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The 'oil vulnerability' of commuter patterns: a case study from Yorkshire and the Humber, UK

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Abstract

Motorised transport infrastructure and increasingly specialised labour markets have resulted in energy intensive commuter patterns in many parts of the world. This is cause for concern due to the possibility of oil price shocks and the need to restrict the combustion of fossil fuels to minimise the chances of runaway climate change. The paper investigates methods to identify the spatial distribution and socio-demographic profiles of those who are vulnerable to high oil prices. It does this by use of four metrics of oil vulnerability which were developed using a spatial microsimulation model and applied to the case study region of Yorkshire and the Humber, UK. The metrics capture different aspects of vulnerability and highlight the importance of translating conceptual definitions into practical metrics. The geographically aggregated results coincide with the literature: rural areas are associated with the highest levels of vulnerability. The individual level results indicate that vulnerability can be prevalent even in seemingly resilient areas. Ultimately, we conclude that the social and spatial distribution of oil vulnerability depends on how an energy-constrained future is envisioned. Creating localised metrics about the future is a challenging task fraught with danger but could, provided that these metrics are interpreted with sufficient humility, aid the development of equitable policies to encourage resilience, as part of a worldwide transition away from fossil fuels.

Keywords: oil vulnerability, commuting, peak oil

"A finales del siglo XX, y gracias a su automovil privado, un simple

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trabajador podía residir en un lugar determinado pero desempeñar su trabajo, diariamente, en otro lugar que se encuentra a 50 o 60 km de distancia. Este hecho, que para tal ciudadano formaba parte de la rutina de su vida cotidiana, constituye, sin duda, uno de los más grandes enigmas de la antropología y la historia" (Ardillo, 2011, p. 99).

> Towards the end of the 20^{th} century, and thanks to the private automobile, a simple worker could live in one place but carry out their work, daily, 50 to 60 km away. This fact, which for the citizen formed part of their everyday routine, constitutes, without doubt, one of the greatest enigmas of Anthropology and History (Ardillo, 2011). Translation by author.

1. Introduction

Commuting is a time-consuming and increasingly expensive activity, yet it has become integral to modern economic life. Due to increased home-work distances in the UK (Green et al., 1999; Nielsen and Hovgesen, 2008) and elsewhere (Rouwendal and Rietveld, 1994; Scheiner et al., 2011; Cervero and Wu, 1998), in combination with the increasing dominance of the car worldwide (Chamon et al., 2008), travel to work has also become highly energy intensive. Energy-intensive commutes are becoming increasingly common in emerging nations today (Kutzbach, 2009). This is problematic, not only due to the economic and environmental costs, but also from an energy security perspective. 78% of commuter kilometres travelled in the UK are made in buses or cars (DfT, 2011) and similar shares of travel by motorised modes are reported in other high-income nations (Poumanyvong et al., 2012). These modes are, at present, almost entirely dependent on oil.[1]

Longitudinal datasets on modal split exemplify the energy impacts of shifting travel to work patterns. Based on data from Turnbull (2000) and assuming that average trip distances and energy intensity for each mode remain unchanged, we estimate that the average trip to work and back required

[1]The shift to electric cars is often cited as a way to reduce the energy costs and oil dependence of personal transport. Recently, however, sales of electric vehicles have been slower than anticipated in the UK (Vaughan, 2011) and other countries (Briscoe, 2012). Electric vehicles are also more expensive than conventional cars due largely to the embodied energy of the batteries (Majeau-Bettez et al., 2011; Tran et al., 2012).

4.9 MJ of direct primary energy stored in either food or fuel at the turn of the 20^{th} century. In the 21^{st} century, this value has increased 10 fold: it now requires approximately 50 MJ for a typical trip to work (Fig. 1). To put this in context, it equates to the combustion of $1^1/_2$ litres of petrol, 11% of average per capita total daily energy use, or double the average daily per capita electricity consumption, in the UK.[2]

Little attention has been directed to the impacts of declining oil production on passenger transport and on commuting patterns in particular. This is surprising, not only because transport to work is highly dependent on oil in many high income nations, but also because of the importance of commuting for getting and keeping a job. Paid employment, and the economic independence it brings, is a foundation for life satisfaction (Jahoda, 1982). Work is "a principal source of identity for most adults" (Tausig, 1999, p. 255) and can promote good health if the work is satisfying (Graetz, 1993). By corollary unemployment, the proportion of working-aged people without a proper job, "is a crucial indicator of the welfare and economic performance of different areas" (Coombes and Openshaw, 1982, p. 141). Yet without accessible means of travelling to and from work each day, these benefits would be impossible to realise in the current economic system.

The social impacts of transport to work extend beyond simply getting to work: commuting can affect job opportunities. Variable transport opportunities amplify social and economic inequalities: 38% of jobseekers find transport a major barrier to getting a job (Social Exclusion Unit, 2002). "No jobs nearby" was cited as the primary reason for inability to work; "lack of personal transport" was the second, in a survey of young people in the UK (Bryson et al., 2000). The average distance travelled to work by respondents of the Understanding Society dataset[3] in 2010-11 was 10.1 miles. 56% of these respondents would not like to move house and it is likely that many more cannot due to financial constraints. These datasets can be a starting

[2] energy content of petrol is 32 MJ/l (Tian et al., 2010); $50 \div 32 = 1.56$. Per capita, the energy consumed in the UK (excluding energy imports in the form of embodied energy) prorates to 125 kWh/p/d (Mackay, 2009). Total domestic electricity use is 120 TWh/yr, the UK's (2011) population is estimated at 62 million (ONS, 2012), so domestic electricity use per person can be calculated as $120 * 10^9 kWh \div 62 * 10^6 \div 365 d/yr = 5.5 kWh/p/d$

[3] Understanding Society was formerly the British Household Panel survey. Only the 5,559 respondents who completed non-zero responses for distance travelled to work are included in this calculation.

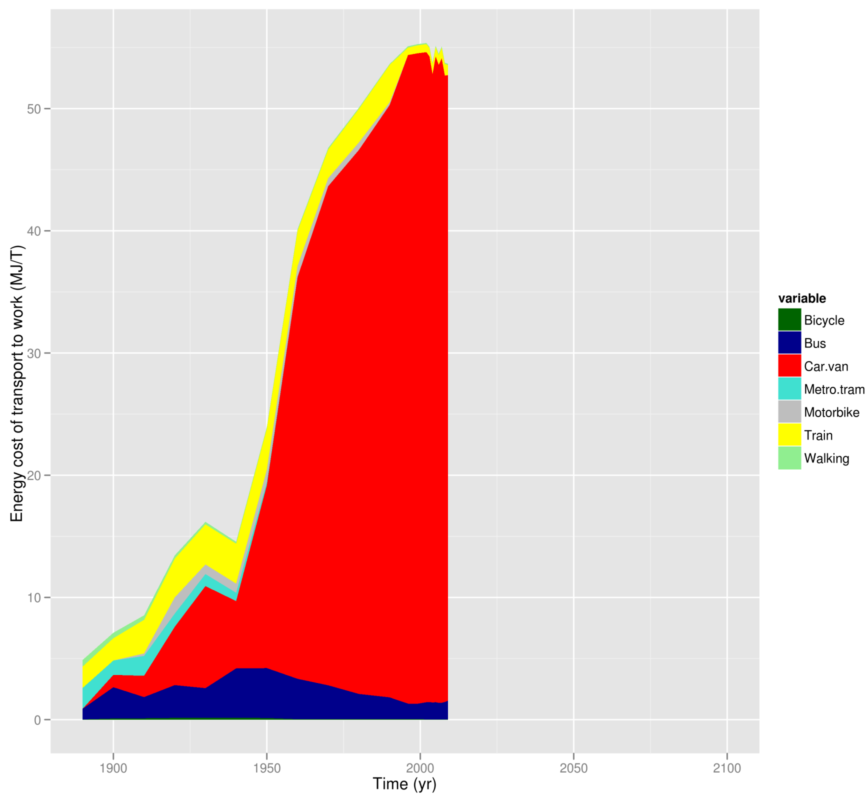

Figure 1: Energy use of the average trip to work, based on the the modal split of commuter trips from Turnbull (2000) and, from 1996 to 2009 from DfT (2011). The extended x-axis is designed to highlight the uncertainty of future energy costs. Energy costs calculated using distance and energy use assumptions from Table 2, using equation 5.

point for deeper analysis using perspectives such as network capital (Urry, 2007) and mobility injustice (Sheller, 2011).

Given the limited uptake of telecommuting, even in Finland which has high rates of working from home (Helminen and Ristimäki, 2007), the uneven distribution of jobs and the aforementioned importance of work, commuting is an essential element of healthy economies. It can safely be assumed that commuting will continue to be a vital part of complex economic activity for the foreseeable future, leaving many people vulnerable to fluctuations in the price of personal travel.

In light of evidence that global oil production will likely peak and enter terminal decline during the first half of the 21^st century,[4] the oil dependence of current transport systems is cause for concern (Gilbert and Perl, 2008; Bridge, 2010). Arguably, the combined threats of peak oil and climate change should form the basis for urgent policy interventions to rapidly decarbonise transport systems (Chapman, 2007). In the UK, these issues have become more pertinent since the country's dramatic shift from being net energy exporter to a net energy importer in 2004 due the depletion of North Sea oil fields (Mearns, 2010). This has increased the importance of assessing 'energy security' as well as the more commonly quantified climate change mitigation objectives of UK energy policies (Skea et al., 2010b). Since the shift to a regime of high oil prices in 2008, energy security has also climbed the political agenda elsewhere, although the precise meaning of the term is often unclear due to its multiple interpretations (Chester, 2010).

This paper explores methods for assessing the geographical and social distribution of the threats posed by peak oil on one group: commuters. To avoid the nation-level connotations and ambiguity of energy security explored by Chester (2010), the concept of vulnerability is used in this paper, to address more localised *potential* impacts of high oil prices rather than the performance of the energy system currently. We use an economically marginal region of the UK — Yorkshire and Humber — as a case study to demonstrate these methods in practice. This case study region was chosen for

[4] Oil is a finite resource that is not replenished on human timescales, so it is inevitable that its production will at some point enter more or less terminal decline (Smil, 2008).However, the timing is contested (Tsoskounoglou et al., 2008). According to a comprehensive review of the best available evidence, the UK's Energy Research Centre concluded that " more than two thirds of current crude oil production capacity may need to be replaced by 2030, simply to prevent production from falling" (UKERC, 2009, p. viii). This would be 'extremely challenging', leading to the conclusion that global oil production is likely to enter terminal decline during the next 20 years (incidentally, 20 years is also the minimum time-frame an influential report (Hirsch R. Bezdek, 2005) suggests would be needed for the impacts to be mitigated): "forecasts that delay the peak until after 2030 rest upon several assumptions that are at best optimistic and at worst implausible" (UKERC, 2009, p. 165). On the other hand, a recent report emphasising new extraction technologies (Maugeri, 2012) has led to recantation of peak oil acceptance by many in the mainstream media (Mouawad, 2012; Monbiot, 2012). The reception of this report in scientific community and the 'oil patch' has been more critical (Sorrell and Mcglade, 2012; Kerr, 2012). Regardless of the final outcome of the debate surrounding the timing of peak oil, the precautionary principle (Charlesworth and Okereke, 2010) implies that governments should plan for declining worldwide production by 2030.

the wide variety of settlements contained within, including the largely rural stretch between Doncaster and Scarborough, the largely built-up zone including Bradford and Leeds and the clearly defined mono-centric city of York, although the method would be applicable to any geographic zone containing small administrative sub-divisions.

1.1. Oil vulnerability

The concept of 'oil vulnerability' was first used to describe how well different areas would respond to high oil prices by Dodson and Sipe (2008b). As a concept, it is closely related to the more widely used objective of 'energy security', which is generally applied at the national level (Kruyt et al., 2009). Oil vulnerability is a more specific measure, focussing only on oil — the most rapidly depleting of the fossil fuels (Sorrell et al., 2009) and applicable to much smaller areas — local administrative zones rather than countries (Dodson and Sipe, 2008b). The term is not formally defined in Dodson and Sipe's papers, although the meaning is implicit in the variables used by the authors: car dependence,[5] income and the tenure of houses purchased in each zone. The resulting maps reflect the areas in which all three risk factors combine, where policy intervention is recommended — generally poor, car dependent suburbs (Dodson and Sipe, 2008b). We can thus interpret oil vulnerability as the combination of local-level variables that would make coping with high oil prices harder. The potential for economic hardship is expected to be the main impact (Dodson and Sipe, 2008a, 2010; Bailey et al., 2010): oil vulnerability is more about the *impacts* of high oil prices or disruptions in their supply in local areas, in contrast to the more commonly used energy security metrics which are more focussed on creating a baseline level of energy independence nationally.

Oil vulnerability is an outcome of complex processes operating at many scales: social and spatial segregation (Green, 1995; Dodson and Sipe, 2007), shifting job/housing markets (Boussauw and Witlox, 2009) and subsidy/tax regimes for different types of vehicles and fuels (Gross et al., 2009) are just some of the factors which conspire to make area or individual more or less exposed to the shifting costs of travel. Clearly not all such drivers can be accounted for in univariate quantitative metrics: the approach taken here is

[5] Car dependence is measured by the proportion who travel to work by car and by the proportion of households that own two or more cars.

to use quantitative analysis as a vehicle to consider what oil vulnerability may mean, in relation to phenomena that are less ambiguous and about which more is known. In addition, it is important to remember that the processes dominant in one location may be less so in another: while spatial segregation was found to be a major driver of oil vulnerability in suburban Australia (Dodson and Sipe, 2007), a study comparing travel behaviours with car ownership across Parisian municipalities found that car-free groups tended to gravitate towards areas with more local amenities, mitigating the buildup of 'transport stress' (related to oil vulnerability) in car-dependent suburban zones (Motte-Baumvol et al., 2010).

For the purposes of this paper, oil vulnerability is defined as the combined probability and magnitude of negative effects resulting from high oil price or shortage scenarios. Its geographical variability has received much attention at the city scale, especially within Australia (Dodson and Sipe, 2008b; Runting et al., 2011; Steele and Gleeson, 2010; Arico, 2007). However, the impacts are felt by individuals, and a convincing case can be made that those who are already vulnerable will be worst affected (Aftabuzzaman and Mazloumi, 2011).

Evidence of the social and economic difficulties faced by 'low income, high car ownership' households from Australia suggest that some people are struggling to cope in the current economic climate (Currie and Delbosc, 2009). Already vulnerable households were also found to be worst affected by oil price rises in suburban USA, with some defaulting on mortgages following the 2008 oil price shock, a possible trigger of the subsequent sub-prime mortgage crisis and related events (Sexton et al., 2011). In both cases, the authors highlighted the close links between housing markets and transport: the structure of the former tends to increase vulnerability in the latter, as poorer household tend to be priced out of areas in close proximity to strong labour markets and public transport links. This paper does not quantify housing variables such as tenure and house prices, but acknowledges the importance of such structural factors encouraging already vulnerable families and individuals to live in inaccessible areas.

1.2. Scope of the paper

The aim of the paper is to explore the potential of quantitative measures to identify which commuters and areas are most vulnerable. A range of metrics are tested, shedding light on different types of 'oil vulnerability' to create a 'vulnerability profile' analogous to a multi-dimensional poverty index of the type advocated by Bourguignon and Chakravarty (2003).

The effects of shortages (e.g. empty gas stations) would inevitably be more severe and less predictable and will not be considered here (see Friedrichs, 2010). In addition, the concept of vulnerability is limited to the impacts for commuter patterns in this paper, a key area of risk (Dodson and Sipe, 2008b).

Our approach is quantitative. In practice, however, many factors would affect how well commuters in different areas would deal with oil shocks (Hopkins, 2008), ranging from psychological — for example how well people cope with adversity — to infrastructure. Quantifying such a concept, which depends on an array of interrelated factors, is therefore a challenge (Adger, 2006): quantifiable proxies require quantifiable input variables. Previous work in different fields have created quantitative proxies of equally complex concepts. These concepts include:

- Energy security (Skea et al., 2010a; Kruyt et al., 2009).
- Vulnerability to natural disasters (see Cutter, 1996 for an overview)
- Ecological resilience: the capacity of ecological systems to maintain core functions and survive after an external shock (Luers et al., 2003).

In each case, a formula with multiple inputs is used to encapsulate the relative importance of different factors. The literature on the measurement of complex concepts generally acknowledges the limitations of quantification. The concluding remarks of Luers et al. (2003, p. 265) concisely summarise the desire not to oversimplify the complex notion of vulnerability: "No single measure will be able to capture completely the multiple dimensions of vulnerability." This statement applies equally to quantifications of oil vulnerability as to 'adaptive capacity' (Gunderson, 2000), 'flexibility', or any other concept that strives to capture the full complexity of the real world (Smil, 1993).

The paper is structured as follows. In the second section, the input data is described. Section 3 describes the metrics of vulnerability that have been developed and outlines the theories on which they are based. Section 4 presents the results. We demonstrate that travel to work behaviour can be modelled at individual and geographical levels simultaneously by harnessing spatial microsimulation to combine individual and aggregate level datasets.

This technique provides detailed disaggregation of commuting variables at the individual as well as aggregate level: for example more than 95% of commuting energy costs are due to the car in Yorkshire and the Humber. Most importantly from the perspective of policy responses to oil price shocks, we show that a variety of vulnerability indices can be constructed from official data. The reliability of the results and methods of validating and refining the model are discussed in section 5. We suggest in section 5 that the results can provide an empirical basis for deeper analysis. The quantitative approach may also provide an opportunity to critically engage with those outside academia involved in policy making (Dorling and Shaw, 2002). Summarising this discussion and the potential uses of oil vulnerability in policy and academia, section 6 concludes the paper.

2. Data

2.1. Input data: travel, energy and income

A summary of the input data used for the vulnerability metrics developed in this paper, the level at which they operate, and reasons for their inclusion, are outlined in Table 1. The two input data sources for the model were the 2001 UK Census (at a high geographic resolution - Medium Super Output Area level) and the the Understanding Society dataset (USd). The USd is an individual-level nationwide survey of socio-economic variables and attitudes. Clearly, the list of variables affecting oil vulnerability taken from these datasets is not comprehensive. Resilience to oil shocks is also affected by other variables including level of education, community cohesion, strength of the local and regional economy and geographic factors such as proximity to farmland and export markets (North, 2010; Bailey et al., 2010). These factors are more difficult to quantify, however: data availability precludes their inclusion in the model.

A notable feature of the variables described in Table 1 is that some operate at the level of individuals, while others operate at the level of geographic zones. This is problematic when developing indices and necessitates methods for combining variables that operate on zonal and individual levels, for indices that are 'scale independent' (Fotheringham, 1989) that can apply to individuals and zones alike. Of course, for the creation of zonal measures of vulnerability, it is possible to aggregate individual variables over geographic areas, for example average incomes. However, this approach may not be appropriate, for a couple of reasons: first, geographic aggregates ignore the

Table 1: Input variables related to vulnerability of commuters to oil shocks

Variable	Symbol Units	Dataset	Level	Comments
Active travel	P_{act} (%)	Census	Zonal	Baseline of walking/cycling
Car dominance	P_{car} (%)	Calculated (Census)	Zonal	Dependence on oil
Car sharing	P_{share} (%)	Census	Zonal	Potential for trip sharing
Density	$Dens$ ppl/km^2	Census	Zonal	Proxy of isolation
Distance to employment centre	D_{cent} km	Calculated (UKB)	Zonal	Based on predefined centres
Distance to work	D_{wk} km	USd/ Census	Individual	Dependence on long-distance travel
Energy cost of commute	E_T MJ/T	USd/ Census	Individual	Calculated from distance and mode
Energy use	E_{ind} MJ/yr	USd	Individual	Proportion of energy budget
Energy use	E_{area} MJ/yr	Nstats	Zonal	Relative importance of commuting
Expenditure on commute	Ex_T (£/T)	Calculated	Individual	Financial vulnerability
Income	I £/yr	USd	Individual	Financial vulnerability
Infrastructure	Inf km/zone	Ordnance Survey	Zonal	Potential for active travel
Mode of commute	M -	USd/ Census	Individual	Fuel requirements and expenditure per km

distribution of continuous variables such as income; second, certain variables such as income are rarely made publicly available for small areas by national governments, for ethical and confidentiality reasons (Lee, 2009).

The solution to these problems adopted in this paper is spatial microsimulation: a method of allocating individuals to zones based on shared variables between individual and geographically aggregated datasets (see Ballas et al., 2005a for an overview of method).

2.2. Energy cost data

The estimation of energy costs is problematic generally, and especially so in the transport sector. Energy use is rarely recorded in the 'chremastitic' (finance-dominated) economy (Martínez-Alier et al., 2010) (see DUKES (2011) for an exception). Personal transport is especially problematic because vehicles are mobile energy consuming devices with constantly varying efficiencies (Daly and Ó Gallachóir, 2011). While heaters and electrical appliances use energy from one supplier at a predictable rate, cars can be refuelled almost anywhere. Therefore, real world energy use datasets are more readily available for electricity and heat, the other two major energy users, than for transport (Mackay, 2009).

Vehicle emissions (and hence energy use) can be estimated based on traffic flow data provided by the Department for Transport (DfT),[6] sales data from petrol stations (where data is available) and inference from transport to work statistics. The third option is used here, as data is available for its estimation (Table 2) and commuting behaviour is well-constrained, at local levels, by the Census.

[6]See the publicly available Inter-Urban Congestion Dataset: http://data.gov.uk/dataset/dft-eng-srn-routes-journey-times

Table 2: Direct energy use and average occupancies of for the 7 most frequently used modes of commuting.

Mode	Ef (MJ/vkm)	Occupancy	EI (MJ/pkm)	Distance (km)^g
Bicycle	0.093^a	1	0.09	4.4
Bus	7.34^b	9^b	0.82	8.3
Car	2.98^c	1.186^d	2.40	15.2
Metro	– ^{e}	1*	0.54	9.4
Motorbike	1.87^f	1.16^f	1.61	10.6
Train	63.4^b	182^b	0.35	37.2
Walking	0.13^a	1	0.13	1.3

a: Coley (2002), b: (Hansard, 2005), b: Treloar et al. (2004), c: Mackay (2009), d: DfT (2011), e: London Underground (2007), f: ORNL et al. (2011), g: Calculated from DfT (2011, Table 4), *: Data provided per person kilometre.

3. Metrics of vulnerability: resources, jobs, money

Four metrics, which reflect economic, energetic and other perspectives on oil vulnerability, were developed and calculated for zones in Yorkshire and the Humber. The inputs into the vulnerability metrics were supplied by the results of the spatial microsimulation model. These metrics are as follows:

- Economic vulnerability: defined as commuter fuel poverty (V_{cfp}), the proportion of people spending more than 10% of their income on work travel.
- Energy based metric 1: proportion of energy use expended on work travel (V_e)
- Energy based metric 2: proportion of individuals spending more than 10% of their 'energy budget' — including gas, electricity and travel energy use — on work travel in each area (V_{ei}).
- Hybrid vulnerability index based on distance to employment centre, dominance of cars and the average energy costs of commute (V_h).

It should be noted that two of these metrics, V_{cfp} and V_e, also operate at the individual level, allowing for the identification of characteristics associated with vulnerability to be assessed in each zone (see Section 4.3). Both financial and energy metrics of commuter vulnerability are used. The former has strong foundations in economics; the latter in systems ecology. Finally, a more complex hybrid vulnerability metric is presented.

3.1. Economic vulnerability — commuter fuel poverty

The total monetary costs per trip (C) can be estimated as a function of the value of time lost (c_s) and direct monetary expenditure (c_m) per unit distance (d) for each mode of transport (Ommeren, 2006). Due to methodological difficulties in measuring c_s (Mokhtarian and Salomon, 2001), we focus on the the direct monetary costs:

$$C = c_m \times d \tag{1}$$

The standard definition of fuel poverty is spending more than 10% of disposable household income — specifically, equivalised income — on adequate home heating and cooking (Boardman, 2010). Thus the attribute 'commuter fuel poverty' can be defined as people for whom commuting costs (C) constitute more than 10% of their income (I). At the individual level, commuter vulnerability can thus be defined either as a continuous (V_{cfp}, equation 2), or a binary ($V_{cfp}bin$, equation 3b) variable. For zones, vulnerability can be defined simply as the proportion of people living in commuter fuel poverty ($V_{cfp}a$, equation 4).

$$V_{cfp} = C/I \tag{2}$$

$$V_{cfp}bin = \begin{cases} 1, & \text{if } V_{cfp} \geq 0.1 \quad \text{(3a)} \\ 0, & \text{if } V_{cfp} < 0.1 \quad \text{(3b)} \end{cases}$$

$$V_{cfp}a = \frac{\sum V_{cfp}bin}{n} \tag{4}$$

3.2. Energy-based metrics

An alternative approach is to take the ecological view that energy is the 'master resource' (Smil, 2006) and measure vulnerability accordingly.[7] The

[7] According to this view, a system's performance can be assessed by the energy flows within it, regardless of the scale or function of the system (Odum, 1971). While this

resulting metric would focus not on the monetary expenditure of transport to work, but on the energy costs. There is an existing body of research about the energy costs of transportation that can provide methodological and empirical insight into oil vulnerability (e.g. Boussauw and Witlox, 2009). In essence, energy use for personal travel is function of the efficiency of the vehicle technology being used and distance travelled. On this basis, Li et al. (2013) combined data on fleet efficiencies with official commuting statistics to calculate the energy costs of commuting in units of litres per trip. This metric shed new light on the spatial variability in oil vulnerability as defined above, by showing that technological disadvantage,[8] manifested in local fleet efficiencies, "exacerbates household exposure to higher transport costs and compounds other forms of disadvantage" (Li et al., 2013, p. 9). The paper concluded that further research into energy metrics is needed in places outside the case study area of Brisbane.

Using the data presented in Table 2, energy costs per trip (E_T) can be calculated based on information on mode ($_m$), distance (d) and energy consumption per kilometre (η):

$$E_T = \eta_m \times d \tag{5}$$

This estimate can be used as a self-standing marker of vulnerability, if one assumes that more energy intensive commuting patterns are inherently more vulnerable. Following the logic of fuel poverty measures, an alternative to monitoring absolute energy use in transport is the *proportion* of one's energy budget expended on commuting (P_{ET}):

$$P_{ET} = \frac{E_T \times T_{yr}}{E_{yr}} \tag{6}$$

where T_{yr} is the number of commuter trips made per year and E_{yr} is total energy use per year. These input values can be calculated at the individual

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perspective is primarily applicable to systems, rather than the individuals and local areas that are the subject of this paper, an energy systems approach can still be useful at many scales, including that of the city, with relevance for sub-national geographies (Odum and Odum, 2001).

[8]For example, not being able to invest in a new and highly efficient car, although the same could apply to bicycles or, at the local authority level, to more technologically advanced and efficient public transport modes such as buses and trains.

level from the survey data. At the individual level, the resulting energy-based vulnerability metrics (V_{ei}) can therefore be calculated as continuous or binary individual level variables. For geographic zones, we can define V_{ei} as the proportion of commuters who spend more than 10% of their energy budget on work travel.

An alternative energy-based vulnerability metric that operates solely at the aggregate level (V_e) is calculated as the total energy expenditure on commuting in the area divided by total domestic energy use:

$$V_e = \frac{\sum E_T \times T_{yr}}{\sum E_{yr}} \tag{7}$$

3.3. Hybrid vulnerability metrics

A criticism of the aforementioned vulnerability indices is their narrow focus, either on energy or money. They take no account of other quantifiable factors that influence vulnerability, such as geographical isolation from employment centres, level of community cohesion or the diversity of transport options in the area (Pickerill and Maxey, 2008; North, 2010; Steele and Gleeson, 2010; Newman et al., 2009). For this reason, a hybrid metric based on multiple risk factors may be more appropriate. The following hybrid index operates at the aggregate level:

$$V_h = (P_{ET} + \alpha) \times \sqrt{\beta D_c} \times P_{car} \tag{8}$$

where P_{ET} is the proportion of the individual's energy budget spent on commuting, D_c is distance to employment centre, P_{car} is the proportion of work trips made by car in the zone in question and α and β are parameters to be set.

V_h acknowledges that the vulnerability of commuting patterns to high oil prices is complex and caused by multiple, self reinforcing factors. By changing the values of the predefined parameters (or by modifying the equation) it is possible to increase or decrease the importance allocated to certain factors. Increasing the value of α, for example makes the result far less sensitive to the proportion of energy used for commuting. Perhaps isolation is seen as a more important determinant. In this case the value of β could be increased.[9]

[9] This assumes that D_c is a valid proxy for isolation. Whether or not the assumption holds is debatable, based on the method used to calculate D_c for each zone: D_c is defined

Each of these metrics has its limitations, not least the reliance on aggregate cost and energy estimates that may vary significantly from place to place and person to person. These limitations are further discussed in Section 5. For now we run on the assumption that they are useful proxies of commuter oil vulnerability and, after exploring aggregate-level findings based on census data, investigate the results of each formulae in turn.

3.4. A spatial microsimulation model of commuter patterns

The data and equations presented above can operate at regional and individual levels: as zonal averages supplied by the Census or individual cases supplied by Understanding Society. Both have advantages. Regional data from the Census (supplied by the Casweb data portal) illustrate the spatial patterns in commuting behaviour, but mask variation at the individual level (Openshaw, 1983). Individual-level data illustrate the inequalities that exist between people and the links between commuting and other individual-level variables such as income, socio-economic class and qualifications. Survey data are not geocoded, however.

To overcome this problem we used spatial microsimulation, a method that allocates individuals from survey data to zones by selective sampling or 'reweighting' — see Tanton and Edwards (2013) and Ballas et al. (2005b) for overviews. The critical first stage in spatial microsimulation is to identify shared variables between survey (individual-level) and census (regional) data (Ballas et al., 2005a). The linking variables used for this microsimulation model were age, sex, mode of transport to work, distance of commute and socio-economic class. We will not go into the deep technical details of the method used to generate the geocoded individual-level data used in this study, prefering to focus on the method's potential for assessing oil vulnerability at the individual level within small areas. Suffice to say that iterative proportional fitting (IPF) and then 'integerisation' were performed in the statistical programming language R to reweight the survey dataset for each or the medium super output area (MSOA) zone in Yorkshire and the Humber. For details of the method used, interested readers are referred to Lovelace

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here as the distance to the nearest employment centre in each transport to work (TTW) zone. D_c was calculated for the population centroid of each medium super output area (MSOA) using the command 'nncross' from the 'spatstat' package in the computer program R.

and Ballas (2013), the appendix of which provides a 'user manual' to demonstrate how the technique works in practice, using free open source software and publicly available data. The end result of the spatial microsimulation method was a table of 2 million commuters replicated from the USd dataset, each allocated to one of the 694 MSOA zones.

Because individuals from the Understanding Society dataset are selected, simulated values for a range of other variables can be made, including income, work times (and therefore frequency of the trip made to work over the year) and domestic energy use (gas and electricity bills). See Tanton et al. (2011) for more details on the method of small area estimation.

4. Results

4.1. Trips, distance and energy use

The spatial microsimulation model allows cross-tabulations of commuter patterns by a range of variables. Fig. 2 illustrates the importance of the three most popular modes in terms of fundamental features: proportion of trips, distance and energy use. Table 3 summarises this information, and provides the additional cross tabulation of distance. The dominance of the car is striking. Drivers (excluding car passengers) account for 55% of trips, 75% of distance travelled and 96% of energy use. This result is predictable as the region's transport infrastructure is focussed on the car and coincides with other findings from the UK (Brand et al., 2013).[10] Overall, cars consume more than 20 times more energy than all other forms of transport to work put together whilst providing transport for 62% of the workers. Another striking result is the unequal use of energy by long-distance commuters: while only 1/3 of commuters travel more than 10 km to work each day, these people account for over 3/4 of commuter energy use in the region (Table 3). The results suggest that very long trips to work consume a disproportionate amount of energy. Indeed further analysis showed that 4% of commutes in Yorkshire and the Humber are greater than 50 km, yet these account for almost 30% of energy costs.

[10]Yorkshire and the Humber's transport infrastructure contains 380 km of motorways, 2,300 km of major roads and over 30,000 km of roads in total. By contrast there are 1,500 km of railways and less than 500 km of bicycle paths in the region.

Table 3: Proportion of trips (T), distance (D) and energy (E) used by the three most popular forms of transport in Yorkshire and the Humber.

Dis.	Car*			Walk			All modes		
(km)	T	D	E	T	D	E	T	D	E
0-5	14.0	3.9	5.0	9.5	1.7	0.1	45.1	8.6	5.8
5-10	15.5	10.4	13.4	0.4	0.3	0.0	23.4	15.7	14.6
10+	25.0	60.7	77.9	0.7	0.8	0.0	31.5	75.7	79.6
All	54.6	75.0	96.4	10.6	2.9	0.2	100	100	100

*Excludes car passengers

4.2. The geography of vulnerability

The spatial variability of the vulnerability indices is shown in Fig. 3. The metrics are closely related, as illustrated by the concentration of high vulnerability in isolated rural areas in all but one of the metrics. Spatially this correspondence can be seen as an arc of vulnerable areas defined in terms of V_{cfp}, V_e and V_h in Fig. 3. This area runs from East Leeds to Castleford Selby and north-east towards Hull and the Yorkshire Wolds. The correlation between the metrics, at the MSOA level, is shown in Fig. 4.

An unexpected result is that some employment centres are associated with high levels of commuter fuel poverty (see measure a in Fig. 3). This can be seen in the dark patches near to Harrogate, Malton and Whitby and a number of urban settlements — for example to the east of Sheffield. This result can be explained by distance of commute: each of the areas mentioned is associated with long commutes[11] and low levels of deprivation scores in the surrounding areas.

In order to test the relationship between commuter oil vulnerability and broader social disadvantage, the vulnerability measures were compared with the Index of Multiple Deprivation (IMD). Because IMD data is available at the lower super output area (LSOA), aggregation was used to find the

[11]The average Euclidean distances of commutes in the area are 18, 15 and 23 km for MSOA areas surrounding Harrogate, Malton and Whitby, respectively. The average for the region is 11 km.

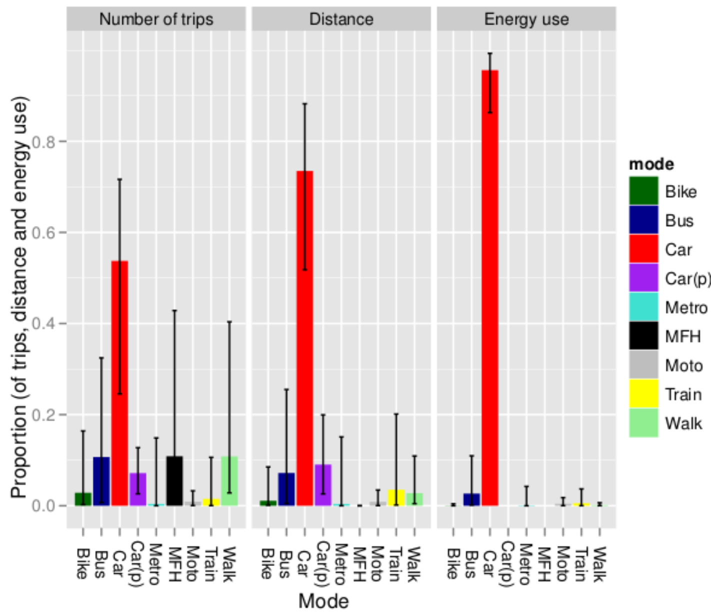

Figure 2: Proportion of trips, distance and energy use accounted for by different commuter modes. The error bars represent the range of values within MSOA areas in Yorkshire and the Humber.

mean IMD score in each MSOA. This allowed correlations to be calculated. Negative correlations were found between aggregated IMD and all four vulnerability metrics; Pearson's coefficient of correlation (r) ranged from -0.59 to -0.22 for the V_{ei} and $Vcfp$ measures respectively, all of which were statistically significant. This result implies that areas at risk from high oil prices are not currently identified as being in urgent need of support. A comparison of the chloropleth maps of IMD in Fig. 5 with the vulnerability metrics (Fig. 3) illustrates the reason for negative correlations: deprivation is primarily an urban phenomenon in Yorkshire and the Humber (the three most deprived MSOA areas are located near central Grimsby and Hull), whereas oil vulnerability tends to be rural. The correlation between average income and the four vulnerability metrics was found to be positive in every case, with r values ranging from a weak positive correlation of 0.20 for V_{cfp} to a strong positive correlation of 0.61 for V_{ei}. This reinforces the notion that the vulnerability metrics developed for this paper are identifying areas that are not traditionally seen as deprived.

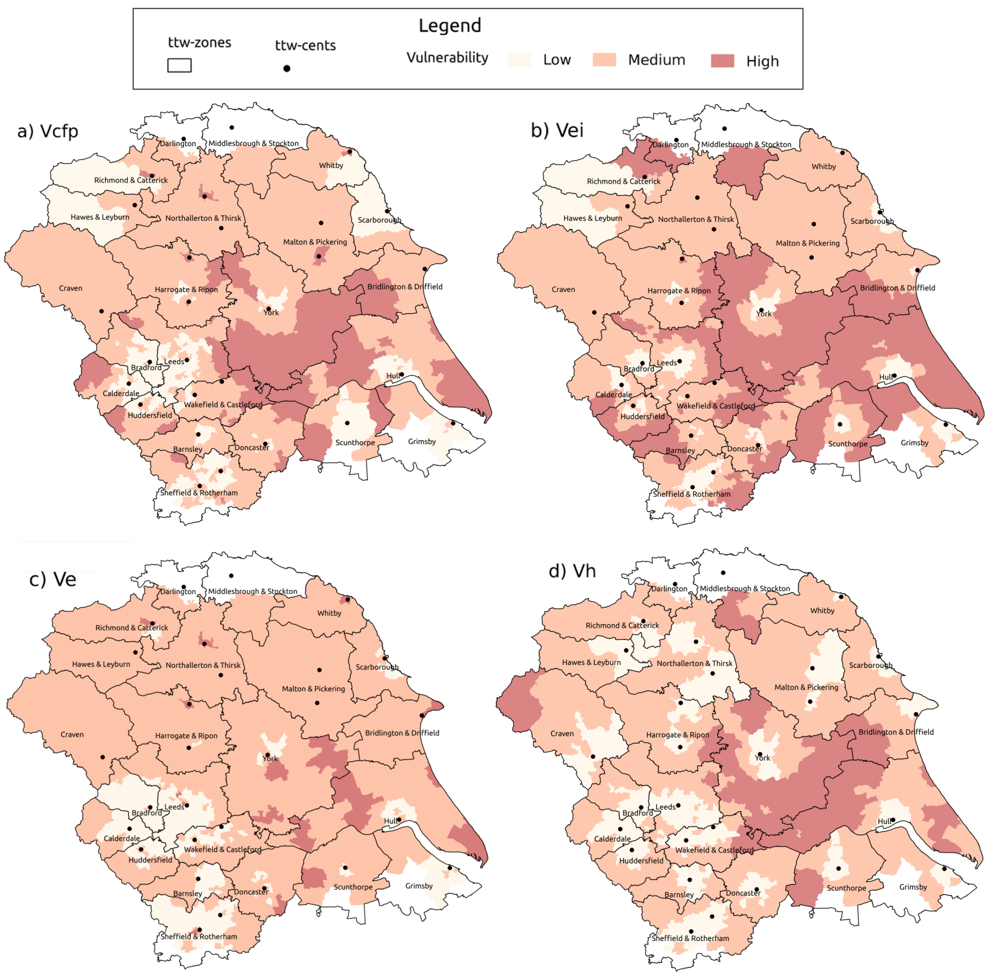

Figure 3: Vulnerability of commuter patterns in Yorkshire and the Humber according to four metrics: a) Commuter fuel poverty, b) individual energetic, c) zonal energetic, d) hybrid vulnerability. Bins were allocated by Jenks' classification of natural breaks.

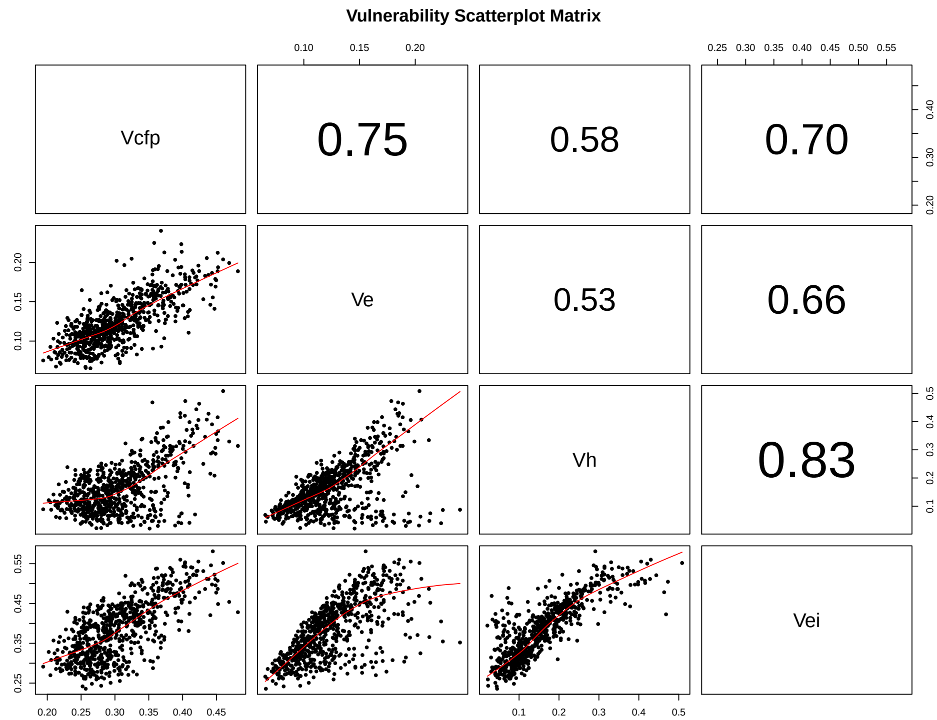

Figure 4: Scatterplot matrix illustrating the relationships between each of the 4 vulnerability metrics.

To explore this link further, the average distance from employment centre[12] was calculated, based on the population-weighted centroids of the MSOA areas and the economic centre of each transport to work area, based on 2001 data. The results (illustrated in Fig. 6) demonstrate the importance of taking account of population clustering in the analysis of zones: population-weighted centroids are often much closer to employment centres than centroids that are based on area alone. The similarities between the metrics plotted in Fig. 3 and the distance from employment centre illustrated in Fig. 6 suggest a strong link between distance from employment hub, energy use and vulnerability.

So far only geographically aggregated results have been presented. A

[12] "Employment centre" here is defined as the towns and cities referred to in the names of the 2001 transport to work areas (TTW) (ONS, 2011).

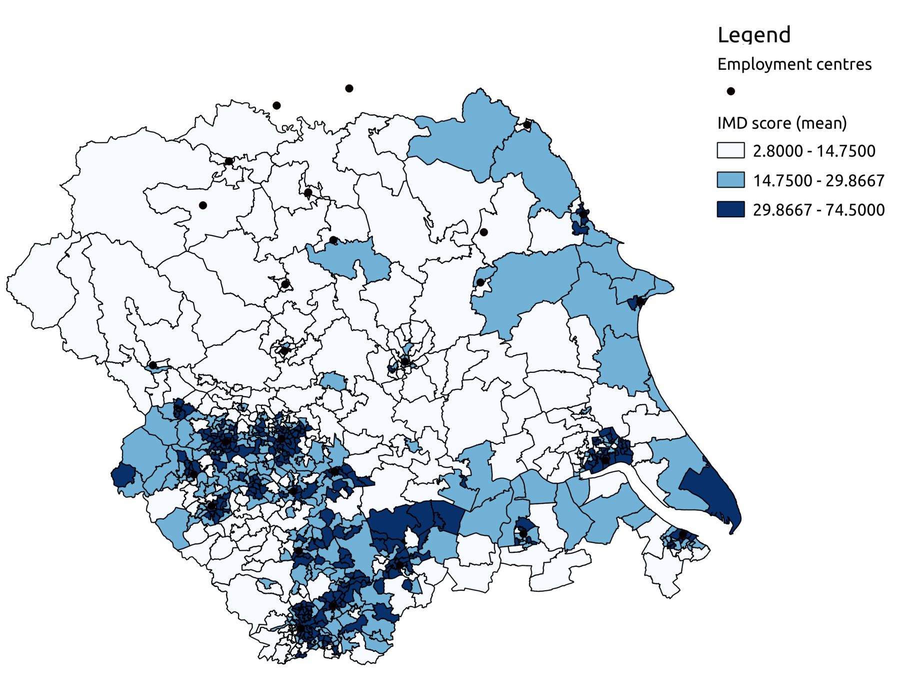

Figure 5: Chloropleth map illustrating the spatial variability of the Index of Multiple Deprivation at the MSOA level. (Values are average IMD scores for LSOA centroids.)

key advantage of spatial microsimulation, however, is that individual-level characteristics can be modelled.

4.3. Local and individual level results

The spatial variability described in the previous section provides insight into the types of places where commuters are expected to be most vulnerable to oil shocks. However, a spatial location may seem not to be vulnerable based on aggregate measures, yet its inhabitants are likely to have a wide range of commuter habits and some may be vulnerable based on individual-level measures. Geographically aggregated data therefore only tell part of the story and, if interpreted incorrectly, can mask intra-zone variability. In a worst-case scenario this could lead decision makers to overlook vulnerable groups. Indeed this situation has been described in Albuquerque, where a new bus network failed to aid those most in need (Tribby and Zandbergen, 2012). Compared to aggregate measures, the spatial micro-simulation method is better able to identify vulnerable people and households.

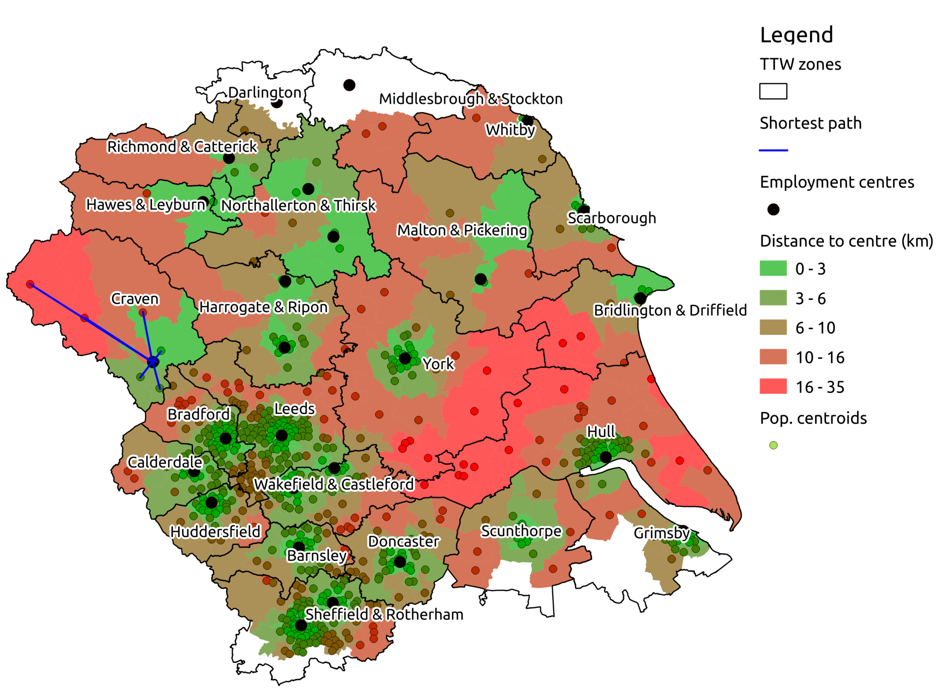

Figure 6: Distance to employment centre, calculated as the shortest distance between zone population centroids and TTW zone employment centres (see blue lines, which illustrate this calculation for zones in Craven TTW zone). Compare with Fig. 3.

Hypothetical commuters illustrate the point. We would expect a high-income manager, for example, to have a low commuter fuel poverty (V_{cfp}) score due to high income. Their individual-level energy vulnerability (V_{ei}) score may be higher, however, especially if they live in an energy efficient home but drive a large car many miles to work and back every day, as is common for high earners (Green et al., 1999). If they live in a car-dominated area far from employment centres in a rural 'commuter belt', the area in which they live may well have a high aggregate energy vulnerability V_e score. These are clearly not the characteristics of a deprived area. By contrast, an unskilled worker living in a deprived urban area (with a poorly insulated house) who travels a few kilometres to work may have have a low V_{ei} but high a V_{cfp} score if they spend a portion of their low income on expensive bus tickets.

These suppositions may seem obvious but the relative numbers and spatial distribution of different groups are not. Spatial microsimulation, by estimating the characteristics of individuals, provides a means of gaining insight into the likely impacts of oil vulnerability on people beyond aggregated statistics associated with the areas in which they live. Based on the individual small area data, vulnerability scores for each individual living in each zone were calculated. The metrics set out in Section 3 applicable to individuals were commuter fuel poverty (V_{cfp}, equation 4) and proportion of energy use spent on work travel (V_e, see equation 6, on which this metric is based). The distribution of these individual metrics in different zones are described in this section. An example of three areas from the city of York (selected because it is the clearest employment hub surrounded by countryside in the region) serves to illustrate the point: one is right in the city centre, the second is a low income suburb and the third is on the rural outskirts of York (Fig. 7).

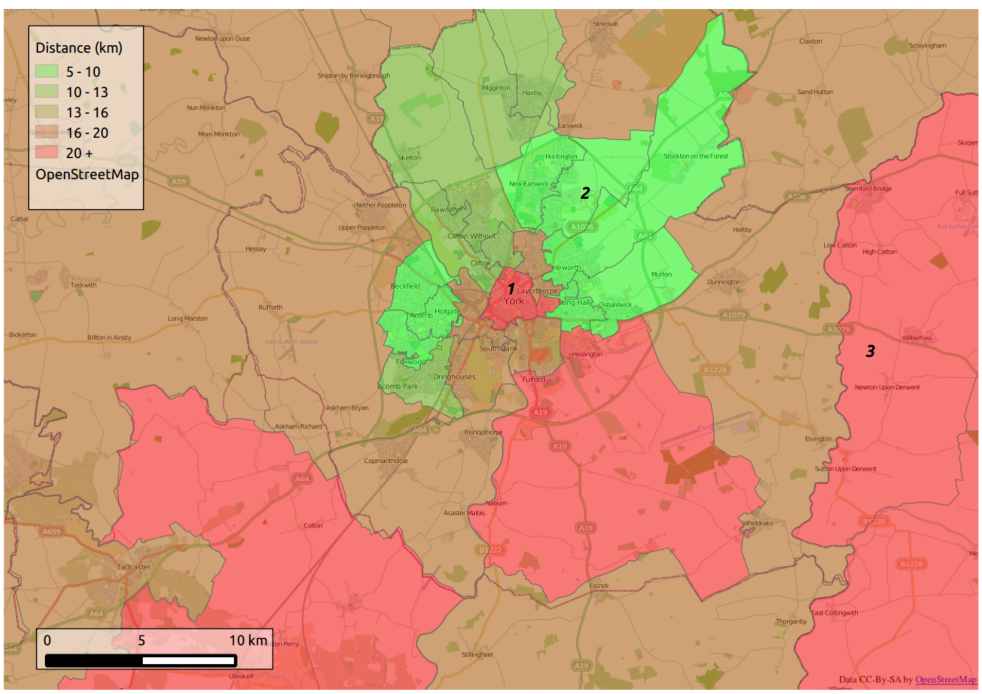

Figure 7: MSOA zones in York, coloured according to distance travelled to work. The zones 1, 2 and 3 are referred to below.

Table 4 illustrates summary vulnerability statistics for each of the three areas numbered in Fig. 7 and the average weekly income for household in each zone.[13] It is interesting to note that the wealthiest zone, in the centre, is also the most oil vulnerable according to V_{ei} and the second most vulnerable in terms of V_e and V_{cfp}. This finding can be explained by the high average distance travelled to work by commuters living in the city centre: wealthy people tend to commute further, leading to higher energy and monetary expenditure on travel to work. Commuters in the rural zone (three) commute, on average, the same distance yet they are deemed to be less vulnerable when vulnerability is measured as the proportion of people spending more than 10% of their energy budget on on commuting. This can be explained by the higher baseline energy use in rural areas (Druckman and Jackson, 2008), meaning that although commuting energy use is high, it does not form a large proportion of total energy use for most. The rural zone is most vulnerable in terms of V_e, V_{cfp} and V_h, illustrating the importance of income, overall energy use and distance from employment centre for these metrics.

Table 4: Summary statistics of vulnerability metrics and income estimates for three areas in York. All results presented as percentages, unless otherwise stated.

Variable	Statistic	1: Central	2: Suburb	3: Outskirts
Income (£/wk)	Mean	440	400	390
Distance (km)	Mean	16.5	8.3	16.5
V_{cfp}	Mean	2.0	1.1	2.1
	SD	3.5	2.8	4.9
	$\geq 10\%$	3.3	1.7	5.9
V_e	Mean	14.9	9.1	8.4
	SD	13.9	11.5	12.3
	$\geq 10\%$	55.7	32.0	28.6
V_{ei}	-	17.0	10.0	18.0
V_h	-	3.0	9.0	33.0

Because V_e and V_{cfp} are also calculated at the individual level, it is possible to estimate the characteristics of vulnerable individuals at the local level.

[13] The income estimates are from the Office of National Statistics Neighbourhood Statistics service. The estimates presented in Table 4 are the central estimates for equivalised income from the table "Income: Model-Based Estimates at MSOA Level, 2007/08".

These results (presented in Table 5) illustrate that different types of people are defined as 'oil vulnerable' in different areas. The average income of people living in commuter fuel poverty (for whom $V_{cfp} \geq 0.1$), for example is much higher in the city centre than in the outskirts. Table 5 illustrates that the characteristics of individuals defined as 'oil vulnerable' can also vary greatly within areas depending on how oil vulnerability is defined. People living in commuter fuel poverty, for example, tend to be older than those for whom $V_{cfp} \leq 0.1$. We could hypothesise whether this is due to a greater reliance on motorised modes amongst generally less active older citizens or perhaps also due to lower domestic energy use amongst young people. Because our model is not constrained by data on either of these variables, we cannot reliably test this hypothesis and suggest explanations of *why* potential oil vulnerability varies between different groups. Estimates of the average number of children under the care of commuters were also generated by the model. These have no bearing on the vulnerability scores, but illustrate how additional socio-demographic variables could be included to provide additional information to the simple univariate oil vulnerability metrics. The distance and mode of school travel, for example, could have a major impact on the viability of working closer to home in cases where travel to work is combined with the school run (Hensher and Reyes, 2000). Based on the results from our metrics, it would seem that commuters living in commuter fuel poverty living in zone 2 and 3 are particularly vulnerable, with high levels of car dependence yet low incomes.

5. Discussion

By providing estimates for a range of individual-level variables, our results shed light on, and provide a basis for discussion of, various types of oil vulnerability. Returning to the two hypothetical commuters mentioned in section 4.3, we could further predict their relation to policy interventions. Policies encouraging telecommuting would be more effective if targeted towards the manager (with the potential co-benefit of freeing-up oil for shorter commutes or public transport). The unskilled worker, by contrast, may be better served by pro-cycling policies or subsidised high-efficiency buses to increase the viability of cheaper and more active forms of travel.[14]

[14]Public transport is generally more active than driving, as people tend to walk to and from bus stops (Besser and Dannenberg, 2005).

Table 5: Individual-level characteristics of 'oil vulnerable' commuters in living in the three zones of York depicted in Fig. 7, estimated by the spatial microsimulation model.

Subset	Statistic	1: Central	2: Suburb	3: Outskirts
$Vcfp$ $\geq 10\%$	N	241	51	151
	Average age	39	41	44
	Average income	19100	15800	14300
	Income SD	9400	10100	8400
	N. children	0.51	0.88	0.67
	% drive to work	45	53	56
Ve $\geq 10\%$	N	1168	990	2466
	Average age	35	31	41
	Average income	18000	16600	19200
	Income SD	11900	8000	10300
	N. children	0.67	0.64	0.67
	% drive to work	43	40	61
All commuters	N	4085	3091	4424
	Average age	36	41	42
	Average income	19500	17900	19686
	Income SD	12600	10800	12000
	N. children	0.56	0.7	0.67
	% drive to work	25	49	61

The model simulated individuals in terms of their age, gender, commuting habits (distance and mode of travel) and socio-economic class. Yet it made no attempt to model the dynamics of behaviour, being instead a *static* simulation to provide insight into the geographical and social distribution of characteristics related to contemporary oil vulnerability. This limitation could be partly overcome by making the model *dynamic* (Ballas et al., 2005a). However, the obvious problem with this approach is that the future is by definition uncertain, meaning that any attempts to project current trends into the future risk being misleading (Smil, 1993), regardless of whether the future scenarios are created by a top-down 'aggregate projection' (Ballas et al., 2005a), in which constraints are imposed for each zone, or via some kind of agent-based model (e.g. Wu et al., 2008). There is much work to be done in this area and we hope that the static model used in this paper could provide ideas (theoretical as well as methodological) for dynamic simulations of the societal responses to changes in the availability of fossil fuels, whether this is imposed by an oil price shock (as assumed in this paper) or planned, for example as a strategy to mitigate climate change.

As with aggregate measures, commuter oil vulnerability at the individual level clearly has multiple meanings and interpretations. The model results support this view and could, if combined with additional vulnerability metrics (e.g. those used in the IMD), be used to help inform a more multifaceted and context specific concept of oil vulnerability than that implied by previous research. All models are simplifications of reality and our vulnerability metrics are no exception. They could clearly be refined, for example by including the accessibility to and ability to ride bicycles in the study region, based on primary survey data. The constraint variables could be altered and expanded to include additional relevant factors such as rate of car ownership and tenure; this would affect the results. Some relevant variables such as income and domestic energy use are not available at the local level but are estimated as a function of their correlation with constraint variables in the individual-level survey; more could be done with these to generate vulnerability metrics.

Some important information, including local perceptions of the viability of work relocation, are unavailable from secondary data, so would require local surveys. In every case where data is simulated or deemed uncertain, this must be taken into account when interpreting the results, a critical point in any situation where environmental policies are based on model data (Smil, 1993). In addition, because only one level of administrative zones is used in this study, the results could be susceptible to the modifiable areal unit problem (Openshaw, 1983; Horner and Murray, 2002), although the individual-level metrics should be more robust to this effect than aggregate-level measures. Validation techniques and sensitivity analyses should be undertaken before policies based on the vulnerability metrics are implemented (Edwards and Clarke, 2009). The results emerging from this paper should therefore be seen as an exploration of *methods* available to investigate and attempt to measure the vulnerability of commuter patterns to high oil prices, rather than finished or prescriptive empirical findings.

Another major shortcoming of the microsimulation method advocated in this paper is its focus on individual commuters rather than whole household units. Some attributes (notably income) were extracted from the household-level microdata, yet the individuals were not placed into household groups in their own right. This is problematic, because some households may be at risk of losing all their earned income due to unaffordable commuting costs, whereas others may contain two or three working members, only one of whom is seriously at risk. Therefore, household composition could either increase or decrease risk levels and alter the type of risk that peak oil poses.

The importance of household composition is further discussed in Green et al. (1999) and illustrated in Table 6. The table serves to illustrate that not only the *level* (high to low) of vulnerability depends on an array of factors, but the *type* of vulnerability is context-dependent also. The table serves to illustrate that not only the level (high to low) of vulnerability depends on an array of factors, but that the type of vulnerability is also context-dependent. The final example, of young mobile professionals serves to illustrate that long commuter distances may be lifestyle choices. If people live in Sheffield but commute to York for social reasons, for example, the risk may amount to being forced to move away from friends. This is a less severe type of vulnerability than the underemployment and reduced salaries faced by low income families who would likely find it much harder to move house. The most severe impacts may apply to isolated single parent households.

Presenting such results without reference to the wider context such, as income disparities or deprivation, could lead to erroneous policy conclusions. V_{cfp} and V_{ei} metrics could potentially be used to portray wealthy, energy-intensive commuters as vulnerable. Arguably, this happens currently in UK

Table 6: Illustrative categorisation of types of household-level vulnerability and socio-economic groups most at risk.

Household type	Type of vulnerability			
Characteristics	Unemployed household	Underemployed household	Reduced salary	Social costs
Rural poor single-parent household	x	x		
Family with 2 adults live in leafy suburbs		x	x	
Wealthy, highly skilled, settled couple			x	
Mobile young professionals				x

energy policy.[15] In this regard, individual-level measures of oil vulnerability such as those presented in this paper could equally help shed light on the overlaps between transport injustice currently and exposure to the impacts of declining fossil fuel consumption.

In terms of its political relevance the model in its current form, it demonstrates that policy decisions made now are likely to have impacts in the future, some of which are foreseeable. More specifically, the approach can shed light onto likely overlaps between transport injustice and oil vulnerability through the inclusion of social class. However, its ability to identify vulnerable *households* is limited because the individuals simulated are not combined into family groups.[16] One explanation for the processes which produce vulnerability are the processes governing how individuals gain and lose elements of network capital (see Urry, 2007, p. 197 for 8 elements of network capi-

[15]The wealthiest 10% of the UK population uses around three times more energy than the poorest 10%, with associated emissions. Yet the costs of 'green' energy policies such as the feed-in tariff fall disproportionately on the poor (Preston et al., 2013).

[16]The information about the reasons for an individual being classified as 'vulnerable' could be extracted from the appropriate household-level variables in the survey data. However, the model was not constrained by living arrangements; this constraint could be added in refined versions of the model, for example following the methodological innovations of Pritchard and Miller (2012).

tal). Each metric presented reflects on different elements of an individual's network capital. The acknowledgement that vulnerability is multi-faceted should encourage flexible thinking about an energy constrained future and who is most at risk from the resulting changes.

The exploration of oil vulnerability is a challenging task, but an important one that currently lacks attention from an explictly policy-orientated perspective (see Grossman and Lovaas, 2012 for a notable exception). The analysis presented here illustrates the inroads that can be made to quantifying the concept based on publicly available data. It is hoped this will encourage further theoretical and critical engagement with the concept of oil vulnerability, as well as offering some guidance for policy makers aiming to tackle the issue. There are clearly many opportunities for further quantitative and mixed methods research which could lead to deeper analysis. Speaking the measurement-orientated language of policy makers on this issue could be seen as reactionary — as stated above the metrics, taken at face value with no deeper engagement with the underlying causes of oil vulnerability, could hypothetically be used to justify a short-sighted policy such as a reduction in fuel taxes.

On the other hand, the metrics could be used to help identify disadvantaged commuters and design policies to reduce their level of vulnerability to high prices. More broadly, quantifying oil vulnerability could help engage with and steer the policy debate towards more long-term conceptions of development: on this matter Boulanger (2007) shows that new metrics can be used not only to inform specific interventions but also as a way to re-frame and alter the policy discourse. There is always a danger that metrics and indicators become distorted for political ends. The presention of a variety of different metrics rather than a single 'right' answer, with associated caveats and acknowledgement of uncertainty and different perspectives on the question, should reduce this danger.

6. Conclusion

The scope of this work has been an examination of oil vulnerability in three main ways: conceptually, methodologically and empirically. First, we took existing insight into the factors associated with oil vulnerability in previous studies and researched the extent to which these could be quantified using census data. Various possible interpretations of oil vulnerability have been illustrated and explored through discussion of the construction and choice of metrics in an attempt to anchor the concept to a policy-relevant empirical bedrock. Second, we described the application of a methodology (Lovelace and Ballas, 2013) to the question of vulnerability to high oil prices. These methods would be applicable to different countries where the data exist. Third, we present results from a case study which shows how the pattern of where and who is predicted to be worst affected by oil shocks can vary greatly depending on one's interpretation of oil vulnerability.

The paper provides much incentive for further work, including:

- The relationship between commuter oil vulnerability and the capacity to continue to make journeys after an oil shock (see Philips et al., 2013).
- How the metrics relate to mobility and mobility injustices overall for commuting and other types of journeys such as shopping.
- Use of the static spatial microsimulation data showcased in this paper as a foundation for more sophisticated models, including dynamic spatial microsimulation and agent-based models of vulnerability.

The four metrics outlined in this paper have shown that data exists for the estimation of 'oil vulnerability' of commuter patterns at a range of levels, from the regional to the individual. The work has built on Dodson and Sipe (2008b) in an attempt to define more specifically what is meant by the term, and used individual-level data allocated to zones, spatial microdata, as the foundation of the analysis. As in most countries,[17] the UK lacks publicly available official spatial microdata so a static spatial microsimulation method was used to generate this empirical foundation. Four carefully chosen geographically aggregated variables, taken from the 2001 Census, were used to constrain the model, allowing insight into not only the spatial variability of variables thought to be linked with oil vulnerability, but also their intra-zone variability within and between small areas.

The metrics illustrate that a range of interpretations are available. We contend that completely objective measures of oil vulnerability are impossible: the concept of vulnerability makes assumptions about the future, which

[17]Sweden is an exception to this rule of not making large spatial microdatasets available: 'fabulously detailed' anonymous spatial microdatasets are available to researchers (Clarke and Harding, 2013).

is of course unknown. This coincides with the view that indicators are primarily useful for conceptualising the importance of certain policy objectives (Gudmundsson and Sørensen, 2012) — in this case resilience of commuters to oil shocks. Even if concrete scenarios of the future are developed (e.g. the price of oil rising above $200 per barrel) the interrelated nature of modern economies worldwide ensure that unforeseen consequences and knock-on impacts are likely.

Taken to its extreme, this argument of interrelated impacts can lead to the conclusion that vulnerability applies to society overall, rather than one aspect of it: "Oil is predominantly a transport fuel, however its demand is tied to production in the wider economy" (Korowicz, 2010, 41). In other words, disruption in one sector of the economy will have knock-on impacts in others, so it makes little sense to focus on one area such as commuting. According to this view, vulnerability operates at the *system level* (Greer, 2008; Kunstler, 2006; Heinberg, 2005), the implication being that prediction of impacts in local areas or sectors may be futile. "We are trapped in the current system" (Korowicz, 2010, 43).

Against this critique we would argue that past impacts of high oil prices have varied geographically. This is supported by evidence from suburban USA where commuters relying on long-distance car journeys to get to work were disproportionately hit by the high oil prices of 2008 (Sexton et al., 2011). Of course future impacts could be more severe, and include the spectre of disruptions in supply rather than 'just' high prices. It is wrong to assume that future levels of oil vulnerability will follow the patterns of the past in every case. However, it is equally wrong to base one's analysis on one scenario alone, such as the scenario of system-level collapse depicted by (Korowicz, 2010). A wide spectrum of future scenarios can be envisioned, from a cornucopian 'Third Industrial Revolution' (Rifkin, 2011) to a catastrophic die-off in which only a loose collection of 'breeding pairs' of humans survive at the poles by the end of the century (Lovelock, 2007). The vulnerability metrics presented in this paper would be of limited use if either of these dichotomous visions came to pass. However, there are many scenarios of the future that involve high oil prices. The vulnerability metrics presented in this paper, used with care and modified according to the context in which they are used, could lead to better decision making in preparation for such scenarios at regional, local and individual levels.

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