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Vulnerability to motor fuel price increases: Socio-spatial patterns in England

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ABSTRACT

In high-motorisation, car-dependent countries, transport affordability is intimately linked to the price of oil derived motor fuels, which may become increasingly volatile in the future due to global oil price movements and environmental taxation. The negative impacts of fuel price spikes in terms of increased household expenditure and economic stress are unevenly spatially and socially distributed. Previous research has found that vulnerability to fuel price increases is higher in peripheral, peri-urban and rural areas, and that low income tends to be co-located with high car dependence and low vehicle fuel efficiency, with a compounding effect on vulnerability. The goal of this article is to test these hypotheses for England, providing new evidence on spatial patterns of vulnerability to fuel price increases at the small-area level. We propose a composite vulnerability indicator combining data on income, accessibility, vehicle inspection and vehicle registration for 2011. *Within English city-regions*, we find little evidence of the socially regressive patterns previously identified in the literature. This is explained by the persistent concentration of poverty in urban cores, as well as by the poor fuel economy of the vehicle fleet in wealthier areas, due to the prevalence of powerful vehicles there. On the other hand, our analysis suggests that the impacts of fuel price increases would be very unequal *between city-regions*, as the least sensitive metropolitan area (Greater London) is also characterised by high levels of adaptive capacity. We conclude by setting out an agenda for future research on spatial vulnerability to fuel price increases.

1. Introduction

Despite the ongoing debate on 'peak car' (Goodwin and Van Dender, 2013; Newman and Kenworthy, 2015), motorisation and car use are still increasing globally (Pojani and Stead, 2017), and passenger mobility in developed countries remains car dependent (Jeekel, 2013), although with considerable variation between spatial contexts. While much is made of the rise of alternative fuels and powertrains, most of the private motor vehicle fleet still consists of internal combustion engine technology running on fossil fuels - with e.g. renewables accounting for just 7% of transport-related energy consumption in the EU in 2016 (Eurostat, 2018).

Passenger mobility in developed countries is thus still largely dependent on the availability of cheap oil derived fuels. This has raised concerns about the vulnerability of transport and urban systems to increases in motor fuel prices (Dodson and Sipe, 2007; Leung et al., 2019; Newman et al., 2009), notably since the long oil price surge in 2005–2014. Oil price fluctuations are notoriously hard to predict and can be sudden (Baumeister and Kilian, 2016; Gronwald, 2016; Alexander, 2017), although the longer-term outlook is for overall increases in the real price of crude oil worldwide (World Bank, 2016). Beyond oil markets, pricing measures are one of the main policy tools available for climate change mitigation in the transport sector (Sims et al., 2014; Schäfer et al., 2009; Stern, 2006) and, with the emphasis currently placed on rapid carbon emission reductions (IPCC, 2014), it is possible that fuel taxation will increase further in the future (Ross et al., 2017).

The level and dynamics of motor fuel prices have great relevance for the spatial development of human settlements. Since the mid-twentieth century, population growth in the Global North has shifted towards car-dependent suburban and peri-urban areas, and this has been predicated upon the availability of cheap fuel (Dodson, 2014; Gonzalez, 2006; Newman and Kenworthy, 1999; Walks, 2015). This shift has occurred alongside changes in 'urban socio-spatial configurations', i.e. the spatial sorting of social groups within city-regions (Kesteloot, 2005), although this has played out differently in different national and local contexts. Therefore, a growing body of research (reviewed in the following section) suggests that the negative impacts of fuel price increases in terms of increased expenditure and economic stress are unevenly spatially and socially distributed.

This paper contributes to this literature by investigating socio-spatial patterns of vulnerability to fuel price increases in England, based on a spatial metric of vulnerability, i.e. a composite indicator covering the dimensions of *exposure*, *sensitivity* and *adaptive capacity* to fuel price increases. Our focus in this paper is on the spatial relationships between the factors behind vulnerability, i.e. the extent to which these tend to

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compound or compensate for each other. Previous research has suggested that the disadvantage of low-income areas is compounded by high levels of car dependence and low fuel efficiency of the vehicle fleet, which results in heightened vulnerability to fuel price increases. The goal of this paper is to test whether these compounding effects are at work in England, or whether the different factors underlying vulnerability tend to compensate for each other. The scope of the paper is concerned specifically with the impacts of motor fuel price increases, and it does not investigate other forms of economic stress arising e.g. from housing costs, although we acknowledge that these can interact with one another (Cao and Hickman, 2018; Coulombel, 2018; Dodson and Sipe, 2008a; Kramer, 2018; Li et al., 2018).

The paper is structured as follows. In Section 2, we review studies on socio-spatial patterns of vulnerability to fuel price increases in metropolitan areas. In Section 3, we provide information on the case study country. In Section 4, we present the composite indicator of vulnerability, the data, and illustrate our analysis approach. In Section 5, we present the main findings of our analysis, which are discussed in Section 6. Section 7 outlines implications for future research.

2. Background

Research on transport poverty and affordability suggests that households facing high motoring costs relative to their economic resources tend to reduce necessary travel, cut expenditure on other necessities and/or to go into debt (Currie and Delbosc, 2011; Currie and Senbergs, 2007; Demoli, 2015; Froud et al., 2002; Lucas, 2011; Mattioli, 2017; Mattioli et al., 2017a; Mullen and Marsden, 2018; Ortar, 2018; Rock et al., 2016; Taylor et al., 2009; Walks, 2018). Rapid fuel price increases exacerbate this, with uneven impacts across population groups and types of area. Among quantitative empirical studies on vulnerability to fuel price rises, only a few focus on households or individuals (Lovelace and Philips, 2014; Mattioli et al., 2018; Nicolas et al., 2012), with the majority taking small areas as the unit of analysis, mainly because of data availability (Akbari and Habib, 2014; Arico, 2007; Büttner et al., 2013; Cao and Hickman, 2018; Dodson and Sipe, 2007; Dodson and Sipe, 2008a; Dodson and Sipe, 2008b; Fishman and Brennan, 2009; Leung et al., 2018; Rendall et al., 2014; Runting et al., 2011). In this paper, we adopt a similar approach, analysing spatially aggregate data instead of focusing on households. This allows us to explore spatial patterns in more detail, complementing recent UK research on vulnerability to fuel price increases based on household survey data (Mattioli et al., 2018).

In the remainder of this section, we discuss the findings of previous research on spatial patterns of vulnerability, focusing on two 'regressive urban structural effects' that have been highlighted: i) the co-location between areas of low income and high car dependence; ii) the co-location between areas of low income and low fuel efficiency of the vehicle fleet. These findings constitute the background for our own investigation of these spatial relationships in England.

2.1. Spatial patterns of income and car dependence

In their seminal study of 'oil vulnerability' in Australian cities, Dodson and Sipe (2007) develop a composite indicator with two components: economic status and car dependence. The study finds wide spatial variability in vulnerability, with suburban and peri-urban areas considerably worse-off than inner cities. The main reason for this is that "low socioeconomic status and high car dependence are *strongly co-located* in Australian cities" (p.57, emphasis added), with outer areas characterised by lower incomes, as well as by fewer alternatives to car driving (as a result of lower residential density and poor public transport provision). Conversely, inner cities are characterised by both higher incomes and better modal alternatives to the car. Subsequent empirical studies of Australian city-regions (Dodson and Sipe, 2008a; Dodson and Sipe, 2008b; Fishman and Brennan, 2009; Nazari Adli et al., 2019; Runting et al., 2011) have confirmed this pattern.

An important implication is that in Australia 'oil vulnerability' "*compounds* existing socio-spatial divisions" (Dodson and Sipe, 2007, p.37, emphasis added) as "the costs of higher fuel prices will be borne most heavily by those with the least capacity to pay" (Dodson and Sipe, 2008b, p.6). Therefore, in the Australian context, oil vulnerability analysis does not bring to light new spatial patterns of inequality, but rather demonstrates that well-known areas of disadvantage are also most at risk from possible fuel price increases (Dodson and Sipe, 2007, p.48).

The relevance of fuel price impacts in Australia can be explained by several factors, including less useful public transport services, lower level of fuel taxation and higher level of subsidies (e.g. fringe benefit schemes) relative to other OECD countries (Hodgson and Pearce, 2015; Kraal et al., 2008; Riedy and Diesendorf, 2003; Ross et al., 2017). Dodson and Sipe also draw attention to the structure of housing markets, which exhibit steep 'price decay gradients' and "tend to allocate modest income home purchasers to outer and fringe localities" (Dodson and Sipe, 2008a, p.385–386), where they then struggle to cope with the costs of intensive car ownership and use (Currie and Delbosc, 2011). In Australia, such urban structure – which Dodson and Sipe (2008b) label as 'regressive' – is a recent historical product: while until the 1980s disadvantage was an inner-city phenomenon, by 2011 it was disproportionally located in outer areas (Randolph and Tice, 2017). This suburban shift in the distribution of disadvantage resulted from neoliberal economic policies, which increased income polarisation and reduced welfare provision and social housing (Randolph and Tice, 2014). A similar trend towards the 'suburbanisation of poverty' has been observed in the US (Kneebone and Berube, 2013; Wang and Woo, 2017), although not at the same scale and pace as in Australia. In the UK, Bailey and Minton (2018) have tracked changes in relative centralisation and concentration of poverty for the 25 largest cities over 2004–2016, based on a spatial analysis of official income deprivation data. They find that "poverty is suburbanising, at least in the larger cities, although poverty remains over-represented in inner locations" (p.892).

The prevalence of different urban socio-spatial configurations may explain why non-Australian research has found different socio-spatial patterns of vulnerability to fuel price increases. In their study of Christchurch (New Zealand), Rendall et al. (2014) find a "less linear pattern" (p.18), as outlying areas are on average higher-income. Therefore, in a price increase scenario, more affluent suburban residents would still be able to afford fuel and maintain their current travel patterns, while poorer inner-city motorists would be able to 'adapt' by shifting to other modes, preserving access to activities. Unlike in Australia, in this socio-spatial configuration (low) income and car dependence tend to *compensate* rather than compound each other. In Europe, Büttner et al. (2013) use a combination of population data, transport model results, travel surveys, and accessibility data to estimate a composite indicator of vulnerability to fuel price increases in Munich (Germany) and Lyon (France). The results show that Munich resembles the Australian pattern, whereby in peri-urban areas lower income is compounded by greater car dependence. The opposite pattern is observed in Lyon, where greater deprivation in inner city areas is compensated by good public transport accessibility, which shields residents from vulnerability.

2.2. Spatial patterns of income and fuel efficiency

In a further series of studies, Dodson and colleagues (Dodson et al., 2009, 2010; Li et al., 2013, 2015) have used vehicle registration data to investigate to what extent low efficiency is co-located with social disadvantage and car dependence. The idea is that where these factors are co-located, vulnerability to fuel price increases is further exacerbated, as the most vulnerable households also have to rely on fuel-hungry vehicles, needing to spend greater sums to drive the same distances.

The results of these studies suggest that in Australian city-regions the fuel efficiency of the vehicle fleet tends to be lower in outer suburban areas (Li et al., 2013, 2015), as result of a greater proportion of old and large-engine vehicles (Dodson et al., 2009, 2010). Across small areas, fuel efficiency is found to be negatively associated with household income – i.e. higher income areas tend to have more efficient vehicles – although the magnitude of the relationship is moderate and net of other intervening factors (Li et al., 2015). The authors also find a positive correlation between the proportion of old and large-engine vehicles and the oil vulnerability index (Dodson et al., 2009). They thus conclude that “the composition of the vehicle fleet exacerbates household exposure to higher transport costs and compounds other forms of disadvantage” (Li et al., 2013, p.277). The low fuel efficiency of the vehicle fleet is a particular concern in Australia and may have been encouraged by low fuel taxation and generous fringe benefit schemes (Hodgson and Pearce, 2015; Kraal et al., 2008; Riedy and Diesendorf, 2003; Ross et al., 2017).

Evidence on spatial patterns of vehicle fuel efficiency from the UK is limited, but seems to show different patterns. Using an earlier version of the vehicle inspection dataset used in this study (see Section 4.1.2 below), Chatterton et al. (2015) explore the spatial patterns of various vehicle-related variables. They find better average fuel efficiency in the poorer North of the country, as compared to the more affluent South-East and London, where fuel efficiency is worse. Their analysis however is based on relatively coarse spatial units, and so does not enable investigation of spatial patterns within city-regions.

3. Context of the case study country

The UK consists of four constituent countries: England, Scotland, Wales and Northern Ireland. The analysis in this paper focuses on England, where > 80% of the UK population lives. Besides data availability, several reasons can be given for the selection of England as a case study.

First, in the last thirty years in the UK, the real price of fuel has changed under the influence of various factors (Fig. 1) including global oil market movements, currency depreciation and environmentally-motivated increases in taxation (Lyons and Chatterjee, 2002; Chatterton et al., 2018). Despite the fluctuations, fuel price is on a long-term increasing trend and, at the time of writing, it was near the all-time high. While the UK has a rich tradition of research on transport and social exclusion (Lucas, 2012; SEU, 2003), we are not aware of previous attempts to map spatial patterns of vulnerability to fuel price increases other than Lovelace and Philips' (2014) and Cao and Hickman's (2018) regional studies.

Second, as discussed in Section 2, most of the research on vulnerability to fuel price increases to date has focused on Australia, which is characterised by very low-density urban development and high levels of car dependence (Newman and Kenworthy, 1999). The UK, like much of the rest of Europe, is characterised by comparatively more compact urban development and lower levels of car ownership and use – with e.g. 24% of English households having no access to cars or vans in 2017 (DfT, 2018). At the same time, the UK is broadly car dependent outside Greater London and to a lesser extent the core of the other major cities (Goodman, 2013). There is a marked contrast between good public transport provision in the capital and the relative absence of rail-based urban public transport in other city-regions (see Table 4 below). These rely largely on buses, whose patronage has declined since deregulation in the 1980s (Bayliss and Mattioli, 2018; Docherty and Shaw, 2003; Shaw and Docherty, 2014). Also, the UK has experienced a long-term trend towards suburbanisation, with large population increases in areas of low population density and high transport-energy consumption until the 1990s (Breheny, 1995). Yet urban sprawl has been limited somewhat by brownfield reuse policies and urban ‘green belts’ (Schulze Baing, 2010), and there has been a recent trend towards re-urbanisation (Thomas et al., 2015). Overall, it is interesting to explore whether the broad conclusions of Australian research on vulnerability to fuel price increases can be extended to a different context such as England.

A third reason for interest has to do with spatial patterns of social inequality. Unlike in Australia, in England deprivation remains relatively concentrated in inner cities (Bailey and Minton, 2018; Hunter, 2016; Rae, 2012), while rural and peri-urban areas are relatively affluent (Eurostat, 2015; Pateman, 2011). There is however an ongoing trend towards the suburbanisation of disadvantage in the UK (Bailey and Minton, 2018; Hunter, 2016), and particularly in London, due to rapidly increasing housing prices in central areas (Cao and Hickman, 2018). Besides inequalities within city-regions, the UK is also characterised by large interregional economic imbalances. Within England, there is a long-standing North-South divide, with higher overall wealth in the South East and particularly London (IPPR North, 2017; The Economist, 2017; Rae, 2012).

While this study focuses exclusively on vulnerability to motor fuel

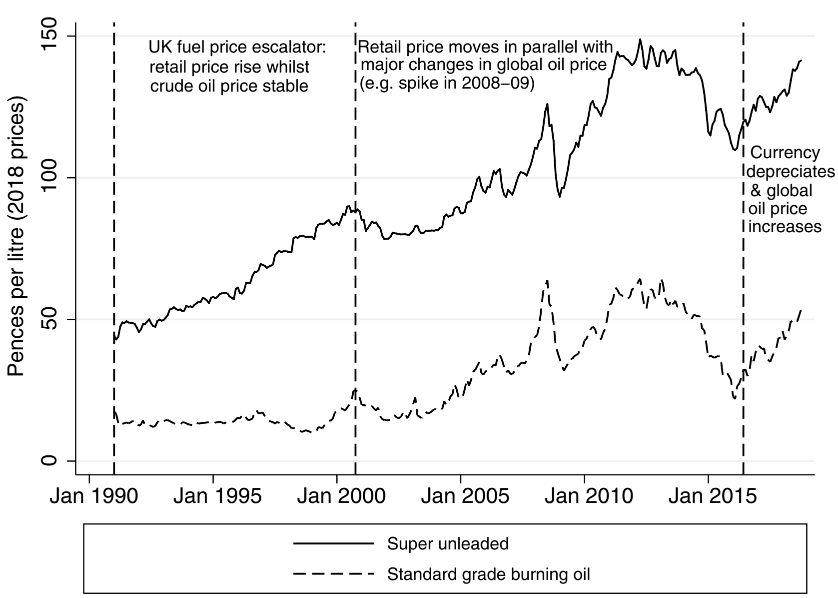

Fig. 1. Real monthly motor fuel and oil prices in the UK, 1991–2018. Source: DBEIS (2018).
Note: Diesel prices are not depicted as they are very similar to super unleaded prices in both levels and trends.

Table 1
Indicators used for the measurement of vulnerability to fuel price increases in selected previous studies, organised according to vulnerability dimension.

Study reference	Exposure	Adaptive capacity	Sensitivity
Dodson and Sipe (2007)	(i) Proportion of households with two or more motor vehicles; (ii) Journey to work car modal share		Socio-economic index for areas (SEIFA)
Arico (2007)	(i) Journey to work car modal share; (ii) Proportion of total expenditure spent on transport	*[Not considered]*	(i) Vulnerable age group population (working population – ages 15 and over); (ii) Incidence of low income
Fishman and Brennan (2009)	(i) Average weekly fuel use; (ii) Percentage of weekday travel (for all purposes) using public transport, cycling or walking		Average personal income
Runting et al. *(2011)*	(i) Proportion of dwellings with two or more low-occupancy vehicles; (ii) Proportion of persons who travel to work by low occupancy vehicles; (iii) Average commuting distance for journey to work	Proportion of area with non-motorised access to public transport	Socio-economic index for areas (SEIFA)
Büttner et al., *2013*	Munich: Vehicle-km per capita Lyon: Per capita commuting distance by private car	Total number of accessible jobs within one hour by public transport at peak time	Munich: Average monthly income Lyon: Unemployment rate
Akbari and Habib (2014)	(i) Proportion of households with two or more vehicles; (ii) Proportion of trips (for all purposes) by car		(i) Median household income; (ii) Prevalence of low income after tax
Lovelace and Philips (2014) *('Hybrid vulnerability index')*	Average proportion of individual's energy budget spent on commuting	(i) Distance to employment centre; (ii) Proportion of work trips made by car	*[Not considered]*
Rendall et al. *(2014)*	Average household car-related energy consumption / costs	Estimation of average 'minimum' required transport energy consumption	Median income
Leung et al. *(2015)*	(i) Average number of motor vehicles owned per dwelling; (ii) Oil-based fuel use of low-occupancy vehicles per commuting trip; (iii) Average commuting distance	(i) Proportion of mode share that does not consume oil; (ii) Proportion of area within 400 m of public transport stop ranked by level of service on weekdays; (iii) Walkability indices; (iv) Employment density; (v) Proportion of area within 400 m buffer of electric transport corridors	(i) Median weekly household income; (ii) Index of relative socio-economic disadvantage

price increases, we acknowledge the existence of other forms of economic stress with uneven spatial impact, which could potentially alter the sensitivity to fuel price rises. These include for example housing affordability, which is worse in the South of England and particularly in London (Clarke et al., 2016). The spatial incidence of 'fuel poverty', i.e. the economic stress associated with domestic energy costs, is also uneven, with rural areas and the North of England more severely affected (Robinson et al., 2018). While we do not consider these further forms of economic stress in our empirical study, we take them into account in the interpretation of our findings.

4. Approach, data and methods

4.1. Construction of the composite indicator

In line with previous research, this study proposes a composite indicator summarising in a single index the multiple constituent components of vulnerability to fuel price increases. The following sections describe three key steps of this process (OECD, 2008): the identification of a sound theoretical framework (4.1.1) to guide the selection of underlying indicators and variables (4.1.3), which are then aggregated in a single composite metric (4.1.4).

4.1.1. Theoretical framework

While much 'oil vulnerability' research to date has relied on 'ad-hoc' theoretical frameworks, more recent contributions (Büttner et al., 2013; Leung et al., 2015, 2018) have drawn on conceptualisations of social vulnerability developed in climate change and natural hazards research (e.g. Adger, 2006; Brooks, 2003). Adger (2006) defines vulnerability as "the state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt" (p.268). It is seen as constituted by three components: *exposure*, i.e. "the nature and degree to which a system experiences (…) stress", *sensitivity*, i.e. "the degree to which a system is modified or affected by perturbations", and *adaptive capacity*, i.e. "the ability of a system to evolve in order to accommodate (stress) and to expand the range of variability with which it can cope" (p.270).

While many studies on 'oil vulnerability' do not explicitly adopt this tripartite framework, most include indicators covering at least two of these dimensions, as shown in Table 1 (for a similar review see Leung et al., 2018; for a discussion of the limitations of the indicators used in previous research see Mattioli et al., 2017b). In this paper, we draw on this conceptualisation to guide the construction of our composite indicator. This is shown in Table 2, which links the three vulnerability dimensions to specific indicators, and the variables we used to measure them. The unit of analysis for all variables is the English Lower-layer Super Output Area (LSOAs).[1] The data sources for the indicators (in the rightmost column) are discussed in detail in the next section.

4.1.2. Data

The variables used for the composite indicator are taken from three sources of data (Table 2): (i) a vehicle inspection dataset, linked to a vehicle registration dataset; (ii) a dataset providing modelled, area-based estimates of household income; (iii) official government 'accessibility statistics'. These are described in this section.

Data collected through periodic (annual) technical inspections of motor vehicles is collected in a number of countries and increasingly made publicly available. In the UK, anonymised 'MOT' vehicle inspection test records have been published since 2010 (Cairns et al., 2014) and have been used for a range of travel behaviour analysis (Cairns et al., 2017; Chatterton et al., 2015, 2016, 2018; Philips et al., 2017). The application of mathematical methods (Wilson et al., 2013a,b) allows the estimation of annual mileage rates for each vehicle, based on odometer readings. As information on fuel type, engine size and vehicle age is also available with this data, it is possible to estimate fuel economy, annual fuel use and related expenditure for each vehicle (for details on methods see Chatterton et al., 2015, 2016, 2018). Through linkage with data provided by the Driver and Vehicle Licensing Agency (DVLA) it is then possible to link private vehicle data to the residential location of the registered keeper at the LSOA level.

LSOA-level estimates of median household income are taken from public sector Experian Demographic Data (Experian Limited, 2007).

[1] LSOAs are UK census dissemination areal units with a mean population of 1500 and target population of 625 households. There are 32,844 LSOAs in England.

Table 2
Vulnerability dimensions and indicators / variables used for the construction of the composite indicator.

Vulnerability dimension	Indicator	Variable	Data sources and year of reference
Exposure	Cost burden of motor fuel	Ratio between: (i) estimated mean expenditure on motor fuel per household; (ii) median income	MOT dataset (2011); DVLA Vehicle Stock Data (2011); Experian Demographic Data (2011)
Sensitivity	Economic resources	Median income	Experian Demographic Data (2011)
Adaptive Capacity	Accessibility to key services by modes alternative to the car (i.e. the opposite of car dependence)	Sum of estimated journey time to eight key services (employment centre, primary school, secondary school, further education establishment, general practitioner's surgery, hospital, food shop, and town centre) by public transport or walking (whichever is the quickest)	DfT Accessibility Statistics (2011)

These are modelled based on a combination of survey, Census and other socio-demographic data (Experian Limited, 2011).

LSOA-level estimates of travel time to key services by transport modes alternative to the car are taken from the UK Department for Transport Official Accessibility Statistics. Since 2007 the government annually publishes measures of accessibility to eight key sites and services that previous research found to be essential for social inclusion (Kilby and Smith, 2012; SEU, 2003). These measures include the travel time required to the nearest key services, by different travel modes (car, public transport, walking and cycling), estimated "using information on public transport timetables, the road network, and information on actual average traffic speeds on the road network" (DfT, 2014, p.1).

4.1.3. Variable selection

Our indicator of *exposure* is the 'cost burden' of motor fuel for households, measured as the ratio of mean household expenditure on fuel and median income in the LSOA. It can be interpreted as an area-based estimate of the proportion of income spent on fuel, which is a metric commonly adopted in studies on vulnerability to fuel price increases based on household-level data (e.g. Lovelace and Philips, 2014; Mattioli et al., 2018; Nicolas et al., 2012). It must be noted that the observed cost burden value is a function of both the *extent* of exposure within the area (i.e. the number of households with vehicles) and its *depth* (i.e. the level of motor fuel expenditure among households with vehicles), without however distinguishing between the two. Since our estimate of fuel expenditure is based on vehicle inspection data, it considers all vehicle travel, regardless of purpose. This is an improvement on previous research, which has generally used estimates of car use for the journey to work only[2] (Table 1).

Our indicator of *sensitivity* – i.e. the extent to which the areas will be affected by fuel price increases - is the level of economic resources available to households in the area, which we measure as median household income in each LSOA in 2011. The rationale here is that higher income households will be more able to maintain current travel patterns, i.e. to increase fuel expenditure without suffering hardship. Our measure is consistent with previous research, which has used measures of income and/or poverty to assess sensitivity, only resorting to alternative indicators (e.g. unemployment rate) when these were not available (Table 1).

While income is included in both the exposure and the sensitivity measures, this does not result in 'double counting', as two LSOAs may share the same cost burden ratio, but once this cost is accounted for, the residual income is likely to be higher in absolute terms in the area with higher income (for further discussion of this point see Mattioli et al., 2017b). In other words, our composite vulnerability indicator will have higher values in areas of higher fuel costs (relative to income) *and* lower income (holding other factors equal). This follows the logic of the 'Low-Income High Costs' indicator proposed by Mattioli et al. (2017a, 2018) for the measurement of vulnerability at the household-level.

Our indicator of *adaptive capacity* to fuel price increases – i.e. the extent to which residents are able to avoid using fuel while maintaining travel activity – is accessibility to key services by modes alternative to the car, which can be construed as a proxy for the level of 'car dependence' in the local area (Rendall et al., 2014; Siedentop et al., 2013). While in the long term households can adopt various adaptive strategies (see e.g. Belton-Chevallier et al., 2018; Gertz et al., 2015; Motte-Baumvol et al., 2010; Ortar, 2018; Philips et al., 2013), mode shift is arguably the main short-term coping strategy available to them. Overall, our indicator is broadly in line with the indicators of adaptive capacity adopted by previous oil vulnerability studies (Table 1), while improving on the state-of-the-art by considering access to more destinations than just employment.

Our measure for this indicator is the summation of travel time to the nearest facility for eight key destinations (listed in Table 2) by public transport or walking (whichever is faster). We do not consider cycling as the mode share of cycling is very low in Great Britain (2% of trips and 1% of distance in 2011 (DfT, 2012)), and many do not have a bike or physical capability to cycle (Philips et al., 2018). The summary measure obtained can be interpreted as the total travel time (one-way) required to access all eight destinations by the main modal alternatives to the car from that LSOA. As a sensitivity test, we computed two alternative measures of accessibility by modal alternatives: the sum of z-scores for the eight destinations, and the summation of the difference between travel time by car and by modal alternatives (for each destination). As we found high correlation between these metrics, we retained the simple sum of travel time, which is more interpretable (for further details on sensitivity testing see Mattioli et al., 2017b).

The three components are mapped in Fig. 2, with red representing the LSOAs with values contributing to high vulnerability (blue for low vulnerability), and Panel A showing the UK government rural-urban classification for context.[3] Descriptive statistics for the three variables are reported in Table 3.

A limitation of the indicators adopted here is that 1172 out of 32,844 LSOAs have missing values, and are thus excluded from the analysis. The reason for this is that income and accessibility data was reported for 2011 using the spatial units used in the 2001 census. Some of these spatial units were split, merged or replaced in the 2011 census,

[2] Our analysis focuses on private vehicles only, i.e. we do not take into account the fuel-related costs embedded in expenditure on public transport, taxis, and ride-hailing. However, the costs of these services reflect labour costs to a much larger extent than fuel costs. While the cost of shared mobility services such as car sharing may be more related to fuel costs, our data refer to 2011, when such services were scarcely present in Europe (Marsden et al., 2016).

[3] The 2011 Rural-Urban Classification for Output Areas in England consists of ten settlement types. This is based on a distinction between built-up areas with resident population above 10,000 people (urban), and other areas (rural), with further disaggregation based on dwelling density profiles and the wider context of each settlement. For further details see Bibby and Brindley (2013). For Fig. 2a, we have aggregated the ten settlement types into three meaningful categories.

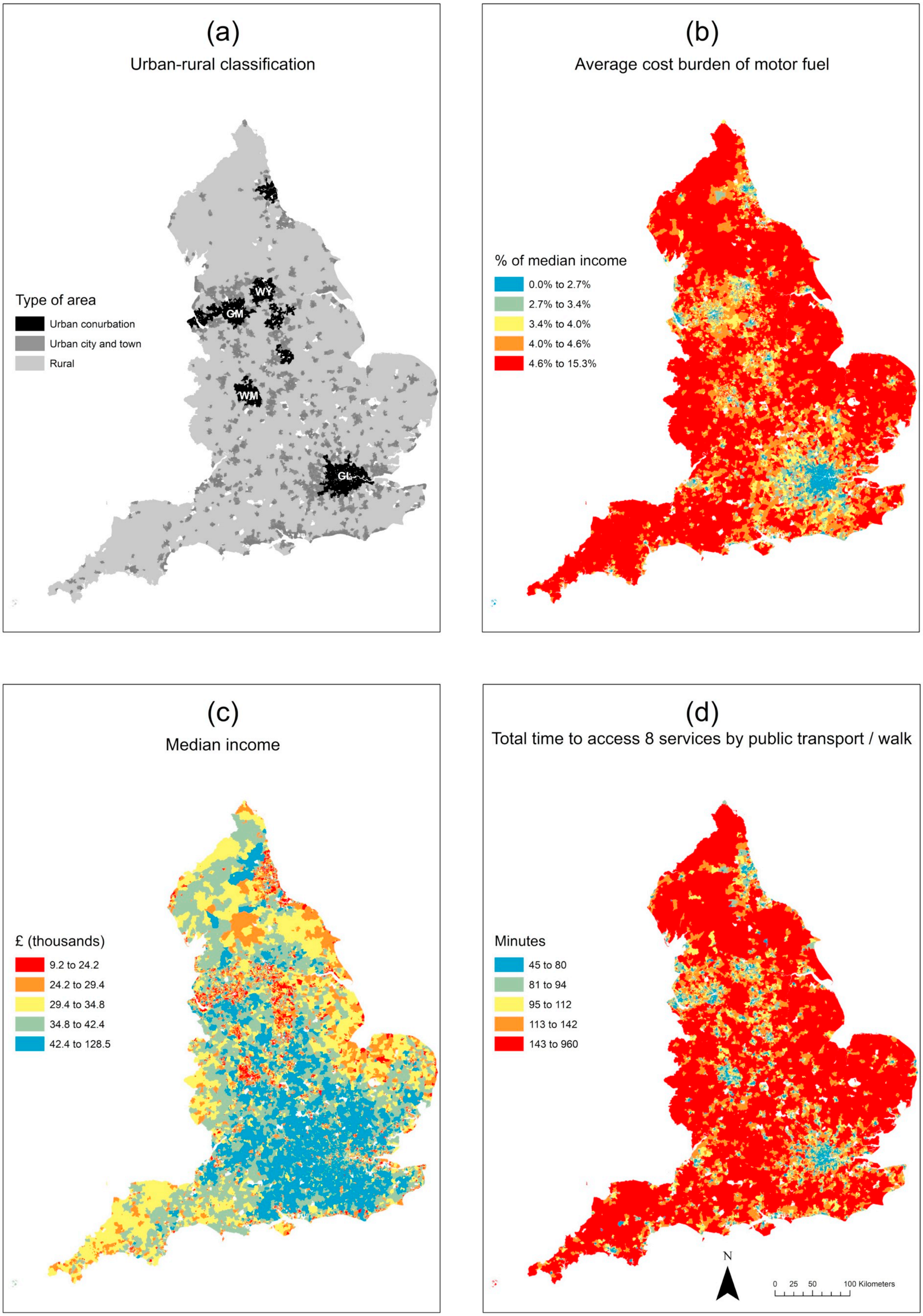

Fig. 2. Panel A: map of rural-urban classification of English LSOAs, with the main city-regions highlighted (GL: Greater London; WM: West Midlands; GM: Greater Manchester; WY: West Yorkshire). Panels B-D: maps of variations in the components of the vulnerability index in England (2011) by LSOA (keys based on quintiles).

Table 3
Descriptive statistics for the three component variables of the composite indicator ($N = 31{,}671$).

	Min	Max	Mean	Median	Standard deviation
Ratio between estimated mean expenditure on motor fuel per household and median income	0.004	0.153	0.037	0.037	0.012
Median income (£)	9168.5	128,508.0	34,264.8	32,037.5	12,944.5
Sum of estimated journey time to eight key services by public transport or walking (whichever is the quickest) (mins)	45	960	116.9	102	61.2

Table 4
Profiles of the four city-regions. Data sources are listed in Table 2.

City-region	No. of LSOAs	Total population	Average LSOA median income	Average LSOA population density (person per hectare)	Public transport supply[a]
Greater London (GL)	4642	7,877,760	44,774	94.6	– Underground (270 stations) – 'Overground' (112 stations) – Light rail (84 stops)
Greater Manchester (GM)	1609	2,581,080	28,854	42.7	– Light rail (93 stops)
West Midlands (WM)	1432	2,309,068	26,266	47.9	– Light rail (26 stops)
West Yorkshire (WY)	1335	2,135,211	29,308	36.3	[no light rail or underground network]

[a] Sources: Transport for London (tfl.gov.uk) and Urban Transport Group (www.urbantransportgroup.org). All city-regions are served by local bus and national rail networks.

making it impossible to directly match them to vehicle inspection and registration data, which use 2011 geographies.[4]

4.1.4. Variable aggregation

We calculate the composite indicator by first standardizing the component variables (z-scores) and then aggregating them in additive format with equal weighting. This is shown in the following formula (adapted from Leung et al., 2018), which also illustrates the correspondence between the vulnerability dimensions and the specific indicators adopted here (note that VFP is vulnerability to fuel price rises).

$$\begin{aligned}\text{VFP} &= \text{Exposure} + \text{Sensitivity} - \text{Adaptive Capacity}\\ &= \text{Z(cost burden)} + (-\text{Z(income)}) - (-\text{Z(travel time)})\\ &= \text{Z(cost burden)} - \text{Z(income)} + \text{Z(travel time)} \qquad (1)\end{aligned}$$

The most vulnerable LSOAs are thus those with a combination of high cost burden of motor fuels (i.e. high exposure), low income (i.e. high sensitivity) and long travel time to services by alternative modes (i.e. low adaptive capacity and high car dependence).

In the absence of a clear theoretical rationale for adopting unequal weights, we assign equal weights to the three dimension-specific indicators. Most oil vulnerability studies (Akbari and Habib, 2014; Arico, 2007; Büttner et al., 2013; Dodson and Sipe, 2007, 2008a; Fishman & Brennan, 2010; Leung et al., 2015, 2018) similarly assign equal weights to each vulnerability sub-dimension, and this is indeed the most common approach for composite indicators (OECD, 2008, p.31). As a sensitivity test, we computed an alternative version of the index with unequal weights (exposure indicator = 50%; sensitivity indicator = 25%; adaptive capacity indicator = 25%), following the rationale that exposure to a stress has logical priority over sensitivity and adaptive capacity to it. The resulting index is extremely highly correlated to the one adopted in this study ($R = 0.99$; Spearman's Rho = 0.99), suggesting that our findings are robust to alternative weighting.

For a more thorough discussion of the composite indicator's construction (variable selection, aggregation, normalisation, weighting and sensitivity testing), see Mattioli et al. (2017b).

4.2. Research hypotheses and data analysis approach

In the results section, we use English data to test the following hypotheses, which we derived from previous international (and notably Australian) research (Section 2):

1. Vulnerability to fuel price increases is higher in peripheral, peri-urban and rural areas (Section 5.1).
2. Low income and car dependence tend to be co-located, with a compounding effect on vulnerability (Section 5.2).
3. Low income and low vehicle fuel efficiency tend to be co-located, with a compounding effect on vulnerability (Section 5.3).

Admittedly, our analysis of the vulnerability index can only highlight the *relative* degree of vulnerability of spatial units as compared to others – not whether they should be considered as inherently 'vulnerable' or 'non-vulnerable'. Yet such a relative assessment is useful from a policy and practice perspective, as it can be used e.g. to identify which areas would be most affected by fuel price rises resulting from the introduction of a carbon tax (Berry, 2019).

We conduct the analysis at two levels: for the whole of England, and for the four most populated city-regions (Clarke, 2016): Greater London (GL), West Midlands (WM), Greater Manchester (GM) and West Yorkshire (WY) (see Table 4 and Fig. 2a). This is for two reasons. First, while most previous research has focused on patterns of 'oil vulnerability' within city-regions (Section 2), it is important to consider inter-regional inequalities as well. Second, transport policy measures are taken at both the national and local level: it is thus important to highlight relative patterns of vulnerability at both scales.

In Section 5.1, we present spatial patterns of vulnerability, based on the composite indicator, using choropleth maps. We also examine the correlation between the vulnerability index and the English Index of Multiple Deprivation, a composite indicator of disadvantage adopted by the UK government (DCLG, 2011). In Section 5.2 and 5.3, we examine the joint distribution of income and travel time to services by public transport and walking (as well as of income and vehicle fuel efficiency)

[4] Further analysis shows that 'unmatched' LSOAs are characterised on average by: i) lower travel time to key services by public transport and walking; ii) lower fuel expenditure per household and; iii) slightly lower income, as compared to other LSOAs. Visual inspection suggests that they are mostly found in large conurbations (typically in city centres), or in their immediate proximity. Overall, it is possible that this biases our analysis as the LSOAs excluded from the analysis are likely to have low levels of vulnerability. On the other hand, missing values account for only 3.6% of LSOAs, so any bias is likely to be of limited consequence for our findings.

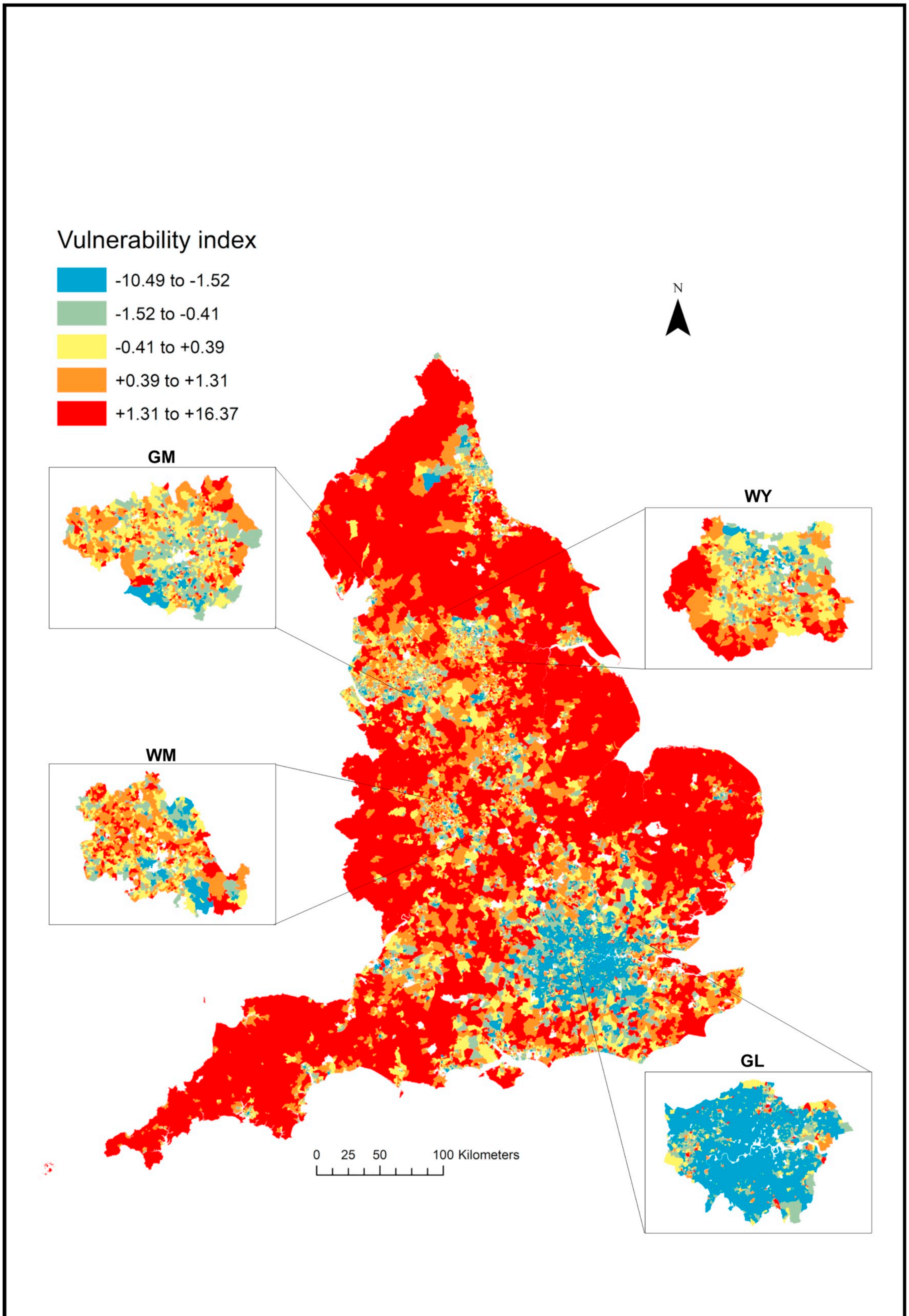

Fig. 3. Map of variations in the composite indicator of vulnerability to fuel price increases in England (2011) by LSOA (key based on quintiles).

using bivariate maps, cross-tabulations, scatterplots and correlation matrices. In Section 5.3, we also briefly examine the correlation between vulnerability, income and two factors underlying vehicle fuel efficiency, i.e. average engine size and average age of the vehicle fleet in the LSOA, both of which are available in the MOT dataset as described in Section 4.1.2.

5. Results

5.1. Spatial patterns of vulnerability

The composite indicator (Fig. 3) shows a clear pattern of lower vulnerability to fuel price increases in Greater London and in the surrounding areas in the South East. This is due to high income and relatively low cost burden of motor fuel (Fig. 2), possibly as a result of proximity and easy rail access to the capital. Areas of low vulnerability are also apparent in the main urban areas, including the three northern city-regions considered here. This is due to low cost burden of motor fuels and relatively low travel time to services by alternative modes, and *despite* much lower levels of income compared to England as a whole, as in England the main concentrations of poverty are in and around the main cities in the North and the Midlands (Fig. 2c). Further analysis shows that the composite indicator of vulnerability is only weakly correlated (Pearson's R = +0.19) with the 2011 English Index of Multiple Deprivation. The fact that the map in Fig. 3 is dominated by red (representing the top quintile of the vulnerability distribution) suggests that high vulnerability is widespread among low-density LSOAs (which, due to the roughly fixed number of households included in an LSOA, have larger surface area).

An alternative classification of areas, based on Jenks' natural breaks instead of quintiles (Fig. S1 in supplementary material) suggests a further distinction at the top end of the scale between: a group of areas with relatively high vulnerability, mostly concentrated in peri-urban areas in and around the main conurbations, and a smaller group of areas with the highest vulnerability levels, mostly concentrated in rural areas on the East Coast, in Cornwall, along the Welsh border and substantial parts of most of England's National Parks (excluding the New Forest South Downs and the Peak District). Further mapping of the local Moran's I measure of spatial autocorrelation (Fig. S2 in supplementary material) shows patterns that are broadly consistent with those presented in Fig. 3.

Fig. 4 shows patterns of vulnerability for the main city-regions. For these maps, the composite indicator was recalculated locally, meaning that the normalisation of the three component indicators and the assignment to quintiles was based on the LSOAs within the respective city-regions. The maps show patterns of *relative vulnerability within each city-region* and, unlike the inset maps in Fig. 3, are not suitable for comparisons between city-regions. In most city-regions, areas of high vulnerability tend to be in outer, lower-density areas, confirming the spatial pattern highlighted by previous research. However, while this pattern is very clear in GL, it is less pronounced in GM and WY. In WM,

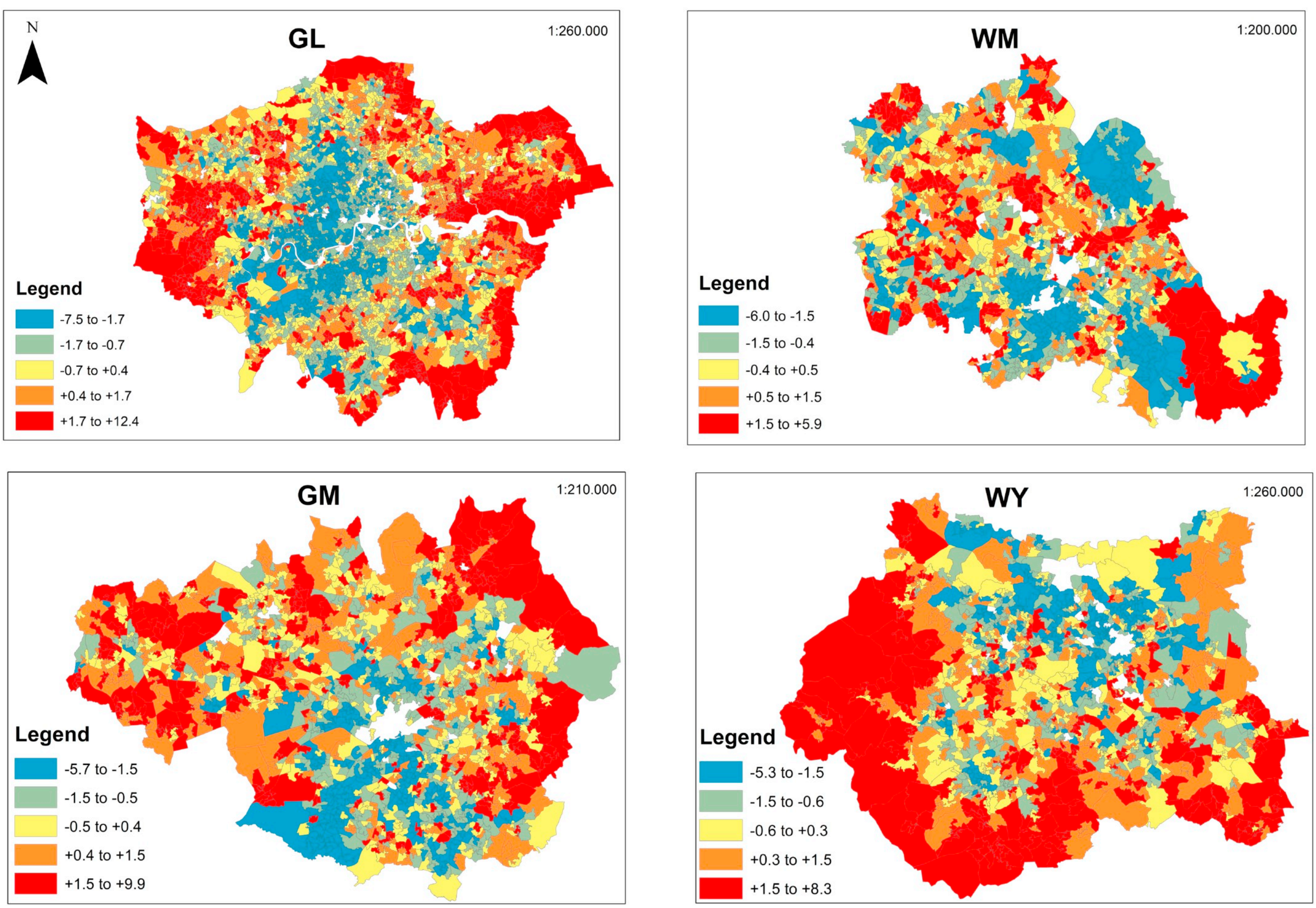

Fig. 4. Maps of variations in the composite indicator of vulnerability to fuel price increases in four city regions (2011) by LSOA (key based on quintiles within city regions).

Table 5
Pearson correlation matrices between components of the vulnerability index, vehicle fuel efficiency and population density in the LSOAs, for England and main city-regions.

	Cost burden	Income	Travel time to services by alternative modes	Fuel efficiency	Density
England [*N* = 31,672]					
Cost burden	+1.00				
Income	−0.38	+1.00			
Travel time to services by alternative modes	+0.45	+0.10	+1.00		
Fuel efficiency	+0.31	−0.60	−0.06	+1.00	
Density	−0.59	−0.03	−0.38	−0.17	+1.00
Greater London (GL) [*N* = 4642]					
Cost burden	+1.00				
Income	−0.42	+1.00			
Travel time to services by alternative modes	+0.44	−0.02	+1.00		
Fuel efficiency	+0.33	−0.46	+0.14	+1.00	
Density	−0.44	−0.17	−0.33	−0.06	+1.00
West Midlands (WM) [*N* = 1432]					
Cost burden	+1.00				
Income	−0.31	+1.00			
Travel time to services by alternative modes	+0.11	+0.23	+1.00		
Fuel efficiency	+0.13	−0.28	+0.01	+1.00	
Density	−0.13	−0.29	−0.15	+0.06	+1.00
Greater Manchester (GM) [*N* = 1609]					
Cost burden	+1.00				
Income	−0.04	+1.00			
Travel time to services by alternative modes	+0.37	+0.22	+1.00		
Fuel efficiency	−0.05	−0.35	+0.02	+1.00	
Density	−0.39	−0.25	−0.33	+0.10	+1.00
West Yorkshire (WY) [*N* = 1335]					
Cost burden	+1.00				
Income	−0.11	+1.00			
Travel time to services by alternative modes	+0.35	+0.23	+1.00		
Fuel efficiency	−0.13	−0.32	−0.16	+1.00	
Density	−0.31	−0.33	−0.39	+0.25	+1.00

there is a mosaic of high- and low-vulnerability areas, with no clear pattern standing out. This difference may be related to the fact that GL is more mono-centric than the other city-regions. Further mapping of the local Moran's I measure of spatial autocorrelation (Fig. S3 in supplementary material) shows patterns that are broadly consistent with Fig. 4.

5.2. Spatial patterns of income and car dependence

Table 5 shows levels of correlation between the three components of the vulnerability index, for England as a whole, and for the four city-regions separately. Correlation coefficients with average fuel efficiency of the vehicle fleet (kms per liter) and population density are reported as well. Focusing for the time being on the relationships between income and car dependence, there is a weak *positive* correlation (R = +0.10) between income and travel time to services by alternative modes at the national level. This suggests that low-income areas are on average *less* car dependent than high-income areas, although the magnitude of the relationship is weak.

To explore the spatial relationship between income and car dependence in more depth, Fig. 5 combines different visualisations to show the joint distribution of income and travel time to services by alternative modes. The distribution of the two variables is broken down into three quantiles (‘low’, ‘medium’, and ‘high’) and a colour scheme is used to highlight LSOAs at the extremes of the joint distribution (for a similar analytical approach see da Schio et al., 2019; Nazari Adli et al., 2019; Rendall et al., 2014).

LSOAs highlighted in green have high income and low travel time to services by alternative modes (relative to other LSOAs in the city region) - a ‘win-win’ situation from a vulnerability perspective. These are mostly concentrated around Greater London, with a few pockets in other metropolitan areas. Areas highlighted in red represent a worst-case situation for vulnerability, i.e. low income and high travel time to services by alternative modes. This type of area, which is common on the periphery of Australian city-regions, is relatively underrepresented in England, as shown in Fig. 5a. Yet there are some concentrations of areas with low income and high travel time to services by alternative modes, e.g. on the eastern coast and around the Sheffield city-region (south of WY).

Mirroring the positive correlation between income and travel time to services by alternative modes, LSOAs where these two vulnerability components tend to compensate for each other are overrepresented. Fig. 5c is dominated by brown areas, with both high income and high travel time to services by alternative modes, which tend to be low-density, and to be located in the peri-urban areas around the main city regions (particularly in the South-East but also in the North). Conversely, areas of low income and low travel time to services by alternative modes (highlighted in black) are mostly concentrated in the core of the city regions, particularly in the North.

Overall, this suggests that there is no regressive relationship between income and car dependence, at least when LSOAs are used as the unit of analysis. On the other hand, Fig. 5 does show a great contrast between Greater London, with high income and low travel time to services by alternative modes, and other city-regions, where the situation is more mixed. This is confirmed by the scatterplot in Fig. 6, showing the income and travel time to services by alternative modes for LSOAs, *averaged at the city-region level* for the ten largest city regions of England (Clarke, 2016). There is a divide between GL and all other city-regions, where income is much lower, and levels of travel time to services by alternative modes are higher (but varying). This is reflected in the average value of the composite indicator of vulnerability in the different city regions.

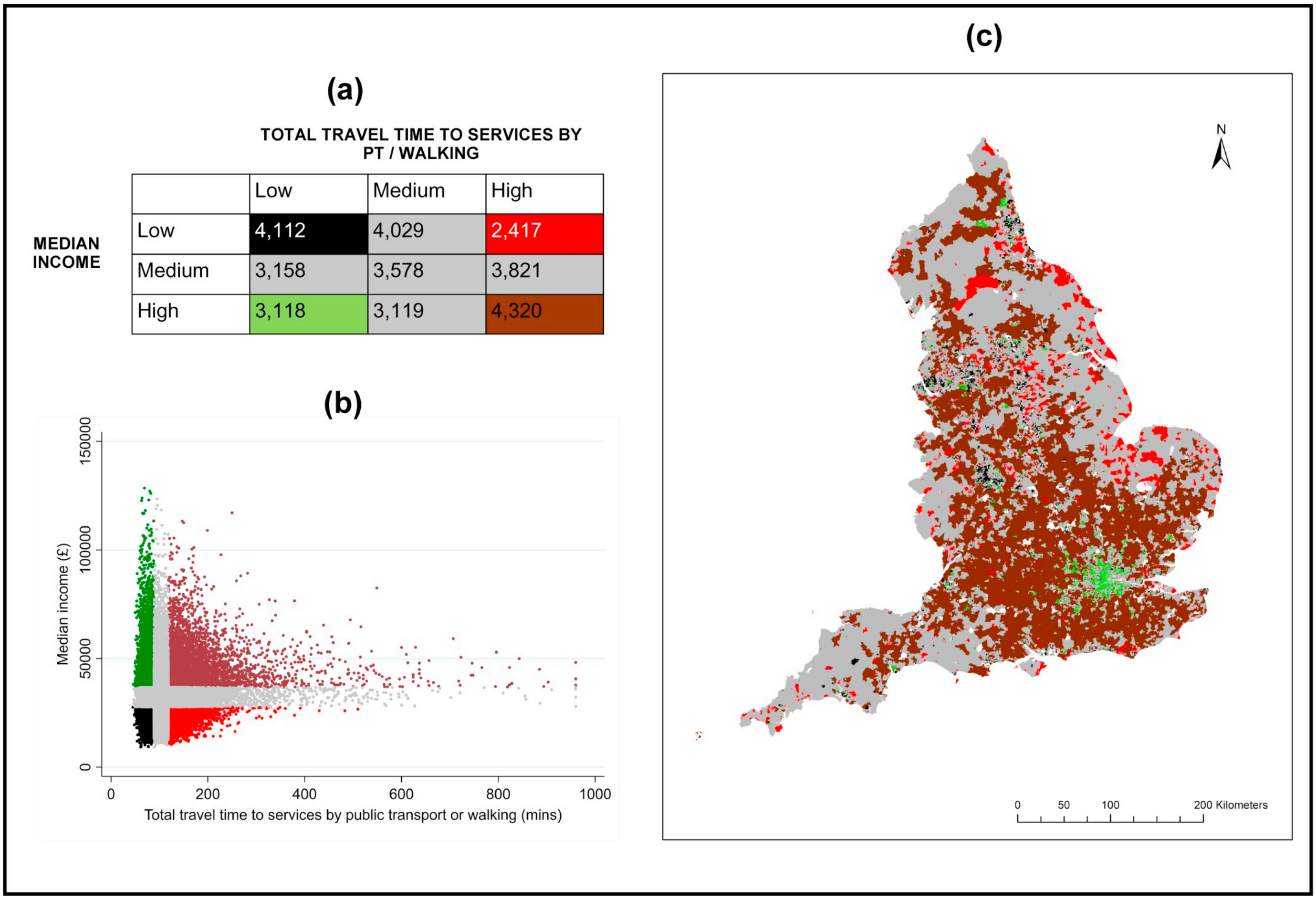

Fig. 5. Joint distribution of the income and travel time to services by alternative modes components of the vulnerability index in England. Unit of analysis: LSOA. N = 31,672. Notes: the table cells in Panel (a) are LSOA counts; classification (high/medium/low) based on three quantiles.

The next step is to look at the relationship between income and travel time to services by alternative modes within city-regions. In WM, GM and WY, the positive correlation between income and travel time to services by alternative modes is slightly stronger (R = +0.20 ca.) than at the national level, while in GL the two are virtually uncorrelated (Table 5). This suggests that, at least within city-regions, low-income areas tend to have *lower* travel time to services by alternative modes than high-income areas, although the magnitude of the relationship is weak.

This is more clearly depicted in Fig. 7, showing the relationship

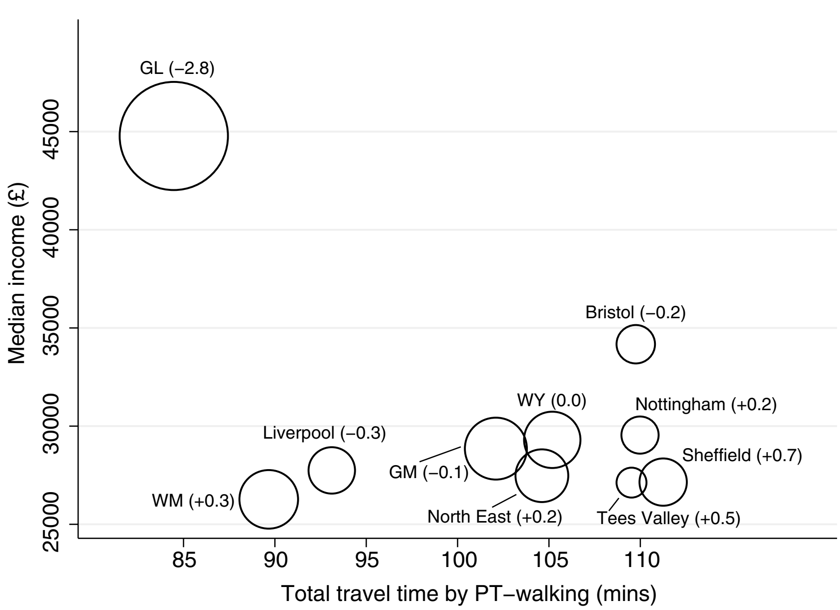

Fig. 6. Average values of the ‘income’ and ‘travel time to services by alternative modes’ components of the vulnerability index in the main ten English city-regions (2011). Notes: the size of the hollow circle markers is proportional to the number of LSOAs in the city-region; the figures in parentheses indicate the average value of the vulnerability index in the city-region.

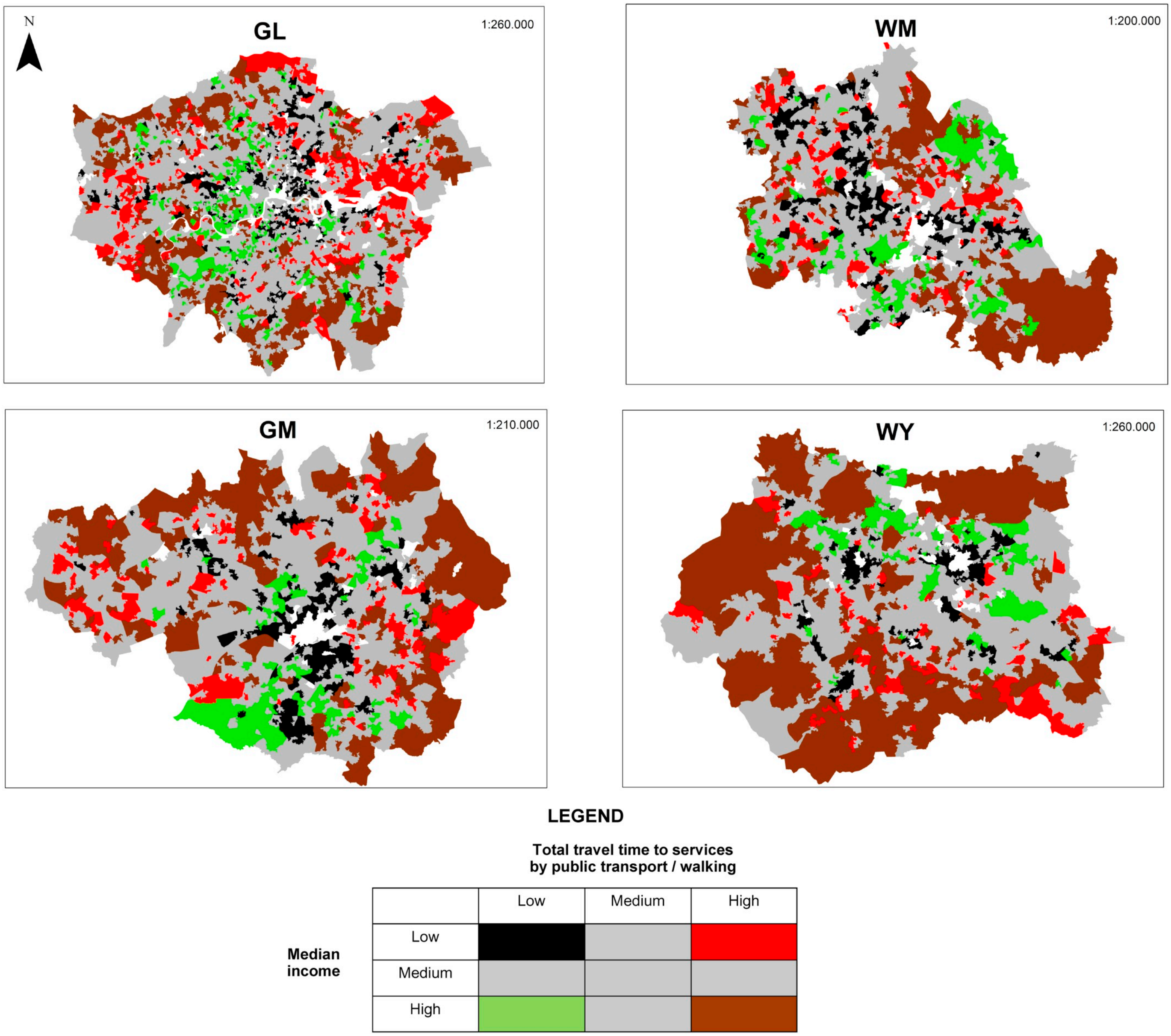

Fig. 7. Maps depicting the joint distribution of the 'income' and 'travel time to services by alternative modes' components of the vulnerability index in four city regions (2011) by LSOA.
Notes: classification (low/medium/high) based on three quantiles of the distribution within the city-region.

between income and travel time to services by alternative modes within city regions.[5] GM, WM and WY all show concentrations of areas with low income and low travel time to services by alternative modes in the central parts of the city-region, while areas with high income and high travel time to services by alternative modes tend to be in the most peripheral and low-density sectors. In these city-regions, areas with high income and low travel time to services by alternative modes seem to cluster in locations near to but slightly removed from the main urban cores. The situation in GL is slightly different, with concentrations of areas with low income and high travel time to services by alternative modes on the periphery, which contrast with large areas of high income and low travel time to services by alternative modes in the central-western sector of the conurbation.

[5] Here again, the threshold values for the quantiles have been recalculated based on each city-region sample - i.e. the maps can be used to compare LSOAs within the same city-region, but not between them.

5.3. Spatial patterns of income and fuel efficiency

Vehicle fuel efficiency is negatively correlated with income at the national level (R = -0.60) (Table 5), suggesting that low-income areas have *better* average levels of fuel efficiency than high-income areas. Further analysis (reported in Table S1 in supplementary material) shows that this is mainly due to the correlation between income and average engine size of the vehicle fleet (R = +0.63) which, in turn, is strongly negatively correlated with fuel efficiency (R = -0.83). While average vehicle age is moderately negatively correlated with income (R = -0.37), its association with fuel efficiency is much weaker (R = -0.17), so the engine size effect dominates.

Fig. 8 uses the same approach as Fig. 5 to depict the joint distribution of income and fuel efficiency in England (Fig. S4 in the supplementary material provides a separate map of fuel efficiency). It shows that areas where the two factors tend to compensate for each other (from a vulnerability perspective) are greatly overrepresented: high-income, low-fuel efficiency areas are concentrated in the South

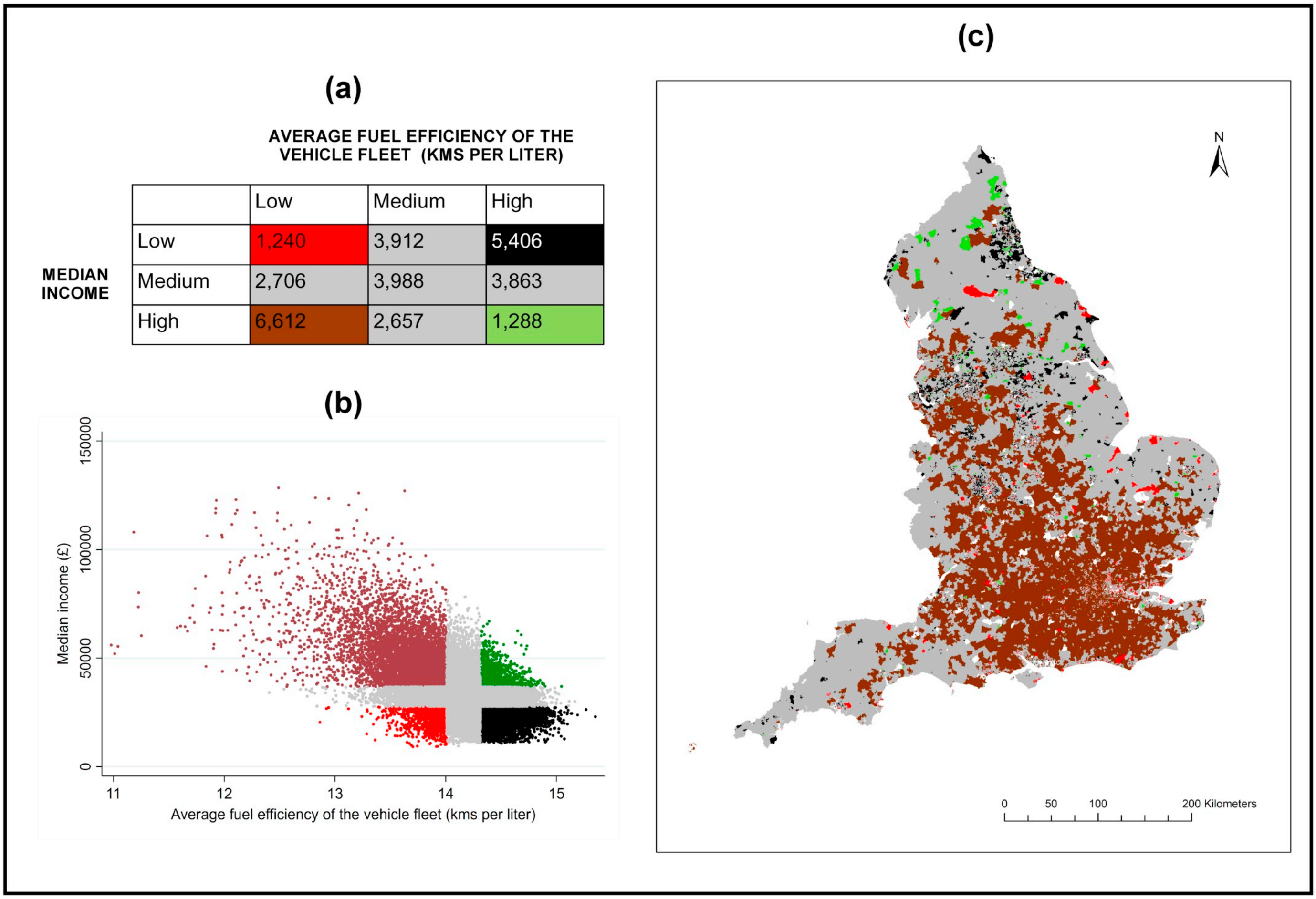

Fig. 8. Joint distribution of vehicle fuel efficiency and income in England. Unit of analysis: LSOA. *N* = 31,672.
Notes: the table cells in Panel (a) are LSOA counts; classification (high/medium/low) based on three quantiles.

East (including London) and in peri-urban areas in the North; low-income, high-fuel efficiency areas are clustered in the cores of the northern city-regions. Areas where the two factors work in the same direction (i.e. high income and high efficiency; low income and low efficiency) are underrepresented and show no clear spatial pattern.

Within the four city regions, the magnitude of the correlation between income and fuel efficiency is smaller than at the national level, but still negative (Table 5). City-region maps (Fig. 9) show a more nuanced picture, with concentrations of low-income, low-fuel-efficiency areas (relative to the rest of the city-region) in the metropolitan core of WM and GM, and in East London. Conversely, high-income and low-fuel efficiency areas cluster on the fringes of the city-regions, with the partial exception of GL where they are mostly in the central-western sector of the metropolitan area. Vehicle fuel efficiency is weakly positively correlated with LSOA population density in all areas except London (Table 5).

Despite these nuances, the analysis suggests that low income and low fuel efficiency are not co-located in the UK, either at the national level or within the main city regions. Where they do appear to overlap, i.e. in the core of some Northern city regions, other countervailing factors (low car ownership and low car dependence) tend to compensate for them, resulting in low overall vulnerability to fuel price increases. As a result, further analysis (reported in Table S1 in supplementary material) shows that, counterintuitively, vehicle fuel efficiency is *positively* associated with the vulnerability index (R = +0.41), i.e. that vehicle fleets in vulnerable areas have better fuel economy.

6. Discussion

Our findings are broadly in line with previous research by confirming that vulnerability to fuel price increases is higher in peripheral, peri-urban and rural areas in England. Yet they contrast with the findings of Australian 'oil vulnerability' research (Dodson and Sipe, 2007; Dodson and Sipe, 2008a; Fishman and Brennan, 2009; Runting et al., 2011), which has shown a strong degree of co-location between low income and car dependence. We do not find such a pattern within the four main English city-regions - if anything, there appears to be a (weak) association between car dependence (as measured by travel time to services by modal alternatives) and *high* income. From a vulnerability perspective, this suggests that *compensatory* (rather than *compounding*) effects prevail in England, whereby areas of high sensitivity tend to compensate for this problem with greater adaptive capacity and vice-versa.

Our findings resonate with research from New Zealand (Rendall et al., 2014), Canada (Akbari and Habib, 2014; Allen and Farber, 2019) and Europe (Büttner et al., 2013), which suggests that the regressive co-location of low income and high car dependence is not a universal feature. This highlights the importance of taking into account urban socio-spatial configurations when investigating spatial patterns of car-related economic stress and vulnerability to fuel price increases (Mattioli and Colleoni, 2016; Mattioli et al., 2017a).

Notably, the socio-spatial configuration still prevalent in English cities (with poor inner cities and wealthier suburbs) seems to have a

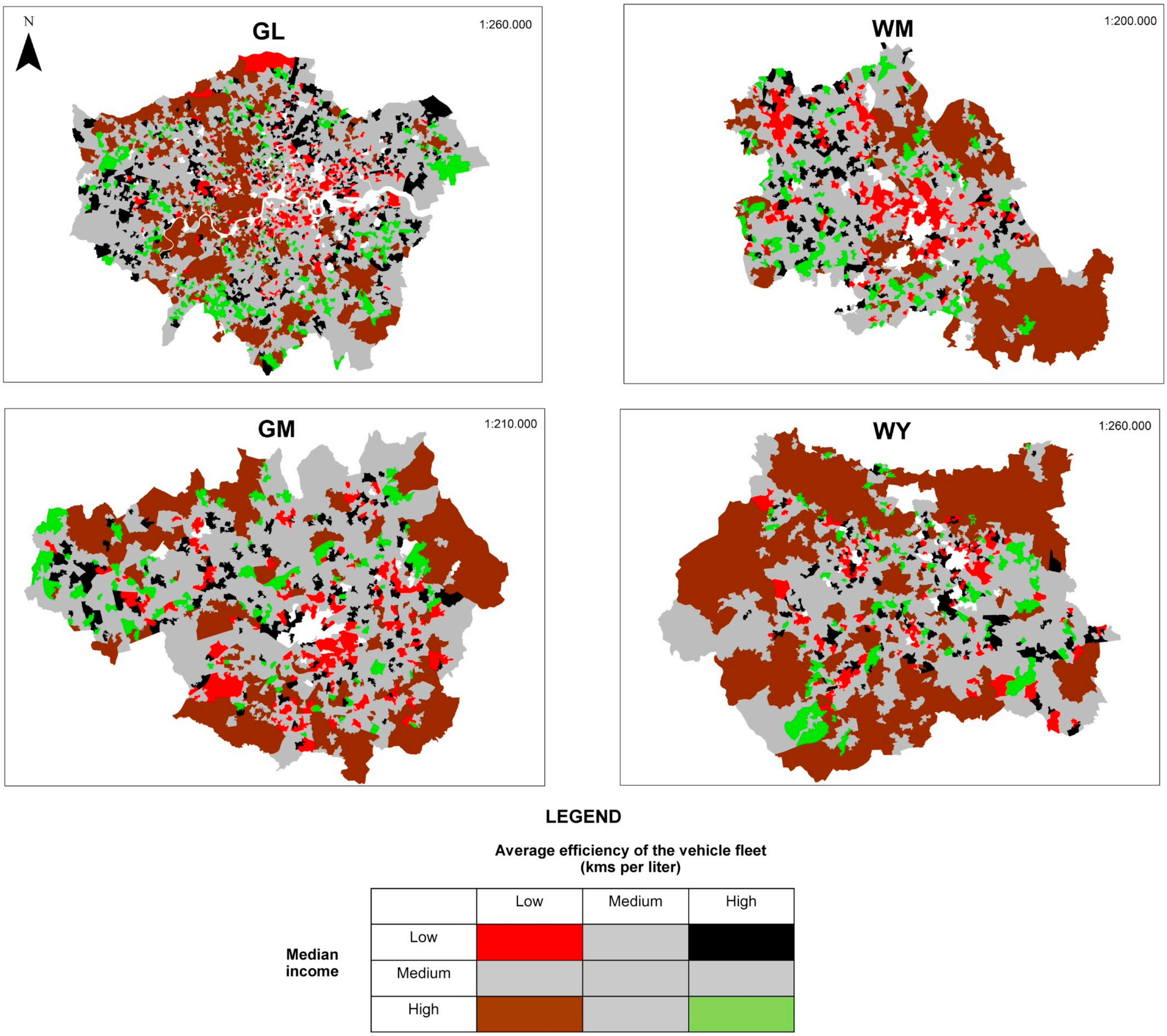

Fig. 9. Maps depicting the joint distribution of median income and average vehicle fuel efficiency in four city regions (2011) by LSOA.
Notes: classification (low/medium/high) based on three quartiles of the distribution within the city-region.

mitigating effect on vulnerability to fuel price increases - even though it can have regressive effects in other domains (e.g. exposure to air pollution – Bailey et al., 2019; Jephcote et al., 2016). Our study further shows that Greater London is the English city-region most similar to the typical vulnerability to fuel price increase patterns found in Australian state capitals, with some clusters of (relatively) low-income, high-car dependence areas on the periphery of the metropolitan area. Our analysis thus suggests that, should the suburbanisation of poverty in British city-regions continue unhindered, issues of vulnerability to fuel price increases would become more severe. Conversely, it is possible that significant increases in motor fuel prices could shift the residential preferences of higher-income groups towards inner cities, thus contributing to further suburbanisation of disadvantage in the medium term (Gertz et al., 2015; Li et al., 2018).

Another key insight from our study is that rather different conclusions can be reached depending on the geographical level of analysis. When taking English city-regions, rather than small areas, as the unit of analysis, income and car dependence (as measured by travel time to services by modal alternatives) do exhibit a strong regressive relationship. Greater London, by far the most affluent city-region, is also the least car dependent, thanks to higher population density and superior public transport provision. This results in large differences in vulnerability *between* city-regions.

Our study thus suggests that well-known economic inequalities between English regions are compounded by the uneven provision of modal alternatives to the car. The allocation of transport funding in the UK has historically been, and continues to be, strongly skewed towards the capital (IPPR North, 2017; Marsden, 2017). At the same time, subsidies to local public transport have been dramatically reduced since the global financial crisis, with most of the cuts being enacted outside of London (Campaign for Better Transport, 2017). From a vulnerability perspective, both developments widen the gap between urban areas in terms of adaptive capacity to fuel price increases.

With regard to the relationship between income and vehicle fuel efficiency, our findings are in contrast with previous research. On average, low-income areas have older, but less powerful vehicle fleets, with better overall fuel efficiency. Therefore, to an extent, the spatial patterning of vehicle fuel efficiency (mainly reflecting vehicle size) compensates for the effect of other drivers of vulnerability. Still, our findings suggest that the geography of vulnerability in England is explained in the first instance by spatial differences in levels of income, car dependence and vehicle distance travelled. Hence - and here we agree with Dodson et al. (2018) - the vulnerability problem cannot be solved by policies that focus primarily on vehicle technology. Yet our results also suggest that higher taxes on high-emission and high-powered vehicles would be progressive, and the ring-fenced revenue could be used to improve modal alternatives in car-dependent areas, enhancing adaptive capacity to fuel price increases.

While the importance of vehicle fuel efficiency for explaining the *current* geography of vulnerability to fuel price increases should be downplayed, this may change with the uptake of electric vehicles, which hold the promise of reducing the level exposure to motor fuel price increases effectively to zero (although they may remain energy intensive, raising new inequality issues). If such vehicles reach higher (or earlier) uptake in areas of high income and low vulnerability like London (Morton et al., 2017), this might compound existing spatial patterns of vulnerability.

7. Conclusions

Research on 'oil vulnerability' initially emerged in Australia, where the marked co-location of low income and car dependence on the urban periphery makes it a very visible phenomenon. Many city-regions around the world, however, present less clear-cut and extreme socio-spatial configurations. In England, the spatial relationships between the different dimensions of vulnerability are complex and multi-layered, and to some extent such dimensions tend to compensate rather than compound each other. For future research on vulnerability to fuel price rises, this suggests the need for context sensitivity, at both the national and local level.

Perhaps counterintuitively, this also highlights the need for robust vulnerability metrics. In the Australian context, research on 'oil vulnerability' has simply brought to light a novel issue affecting areas of well-known socio-economic and locational disadvantage. In England though, spatial patterns of vulnerability to fuel price increases do not simply replicate those of generic disadvantage, as measured e.g. by official Indices of Multiple Deprivation. In such a context, bespoke indicators of vulnerability to fuel price increases are even more of a necessity. This article has put forward one such metric, based on data on income, motor vehicle use and accessibility at the small-area level. To the extent that similar data are available in other countries, the approach proposed here could serve as a blueprint for studies elsewhere. It could be especially useful to assess the distributional impacts of environmental taxes on fuel, identifying areas to be prioritised for accompanying measures aimed at increasing acceptance.

An area where the metric could be improved is the use of indicators of *disposable* income to better assess the sensitivity dimension. In contexts where housing affordability exhibits strong spatial patterning, data on overall income (i.e. pre-housing costs) may give an inaccurate picture of sensitivity. In our study, this may for example lead to reconsidering the conclusion that Greater London is the least vulnerable city-region in England, due to the higher housing costs there. More broadly, there is a need for a more comprehensive understanding of the complex and iterative relationships between housing and transport affordability.

Future studies should also consider the spatial relationships between transport and domestic energy affordability. Many of the factors that could result in motor fuel prices increases (e.g. changes to fossil fuel prices and subsidies, carbon taxes) would similarly affect domestic energy costs, at least in countries like the UK where gas is the most common method of heating. It is therefore relevant to investigate whether the two types of vulnerability tend to follow the same spatial patterns, which would give rise to a problem of 'double energy vulnerability'.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jtrangeo.2019.05.009.

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Declaration of interest

None.

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