).

2.5. Sensitivity analyses

As health effects of air and noise pollution occur under the established 'health thresholds' (Health Effects Institute, 2010; WHO, 2009), we also estimated preventable premature deaths under the *lower limit* scenarios that assume that the smallest measured annual mean $PM_{2.5}$ concentrations of $1.3 \,\mu$ g/m³ (Khreis et al., 2017; Morgenstern et al., 2008) and 'quiet urban area' ambient noise levels of 40 dB L_{den} (WHO, 2009) were not exceeded. Moreover, we compared our air pollution impact estimations for Bradford to the AirQ+ software (v 1.0) calculations provided by the WHO (WHO, 2016b). Similarly to the UTOPHIA methodology, the freely-accessible AirQ+ software performs calculations that allow the quantification of the expected health impacts of exposure to air pollution. To make the UTOPHIA methodology and AirQ+ software calculations comparable, applying the same counterfactual scenario (i.e. $PM_{2.5}$ annual mean should not exceed $10 \,\mu$ g/m³) and considering that AirQ+ in contrast to UTOPHIA provides only a district-wide impact estimation that does not allow for spatial stratification by LSOA, in AirQ + we used the mean PM_{2.5} exposure of those LSOAs with a mean annual exposure > 10 μ g/m³ (i.e. 11.03 μ g/m³) as our input value (i.e. 55% of the population exposed) (Table 4). We also applied the same mortality risk estimate in AirQ + as in the UTOPHIA methodology (i.e. RR = 1.07, 95% CI: 1.04, 1.09), for comparability reasons.

3. Results

Half of Bradford's adult population was insufficiently active (Table 2). District-wide $PM_{2.5}$ and noise levels exceeded recommended annual mean levels only slightly (i.e. $PM_{2.5} + 1.03 \,\mu g/m^3$ in 172 LSOAs and noise + 2.43 dB L_{den} in 113 LSOAs) (Table 4). 18% of Bradford's adult population did not live within the recommended 300 m linear distance to a green space ≥ 0.5 ha (corresponding to a necessary 25% GS of each LSOA).

Across all the exposures, 375 annual premature deaths (95% CI: 276-474) were estimated to be preventable if there would be compliance with international exposure recommendations. The largest share in preventable deaths was estimated to be attributable to increases in PA levels (327 deaths, 95% CI: 245-441), followed by reductions in air pollution exposure (17 deaths, 95% CI: 10-22), increasing access to green space (16 deaths, 95% CI: 0-32) and reductions in noise levels (15 deaths, 95% CI: 7-22) (Fig. 3). Bradford male residents were estimated to loose on average 348 days (95% CI: 263-432) of their LE which corresponded to economic losses of £56,295 per person (95% CI: 42,599-69,991) (Table 4). Female residents were estimated to loose on average 314 days (95% CI: 238-391) of their LE which corresponded to economic losses of £50,897 per person (95% CI: 38,518-63,276). The biggest loss in LE resulted from insufficient PA performance (63% of estimated lost days for males and females) (Fig. S2).

Stratified analyses by SEP showed that residents of more deprived and more ethnically-diverse LSOAs were at higher risk for adverse environmental exposures and mortality (Fig. 2) [i.e. 6–7 expected deaths/ 100,000 persons for the most deprived versus 0–1 expected deaths/ 100,000 persons for the least deprived across the environmental exposures (i.e. air pollution, noise, green space) and 8–11 expected deaths/100,000 persons in LSOAs with the highest proportion of non-White residents versus 1–2 expected deaths/100,000 persons in LSOAs with the lowest proportion of non-White residents across the environmental exposures] (Figs. 4 and 5 and Tables S3 and S4).

3.1. Sensitivity analyses

The *lower limit* air and noise pollution scenarios resulted in 253 preventable deaths (95% CI: 149–320) for PM_{2.5} and 145 preventable deaths (95% CI: 74–215) for noise < 40 dB L_{den} annually. Using the WHO AirQ+ software to estimate mortality impacts under the compliance of the PM_{2.5} air quality guideline, we estimated 17 preventable premature deaths (95% CI: 10–21) for Bradford which confirms the 17 premature deaths we estimated using the UTOPHIA methodology.

4. Discussion

We applied the UTOPHIA methodology to Bradford and estimated that 375 (i.e. almost 10% of total) annual premature deaths could be prevented if international exposure recommendations for PA, air pollution, noise and access to green space were complied with. An even larger number of premature deaths could be prevented by lowering air pollution and noise levels well below the guidelines. Over 300 days of LE were estimated to be lost among Bradford residents due to current incompliance which translated in economic losses of over £50,000 per person. Residents of neighborhoods characterized by lower SEP (most deprived and more ethnically-diverse) had the highest risk of



Fig. 2. Multiple environmental burdens by SEP at LSOA level.

The multiple environmental burdens index was built by using the quintile distribution of the environmental exposures (air pollution, noise, green space). The sum of the quintiles represent the different cutoffs. The national Index of Multiple Deprivation (IMD) rank quintiles were used to define the cutoffs for the socioeconomic position (SEP) index.

environmental exposures and premature death.

HIA work in the West Yorkshire study area has so far solely focused on air pollution exposure. A 2014 HIA study investigating different low emission zone scenarios, estimated 222 premature deaths attributable to slightly lower annual mean PM2.5 concentrations in Bradford (Cooper et al., 2014), which is comparable to the 253 deaths we estimated in the lower limit air pollution sensitivity scenario. Moreover, Cooper et al.'s (2014) different low emission zone scenarios resulted in 15 to 19 deaths preventable. Subsequently and building on Cooper et al.'s (2014) work, a 2016 HIA study, estimated 10 premature deaths preventable in the study area, assuming air quality improvements achieved through an upgrade of EURO 4 buses and heavy goods vehicles to EURO 6 (Lomas et al., 2016). Recently, two HIA studies looking at childhood asthma cases attributable to air pollution in Bradford found similar districtwide averages for $PM_{2.5}$ and NO_2 concentrations (11.2 μ g/m³ $PM_{2.5}$ and $21.93 \,\mu\text{g/m}^3 \text{ NO}_2$) and estimated between 279 and 687 attributable asthma childhood cases depending on the pollutant studied (Khreis et al., 2018a, 2018b). To our best knowledge, until now, only two HIA studies, both conducted for Barcelona, Spain, holistically estimated premature mortality impacts of the multiple urban and transport planning related exposures (Mueller et al., 2017a, 2017b). In Barcelona, almost 20% of premature mortality were estimated to be attributable to

non-compliance with recommended levels for PA, air and noise pollution, heat and access to green space (Mueller et al., 2017a). Barcelona had similar exposures of low PA, but in addition exceeded more prominently the recommended air and noise pollution levels and had less green space. Also for Barcelona heat effects of extreme summer temperatures were studied, but were considered as less relevant for Bradford and thus were ignored. Barcelona is a more compact and dense city (16,000 persons/km²) than Bradford and has with 6,000 vehicles/km²: the highest traffic density in Europe (Barcelona City Council, 2018). The lower estimates of mortality in Bradford appear to be due to less traffic (Bradford is ranked 18th on the list of the UK's most congested cities (TomTom International BV, 2018)) and subsequent less air pollution and noise and greater availability of green space.

The largest mortality impacts in Bradford resulted from non-compliance of recommended PA performance (i.e. 327 deaths), which is in agreement with HIA studies of transport that considered (besides other risk factors) the impacts of PA (Buekers et al., 2015; De Hartog et al., 2010; Macmillan et al., 2014; Mueller et al., 2015; Rojas-Rueda et al., 2011, 2012, 2016; Woodcock et al., 2009, 2013, 2014; Xia et al., 2015). The breach of air pollution and noise exposure guidelines were estimated to contribute to a health burden of similar magnitude in Bradford (i.e. 17 and 15 premature deaths, respectively). Despite sharing the

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Life table and ϵ	conomic anlyses.							
Expsoure	Exposure threshold	Mean incompliant exposure level across incompliant LSOAs	Incompliant LSOAs (<i>n</i>)	Population exposed (n (%))	Loss in LE (days) males across incompliant LSOAs	VSLY males 1.5% discounted across incompliant LSOAs	Loss in LE (days) females across incompliant LSOAs	VSLY females 1.5% discounted across incompliant LSOAs
Physical activity ^a	< 600 MET min/week	– 476.49 MET min/week	1	194,187 (49.40)	221 (95% CI: 176–274)	35,722 (95% CI: 28,507–44,446)	199 (95% CI: 159–248)	32,289 (95% CI: 25,771–40,166)
$PM_{2.5}$	$> 10 \mu g/m^3$	$+1.03\mu g/m^3$	172	216,269 (55.02)	27 (95% CI: 15–34)	4,337 (95% CI: 2,508–5,535)	24 (95% CI: 14–31)	3,923 (95% CI: 2,268–5,006)
Noise	> 55 dB L _{den}	+ 2.43 dB L _{den}	113	142,813 (36.33)	35 (95% CI: 17–53)	5,620 (95% CI: 2,825–8,534)	31 (95% CI:16–48)	5,084 (95% CI: 2,555–7,719)
Green space	< 25% GS	– 17.17%GS	186	70,143 (17.84)	66 (95% CI: 0–132)	10,616 (95% CI: 0–21.318)	59 (95% CI: 0–119)	9,601 (95% CI: 0–19.276)
Total	I	I	I	I	348 (95% CI: 263–432)	56,295 (95% CI: 42,599–69,991)	314 (95% Cl: 238–391)	50,897 (95% CI: 38,518–63,276)

dB = decibel; LE = life expectancy; LSOA = Lower Super Output Area; L_{dem} = EU noise indicator with 5 dB penalties for the evening time and 10 dB penalties for the night time; MET = metabolic equivalents of taks; 95% = 95% confidence interval; %GS = percentage green space; VSLY = value of a statistical life year. U

^a Physical activity data was not available at the LSOA level. Presented values correspond to the average insufficiently active person.

400 Attributable premature deaths 0 Green space Noise PM_{2.5} Physical activity Exposures

Fig. 3. Attributable premature mortality due to non-compliance of exposure level guidelines.







Fig. 5. Standardized mortality impacts by LSOA-level ethnicity.

common source of motor traffic, the health effects of air and noise pollution are suggested to be independent, but of similar extent (Mueller et al., 2017a; Tétreault et al., 2013; Vienneau et al., 2015). The green space analysis for Bradford, resulted in 16 preventable premature deaths and therefore highlights the increasing epidemiological

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importance of natural outdoor environments in times of ongoing urbanization processes, space scarcity and increasing population densities (Dadvand et al., 2016; Gascon et al., 2016).

In Bradford, residents of lower SEP and more ethnically diverse neighborhoods were more adversely exposed to the multiple environmental exposures (i.e. higher air pollution, higher noise, less green space) (Fig. 2) and therefore were more susceptible to adverse health outcomes. Spatial exposure differences that especially discriminate against the most unprivileged populations have been observed in other settings (Casey et al., 2017; Clark et al., 2017; Eime et al., 2015; Pan et al., 2009; Schüle et al., 2017). A recent US study demonstrated that NO₂ exposure concentrations were 37% higher for non-Whites than for Whites and that these exposure differences were larger by race-ethnicity, than by income (Clark et al., 2017). A study for Dortmund, Germany showed that the multiple environmental burdens were significantly correlated and strongest in low SEP neighborhoods (Flacke et al., 2016). Identifying these hotspots of environmental injustice (and resulting health inequity) is an issue that needs urgent consideration and emphasizes that for successful urban and transport planning interventions, the specific vulnerabilities of the populations affected need to be taken into account (Flacke et al., 2016).

4.1. Public health implications

Nowadays, motor traffic is the most prominent and common source for all exposures (low PA, high air and noise pollution, little green space) in cities. Hence, in Bradford (and elsewhere) healthy living could be best promoted by reducing motor traffic. In this context, interventions at the community level (such as urban and transport planning interventions) that change peoples' default decisions were shown to be more effective than interventions at the individual level (Daumann et al., 2015; Frieden, 2010; Nieuwenhuijsen, 2016).

Active transport (i.e. walking and cycling for transportation in combination with public transport use) is a healthy and sustainable alternative to motor transport. Active transport serves the multi-purpose of (1) providing transport, (2) opportunities for routine PA engagement (a policy priority in Bradford as 90% of the mortality impact resulted from low PA performance) and (3) simultaneously improves environmental quality by being low to zero emission transport modes (Dons et al., 2015; Mueller et al., 2015; Saris et al., 2013). Moreover, active transport is a very accessible and equitable mode of transport and PA opportunity. By being economically affordable, it can also reach population sub-groups that are irresponsive to the appeals of leisure time PA (Dons et al., 2015).

Moreover, the proximity to green space has been identified as one urban planning related feature that promotes an active lifestyle (Sallis et al., 2015). Green spaces add aesthetic appeal (Triguero-Mas et al., 2015), provide a space for PA performance (Gladwell et al., 2013; Lee et al., 2015) and reduce harmful environmental exposures of air pollution, noise and heat (Abhijith and Gokhale, 2015; Doick et al., 2014; Raji et al., 2015; Van Renterghem et al., 2015). Nonetheless, as green space allocation of ≥ 0.5 ha in established cities might be difficult and the decisive mechanisms of green space providing health benefits remain uncertain (Gascon et al., 2016; Markevych et al., 2017), the reinforcement of surrounding greenness (i.e. green corridors, street trees, pocket parks, etc.) should be considered because already visual access to nature has been associated with health benefits of stress reduction and restoration (De Vries et al., 2013; Triguero-Mas et al., 2015) and this type of greenness may be more feasible to implement. The fact that in Bradford (and elsewhere) residents of neighborhoods of lower SEP face multiple environmental burdens (high air pollution, high noise, little green space) and are thus more vulnerable to adverse health outcomes, suggests that these residents would benefit the most from health promoting interventions, such as reducing motor traffic, promoting active transport and developing green space. Persons of lower SEP tend to be less mobile (e.g. persisting relationship between income and car ownership in England and Wales (Yeboah et al., 2015)) than persons of higher SEP and their activities and social contacts are often situated closer to their homes (Dadvand et al., 2014; Maas, 2008; Schwanen et al., 2002). Active transport can help improve their mobility, and green space access in their direct residential proximity can increase the likelihood for these residents to actively use them, which in itself will provide health benefits (Dadvand et al., 2014; McEachan et al., 2016).

4.2. Strengths and limitations

This study adds to the limited evidence base documenting expected health impacts of the multiple urban and transport planning related exposures (beyond air pollution) and their directions and magnitude (Briggs, 2008). This allows for comparison of the severities of the exposures that with other study designs would not be possible and helps to identify priorities for policy action (see implications for public health). By also studying the distribution of health impacts among the population (and in the case of Bradford identifying the residents of lower SEP neighborhoods as most exposed and hence at the highest risks), HIA studies can provide valuable information on inequalities and can help to overcome misperceptions that health disparities are exclusively due to lifestyle choices, genetic predispositions and access to medical care (Collins and Koplan, 2009; National Research Council Of The National Academies, 2011).

However, as with all HIA studies, their validity is limited by assumptions on causal inferences were evidence is lacking. We estimated health impacts corresponding to the counterfactual scenario of complying with international exposure recommendations. Larger impacts are expected when choosing lower comparison thresholds for air and noise pollution (as demonstrated in the *lower limit* sensitivity analyses), and more ambitious thresholds for PA and access to green space. Moreover, there might have been exposure and outcome misclassification, as the different UTOPHIA inputs (i.e. exposures, health statistic and population data) were only available for different years (2006–2016). Nevertheless, we are unaware of any major policy changes over this 10-year timeframe that might have changed exposure levels drastically. Therefore, we believe that our results are a robust estimation of the overall health impact to be expected.

In the context of exposure misclassification, road traffic noise data was only available for the Bradford agglomeration and was assigned area-weighted at LSOA level. This might have underestimated the overall noise exposure of LOSAs that are not or only partially part of the Bradford agglomeration. Furthermore, in terms of personal exposure, we have no insight on whether people spend most time of their day at their LSOA of residence. Also, PA data was unavailable at the LSOA level. Consequently, we do not know how PA is distributed among the population within different areas of Bradford. Research evidence, nevertheless, demonstrated more available resources for PA participation, including parks and walking and biking trails, in higher SEP neighborhoods (Estabrooks et al., 2003), and correlated increasing PA performance with increases in SEP (Eime et al., 2015; Pan et al., 2009). If this finding holds true for Bradford, then residents of lower SEP neighborhoods are performing the lowest levels of PA, adding to socioeconomic inequalities in the total health burden. In terms of air pollution exposure, we exclusively considered PM2.5 in our analyses as a general marker for air pollution from all fossil fuel combustion sources (Mueller et al., 2015). Despite having NO₂ data available, no LSOA exceeded the recommended value (i.e. $> 40 \,\mu g/m^3$) and the high correlation between pollutants of traffic exhaust (e.g. PM_{2.5} and NO₂) needs to be considered with caution because it complicates the distinction of pollutant-specific effects (Khreis et al., 2018a).

In terms of outcome misclassification, all-cause mortality was our health outcome of interest. Yet, for noise exposure only evidence for L_{den} and cardiovascular mortality exists (Héritier et al., 2017). It is believed, though, that the greatest contribution of noise to mortality is

through cardiovascular effects, according to current evidence on the effects of noise on different conditions (Basner et al., 2014; Héritier et al., 2017). Therefore, we considered the applied risk estimate as a valid proxy to estimate overall mortality impacts associated with noise exposure. For the association between green space and mortality more recent evidence exists. However, despite being of longitudinal study design and providing continuous ERFs, these studies are setting and population-specific (i.e. Canadian cities, American women) and use another exposure unit (i.e. the Normalized Difference Vegetation Index (NDVI)) (Crouse et al., 2017; James et al., 2016). Moreover, a recent meta-analysis provides an odds ratio for all-cause mortality of 0.69 comparing high with low green space exposure (Twohig-Bennett and Jones, 2018). Generally, this new evidence is suggesting stronger health benefits of green space than the risk estimate we applied (i.e. RR = 0.99per 10% increase in greenness). The latter we chose because it originates from the only existing meta-analysis providing a continuous ERF that corresponds to our exposure unit (i.e. % increase in greenness) (Gascon et al., 2016). Therefore, one can argue that our estimated impacts are conservative and possibly more premature deaths could be attributed to the lack of green space in Bradford. Moreover, a stratification of the applied all-cause mortality ratio by SEP was unavailable. Stratified mortality ratios would probably have amplified the estimated mortality differences by SEP, making the consideration of inequalities an even more pressing issue. Likewise, life tables specifically for the Bradford population were unavailable, therefore national life tables were used. This possibly has led to an underestimation of the LE changes as the Bradford population has higher levels of deprivation (Cooper et al., 2014; Fielding, 2012).

Even though we suggest that community-level interventions (i.e. the promotion of active transport and the development of green space) may lead to improvements in exposure levels, HIA studies are unable to capture individuals' intrinsic motivations and personal choices as fostered by the sociocultural environment. Hence, for successful policy (health) outcomes, it is important to keep in mind the sociocultural drivers for behavior change that we were unable to quantify. Therefore, integrated, participatory engagement of the communities affected in the policy planning process helps to gain a better understanding of necessities and expected behaviors and ensures that policy outcomes are realistic, practicable and acceptable (Collins and Koplan, 2009; Forsyth et al., 2010; Joffe and Mindell, 2005; Nieuwenhuijsen et al., 2017b).

5. Conclusions

In Bradford, 10% of all premature deaths are due to urban and transport related exposures. Residents of lower SEP neighborhoods were estimated to experience the highest exposure and mortality burden. Reducing motor traffic and promoting PA through the promotion of active transport together with the development of green space should be a focus for urban and health planners that most likely will help to reduce harmful environmental air and noise pollution. The focus of these health promoting interventions should be on the most deprived and ethnically-diverse neighborhoods as the largest health gains are to be expected in these areas.

Declarations of interests

None.

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Appendix A. Supplemental Material

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