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Effectiveness and equity impacts of town-wide cycling initiatives in England: A longitudinal, controlled natural experimental study☆

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ABSTRACT

Cycling confers health and environmental benefits, but few robust studies have evaluated large-scale programmes to promote cycling. In England, recent years have seen substantial, town-wide cycling initiatives in six Cycling Demonstration Towns (funded 2005–2011) and 12 Cycling Cities and Towns (funded 2008–2011). The initiatives involved mixtures of capital investment (e.g. cycle lanes) and revenue investment (e.g. cycle training), tailored to each town. This controlled before-after natural experimental study used English census data to examine impacts on the prevalence of travelling to work by bicycle and other modes, comparing changes in the intervention towns with changes in three comparison groups (matched towns, unfunded towns and a national comparison group). We also compared effects between more and less deprived areas, and used random-effects meta-analysis to compare intervention effects between towns. Among 1.3 million commuters in 18 intervention towns, we found that the prevalence of cycling to work rose from 5.8% in 2001 to 6.8% in 2011. This represented a significant increase relative to all three comparison groups (e.g. +0.69 (95% CI 0.60,0.77) percentage points for intervention vs. matched towns). Walking to work also increased significantly compared with comparison towns, while driving to work decreased and public transport use was unchanged. These effects were observed across all fifths of area deprivation, with larger relative changes in deprived areas. There was substantial variation in effect sizes between towns, however, and the average town-level effect on cycling was non-significant (+0.29 (−0.26,0.84) percentage points for intervention vs. matched towns). We conclude that to date, cycling to work has increased (and driving to work decreased) in the intervention towns, in a relatively equitable manner. The variation in effects between towns indicates uncertainty regarding the likely impact of comparable investment in future towns. Nevertheless these results support the case for implementing and evaluating further town-wide cycling initiatives.

Introduction

Increasing levels of cycling is expected to increase overall physical activity (Sahlqvist, Goodman, Cooper, & Ogilvie, 2013) and improve individual and population health (Garrard, Rissel, & Bauman, 2012; Haines et al., 2009; de Hartog, Boogaard, Nijland, & Hoek, 2010; Rojas-Rueda, de Nazelle, Tainio, & Nieuwenhuijsen, 2011). Cycling for transport also has considerable potential to displace journeys by motor vehicles (Goodman, Brand, & Ogilvie, 2012; Sustrans, 2005; Transport for London, 2010), which may confer health, environmental benefits and economic benefits (Kahn Ribeiro et al., 2007; Rabl & de Nazelle, 2012; Woodcock et al., 2009). Yet although it is well recognised that community-level approaches may be needed to achieve enduring increases in cycling and other forms of physical activity (Giles-Corti et al., 2013; McCormack & Shiell, 2011), a recent systematic review found few robust evaluations of community-wide cycling initiatives (Yang, Sahlqvist, McMinn, Griffin, & Ogilvie, 2010). Those studies that do exist support the potential effectiveness of intensive, town-wide interventions. Specifically, all three such studies in the review (from Denmark, England and the Netherlands) reported increases in cycling two or three years after fairly substantial infrastructure improvements, including building or resurfacing segregated bicycle paths, creating other new infrastructure (e.g. cycle bridges), and

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installing new cycle parking (Sloman, Cavill, Cope, Muller, & Kennedy, 2009; Troelsen, Jensen, & Andersen, 2004; Wilmink & Hartman, 1987). In the Danish and English studies, these were complemented by a range of other measures such as widespread publicity campaigns, personalised travel planning, cycle training and bicycle loan schemes. Similarly, a subsequent American study reported that cycling increased following the introduction of over 50 km of on- and off-street urban cycle paths across the city (Krizek, Barnes, & Thompson, 2009).

In England, the past decade has seen a series of large-scale programmes seeking to increase cycling in 18 towns. A previous survey-based evaluation reported that the prevalence of 'cycling for at least 30 min at least once a month' increased by 1.9% between 2006 and 2009 in the first six intervention areas relative to matched comparison areas (Sloman et al., 2009). This study was, however, limited in having a response rates of only 20–25% (MORI, 2007, 2011), increasing the potential for bias. In addition, although this study reported an apparently similar increase in cycling across all social classes, it may have been underpowered to allow robust subgroup analysis (Sloman et al., 2009). Finally, this study was limited to the first six intervention towns.

We therefore evaluated all 18 town-wide cycling initiatives with a large and representative dataset derived from the English census. Our primary aim was to examine whether the prevalence of cycling to work increased in intervention towns relative to matched comparison towns. Our secondary aims were to examine: (1) changes in the prevalence of walking, driving or using public transport to travel to work; (2) whether effects differed by levels of small-area deprivation; and (3) whether intervention effects differed between towns.

Methods

Intervention: 'Cycling Demonstration Towns' and 'Cycling Cities and Towns'

The intervention comprised a programme of town-level initiatives aiming to 'get more people cycling, more safely, more often'. It was implemented in urban areas of England outside London. Between October 2005 and March 2011, six Cycling Demonstration Towns (CDTs) increased their spending on cycling to £17 per person per year, through a combination of central government and matched local funding. This is much higher than the average of £1 per person per year for England as a whole, and is comparable to many high-cycling European cities (Sloman et al., 2009). Between April 2008 and March 2011, a further 12 Cycling Cities and Towns (CCTs) increased their spending up to an average of £14 per person per year (personal communication from the Department for Transport). These 17 towns and one city (henceforth 'towns') were chosen through a competitive process whereby local authorities submitted detailed plans to the Department for Transport. They were then selected on the basis of strong leadership; a deliverable strategy that seemed likely substantially to increase cycling; and evidence of local matched funding (Sloman et al., 2009; plus personal communication from the Department for Transport). In each selected town, dedicated specialist cycling teams designed and delivered a tailored programme of interventions that aimed to deliver a marked and visible improvement in the facilities for cycling and in the profile of cycling (Box 1 and Supplementary File S1).

Box 1
Summary of the intervention programme

The 18 intervention towns were located across England (see Supplementary File S1) and varied considerably in their size, cycling infrastructure and cycling cultures. Initiatives were therefore tailored to each setting, but all towns spent a mixture of capital investment (e.g. building cycle lanes, creating cycle parking) and revenue investment (e.g. promotional activities, cycle training), with an average capital:revenue ratio of 3:1. Towns also shared an emphasis on taking a 'whole town' rather than a piecemeal approach, and tended to focus particularly on the following investment themes:

1) Cycling to workplaces: Commuter cycling was a central component of most initiatives, both through interventions at workplaces and in communities more generally. Almost all towns selected a number of workplaces with which to engage intensively, with these workplaces ranging in size from 20 to over 18,000 employees, and employing an estimated average of 2% of all commuters living in these towns (see Supplementary File S1 for numbers stratified by town). The nature of this intensive engagement varied by town and by workplace, but included supporting workplaces to become more cycle friendly by helping them develop travel plans and by providing grants for lockers, showers and cycle parking. For example, in total the towns created around 5000 new cycle parking stands at workplaces between 2008 and 2011, including secure and covered cycle parking at many workplaces. Other components involved services offered directly to employees, such as free personalised travel planning, cycling 'taster' sessions, on-site cycle repairs and training in cycle maintenance. A third category of components aimed to create a supportive social and organisational culture for cycling, for example by organising Bicycle User Groups, 'bike breakfasts' and annual workplace cycling challenges. Some of these services or activities were also offered to other workplaces engaged with at a less intensive level. Finally, many towns also sought to encourage cycling to work through wider community interventions, for example by creating cycle paths or greenways to link employment sites with residential areas.
2) Schools and colleges: All towns invested in 'Bikeability' cycle training in schools, with over 32,000 pupils receiving basic, off-road training and 46,000 receiving more advanced, on-road training between 2008 and 2011 (see Supplementary File S1). Most towns sought to improve school access and school facilities, e.g. improving some key routes and building over 10,000 new cycle parking spaces. Other initiatives included producing and distributing maps showing off-road or backstreet routes to schools, and providing dedicated 'Bike it' officers to help incorporate cycling in school travel plans. Some similar techniques were also used to promote cycling among staff and students at universities and colleges, but this was less of a focus in most towns.
3) General infrastructure improvements: This theme accounted for by far the largest fraction of total programme investment. Around 70% of investment in general infrastructure was spent on creating and managing on-road cycle lanes and off-road cycle paths. On-road facilities included contra-flow cycle lanes (allowing bicycles to travel in both directions along a street that is one-way for motor vehicles), advanced stop lines (dedicated space for bicycle at the front of a queue for traffic lights, often accompanied by feeder routes into the advanced stop space) and mandatory cycle lanes (on-road cycle lanes indicated by a solid painted line which motor vehicles are not allowed to cross). Off-road facilities included fully-segregated cycle routes

next to a road or across green space, and shared use facilities for both cyclists and pedestrians. Each town implemented a different mixture of infrastructure, tailored to its specific context. In total, 98 km of on-road lanes and 264 km of off-road paths were created between 2008 and 2011. This represented a 28% increase in the length of such routes previously available (percentage increase based on 16/18 towns reporting sufficient data on pre-intervention facilities). In addition, the 18 towns created over 250 advanced stop lines between 2008 and 2011 and installed over 27,000 new cycle parking spaces, almost doubling the number of parking spaces previously available. In 15 towns with available data, 4126 signs were installed, leading to comprehensive signage along 814 km of the cycle network. These improvements to cycle lanes and paths, cycle parking and cycle signage were the main focus for investment, but were also complemented by other measures in some settings such as dropping kerbs at crossing points and implementing some wider traffic calming techniques. A summary of the core infrastructural changes implemented by each town is presented in Supplementary File S1.

4) Cycling to stations: Many towns substantially expanded cycle parking at stations, sometimes also enhancing security by e.g. installing security cameras or electronic key access. Several towns improved cycle routes and/or access within stations (e.g. adding wheel channels to staircases). Most towns provided cycle route maps containing other transport information such as bus or rail timetables. Some towns also located 'cycling hubs' near stations, offering multiple services such as cycle hire, information, retail and repairs.

5) Targeting specific neighbourhoods or groups: Most towns targeted part of their investment at specific populations, often focussing in particular on deprived areas and/or lower socio-economic groups. Other groups targeted included, for example, 'families with children'. In targeted areas, cycling infrastructure was often improved to increase access to destinations inside and outside the neighbourhood. Individuals in targeted areas or groups were also typically offered services such as organised cycle rides, personalised travel planning, training in cycling and cycle maintenance, and opportunities to receive second-hand bicycles. These were complemented in many towns by broader, town-wide events such as cycling festivals. A summary of the core railway station, neighbourhood and town-wide initiatives implemented by each town is presented in Supplementary File S1.

(Sources: Department for Transport, 2012; Sloman et al., 2009, plus personal communication from the Department for Transport.)

Comparison towns

Programmes such as these town-level cycling initiatives represent 'natural experiments', namely events, policies or interventions not designed for research purposes but which may nevertheless provide opportunities for evaluation (Craig et al., 2012). Choosing suitable comparison groups is a key methodological challenge for natural experimental studies, and needs to be based on an understanding of the underlying allocation process. CDT/CCT status was not assigned at random, but rather was awarded to towns which (1) applied for funding and (2) best met the criteria of leadership, strategy and evidence for matched funding. Whilst it was known which towns applied for funding, no information was available regarding their appraisal against the selection criteria. We therefore could not control for these factors directly, but instead sought to make our evaluation more robust to confounding by defining multiple comparison groups with complementary strengths (Craig et al., 2012). These were: a matched comparison group (selected *a priori* as the primary comparator); an unfunded comparison group; and a non-London national comparison group (Table 1).

In each intervention and comparison urban area, we identified 2001 census output areas (average population around 300, available from http://edina.ac.uk/ukborders/). In consultation with the Department for Transport, we then used ArcMap10.0 to refine the boundaries of intervention towns in order to include all areas which benefitted from initiatives. We converted the 2001 output areas to the near-identical 2011 census output areas, and also to the former 'enumeration districts' used in the 1981 and 1991 censuses (see Supplementary File S2).

Outcomes: census data on travel to work

The primary outcome was prevalence of cycling to work, defined as the proportion of commuters who reported cycling to be their usual, main mode of travel to work. In order to examine which modes were displaced by any increases in cycling, we also included as secondary outcomes the prevalence of walking to work; of travelling to work by car, van or motorcycle as either driver or passenger (henceforth 'driving'); and of taking public transport to work.

We calculated these outcomes using the decennial English census, most recently conducted on 27th March 2011. The 2011 English census covered an estimated 96% of the population outside London (Office for National Statistics, 2012); response rates were slightly higher in previous decades (Office for National Statistics, 2011). For all individuals aged 16–74 with a current job, the census asked "How do you usually travel to work? (Tick one box only, for the longest part, by distance, of your usual journey to work)". These data are available at the small-area level (average population 300–450 people) for all participants in the 2001 and 2011 censuses and for a 10% random sample of the 1981 and 1991 censuses (available from http://www.ons.gov.uk/ons/guide-method/census/2011/index.html and http://casweb.mimas.ac.uk/). We calculated the prevalence of each of these modes as a proportion of all commuters, i.e. excluding people not in work or people working at or from home. All adults reporting that their home address was also their place of work were treated as non-commuters.

This prevalence of cycling to work has previously been shown to provide a reasonably good proxy for the proportion of *total* travel time spent cycling in a population, with the two measures showing a correlation of $r = 0.77$ across populations defined by years of data collection, by region of England and Wales, and by fifth of household income (Goodman, 2013). The same is true for private motorised travel ($r = 0.94$), public transport ($r = 0.96$) and in general for walking ($r = 0.88$ excluding London, which is anomalous because of higher public transport use).

Measure of small-area deprivation

To compare effects across socio-economic groups, we used the 2010 English Indices of Multiple Deprivation (Department for Communities and Local Government, 2011). Most of the 42 constituent variables for these Indices were collected in 2008, i.e. midway through the CDT programme and at the start of the CCT programme. Adapting an approach used elsewhere (Adams &

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Table 1
Summary of comparison groups.

Comparison group	Definition	Rationale	Key limitations
Matched comparison group	Largest urban region within the English local authority 'most similar' to each intervention local authority. The 'most similar' local authority was identified using the National Statistics '2001 Area Classification for Local Authorities', which measures the similarity of pairs of local authorities in terms of a range of demographic, socio-economic, employment and industry characteristics (National Statistics, 2011) (see Supplementary File S2). A comparable approach was used in the previous CDT evaluation (Sloman et al., 2009).	Control for demographic and socio-economic factors Separately matches each town, permitting town-specific estimates of relative and absolute effects	Confounding by factors (a) prompting application for funding and (b) leading to success in the application
Unfunded comparison group	Largest urban region within the 67 local authorities which applied unsuccessfully for CDT or CCT funding	Control for factors prompting application for funding	Confounding by factors leading to success in the application.
Non-London national comparison group	All non-intervention, urban areas outside London with a population of over 30,000 (close to the size of the smallest intervention town)	Provide national context Compare CDT/CCTs to areas with similar pre-intervention cycling	Little or no control for confounders

See Supplementary File S2 for towns in the matched comparison group; list of unfunded towns available on request.

White, 2006; Goodman, Wilkinson, Stafford, & Tonne, 2011), we excluded four indicators relating to geographical remoteness as these may represent a straightforward proxy for average commute distance (see Supplementary File S2). We then ranked all English Lower Super Output Areas from the most deprived to the most affluent percentile, and assigned this rank to the constituent census output areas (each Lower Super Output Area has a population of around 1500 and contains around five census output areas).

Statistical analyses

To control for unmeasured confounders and for historical trends we used a difference-in-differences approach (Craig et al., 2012), comparing changes between 2001 and 2011 in the intervention towns with changes over the same time period in the comparison towns. We treated absolute change (difference-in-differences) as the primary measure of intervention effect but, in keeping with reporting recommendations (King, Harper, & Young, 2012; Vandenbroucke et al., 2007), we also considered relative changes (ratio-of-ratios). The equations we used were as follows, with 'Int' representing intervention towns, 'Comp' comparison towns and $\%\mathrm{Int}_{2011}$ (for example) representing the percentage of commuters in the intervention towns who cycled to work in 2011.

Difference in absolute percentage point increase ('difference-in-differences'):

$$[\%\mathrm{Int}_{2011} - \%\mathrm{Int}_{2001}] - [\%\mathrm{Comp}_{2011} - \%\mathrm{Comp}_{2001}]$$

Ratio of relative percentage increase ('ratio-of-ratios'):

$$[\%\mathrm{Int}_{2011}/\%\mathrm{Int}_{2001}]/[\%\mathrm{Comp}_{2011}/\%\mathrm{Comp}_{2001}]$$

To compare impacts across socio-economic groups, we calculated equivalent effect estimates after stratifying by fifth of small-area deprivation, the fifths being defined *a priori* using national quintiles. The calculation of confidence intervals is described in Supplementary File S2.

As our primary interest was in effects across the entire commuting population, we estimated intervention effects using individual-level data from all towns combined (i.e. towns containing 200,000 commuters contributed twice as much data as towns containing 100,000 commuters). To investigate the possibility of differential effects between towns, we also estimated the intervention effect separately for each pair of intervention and comparison towns. These estimates are shown in forest plots, together with an I^2 value representing between-town heterogeneity (i.e. variation in intervention effect sizes) and with an overall pooled effect size estimated using random effects meta-analysis (Higgins & Thompson, 2002). We used meta-regression (Harbord & Higgins, 2008) to examine whether any heterogeneity in intervention effects between pairs of towns could be explained by four pre-defined characteristics of the intervention towns: CDT vs. CCT status; baseline (2001) cycling prevalence; median affluence (Index Of Multiple Deprivation percentile in 2010); and an estimate of the relative emphasis placed on cycling-to-work initiatives in each town. This final characteristic was modelled as a latent variable by combining the three relevant measures routinely available from each town's end-of-programme report: percent of revenue budget spent on workplaces; number of employees 'intensively' engaged per 1000 commuters; and number of new workplace cycle parking spaces created per 1000 commuters (Box 1; see Supplementary File S2 for further details). For baseline cycling prevalence, we verified that the findings of the meta-regression did not change when using a method implemented in OpenBUGS (Release 3.2.2) to correct for potential bias which can occur if the exposure also forms one component of the outcome (Sharp & Thompson, 2000). All other statistical analyses were performed using Stata 12.

Ethical approval for this study was not needed, as all data are in the public domain.

Results

Comparability of intervention and comparison towns

Intervention towns were similar to the matched comparison group in terms of population size, population density and affluence, and were also reasonably similar to the national comparison group (Table 2). Prior to the intervention, cycling and (to a lesser extent) walking to work were more common in absolute terms in the intervention towns, and driving to work was less common (Fig. 1). This discrepancy in cycling levels partly reflected the uniquely high prevalence of cycling in one medium-sized intervention town (Cambridge); all substantive findings were unchanged in sensitivity analyses excluding this high-cycling town.

Despite these differences in absolute levels, the intervention group and matched comparison group generally showed very similar pre-intervention trends (Fig. 1). Across the four commuting modes, most difference-in-differences and ratio-of-ratios effect

Table 2
Characteristics of intervention and comparison towns, and absolute and relative changes in the prevalence of cycling to work between 2001 and 2011.

Group	Group characteristics					Prevalence of cycling to work (%)		Absolute change		Relative change	
	No. units/ sub-regions[a]	No. residents, census 2011	No. commuters, census 2011	Pop. density, census 2011[b]	Median affluence rank,[c] 2010 (IQR)	Census 2001 (95%CI)	Census 2011 (95%CI)	Percentage difference, 2011–2001 (95%CI)	Difference-in-differences (95%CI)[d]	Ratio of increase, 2011/2001 (95%CI)	Ratio-of-ratios (95%CI)[d]
Intervention group (CDT/CCTs)	18/37	2,751,198	1,266,337	27.2	46.1 (26.1, 71.2)	5.81 (5.77, 5.86)	6.78 (6.74, 6.83)	0.97 (0.91, 1.03)	N/A	1.17 (1.16, 1.18)	N/A
Matched comparison group	18/27	2,178,498	969,605	27.4	44.0 (23.4, 68.9)	4.03 (3.99, 4.08)	4.32 (4.28, 4.36)	0.29 (0.23, 0.34)	0.69 (0.60, 0.77)	1.07 (1.06, 1.09)	1.09 (1.07, 1.11)
Unfunded comparison group	67/81	9,709,750	4,195,540	29.7	35.9 (14.8, 59.9)	3.47 (3.45, 3.49)	3.42 (3.40, 3.44)	−0.05 (−0.07, −0.02)	1.02 (0.95, 1.09)	0.99 (0.98, 0.99)	1.18 (1.17, 1.20)
National comparison group	–/282	23,387,677	10,356,452	25.3	43.4 (20.6, 69.4)	3.38 (3.37, 3.39)	3.12 (3.11, 3.13)	−0.26 (−0.27, −0.24)	1.23 (1.16, 1.29)	0.92 (0.92, 0.93)	1.26 (1.25, 1.28)

CI = confidence interval, IQR = inter-quartile range.
[a] Units refer to contiguous urban areas forming units of analysis (e.g. 'Brighton' and 'Hove' combined); sub-regions refer to the official urban sub-regions recognised by Office for National Statistics (e.g. 'Brighton' and 'Hove' separately).
[b] Population density, people per hectares.
[c] Median ranking according to the Index of Multiple Deprivation of constituent Lower Super Output Areas using national percentiles, with 1 corresponding to the most deprived 1% in England and 99 to the most affluent 1%.
[d] Difference-in-differences and ratio-of-ratios columns present contrasts between the intervention group and each of the comparison groups in turn.

sizes were non-significant ($p > 0.05$) for comparisons between 1981 and 1991 or between 1991 and 2001. The only exceptions were evidence that between 1981 and 1991 the matched comparison towns experienced a somewhat larger decrease in public transport and a somewhat larger increase in driving. By contrast, trends were less comparable between the intervention towns and the unfunded or national comparison group. Specifically, there was strong evidence that these two comparison groups experienced larger decreases in cycling between 1991 and 2001; larger decreases in walking and public transport use between 1981 and 2001; and larger increases in driving between 1981 and 2001. These findings therefore reinforced our decision to treat the matched comparison group as the primary comparator, and indicate the need for some additional caution in interpreting comparisons with the unfunded and national comparison groups.

Changes in cycling to work between 2001 and 2011

Among commuters living in the intervention towns, the prevalence of cycling to work increased from 5.81% in 2001 to 6.78% in 2011. Compared with the matched comparison group, this represented an absolute intervention effect of +0.69 (95% CI 0.60, 0.77) percentage points, or a relative effect of 1.09 (95% CI 1.07, 1.11). Larger absolute and relative effect sizes were seen when the intervention towns were compared to the unfunded or national comparison towns (Table 2).

The increases in the intervention towns relative to any of the three comparison groups could not be attributed to the higher baseline cycling prevalence in the intervention towns for two reasons. Firstly, the increase in the intervention towns was significant for both absolute and relative measures of effect. Secondly, the national background trend was for cycling prevalence in 2001 to be negatively associated with change in prevalence between 2001 and 2011 (Fig. 2). As Fig. 2 also shows, 14 of the 18 intervention towns had a higher cycling prevalence in 2011 than would be expected from their cycling levels in 2001. It is also interesting to note that intervention towns made up four of the five urban areas outside London in which the prevalence of cycling to work increased by more than one percentage point.

Changes in walking, driving and use of public transport to travel to work

Between 2001 and 2011, there was an increase in the intervention towns in the prevalence of walking to work (+1.71 (95% CI 1.62, 1.81) percentage points) and, to a lesser extent, of using public transport (+0.32 (0.24, 0.41) percentage points). This was counterbalanced by a decrease in the prevalence of driving to work (−3.01 (−3.13, −2.88) percentage points: Fig. 1). Although there were similar trends in the comparison towns, the increase in walking was always significantly larger in the intervention towns in both absolute and relative terms. For example, the difference-in-differences for the intervention vs. matched comparison group was +0.73 (95% CI 0.59, 0.87) percentage points and the ratio-of-ratios was 1.04 (1.03, 1.05). Similarly the decrease in driving to work was larger in the intervention towns than in the three comparison groups in both absolute and relative terms (e.g. difference-in-differences −1.39 (−1.57, −1.20) percentage points for intervention vs. matched comparison group and ratio-of-ratios 0.977 (0.974, 0.980)). By contrast, the small increase in using public transport was similar to that observed in the comparison groups (e.g. difference-in-differences 0.04 (−0.09, 0.17) percentage points for intervention vs. matched comparison group and ratio-of-ratios 1.00 (0.99, 1.01)). In summary, therefore, the intervention appeared to increase cycling and, to a more modest extent, walking to work,

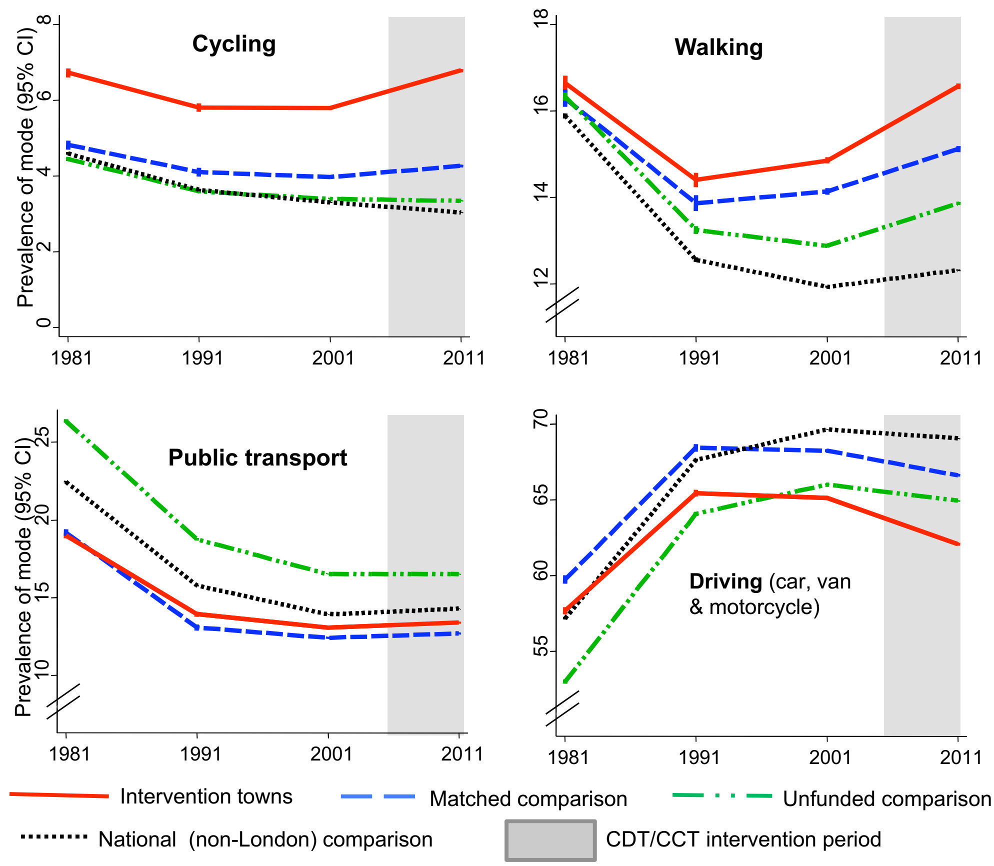

Fig. 1. Prevalence of cycling, walking, driving and use of public transport to travel to work among commuters living in the intervention towns and in the comparison towns, 1981–2011.

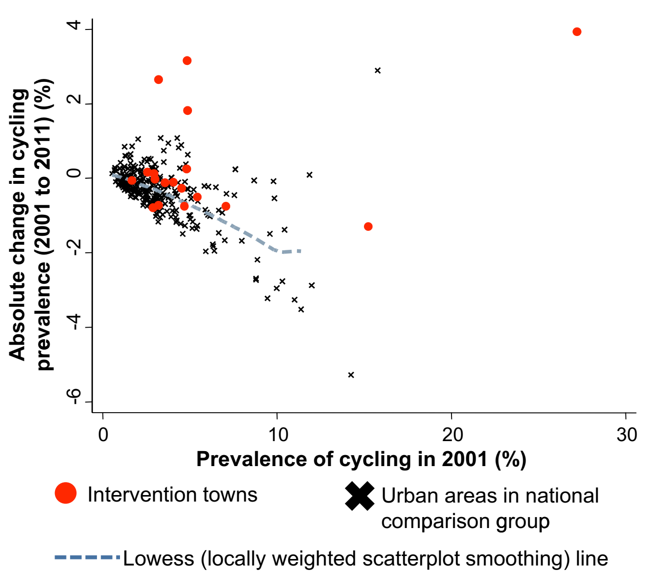

Fig. 2. Association between the prevalence of cycling to work in 2001 and change in cycling prevalence between 2001 and 2011, among non-London urban areas in England with a population of over 30,000. Scatterplot presents the 18 intervention towns and the 282 urban sub-regions in the non-London national comparison group. Locally weighted scatterplot smoothing ('lowess') line fitted using running-line least-squares smoothing, based on all 300 data points.

and to increase the use of these active modes at the expense of driving to work.

Equity impacts

Cycling in the intervention towns increased significantly among commuters living in all fifths of small-area deprivation (Fig. 3). In percentage-point terms, this increase was smaller among those living in the most deprived areas. Nevertheless this compared favourably with the three comparison groups, which all experienced larger socio-economic differentials (as indicated by the steeper gradients of their lines) and which all experienced declines in cycling in the most deprived fifth. Thus relative to what might otherwise have been expected, the increase in cycling in the intervention towns was actually greatest among those living in more deprived areas. For example, the difference-in-differences was 0.77 (95% CI 0.60, 0.94) percentage points for the intervention vs. matched towns in the most deprived fifth, as compared to 0.39 (0.19, 0.59) percentage points in the least deprived fifth. The corresponding ratio-of-ratios was 1.22 (1.16, 1.28) as compared to 0.98 (0.94, 1.03).

Walking to work showed a similar pattern: the prevalence of walking in the intervention towns increased across all fifths of deprivation, and increased by more than any of the comparison groups (although in the most affluent fifth this difference was not significant: see Supplementary File S3). Likewise driving to work in the intervention towns decreased in all groups, although in the most deprived fifth this was not significant. For all fifths, this represented a larger decrease than in the three comparison groups. The change in public transport use across deprivation fifths was

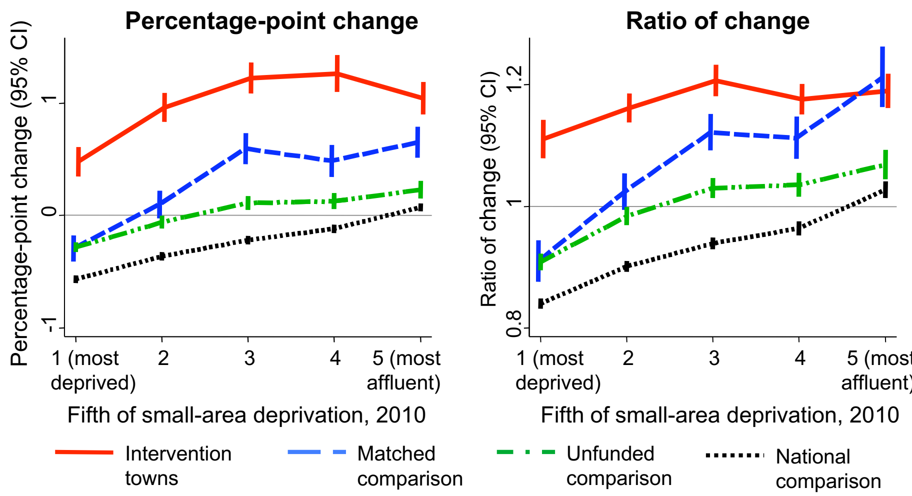

Fig. 3. Association between small-area deprivation and change in the prevalence of cycling to work between 2001 and 2011, stratifying commuters by small-area deprivation. CI = confidence interval. Deprivation fifths defined using national quintiles. See the Supplementary File S3 for equivalent comparisons for walking, driving and public transport.

generally similar between all groups, with no significant differences between the intervention and matched towns.

Heterogeneity in intervention effects

The analyses presented above combined commuters in the 18 towns into a single sample, and therefore estimated the total-population effects of the intervention. Fig. 4 presents forest plots which instead show effects on cycling prevalence at the town level, and which reveal the very large heterogeneity between intervention towns (I^2 statistics 97–99%). Although some towns experienced large percentage-point increases or decreases, the average town-level effects were non-significant (e.g. difference-in-differences 0.29 (95% CI −0.26, 0.84) percentage points for intervention vs. matched comparison towns). This discrepancy with the population-level analyses stems from the fact that the significantly positive population-level effects were partly driven by large increases in a few large towns, particularly Bristol (the largest town) and Brighton and Hove (the third largest). By contrast, in random-effects meta-analysis towns of different sizes are weighted more similarly, and the substantial variation in the effect sizes between the towns means that there is greater uncertainty about the average town-level effect of the intervention.

Predictors of intervention effect

Table 3 presents the result of meta-regression analyses which sought to explain the marked heterogeneity between intervention towns in terms of town characteristics. There was no evidence that town status (CDT vs. CCT) predicted the magnitude of the increase in cycling prevalence (see also Fig. 4, in which the six CDT towns are displayed first). There was likewise no evidence of an effect of

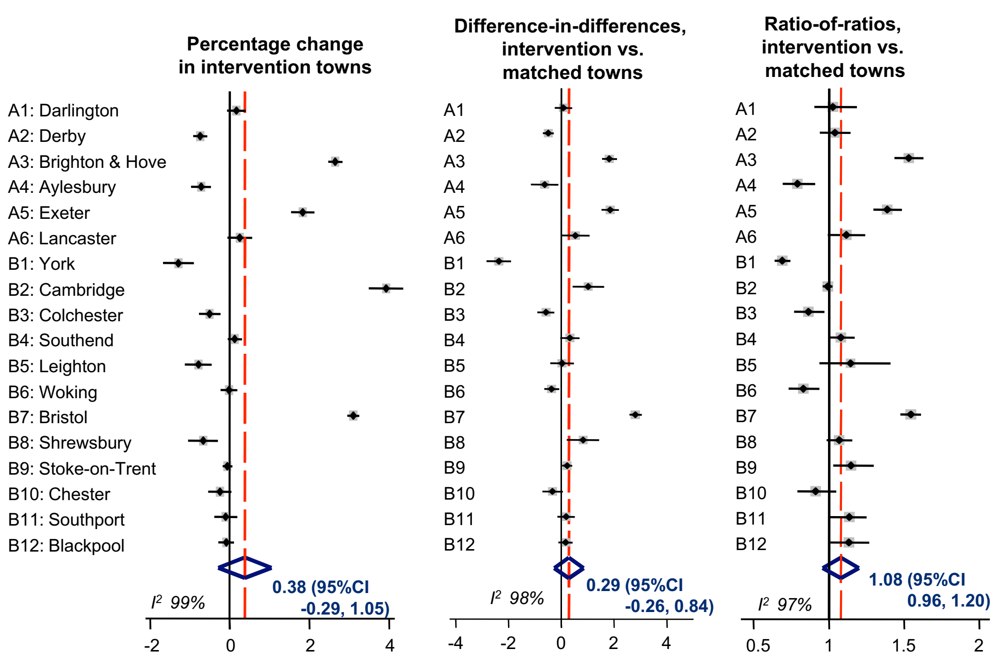

Fig. 4. Town-specific changes in the prevalence of cycling to work between 2001 and 2011. The first six towns (A1–A6) are the Cycling Demonstration Towns, funded 2005–2011; the second 12 towns (B1–B12) are the Cycling Cities and Towns, funded 2008–2011. Town abbreviations: Lancaster = Lancaster with Morecambe, Southend = Southend-on-Sea, Leighton = Leighton-Linslade, Southport = Southport & Ainsdale.

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Table 3
Results of univariable meta-regression analyses examining associations between town characteristics and changes in cycling prevalence in the intervention vs. matched comparison towns.

Town-level characteristics	Change in difference-in-differences		Change in ratio-of-ratios	
	Regression coefficient (95% CI)	Adjusted R^2	Regression coefficient (95% CI)	Adjusted R^2
CDT status (vs. CCT status)	0.37 (−0.87, 1.61)	−3.7%	0.11 (−0.15, 0.36)	−0.9%
Baseline cycling (change per 1% increase in 2001 cycling prevalence)	−0.03 (−0.15, 0.09)	−4.4%	−0.01 (−0.04, 0.01)	2.6%
Affluence (change per decile increase in median affluence)	−0.21 (−0.52, 0.11)	4.9%	−0.07 (−0.13, −0.01)	24.2%
Emphasis on cycling to work initiatives (change per SD)	0.75 (0.30, 1.21)	41.9%	0.14 (0.04, 0.24)	32.0%

CDT = Cycling Demonstration Towns, CCT = Cycling Cities and Towns, SD = standard deviation. Affluence measured using national percentiles of the Indices of Multiple Deprivation, emphasis on cycling to work measured using a latent variable (see Supplementary File S2). Graphs illustrating the significant associations are presented in Fig. 5 and in Supplementary File S3.

baseline cycling prevalence, but there was a suggestion of smaller intervention effects in more affluent towns. This association with affluence was, however, only significant using the ratio-of-ratios. The discrepancy reflected the fact that baseline cycling was on average lower in more deprived towns, meaning that a given percentage-point increase in these deprived towns translated into a larger relative increase.

Finally, there was evidence of larger effects in towns placing greater emphasis on workplace cycling initiatives, with this variable explaining around one third of the observed between-town heterogeneity (Table 3). As shown in Fig. 5, this was partly driven by the three towns (Exeter, Bristol and Shrewsbury) which appeared particularly to have emphasised workplace initiatives, and which were all among the top five towns in terms of difference-in-differences effect sizes.

Discussion

Principal findings

This controlled, natural experimental study used English census data to evaluate a programme of town- and city-wide initiatives aiming to increase cycling. Following these initiatives, the prevalence of cycling to work increased in both absolute and relative terms among commuters living in the intervention towns. Walking to work also increased somewhat, while driving to work declined and public transport use remained unchanged. These changes were seen across all fifths of small-area deprivation, with larger changes (relative to comparison groups) in more deprived areas. There was, however, substantial heterogeneity between towns, with the population-level increase partly reflecting large cycling increases in a few large towns. As such, although there is evidence that cycling to work *has* increased overall among commuters living in the 18 intervention towns chosen thus far, there is uncertainty about whether cycling *would in general* increase if comparable investments were made in other towns.

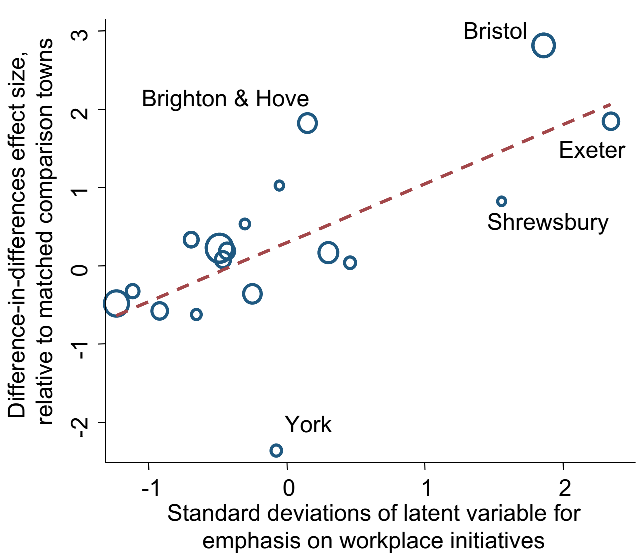

Fig. 5. Association between intervention effect size and relative emphasis on workplace cycling initiatives in each intervention town ($N = 18$). Larger circles represent more precise estimates, with the size of the circles equal to the inverse of the within-town variance. The dashed line indicates the line of best fit from univariable random effects meta-regression (Table 3). See the Supplementary File S3 for an equivalent ratio-of-ratios graph, and for graphs relating to area deprivation.

Strengths and weaknesses

A key strength of this study is its use of a uniquely large and representative dataset, and its ability therefore to generate precise and largely-unbiased estimates at the local level. This use of the census highlights how routine, publicly available data can be used to evaluate a 'natural experiment', as advocated and exemplified in recent guidance from the Medical Research Council (Craig et al., 2012). This paper also demonstrates that meta-analytical techniques can be used in natural experimental studies to investigate heterogeneity when interventions are delivered at group level (e.g. at the level of towns, schools or hospitals).

One important limitation of this study is that the census provides evidence on changes in only one, very simple measure, namely the usual mode of travel to work. Whilst commuting is an important target for active travel interventions (Sugiyama, Ding, & Owen, 2013) and provides a reasonable proxy for overall population travel behaviour (Goodman, 2013), the restricted outcome measure may have under- or over-estimated the overall impact of the intervention on cycling. This represents a weakness in comparison to survey-based evaluations of the intervention which have documented increases in cycling in general (Sloman et al., 2009). Like previous evaluations (Krizek et al., 2009; Sloman et al., 2009; Troelsen et al., 2004; Wilmink & Hartman, 1987), ours included only one post-intervention time point and was therefore unable to examine how the effects of the intervention unfolded over time or to examine longer-term effects. Like many previous evaluations, ours also lacked information on individual-level characteristics such as age and gender. On the other hand, this study extends some other evaluations by examining which travel modes were displaced by increased cycling levels.

The absence of randomisation in this and all previous published evaluations of large-scale cycling initiatives (Krizek et al., 2009; Sloman et al., 2009; Troelsen et al., 2004; Wilmink & Hartman, 1987; Yang et al., 2010) limits our ability to make strong causal inferences (Craig et al., 2012). However, randomisation of interventions to change the wider determinants of health is challenging and rarely seen in practice (House of Commons Health

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Committee, 2009). Support for a potential causal effect is provided by the fact that our outcome behaviour (cycling to work) was a key focus of the initiatives of most towns (Department for Transport, 2012), and by the fact that this outcome increased more in towns which focused more of their investment on workplaces. Nevertheless the fact that towns were selected partly according to their perceived likelihood of success suggests the possibility of a problem analogous to 'confounding by indication' in clinical studies (Craig et al., 2012). In other words, intervention towns may have possessed socio-demographic or other characteristics (e.g. strong leadership) which would have been associated with some increase in cycling even without additional investment. To the extent that this is true, we may have overestimated the effectiveness of the intervention. This also means that the generalisability of these results is unclear: if the intervention towns chosen represented particularly promising sites for intervention, the effects of comparable investment in other towns might be smaller.

Meaning of the study and directions for future research

Our findings broadly support the international evidence that town-level interventions can be effective in increasing cycling (Sloman et al., 2009; Troelsen et al., 2004; Wilmink & Hartman, 1987). The increases we report in cycling to work are smaller in absolute terms than the increases in overall cycling reported following interventions in high-cycling countries (unadjusted difference-in-differences 0.7 percentage points in our study vs. 2.0 in Holland (Wilmink & Hartman, 1987) and 2.3 in Denmark (Troelsen et al., 2004)), but are similar in relative terms (unadjusted ratio-of-ratios 1.09 vs. 1.05 and 1.11). Although the changes we report are modest, small initial changes can become larger over time. For example, London experienced a similarly modest increase in the prevalence of cycling to work between 1991 and 2001 (+0.4%), followed – in the context of multiple ongoing initiatives (Transport for London, 2012) – by a much larger increase between 2001 and 2011 (+1.7%) (Goodman, 2013). Moreover, even modest increases in cycling may confer physical activity, health and environmental benefits (Sahlqvist et al., 2013; Sloman et al., 2009), and a previous evaluation of the first six intervention towns indicated a favourable cost–benefit ratio (Sloman et al., 2009).

In considering the potential health and environmental benefits of the intervention programme, it is encouraging to note that the increases in cycling were accompanied by decreases in driving to work. Notably, walking to work also increased somewhat in the intervention towns, suggesting the possibility for cycling initiatives to have wider beneficial effects on active travel behaviour. This was not an aim of the intervention programme, but it is possible that some intervention components did simultaneously encourage walking. For example, some of the new off-road cycling facilities (particularly greenways) seem often to have been perceived and used as shared spaces for cyclists and pedestrians, thereby providing improved walking opportunities (Department for Transport, 2012). Similarly, one key workplace intervention was personalised travel planning, which may also have included or encouraged other forms of active travel besides cycling. This resonates with a previous review of workplace travel initiatives in the UK, which noted that facilities implemented for cyclists (e.g. changing rooms or lockers) were sometimes also popular among walkers (Cairns, Newson, & Davis, 2010).

Our findings also suggest the potential for town-wide cycling initiatives to promote not only population health improvement but also health equity. In the past decade in England and Wales, cycle commuting has shown the largest increase among people living in more affluent areas (Goodman, 2013), and this paper confirms this gradient for English urban areas outside London. Set against this backdrop, the intervention programme may have narrowed the socio-economic gradient in cycling relative to what would otherwise have been expected. This perhaps reflects a tendency in the intervention towns to focus on deprived areas when targeting specific neighbourhoods (Box 1). Our findings therefore replicate a previous evaluation of the first six intervention towns (Sloman et al., 2009) in suggesting that the intervention has been broadly equitable in its impacts.

In summary, our findings indicate that the Cycling Demonstration Town and Cycling City and Towns initiatives have thus far encouraged commuter cycling in a way which is likely to promote health and health equity while also realising environmental benefits. Nevertheless, although the intervention appears to have 'worked' so far, heterogeneity between towns means that there is much more uncertainty about the likely effects of comparable investment in other towns in the future. Thus although these findings are promising, further monitoring and evaluation would be warranted in any future intervention towns. The extreme heterogeneity between existing cycling towns also warrants further investigation, perhaps drawing on process evaluations to investigate our finding that intervention effect size was associated with the emphasis placed on workplace initiatives. Such investigations could also use further qualitative or quantitative data collection to explore in more detail the mechanisms of behaviour change and the role played by contextual factors (e.g. pre-existing cycling cultures or cycling infrastructure). Other important directions for future research include comparing changes across cycling for different purposes; examining the individual-level predictors of increases in cycling; and extending follow-up beyond the immediate post-intervention period to examine longer-term effects.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.socscimed.2013.08.030.

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