A geographical exploration of the factors associated with changes in bicycle commuting in England between 2001 and 2011

Introduction

During the early years of the 21st century the nature of threats to the long-term well-being of the planet and its inhabitants have become increasingly clear. We have more data than ever about the problems, from satellites monitoring the impacts of climate change (McMillan et al., 2014) to detailed global statistics on likely decline rates of unconventional oil and gas supplies (Hughes, 2013). Yet collectively humanity seems unable to act on these cues, raising the spectre of past civilisational collapse and potentially bleak prospects for future generations (Beddoe et al., 2009; Ehrlich and Ehrlich, 2013).

The current energy predicament is often framed in purely environmental terms yet climate change and resource depletion are likely to have substantial negative impacts on human health (McMichael et al., 2006). On the other hand, some proposals to reduce reliance on fossil fuels have potential health benefits (Cifuentes et al., 2001). Nowhere is this more noticeable than in the transport sector where the replacement of motorised modes by walking and cycling could provide physical activity to increasingly sedentary populations (Michaelowa and Dransfeld, 2008; Gross et al., 2009; Jarrett et al., 2012; Woodcock et al., 2009)

Although the problems of sedentary lifestyles and fossil fuel dependence are well understood, effective solutions are elusive. In some instances unintended consequences have led to 'solutions' that worsened the situation while leaving the root causes un-addressed (e.g. Sheehan, 2009). Various theories have been developed to explain our collective failure to change direction (Berners-Lee and Clarke, 2013). Generally these revolve around a failure to understand that long-term problems at the interface between the human economy and the Earth's physical systems are entrenched, complex and interdependent (Smil, 2008).

It is within this wider context that questions of transport and health should be considered (Woodcock et al., 2009). The 'global energy challenge' (Lewis and Nocera, 2006) and associated long-term health implications form the backdrop of this paper. Rather than tackle the issues head-on, this paper focusses on one area of policy where reductions in energy use have great potential to improve health outcomes and improved quality of life more generally: personal travel. The research is targeted in terms of its geographic scope (focussing solely on England), time scales (analysing shifts over a decade) and type of travel (focussing on commuting), but relevant to the global context.

Framed in this way, cycling to work is relevant to discussions of humanity's short term well-being and longer term survival: the full benefits of a shift to cycling now may only be realised in the future. A striking feature of the bicycle is that it is a highly accessible technology (almost everyone worldwide can realistically aspire to own one), yet it tackles a very wide range of issues (Komanoff, 2004). Interventions that can simultaneously provide health, energy, economic and social benefit are the mythical 'golden bullets' that policy makers dream of yet almost never encounter. Switching from driving to cycling is just such a 'win-win' solution (Robinson, 2005). It helps solve an array of issues in one simple step. Indeed, the sustainability challenge can be seen as an overinflated balloon: squeeze one area of it and a bulge generally appears elsewhere (Berners-Lee and Clarke, 2013).

This paper starts from the premise that cycling is a desirable outcome for health and other reasons. There is much research supporting this premise and the benefits of active travel more broadly. Less research investigates which policies are most likely to boost cycling in different places at the sub national level (Fraser and Lock, 2011). International comparative studies have helped explain why cycling flourishes in some countries whilst barely accounting for 1% of trips in others (Pucher and Buehler, 2008). A growing body of research seeking to explain variation in bicycle use between smaller administrative zones (see the Literature Review section).

The decision to focus at the sub-national scale was not driven solely by lack of evidence at the local level. There are important social, cultural and spatial-economic differences between nation states, meaning that what works in one country may not always work in another. In addition, we argue that explaining national-level variation is a higher priority from the perspective of local transport planners - those who implement the details of strategic plans and decide precisely how investment in cycling is spent.

The conditions associated with growth in cycling is a policy relevant area of knowledge about which more evidence is needed (Fraser and Lock, 2011). A central motivation of this paper is to provide information to help fill this 'knowledge gap'. The aim is to inform the policy making process by supplying evidence about which important factors are within the scope of local transport planners to influence. (For example, if topography and weather are found to completely explain growth in cycling, there is little transport planners can do compared with if provision of cycle paths is found to explain much of the change.) Within this question, the following hypotheses were generated, based on the literature on the spatial distribution of cycling (see section x). The expectations were, certeris parabis (all things being equal), that:

- Areas with high incomes would see disproportional increases in cycle commuting.
- Length of cycle paths (a proxy for investment in cycling) will be associate with higher than expected growth rates in cycling.
- A good safety record on cycling (relative to the number of bicycle commuters) will be associated with high growth rates.

- Areas that had received central government support for cycling, through the Cycling Demonstration Towns initiative, would see growth in cycle commuting.

The benefits of cycling

Unlike some other types of environmental intervention, there are no major downsides to bicycle uptake: cyclists (often unwittingly) provide many benefits to the wider system whilst simply enjoying a fast and healthy for of transport. To be specific, there is strong evidence of social, environmental and economic benefits of cycling in the following areas:

- Improved health of cyclists (Oja, 2011; Rojas-Rueda et al., 2011; Saunders et al., 2013).
- Economic benefits at the individual level, for example due to lower trip times (Borjesson and Eliasson, 2011), and reduced car use (Semlyen, 2005).
- Economic benefits for society at large via reduced public health bills (Rutter et al.,2013; Jarrett et al.,2012) and wider impacts (Cavill et al., 2008; Krizek, 2007; Saelensminde, 2004).
- Environmental benefits including lower greenhouse gas emissions and demand for roads and motor vehicles (Lenzen, 1999; Lindsay and Macmillan, 2011; Lovelace et al., 2011).
- Reduction in congestion during rush hour - this is a particular benefit of cycle commuting (as opposed to leisure cycling) via improved traffic flow (Arnott et al., 2005; Downs, 2004).
- Bicycles pose a lower risk to other road users than do cars, with benefits for social equality (Jacobsen et al., 2009; Furness, 2010).
- 'Wide boundary' impacts including heightened sociability of public space and the hope that society may one day be able to operate without burning valuable finite resources (Furness, 2010; Komanoff, 2004; Sustrans, 2012).

Pro-cycling policies: a UK perspective

Due in part to these benefits, there has been a noticeable increase in political commitment to cycling in many countries, as exemplified by rapid growth in public investment in bicycle share schemes (Fishman et al., 2013). In the UK, for example, Prime Minister David Cameron announced that "we want to see cycling soar" (Prime Minister's Office, 2013) as well as providing a more specific statement of intent: "This government wants to make it easier and safer for people who already cycle as well as encouraging far more people to take it up" (ibid).

Within this context of widespread political and academic support of policies to promote modal shift to cycling, a major barrier is specific evidence on the effectiveness of different interventions. Clearly, the number of new cyclists resulting from a new bicycle path or policy cannot precisely be known. However, using an analogy from medicine, 'dose-response' type studies can greatly help predict the impact of planned interventions (Pucher et al.,2010). Transport planning is a long-term process with even longer-term impacts and such evidence can aid the strategic decision making process (Schweizer and Rupi, 2014) With limited public funds, it is critical to maximise the cost-effectiveness ratio of cycle-related expenditure.

More numerous and rigorous studies could therefore help increase the rate of cycling in many areas, assuming that funding and political will are abundant. The purpose of this paper is to help fill this knowledge gap by analysing the change in bicycle commuting across administrative zones across the UK. A geographically weighted regression methodology will be used to estimate how effective different types of intervention - including investment from the Cycling Demonstration Towns (CDT) initiative (see Gross et al., 2009) and an estimate of the quality of the cycle network - have been.

Literature review: the spatial distribution of cycling

A systematic review of the impact of various policy relevant factors on cycling was undertaken by Fraser and Lock (2011). This paper condensed the literature on the subject down to 21 papers. Of these, 11 found statistically significant relationships between environmental factors and the *rate* of cycling (not growth in cycling, as reported in this study). Cycle paths, land use, distance of trip and the presence of green space were the only factors found to be significantly correlated with cycle use in more than one study, leading to the conclusion that more studies are needed to explore the impacts of different policies and environmental conditions on cycling uptake (Fraser and Lock, 2011). This paper fits into this call for evidence, with an *ecological* (administrative zones are the unit of analysis) appraisal of the impact of different variables in change in cycling to work, based on Census data.

The Census travel to work statistics have been used in many studies to investigate the spatial distribution of travel patterns overall (e.g. Titherage and Hall, 2006). However, the number of studies focussed on active travel, and cycling in particular, is much lower. Goodman (2013) provides a detailed and up-to-date account of the spatial distribution of walking and cycling at the national level across England and Wales and describes how it has changed between 2001 and 2011.

The overall rate of walking and cycling to work was found to have changed little, but important regional differences were identified: at the regional and local authority level cycling growth was largely concentrated in high density urban centres, notably London and Bristol. The paper also provided new insight into the shifting social distribution of travel to work mode: affluence is associated with motorised modes, although this association is weakening. Walking and cycling was found to have grown most in the least deprived areas, with car use tending to fall in the wealthiest areas (Goodman 2013). The underlying reasons for these shifts was not explored: "Future analyses could also explore associations with geographic factors such as hilliness, climate and land use patterns; although outside the scope of this paper, these may play a key role in explaining local and regional variation" (Goodman, 2013, p.9). The present paper follows this suggestion by exploring the factors associated with growth in bicycle commuting.

Multivariate regression models have been used to help explain the spatially uneven distribution of the proportion of commutes made by bicycle. Parkin et al. (2008) used a logistic regression model to identify the most important factors related to cycling at the ward level in England and Wales. 81% of the variability in the proportion of commuters cycling to work could be explained by the model. The proportion of white male commuters (positive), number of cars per household (negative) and income deprivation (negative) were found to be powerful socio-economic explanatory variables. Interestingly, hilliness was found to have a negative impact on cycle commuting in the model. Road traffic (via the proxy 'transport demand intensity') was negatively related to cycling to work whereas the proportion of off-road routes had a positive impact. These latter findings indicating transport infrastructure is an important policy area for encouraging cycling.

Another useful output from this paper was the estimation of a 'saturation point', referred to as 'carrying capacity' in population ecology (Lovelace et al., 2011), a theoretical upper limit on the proportion of people cycling to work in any particular area. This was calculated to be 43% of trips, higher than any wards in the UK, but comparable with the proportion cycling to work in some Dutch areas (Parkin et al.,2011)

Data

British Census data on commuting provided the dependent variable for this paper. The Census was chosen because it has the greatest spatial resolution of transport data in the UK and the highest response rate and number of participants of any national survey, due to the legal requirement to complete it. Downsides for transport researchers include its inclusion of only one reason for trip (commuting) and poor temporal resolution, although these problems can to some extent be overcome by integrating census data alongside more detail surveys. Recent work suggests that the modal split for commuting is highly correlated with modal split for all trips (r > 0.9 for private modes and public transport, dropping to r = 0.77 for cycling), indicating that commuting may be a reasonable proxy for travel behaviour overall (Goodman2013). In addition, the annual publication of results from the National Travel Survey provide higher temporal resolution to complement the 10 year cycle of the census.

The input data for the independent variable were tables of commuter mode share by administrative zone between the 2001 and 2011 Census. England was used instead of the wider area of Great Britain because the compatibility issues associated with comparing spatial units is made more complex with the addition of Wales and Scotland. In the case of Scotland, travel to work data are not available on the data dissemination portal Casweb. An additional reason for excluding Scotland and Wales from the analysis is that they have different travel to work characteristics than England, with much lower population densities and generally levels of isolaiton and car reliance (Gray et al., 2001; Nutley, 1980).

A data problem that had to be overcome early in the analysis was the conversion of 2001 354 Local and Unitary Authorities (combined with the 'merge' function in QGIS) into 2011 local authority areas (LAs), composed of English Districts, Unitary Authorities and London Boroughs. As shown in Fig. x, there are 8 2011 LAs which encapsulate many (38) 2001 administrative zones. The result of this process of spatial aggregation was all 324 'lower tier' 2011 LAs, for which the travel to work data was directly comparable between 2001 and 2011.

The other scales of analysis used in this study were Medium Super Output Areas and Lower Super Output Areas (MSOAs and LSOAs with average working populations of x and y people, respectively). Output Areas are the smallest administrative units in the UK, which contain on average around 100 households. These were not used as the units for analysis because their small size makes it impractical to extract geographic information all of them across England. In addition small values in OA data are "randomly adjusted" in the Census tables for low counts (see, for example, http://www.nomisweb.co.uk/livelinks/4652.xls).

The data pre-processing for these areas was simpler as there has been less change between 2001 and 2011 for Output Areas than other types of administrative geography. Of the 6,781 2001 MSOAs, 98% (6,640) are unchanged in the 2011 dataset. The remaining 141 zones are contiguous with the more numerous (n = 6791) 2011 zones (fig. 1). Because many of 2001 MSOAs were split-up into small 2011 zones, the solution was not as simple as allocating the misfits to the nearest 2011 zones. Instead, we took advantage of the unchanging geometry of the OA zones and calculated incomplete records by aggregating 2001 data from OA-zones in each incomplete 2011 zone.

The explanatory variables used in the baseline model to test the hypotheses listed in section 1 were:

- *Avinc*, the mean average income for households in each area, downloaded at the MSOA level from the official data repository data.gov.uk.

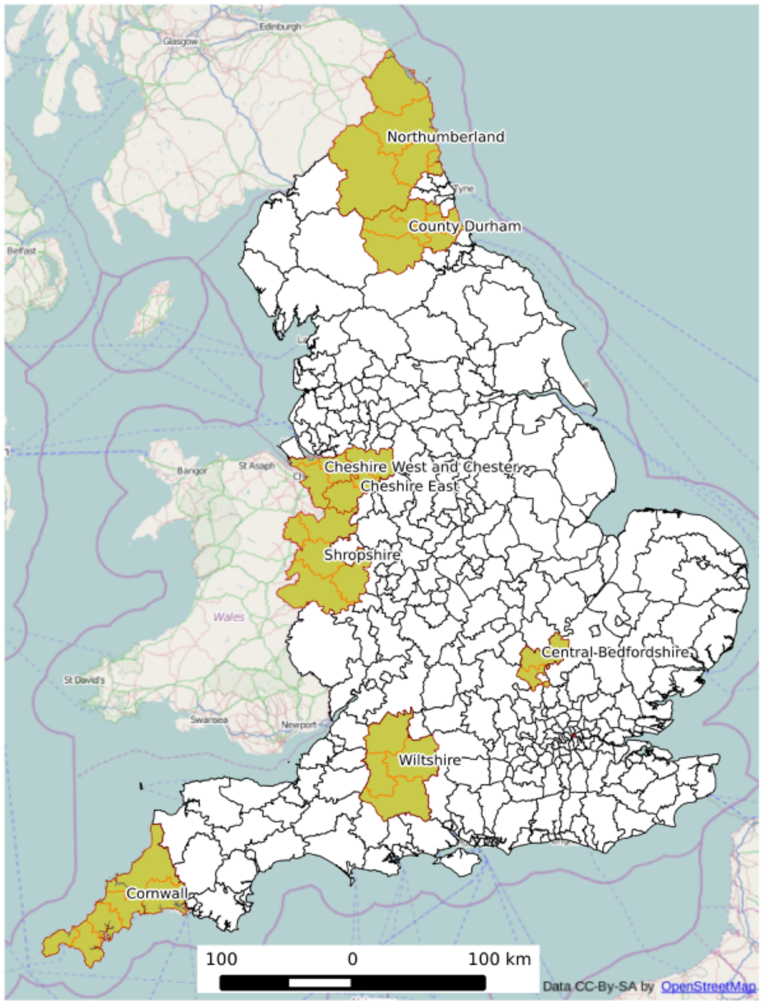

Figure 1: Map illustrating the mismatches between 2011 Local Authorities and 2001 Unitary Authorities and Districts

- *Lpath*, the of high quality cycle paths within each area. This dataset was provided in a series of MySQL databases by CycleStreets.net and processes in R.
- *Bcrash*, a proxy on the safety record on cycling in each area defined as a severity-weighted count of the number of cycle-related road traffic incidents reported in the STATS19 database from the beginning of 2005 until the end of 2012.
- *CDT*, a crude proxy of investment in cycling in each zone, defined as a binary variable: 0 for areas outside the scope of the CDT project and 1 for areas that did receive funding.

The range and distribution of these variables is displayed graphically and numerically in fig. 2. This *plot matrix* shows the relationship between each of the input variables in the model. Of note is the strong positive correlation between *Bcrash* and $\Delta pCycle$ ($Q\ pCycle$ is not shown for space reasons, but *Bcrash* had a similarly strong negative correlation with this variable, of 0.31).

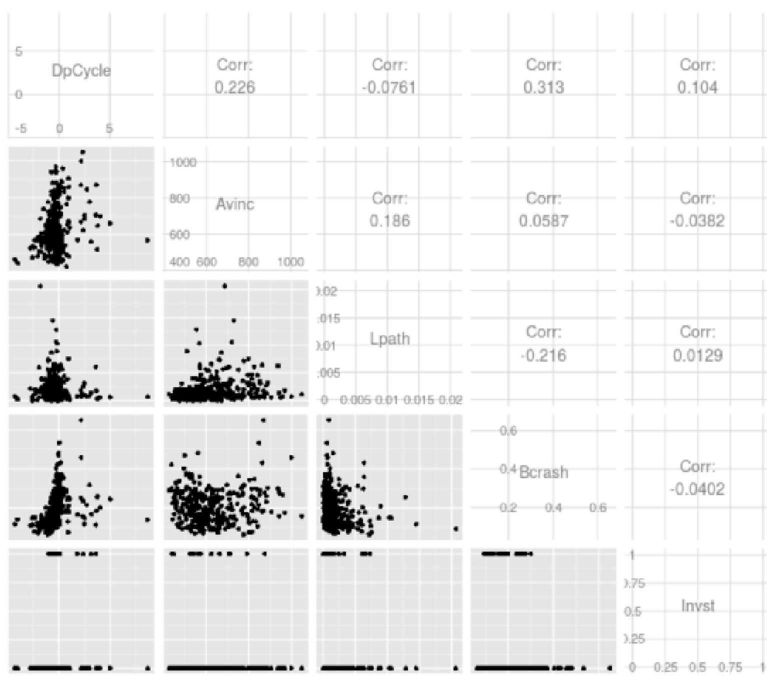

Figure 2: Scatter plot matrix showing distributions and relationships between the variables of the baseline model

Additional variables

In addition to these baseline input datasets, a number of other variables were tested to investigate the relationship between other variables and cycling to work. These were, in order that they were tested:

- The proportion of trips made by car in 2001 ($pCar$)
- The change in the proportion of young (18 - 39), white males in each area, 2001 to 2011 ($\Delta pYWM$), following Parkin et al. (2008) who found this to be an important explanatory variable.
- The number of cars per household in 2001 ($carOwn$) and change in car ownership ($\Delta carOwn$)

Method

In line with the principle of parsimony, the modelling approach was to start simple by reporting key statistics about changes in cycle commuting in England before progressing to a regression model.

The proportion of people cycling to work (*pCycle*) was calculated as the total number of bicycle commuters (*Cycle*) divided the number of people commuting by all modes (*Commute*) for each area (a). At the national level, this can be represented as the population-weighted sum of *pCycle* for all areas:

$$PCycle = \sum_{a=1}^{n} \frac{Commute_a}{\sum_{a=1}^{n} Commute_a} \frac{Cycle_a}{Commute_a}$$

where $PCycle$ is the proportion cycling overall. This is expressed more concisely as the total number of cyclists divided by the total number of commuters ($PCycle = Cycle/Commute$). However, the above equation is useful in demonstrating how a single national value can mask substantial regional variation and highlights the importance of a zone's total population: while the *average* value of *pCycle* dropped from 3.3 to 3.1% across English LAs from 2001 to 2011, *PCycle* remained constant. In other words cycling grew in the (urban) LAs with higher than average populations.

The categories of "unemployed" and "work from home" were deliberately excluded from the *Commut* count, to prevent changes in employment structure influencing the result: if a commuter belt shifted away from car driving towards 'teleworking' (working from home), for example, this method could provide an unfairly optimistic impression of the uptake of cycling.

The dependent variable, *change* in the proportion of people cycling to work, can be defined in two ways. First, the *absolute difference* in the percentage of people cycling to work ($\Delta pCycle$) was calculated by subtracting the 2011 results from the 2001 results. Second, *relative change* (*QpCycle*) was defined as proportion of people cycling in 2011 divided by the rate in 2001.

A linear regression model was used to test the impact of the explanatory variables on model fit, and to elucidate the direction of influence. Following the principle of parsimony in model design, a simple model based on the hypotheses presented in the introduction was developed first. Against this baseline the performance of different model runs was compared. To this end the following alterations were made:

- Changes to the number and type of explanatory variables used.
- Subsetting the observations used for the model (e.g. to exclude London)
- Altering the dependent variable itself to explore the relationship between absolute and relative increases in cycling.

Results

The rate of cycling between 2001 and 2011 census was found to have changed very little, being 3.1% in both cases. However, there was substantial variation between the zones in terms of change in cycling. There is a strong positive skew in the distribution the growth rate (fig. 3): less than a quarter (74) of LAs saw the modal share of cycling rise, by an average of 30% whereas the majority of LAs (250) saw small declines in the proportion of people cycling.

In terms of absolute growth, the distribution is more symmetrical, with the vast majority of zones (264 zones, 81%) seeing less than a 1% change either way in absolute proportion of people cycling to work. These results are plotted geographically in fig. 4.

It is interesting to note that the average cycling rate in 2001 was lower for zones where cycling dropped (3.3 %) compared with zones where cycling grew (3.7%). Indeed, the variability in the proportional of people cycling grew between 2001 and 2011, despite the mean remaining the same: the standard deviation increased from 2.5 percentage points in 2001 to 2.7 in 2011. At the MSOA level the standard deviation of the percentage of people cycling to work also grew noticeably, from 2.7 to 2.9.

Far from cycling becoming more accessible to everyone everywhere, these results provide some geographical evidence for a divergence between the cycling 'haves' and 'have nots'. Spatial inequality in cycling as a mode of travel to work in recent years in England, supporting the hypothesis of positive feedback loops in modal shift to cycling through 'strength in numbers' and the normalisation of cycling culture (borjesson2012benefits, goetzke2011bicycle).

The regional distribution of growth in cycling, with its focus on London, is also evident from fig 5, which shows the expected high correlation between the

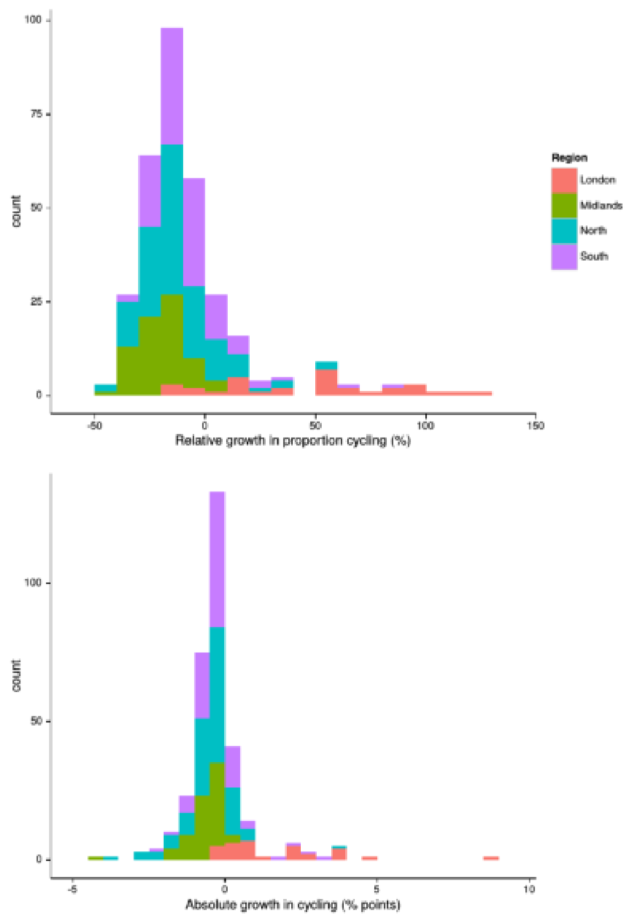

Figure 3: Histograms of the distribution in the growth in cycling in absolute (above) and relative (below) terms

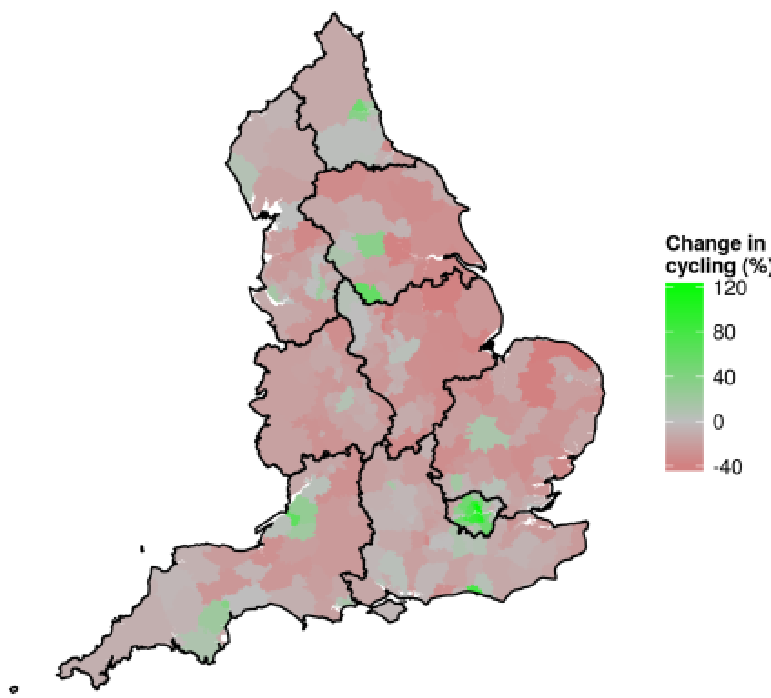

Figure 4: Change in proportion of cycle commuters in England, 2001 to 2011

percent cycling to work in 2001 and 2011 (r-squared = 0.82). The $x = y$ line in fig x represents the 'break even' point above which cycling has grown and below which it has dropped. Thus, there are 74 points above the line and the rest fall below. The further points are located from this break even line the more cycling has changed in that area. The colours illustrate that many of the zones with the greatest growth in cycling are located within the Greater London Authority.

The regional pattern represented by the colours in fig. 5 is emphasised in Table 1, which shows that outside London there were falls in the proportion of people cycling to work, with the greatest declines in the Midlands and the North: the average LA in the Midlands saw the proportion of people cycling to work drop by a fifth.

Table 1: regional differences in the change in cycling as a commuter mode in England, 2001 to 2011.

Region	Relative change	Absolute change
London	47.4	1.6
Midlands	-19.7	-0.7
North	-12.3	-0.5
South	-7.8	-0.2

Because of this apparent "London exceptionalism", the analysis was re-run with London removed. It was found that outside London, the proportion of all people cycling to work dropped substantially, from 3.2% in 2001 to 2.9% in 2011. *The average LA outside London saw a 12% drop in the proportion of people cycling.* These results suggest that attempts to 'get Britain cycling' have so far failed outside of the capital, which has seen the country's only large 'congestion charge' scheme encourage active travel (nakamura2014economic).

Some urban areas outside London broke the trend, seeing cycling as a mode of travel to work grow, yet only in 12 zones did the cycling to work increase by more than half a percentage point. (These were, in descending order of growth rate, were Cambridge, Bristol, Oxford, Brighton, Exeter, Newcastle, South Cambridgeshire, South Gloucestershire, Manchester, Sheffield and Bournemouth.) Of these, only 5 had growth rates above 1 percent. In the name of balance, it was decided to focus equally on the areas where cycling has fallen greatly: there is a tendency towards picking 'best case' studies in the cycling literature. This can be seen as analogous to the disproportionate non-publication of medical trials that have negative results: it is important to focus on 'failures' as well as 'success stories' to provide impartial evidence to policy makers (Jones et al., 2013).

Table 2 presents the growth in cycling in the top 5 and bottom 5 areas in terms of absolute shift in the proportion of people cycling to work. It is noticeable that

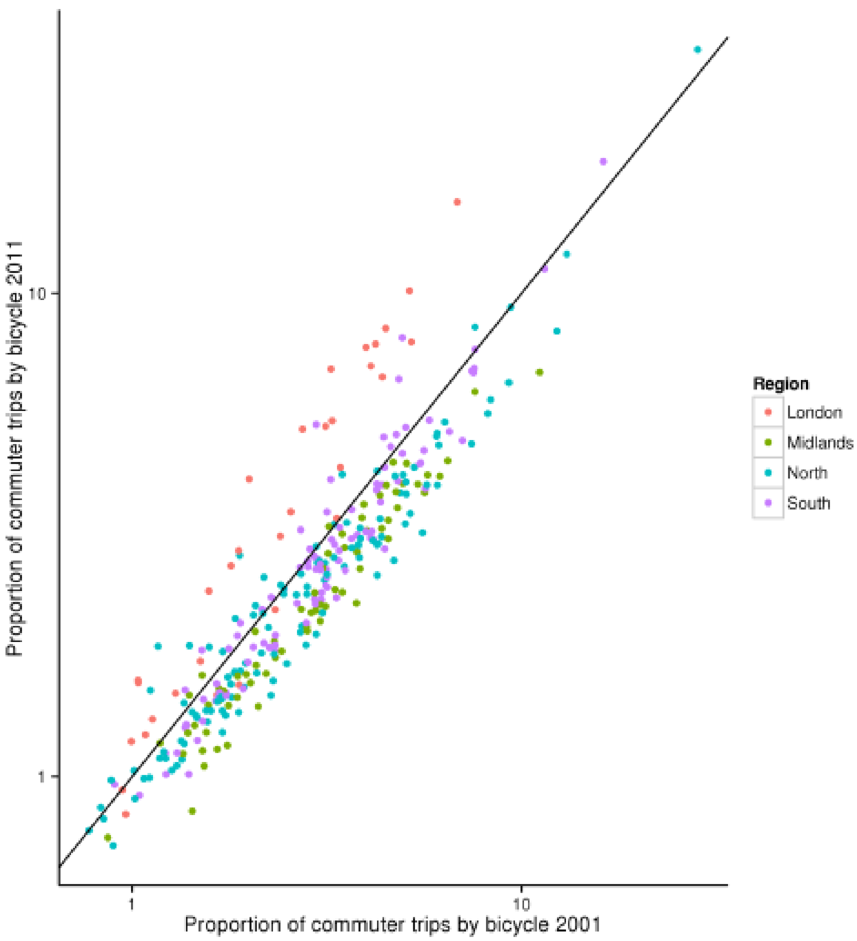

Figure 5: Scatterplot of the proportion of commuters who report using a bicycle as their main means of travel to work in 2001 (x axis) and 2011 (y axis). Colours correspond to English regions.

while 4 of the top 5 received central government funding between 2001 and 2011 from the CDT initiative, none of the bottom 5 did. (Oxford is conspicuously missing from the list of CDT beneficiaries, and some cycle campaigners have accused the local council of failing to properly maintain the city's existing cycle infrastructure (Horne, 2008).) This suggests that, in addition to investment helping to increase the rate of cycling, it can also serve to maintain it and prevent declines in areas that have an already high rate of cycling.

Table 2: Statistics on cycle commuting from the top 5 and bottom 5 local authorities in England in terms of the absolute change in the proportion of commuters cycling to work. Note

Local Authority	pCycle 2001	pCycle 2011	Abs. growth ($\Delta pCycle$)	Rel. growth ($QpCycle$)	C
Cambridge	28.3	31.9	3.6	12.7	2
Bristol, City of	4.9	8.1	3.1	63.7	2
Oxford	16.2	18.7	2.5	15.5	N
Brighton and Hove	3.0	5.3	2.4	80.1	2
Exeter	4.8	6.6	1.8	37.3	2
:———————-	———:	——-:	———:	——-:	:
Boston	11.1	6.9	-4.3	-38.4	N
Hull	12.3	8.3	-4.0	-32.2	N
Waveney	9.3	6.5	-2.7	-29.6	N
Fenland	7.4	4.9	-2.6	-34.4	N
North East Lincolnshire	8.2	5.6	-2.6	-31.2	N

Regression model results

The baseline model was able to explain 16% of the variation in $\Delta pCycle$ and 14% of the variability in $QpCycle$ across all zones, with adjusted R-squared (aR^2) values of 0.16 and 0.14 respectively. This is a statistically significant by not particularly impressive result. In addition, the most significant variable, $Bcrash$, had the opposite sign as expected, indicating that cycling may have become proportionally riskier in places where cycling has grown the most (see Table 3). Indeed, the correlation between $Bcrash$ and $\Delta pCycle$ was strongly positive (r = 0.31).

We can speculate why this may be - perhaps car drivers in growth areas were relatively unused to high cyclist volumes or perhaps accident rates are higher amongst new cyclists. Yet correlation does not prove causality and the number of cycle commuters is a poor indication of *exposure*, meaning that the results do not show with any certainty that cycling really did tend to become less safe in areas where cycling grew. It is implausible to assume that growth in cycling was *caused* by the increase in *Bcrash* (although the reverse may be true), so this variable was removed from subsequent model runs.

Avinc and *CDT* had a statistically significant ($p < 5\%$) impact on $\Delta pCycle$ in the baseline model in the direction expected. *Avinc* had a strong positive correlation with $\Delta pCycle$ ($r = 0.22$) and *QpCycle* ($r = 0.21$). Despite there being only 17 CTD projects (their impact spread across 19 LAs), the impact on the model was statistically significant: CDT funding increased the proportion of people cycling in an LA by on average 0.6 % points in the baseline model. To explain a greater proportion of the variability in change in cycling to work, the additional variables were added in place of *Bcrash*.

Table 3: Results from the baseline model.

Variable	Estimate	Std. Error	t value	P
(Intercept)	-2.32	0.33	-7.1	0.00
Avinc	0.00	0.00	4.3	0.00
Lpath	-28.08	26.88	-1.0	0.29
Bcrash	3.91	0.71	5.5	0.00
CDT	0.61	0.25	2.4	0.02

Additional variables

Adding more variables improved the model fit. With *Bcrash* removed, the additional variables mentioned in the Data section were tested one by one. The variable that had by far the greatest impact on the model was the proportion of trips made by car drivers in 2001. Replacing *Bcrash* with *pCar* in the baseline model meant that half of the variation in $\Delta pCycle$ could be explained, rising to 2/3 when *QpCycle* was predicted (aR^2 0.50 and 0.66, respectively).

Replacing $pCar$ with $\Delta pYWM$ led to a poorer model fit, although the variable had a statistically significant impact on the model at the 5% level in the expected positive direction as a predictor of *QpCycle*. $\Delta carOwn$ also had a minimal effect on the model at this stage.

Removing London

As can be seen in fig. 5, LAs within London had anomalously high growth rates, some of which can be explained by factors exclusive to the capital such as the congestion charge, slow traffic speeds and an influx of young, mobile workers. A strong case can thus be made for treating London separately. When London was removed, this had a large impact on the baseline model: the p value of CDT fell dramatically, from 0.02 in the baseline model to less than 1 in 100,000 with London excluded. In addition the slope of the estimated impact of CDT funding increased to 0.8% points.

With London removed, the influence of $\Delta pCar$ dropped substantially although it was still highly statistically significant in the expected direction. The impacts of the other additional variables were statistically insignificant.

The final model

Following the principle of parsimony, the simplest solution that explained a high proportion of variability in cycling to work was chosen. This was found to be the following equation:

$$QpCycle \sim Avinc + pCar + CDT$$

Across all Local Authorities, this model accounts for 2/3 of the change in cycling. However, the final model results presented in Table 4 exclude London LAs which were deemed to be anomalous. This final model explains roughly 1/3 of the change in the rate of cycling ($aR^2 = 0.27$) based on only 3 variables, all of which are significant at the 5% level. As before, $pCar$ was the most powerful explanatory factor.

Table 4: Results from the final model

Variable	Estimate	Std. Error	t value	P
(Intercept)	55.825	8.783	6.356	0.000
Avinc	0.032	0.008	4.178	0.000
pCar	-134.211	14.078	-9.534	0.000
CDT	6.803	3.424	1.987	0.048

Discussion

The analysis presented in this paper sheds some new light onto the spatial distribution of change in cycle commuting across England. Furthermore, the results provide an empirical basis for discussion of how best to make cycling grow in the future. The results show that changes in cycle commuting have not happened randomly across space over the course of the last 10 years or so: clear patterns can be seen from the maps and graphs of cycling change and these have implications for policy makers tasked with making cycling soar.

The first point of discussion should be that cycling for personal transport, like many other geographic variables related to health and the economy (Dorling, 2011), has become more unequal over space in the last 10 years: most of the growth in cycle commuting has happened in London. Excluding London from the analysis, cycle commuting has declined overall from 3.2 to 2.9% of trips. Within this aggregate figure, a few areas have seen very impressive rates of growth in cycling and a number of these received central government funding through the Cyclind Development Towns project. Yet the trend for a typical English LA outside London has been decline: the median value of pCycle dropped by 0.4% points from 2.9 to 2.5%, a worrying trend about which academics and cycle campaigners are either unaware or tend to gloss over.

That is not to downplay the success stories, but it does raise the question: why did cycle commuting in some areas grow against a backdrop of decline? The paper has been able to provide some answers here: areas with high incomes, historically low rates of car use and government support have tended to do well. Of course, this does not prove cause and effect: it is plausible to suggest that areas received cycle funding precisely because they were seen as success stories.

Let us return to the four hypotheses posed in the introduction. We have provided statistically significant evidence that the health and other benefits of cycling are disproportionately being enjoyed in high income areas, where much of the growth has occurred. We have found no significant evidence of safe roads or bicycle path provision leading to increased uptake of cycling, although more research is needed in both areas and the study has by no means disproved a link. The findings support previous calls for more rigorous studies exploring the impact of different environments and policies on active travel (Fraser and Lock, 2011). Specifically, there is a need for a database on public expenditure on cycling and an up-to-date database on cycle paths and other pro-cycling features. Only with official high quality databases (or improvements in Open Street Map) will we able to compare the impacts of different interventions.

There are a number of limitations to the study. Using areal units to explain any issue that is ultimately played out at the individual level risks committing the 'ecological fallacy': falsely inferring things about individuals based on aggregated data (Openshaw, 1983). To avoid this problem we have been careful to state that the findings apply only to areas and not necessarily to the citizens who occupy them. We cannot know from the results, for example, that individuals on high incomes are tending to cycle more, just that the number of people reporting cycling to work in areas with high average incomes has grown. There is, however, verbal evidence of the importance of class and cultural identity in the context of cycling growth in wealthy areas (Aldred and Jungnickel, 2014), with which our results coincide.

The research presented in this paper also raises important questions about data quality. From a health perspective, the number of people who use bicycles as their *main* form of transport to work is far less important than the number of people who cycle once or twice per week. The marginal benefit of exercise decreases after a few hours of moderate exertion per week and a roughly typical cycle commute of 3 miles each way could easily reach this amount. More important from a health perspective (and potentially from an environmental perspective) is the number of people who *sometimes* cycle to work, once or twice per week, but not always. Because cycling is often a 'plan B' mode to be used occasionally, the potential impact of under-reporting of trips is large. Conversely, there may be many people who entered cycling as their primary mode of transport to work as 'aspirational cyclists' who cycle occasionally but would like to think that they always do. These questions of data quality require further analysis and the National Travel Survey could provide a useful empirical starting point for future research into this area.

In terms of monitoring the geographical distribution of a shift to cycling, a more suitable independent variable would be the total number of trips taken by residents of each area per year. Even more specifically, estimates of the total distance cycled in each area, and the social distribution of this cycling activity across society as a whole would be preferable. Indeed, if cycling is concentrated amongst healthy men, it is realising only a fraction of the potential health benefits.

Conclusion

This study provides new evidence about the relationships between a range of geographic factors and change in the proportion of people cycling to work across England. Regression analysis at the level of Local Authorities was used to test the hypothesis that wealth, road safety, cycle infrastructure and public investment are associated with growth in cycling. Of these hypotheses statistically significant results were obtained supporting the positive impact of the first two factors. The paper provides statistical evidence to support the idea that high income groups are cycling more which supports the wider 'peak car' narrative (Goodwin and Van Dender, 2013).

Perhaps more relevant for local policy makers is the finding that cycling grew significantly *more* in areas that received central government funding in the form of CDT status. Correlation does not prove causality, but the results certainly support additional tranches of central government funding for cycling.

The study uses *change* in the rate of cycling to work over 10 years as the dependent variable, thereby providing policy relevant insight into the factors that may be able to increase the rate of cycling in future years. This differs from the majority of geographical studies on the subject, which have sought to explain the rate of cycling at one specific point in time (e.g. Parkin et al., 2008). These studies have tended to focus on variables that are either inherent to the natural environment (e.g. topology, weather) or which are not easy to alter through policy interventions (e.g. average distance of trips) (Fraser and Lock, 2011). This paper, by contrast, deliberately focussed on factors over which policy makers have some control or ability to target: bicycle paths, investment in cycling, the spatial distribution of average incomes.

Amongst these factors, average income was found to be most strongly associated with cycling, providing further evidence that growth in cycling has been driven in recent years primarily by the wealthy (Goodman, 2013). This coincides with evidence from the 'peak car' literature that high income groups are tending to drive less each year (Metz 2013). Of course, the average income of people in different areas is a factor outside the control of most policy makers (although they may wish otherwise). Yet the finding is important in terms of policy design as it provides additional evidence that more needs to be done to promote cycling amongst the most disadvantaged in society (Christie, 2011). The study provides strong support to a conclusion derived from qualitative analysis that "care needs to be taken to also develop interventions in lower-income areas" (Aldred and Jungnickel, 2014).

An unexpected finding that merits further analysis was the strong negative relationship between people driving to work in 2001 and growth in cycling. We can speculate that the result may be linked to confounding factors such as average distances between home and work locations. The strength of the correlation provides some evidence that cars and bicycles can be seen in ecological terms as 'species' in direct competition (Lovelace et al.,2011). The policy implication of this finding is that in some cases the best way to promote active travel from a health perspective may be to implement policies discouraging car use (Jacobsen et al., 2009).

There are limitations to study inherent to the methodology and use of administrative zones as the unit of analysis. The focus on reported cycling to work as the dependent variable is problematic because cycling to work is not an either/or decision but something that can vary widely, from every day to a few times per month (Stinson and Bhat, 2004). Such subtleties are simply not collected in the Census: there is a trade-off between geographic resolution and coverage from census data and depth and insight from individual-level surveys. The paper therefore advocates further studies that seek to integrate detailed survey datasets with information from the Census, for example by comparing correlations between Census and individual level variables (Goodman, 2013) or more complex techniques such as spatial microsimulation (Lovelace et al.,2014).

It is clear that more research is needed in the rapidly evolving global debate about how best to promote cycling. Returning to the mounting evidence to society mentioned in the introduction, we can also say that we have a mounting body of evidence on how best to deal with these threats. Policies to promote cycling represent one small option amongst many, but their relative simplicity and low cost make them ideally suited to an economic context of risk aversion and austerity. Pro bicycle interventions are also exceptional in the wide range of interrelated problems they tackle, often as an unintentional 'co-benefit' to an efficient and enjoyable urban transport system. There is a limited time horizon in which to invest still abundant physical and human energy into a sustainable future, so the pro-cycling policies should continue to be pursued with urgency. It is hoped that the evidence provided in this paper will help ensure that such policies are implemented with swiftness, but not haste.

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