Evaluating the impacts of new walking and cycling infrastructure on carbon dioxide emissions from motorized travel: a controlled longitudinal study

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ABSTRACT

Walking and cycling is widely assumed to substitute for at least some motorized travel and thereby reduce energy use and carbon dioxide (CO_2) emissions. While the evidence suggests that a supportive built environment may be needed to promote walking and cycling, it is unclear whether and how interventions in the built environment that attract walkers and cyclists may reduce transport CO_2 emissions. Our aim was therefore to evaluate the effects of providing new infrastructure for walking and cycling on CO_2 emissions from motorised travel.

A cohort of 1849 adults completed questionnaires at baseline (2010) and one-year follow-up (2011), before and after the construction of new high-quality routes provided as part of the Sustrans Connect2 programme in three UK municipalities. A second cohort of 1510 adults completed questionnaires at baseline and two-year follow-up (2012). The participants reported their past-week travel behaviour and car characteristics from which CO_2 emissions by mode and purpose were derived using methods described previously. A set of exposure measures of proximity to and use of the new routes were derived.

Overall transport CO_2 emissions decreased slightly over the study period, consistent with a secular trend in the case study regions. As found previously the new infrastructure was well used at one- and two-year follow-up, and was associated with population-level increases in walking, cycling and physical activity at two-year follow-up. However, these effects did not translate into sizeable CO_2 effects as neither living near the infrastructure nor using it predicted changes in CO_2 emissions from motorised travel, either overall or disaggregated by journey purpose. This lack of a discernible effect on travel CO_2 emissions are consistent with an interpretation that some of those living nearer the infrastructure may simply have changed where they walked or cycled, while others may have walked or cycled more but few, if any, may have substituted active for motorised modes of travel as a result of the interventions.

While the findings to date cannot exclude the possibility of small effects of the new routes on CO_2 emissions, a more comprehensive approach of a higher ‘dosage’ of active travel promotion linked with policies targeted at mode shift away from private motorized transport (such as urban car restraint and parking pricing, car sharing/pooling for travel to work, integrating bike sharing into public transport system) may be needed to achieve the substantial CO_2 savings needed to meet climate change mitigation and energy security goals.

Keywords: transport; CO_2 emissions; walking and cycling; infrastructure; longitudinal analysis; impact evaluation

1 INTRODUCTION

Passenger transport has been a priority sector for reducing its significant impacts of fossil energy use and associated greenhouse gas emissions for many years. Replacing motorised travel with low carbon modes such as walking and cycling is increasingly recognised as important in low carbon and energy demand reduction strategies [1-7]. In many countries, the majority of trips made by car are short-distance journeys to work, education or shopping [6, 8]. In the United Kingdom (UK), for instance, about one fifth of carbon dioxide (CO_2) emissions[1] and transport energy use come from car journeys of less than 8 kilometres which could be made by foot or bicycle [10, 11]. Walking and cycling for transport ('active travel') are widely assumed to substitute for at least some motorized travel and thereby reduce CO_2 emissions [3, 12-16]. This assumption is supported by the findings that bicycle access is negatively correlated with CO_2 emissions from motorized travel [17], that energy expenditure from walking is negatively correlated with fossil fuel use from car driving [18] and that individuals in more 'walkable' neighbourhoods make more walking trips and travel fewer vehicle kilometres [19]. For these reasons, promoting active travel has been discussed as one area with potential climate change, energy and health 'co-benefits' [4, 20, 21].

While it has been argued that a supportive built environment may be needed to promote and sustain increases in population physical activity [22, 23], a number of reviews have highlighted the lack of controlled, longitudinal studies evaluating the effects of new infrastructure on walking and cycling [24-27]. More recently we have shown that new high-quality walking and cycling routes in the UK were well-used at both one- and two-year follow-up [28] and were associated with population-level increases in walking, cycling and physical activity at two-year follow-up [29]. In all these studies, however, it was unclear whether increased activity and/or infrastructure use reflected (i) the generation of new walking and cycling trips, (ii) the substitution of trips previously made by motorized modes of transport, or (iii) the displacement of walking and cycling trips formerly conducted elsewhere. Reductions in transport CO_2 emissions would only be expected if motorised trips were substituted (scenario ii) or if, for example, recreational walking trips at locations formerly reached by car [14] were now conducted closer to home (a special case of scenario iii). We are not aware of any controlled, longitudinal studies evaluating the effects of new infrastructure on CO_2 emissions from (displaced) motorized travel.

This paper therefore sought to extend our previous evaluation of high-quality, traffic-free walking and cycling routes [28, 29] by examining impacts on CO_2 emissions from motorized travel. Specifically, given that the routes were well used and associated with population-level increases in walking, cycling and physical activity (after two years), we aimed to explore the extent to which proximity to and use of the routes predicted decreases in transport CO_2 emissions over one- and two-year follow-up, and whether any

[1] For land-based passenger transport, CO_2 is by far the most important greenhouse gas, comprising approximately 99% of direct greenhouse gas emissions [9].

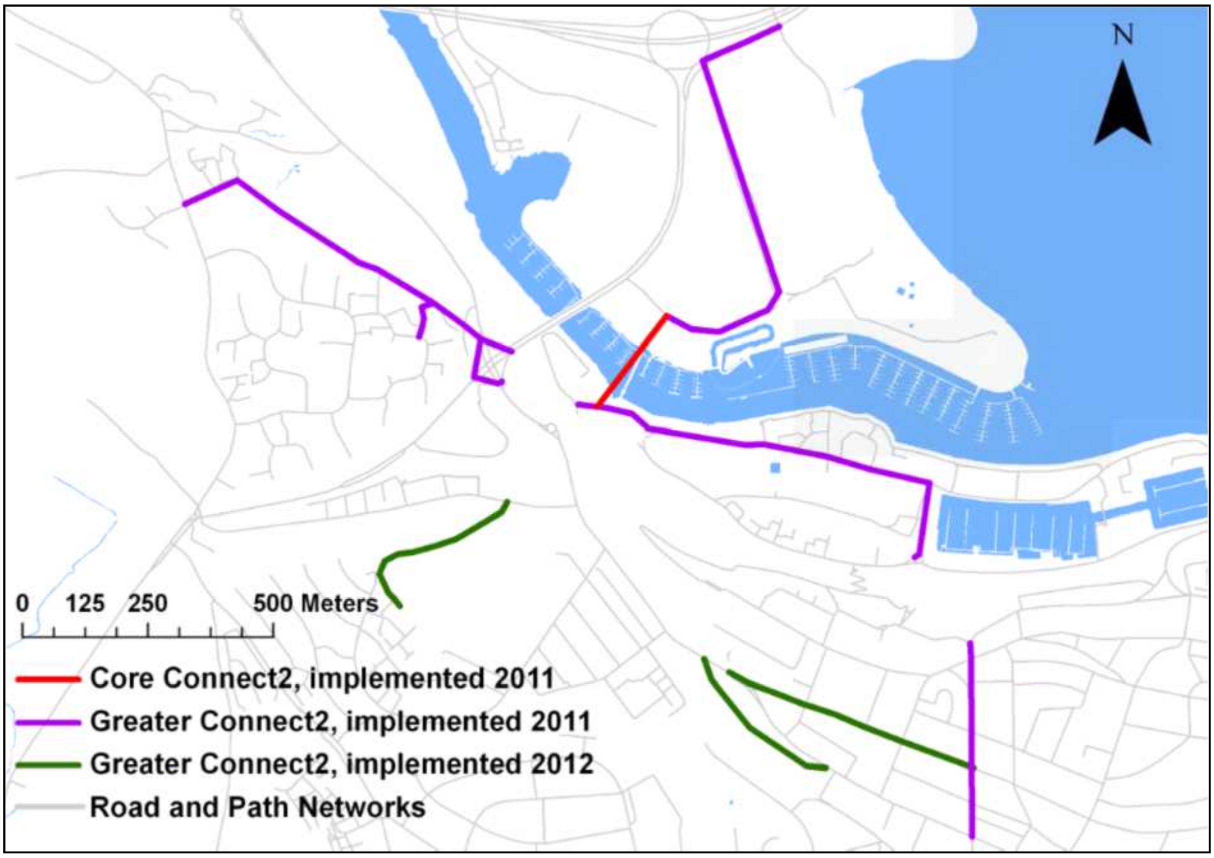
associations varied across different journey purposes. In other words, we aimed to answer the questions: do people living closer to the new routes or use them have lower/higher CO_2 emissions from motorised travel than people living further away or do not use them?

2 METHODS

2.1 Intervention, study sites and sample

Led by the sustainable transport charity Sustrans, the Connect2 initiative is building or improving walking and cycling routes at multiple sites across the United Kingdom (map in Appendix A). Each Connect2 site comprises one flagship engineering project (the 'core' project) plus new or improved feeder routes (the 'greater' project) (Figure 1). These projects are tailored to individual sites but all embody a desire to create new routes for *"everyday, local journeys by foot or by bike"* [30].

Figure 1: 'Core' and 'greater' Connect2 projects in the Cardiff study site



Purple lines show the sections of the greater Connect2 network which were operational at the time of both the 2011 and the 2012 surveys; green lines show the sections of the network only operational at the time of the 2012 survey. Map contains Ordnance Survey data © Crown copyright and database right 2011. See Appendices for equivalent maps of Southampton and Kenilworth, and for the locations of these three study sites.

The independent iConnect research consortium (www.iconnect.ac.uk) was established to evaluate the travel, physical activity and CO_2 emissions impacts of Connect2 [31, 32]. As previously described in detail [31], three Connect2 projects were selected for detailed study according to criteria including urban/rural location, relative size, implementation timetable, likelihood of measurable population impact and heterogeneity of overall mix of sites. These core study sites were: Cardiff/Penarth, where a traffic-free bridge was built over Cardiff Bay to Penarth; Kenilworth, where a traffic-free bridge was built over a busy trunk road; and Southampton, where an informal riverside footpath was turned into a boardwalk (see also [31]). None of these projects had been implemented during the baseline survey in April 2010. At one-year follow-up, most feeder routes had been upgraded and the core projects had opened in Southampton and Cardiff in July 2010. At two-year follow-up, almost all feeder routes were complete and the core Kenilworth project had opened in September 2011.

The baseline survey used the edited electoral register to select 22,500 adults living within a 5 km road network distance of the core Connect2 projects, using a stratified (by distance), randomised sampling approach [14, 17, 31]. In April 2010 potential participants were posted a survey pack, which 3516 individuals returned. These 3516 individuals were posted follow-up surveys in April 2011 and 2012; 1885 responded in 2011 and 1548 in 2012. After excluding individuals who had moved house, the one-year follow-up study population cohort comprised 1849 participants (53% retention rate, 8% of the population originally approached) and the two-year study population cohort comprised 1510 (43% retention, 7% of the original population). The University of Southampton Research Ethics Committee granted ethical approval (CEE200809-15).

2.2 CO_2 emissions calculations

The CO_2 emissions[2] calculation methods for motorized travel modes have been published previously in [14, 17]. In brief, weekly travel activity was measured using a seven-day recall instrument [31] covering five journey purposes: ‘commuting for work’, ‘travel for education’, ‘travel in the course of business’, ‘shopping or personal business’, and ‘social, visiting friends or other leisure activities’. For each journey purpose, participants recalled the total number of trips made, distance and time spent travelling by seven modes: ‘walking’, ‘cycling’, ‘car/van as driver’, ‘car/van as passenger’, ‘bus’, ‘train’ and ‘other’ (taxi, motorcycle, etc.). From this information, mean speeds and mean trip distances were derived for each journey purpose. If only distance or time was reported then the counterpart was imputed using the mean observed speed for each mode and journey purpose.

As fully described previously [14, 17], we used these travel activity data to derive CO_2 emissions, with different methods for car and non-car modes. For cars and vans, the self-reported data on weekly travel activity, vehicle fuel, size and age allowed for the use of a

[2] We used CO_2 and not CO_2 equivalent (CO_2e) as our primary outcome measure because (a) CO_2 emissions dominate direct CO_2e emissions from surface passenger transport, making up approximately 99% of direct CO_2e [9], and (b) vehicle emissions rates for the non-CO_2 greenhouse gases methane (CH_4) and nitrous oxide (N_2O) are much less certain than for CO_2 [33], thus potentially introducing uncertainty in outcome measures for little added benefit.

disaggregate method including the estimation of 'hot' CO_2 emissions, which are a function of distance travelled, mean speed, fuel type, size and age (calculated separately in 2010, 2011 and 2012 to reflect the ageing vehicle fleet), and 'cold start' CO_2 emissions (excess emissions during the warm-up phase). Emissions from travel 'commuting for work' and 'travel for education' were combined into a 'commuting' category. As we lacked detailed data on car-sharing we modelled CO_2 in two ways, (a) one dividing emissions from car travel between passengers and drivers and (b) one assigning all emissions to the driver. The substantive findings were generally identical and we therefore report in the main text the results for CO_2 shared between drivers and passengers. For travel by bus, train and 'other' modes, self-reported data on distance travelled by trip purpose were multiplied by mode-specific, average CO_2 emissions factors obtained from the UK Department of Environment, Food and Rural Affairs [34].

2.3 Use of the Connect2 infrastructure

At each follow-up, participants were given a description of their local Connect2 project and asked "Do you use the [Connect2 infrastructure]?" (yes/no). Participants reporting using Connect2 were then asked whether they (a) walked or (b) cycled on Connect2 for any of the five 'transport' journey purposes given above or for 'recreation, health or fitness'. We used these to create a measure of any Connect2 use for transport; any Connect2 use for commuting/business purposes; or any Connect2 use for shopping/social purposes. We also counted the number of transport journeys they reported.

2.4 Baseline characteristics of the participants

Table 1 presents the baseline characteristics examined as predictors of transport CO_2 emissions. Most characteristics were based on self-reported measures, including demographic and socio-economic variables and measures of access to cars and bicycles. 'Total past-week walking and cycling' was derived by summing the four constituent times of self-reported walking and cycling for both transport and recreation.[3] Participants also provided self-reported height and weight, from which we calculated body mass index (kg/m^2). Applying standard cut-offs, we used BMI to classify participants as being of normal weight ($BMI<25$), overweight ($25\leq BMI<30$) or obese ($30\leq BMI$). Site and urban/rural status were derived by matching home postcodes to Lower Super Output Areas, using mid-2010 population estimates for the latter [36]).

2.5 Exposure to the intervention

Given that our main aim was to answer the question whether people living closer to the new routes have lower CO_2 emissions from motorised travel than people living further away, we developed a hierarchical set of proximity measures. The primary measure of exposure was proximity to Connect2 [31], operationalized as the distance from the

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[3] Past-week recreational walking and cycling were measured by adapting the short form of the International Physical Activity Questionnaire (IPAQ) [35].

weighted population centroid of the unit postcode[4] containing the participant's home to the nearest access point to a completed section of the 'greater' Connect2 project (calculated separately in 2011 and 2012 to reflect ongoing upgrades: Figure 1). Distance was calculated in ArcGIS 9 using the Ordnance Survey's Integrated Transport Network and Urban Path layers, which include the road network plus traffic-free or informal paths. For ease of interpretation, we reverse coded distance from the intervention to generate a measure of proximity – i.e. treating those living within 1km as having a higher proximity than those living over 4km away (Table 1).

Secondary exposure measures were: distance to the 'core' (flagship) Connect2 project (e.g. the 'core' infrastructure element of the Kenilworth scheme illustrated in Figure 2); using Connect2 for any purpose ('general' use); and using Connect2 for the specific mode and purpose in question (i.e. using Connect2 for walking for transport as the exposure when change in past-week time spent walking for transport was the outcome).

Figure 2: Illustration of the 'core' (flagship) element of the Kenilworth Connect2 scheme, a walking and cycling bridge

2.6 Analysis

Missing data ranged from 0% to 1.2% across exposure and outcome variables, and from 0 to 8.1% among covariates. These data were imputed using multiple imputation by chained equations (five imputations) under an assumption of missing at random. To allow for potential correlations between participants living in the same neighbourhood, robust

[4] In the UK residential unit postcodes (such as 'SO17 1BJ') typically relate to around 15 residential addresses and 36 people (based on the average household size of 2.4) [37].

standard errors were used clustered by Lower Super Output Area (average population 1500).

Effects on CO_2 emissions were examined by calculating change in past-week CO_2 emissions for all travel; for commuting and travel in the course of business only; and for travel for shopping, personal business, social and leisure only. Linear regression was used to examine how the different exposure measures predicted these three change scores. Multivariable models were initially adjusted for age, sex and site, and then adjusted for all baseline demographic, socio-economic, geographic, and health characteristics (entered categorically, as in Table 1).

Statistical analyses were conducted in 2012 and 2013 using Stata 11.

3 RESULTS

3.1 Characteristics of study participants

The one- and two-year study samples had very similar characteristics (Table 1), and all findings were unchanged in sensitivity analyses restricted to those who provided data at both time points. Comparisons of the study population with the general population (given in Appendix B) showed that participants included fewer young adults than the general population (e.g. 7% in the two-year sample vs. 26% of adults locally) and were also somewhat healthier, better-educated and less likely to have children. Otherwise the study population appeared to be broadly representative in its demographic, socio-economic, travel and activity-related characteristics.

Table 1: Study participants' characteristics at baseline†

Domain	Variable	Level	N (%) in 1-year sample	N (%) in 2-year sample
Geographic	Site	Southampton	523 (28%)	425 (28%)
		Cardiff	596 (32%)	487 (32%)
		Kenilworth	730 (39%)	598 (40%)
	Proximity of home to greater Connect2 (km)	≥4	178 (10%)	144 (10%)
		3-3.99	137 (7%)	106 (7%)
		2-2.99	291 (16%)	229 (15%)
		1-1.99	631 (34%)	490 (33%)
		<1	612 (33%)	541 (36%)
Demographic	Sex	Female	1006 (54%)	857 (57%)
		Male	843 (46%)	653 (43%)
	Age (years) at baseline	18-34	241 (13%)	144 (10%)
		35-49	379 (21%)	300 (20%)
		50-64	607 (33%)	532 (35%)
		65-89	616 (33%)	530 (35%)
	Ethnicity	White	1771 (97%)	1460 (97%)
		Non-White	64 (3%)	45 (3%)
	Any child under 16	No	1547 (84%)	1276 (85%)
		Yes	301 (16%)	234 (16%)
Socio-economic status	Highest educational level	Tertiary or equivalent	715 (39%)	590 (39%)
		Secondary school†	619 (34%)	490 (33%)
		None or other	495 (27%)	425 (28%)
	Annual household income	>£40,000	582 (34%)	451 (32%)
		£20,001-40,000	543 (32%)	469 (33%)
		≤£20,000	565 (33%)	488 (35%)
	Employment status	Working	938 (51%)	740 (49%)
		Student	48 (3%)	25 (2%)
		Retired	704 (38%)	609 (40%)
		Other	152 (8%)	134 (9%)
Car and bicycle access	Any car in household	No	247 (13%)	215 (14%)
		Yes	1599 (87%)	1290 (86%)
	Any adult bicycle in household	No	768 (45%)	620 (45%)
		Yes	948 (55%)	768 (55%)
Health	Weight status	Normal/underweight	879 (50%)	702 (49%)
		Overweight	633 (36%)	534 (37%)
		Obese	244 (14%)	201 (14%)
	General health	Excellent/good	1437 (79%)	1168 (78%)
		Fair/poor	388 (21%)	324 (22%)
	Long-term illness or disability that limits daily activities	No	1295 (75%)	1046 (74%)
		Yes	441 (25%)	374 (26%)

Notes: km=kilometres. † 'A' Levels, GCSEs or equivalent. Results based on 1849 British adults participating in 2010 and 2011, and 1510 participating in 2010 and 2012: numbers add to less than the total sample size for some variables due to missing data.

3.2 Trends in levels and sources of CO_2 emissions from motorised travel

Mean CO_2 emissions from all motorised surface passenger travel decreased slightly over the study time horizon. At one-year follow-up, mean CO_2 emissions were 31 kilograms of CO_2 ($kgCO_2$) per person per week, an estimated 1.7 $kgCO_2$ lower than at baseline (95%CI 0.4, 2.9). At two-year follow-up, mean emissions were 3.0 $kgCO_2$ lower than baseline (1.6, 4.3). These mean levels correspond to about 1.5 to 1.6 tonnes of CO_2 (tCO_2)

per person per year,[5] figures comparable to government estimates of per capita road transport emissions in Great Britain [38, 39].[6] The proportion of transport emissions attributable to car travel decreased from 89% (baseline) to 88% (one-year follow-up) and 86% (two-year follow-up), with the shortfall being made up by other public and private motorised travel. Further details on raw levels and changes in CO_2 emissions by journey purpose can be found in the Appendix C.

3.3 Effect of Connect2 exposure on CO_2 emissions from motorized travel

Table 2 provides evidence as to whether the changes in CO_2 emissions described above were associated with distance from or use of Connect2. For illustration, Figure 3 depicts this information for changes in total CO_2 emissions at two-year follow-up with additional subdivision of some exposure categories (one-year follow-up results are illustrated in Appendix C). Overall we could not detect any significant effects of either use or proximity on CO_2 emissions, regardless of whether these were examined overall or disaggregated by journey purpose ('commuting' or 'social/leisure'). Specifically, there was no evidence that distance from the 'greater' Connect2 projects predicted changes in total CO_2 emissions (all $p>0.36$ for heterogeneity), and visual inspection did not indicate any consistent sense of non-significant trends. There was likewise no evidence of an association when using distance from the 'core' Connect2 project (all $p>0.17$) or Connect2 use (all $p>0.05$, most $p>0.2$: see Table 2) as the exposure, or of a difference between use of the more-complete projects at Cardiff and Southampton and that of the less-complete project at Kenilworth (data not shown). Finally, there was no convincing evidence of differential effects across subpopulations in tests for interactions between Connect2 exposure and pre-specified individual and household characteristics.

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[5] We multiplied the weekly total by 47 (not 52), thus discounting 5 weeks of 'time away from home' (e.g. school holidays, public holidays). This was deemed appropriate since the measurement week fell outside those periods.

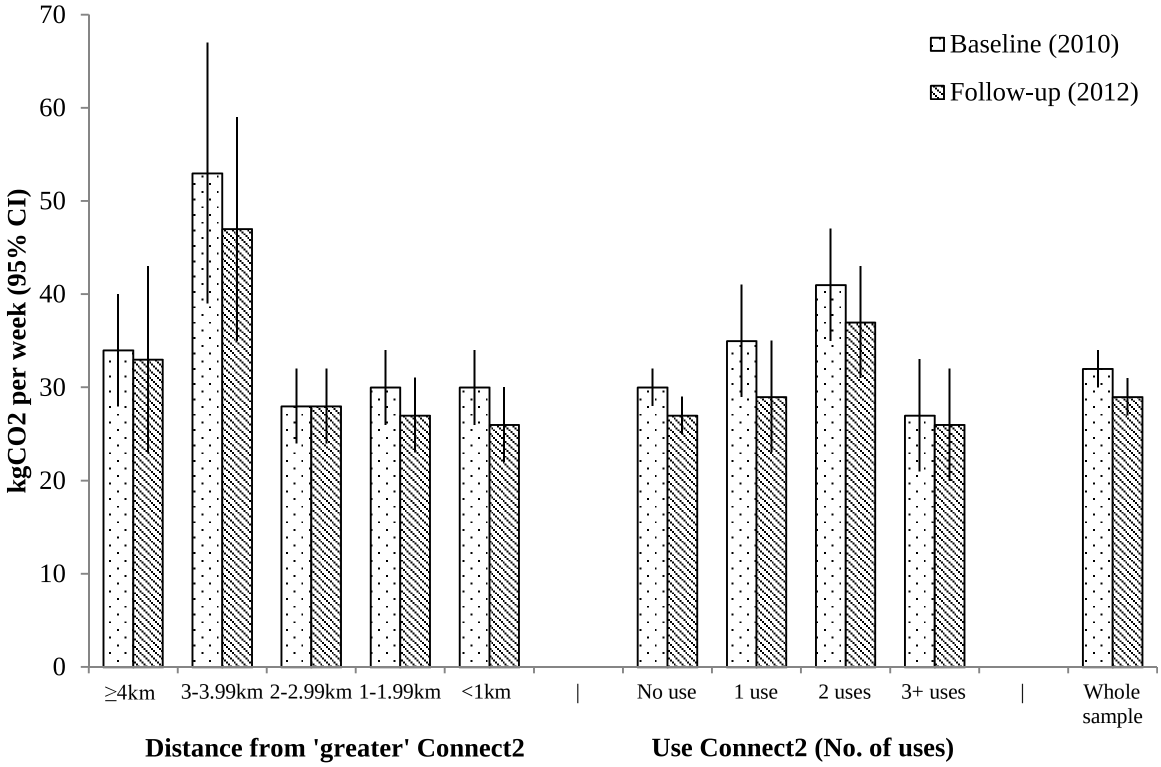
[6] Mean road transport emissions per capita in 2010 were 2.2 tCO_2. Taking away emissions from road freight (about 30% of total road transport emissions) we arrive at 1.54 tCO_2 per capita.

Table 2: Impact of various measures of Connect2 exposure upon one- and two-year change in total CO_2 emissions

Outcome behaviour	Exposure	One-year change, from 2010 to 2011: unstandardised regression coefficients (95%CI)			Two-year change, from 2010 to 2012: unstandardised regression coefficients (95%CI)		
		Minimally-adjusted for sex, age & site	Adjusted for baseline characteristics	Sensitivity analysis (adjusted, excluding outliers)	Minimally-adjusted for sex, age & site	Adjusted for baseline characteristics	Sensitivity analysis (adjusted, excluding outliers)
Total transport CO_2 emissions	Change per km closer to greater Connect2	0.03 (-1.80, 1.86)	-0.08 (-1.93, 1.77)	0.39 (-0.59, 1.38)	-0.81 (-2.67, 1.04)	-0.75 (-2.59, 1.09)	0.39 (-0.63, 1.41)
	Use Connect2 for any purpose (yes vs. no)	-1.60 (-8.60, 5.40)	-2.39 (-9.40, 4.62)	1.21 (-2.61, 5.04)	0.36 (-6.23, 6.96)	0.37 (-6.20, 6.94)	-1.32 (-6.37, 3.73)
Transport CO_2 emissions (work/business/education)	Change per km closer to greater Connect2	-0.04 (-1.62, 1.54)	-0.10 (-1.67, 1.46)	0.01 (-0.75, 0.76)	-0.47 (-2.16, 1.22)	-0.48 (-2.15, 1.18)	0.03 (-0.84, 0.91)
	Use Connect2 for work/ business/education (yes vs. no)	-1.03 (-9.18, 7.11)	-0.78 (-8.04, 6.49)	-0.25 (-6.37, 5.87)	-6.35 (-14.9, 2.22)	-5.30 (-14.1, 3.44)	-7.07 (-14.4, 0.27)
Transport CO_2 emissions (personal/business/social/leisure)	Change per km closer to greater Connect2	-0.14 (-0.96, 0.68)	-0.19 (-1.01, 0.64)	0.13 (-0.55, 0.81)	-0.54 (-1.69, 0.61)	-0.47 (-1.60, 0.66)	0.26 (-0.59, 1.11)
	Use Connect2 for personal business/social/ recreation (yes vs. no)	1.74 (-1.33, 4.81)	1.54 (-1.52, 4.61)	-0.46 (-2.74, 1.82)	-0.46 (-3.29, 2.36)	-0.01 (-3.08, 3.06)	-0.91 (-3.49, 1.67)

†p<0.1, *p<0.05, **p<0.01, from linear regression analyses predicting change in CO_2 emissions. P-values for linear trend if continuous variables and for heterogeneity if categorical. CI, confidence interval; km, kilometres. Adjusted analyses adjust for baseline demographic, socio-economic, car/bike access and health characteristics (categorised as in Table 1). Adjusted sensitivity analyses are the same as the adjusted analyses except that we excluded those participants whose CO_2 emissions changed by more than 100 kg/week. Note that proximity is distance reverse scored, such that a positive association means a larger increase among those living close to Connect2. Binary use variables presented, as there was never evidence of heterogeneity among the different levels of ≥1 use.

Figure 3: Weekly CO_2 emissions at baseline and two-year follow-up, stratified by Connect2 exposure (N=1510)



In interpreting these findings it should be noted that the confidence intervals in Table 2 are comparatively wide, due to the high variability in CO_2 emissions. This in turn reduced our statistical power to detect effects. To explore this issue further, post-hoc power calculations were performed using the observed number of individuals in different exposure categories and the observed standard deviations in change scores (see Appendix D). These calculations indicated that when comparing participants living <2km versus ≥2km from greater Connect2, this study had 80% power to detect net changes between groups of 6-7 $kgCO_2$/week in total transport CO_2 emissions. These thresholds were very similar when comparing Connect2 users with non-users.

4 DISCUSSION

4.1 Key findings

Overall, we found a small but significant decrease in mean population-level emissions over the study time horizon. We believe that this reflects a secular trend in the case study regions where fuel consumption [40] and CO_2 emissions [41] from land surface passenger transport have decreased by similar rates during the time period.[7] This may largely be due to (a) the effect of the recession and increases in private motoring costs and rail ticket

[7] The latest local and regional data available to us, published in July 2013, are up to the year 2011 only. However, the trends on road transport fuel consumption and CO_2 emissions have been downward since 2008.

fares on personal mobility [9, 42] and (b) a significant decrease in average new car CO_2 emissions [43].

Against the background of this overall decreasing trend in emissions, we found no statistically significant evidence that living near Connect2 or using Connect2 predicted changes in CO_2 emissions from motorised travel at one- and two-year follow-ups. This was true across aggregated and disaggregated outcome measures, and with respect to both the primary exposure measure (distance from the infrastructure) and several secondary measures (e.g. infrastructure use).

This lack of a discernible effect on CO_2 emissions may at first be surprising given our previous findings that the new infrastructures were well-used at both one- and two-year follow-up [28] and were associated with population-level increases in walking, cycling and physical activity at two-year follow-up [29]. However, it is perhaps less surprising given the observation that our participants used Connect2 more for recreational than for transport purposes, and more for walking than for cycling – neither of which tends to substitute for motorised travel on the longer (>8 kilometres) journeys that are responsible for around 80% of CO_2 emissions from passenger transport [6, 10]. Moreover, we have previously shown that the effects of Connect2 upon walking and cycling were greatest among participants with no household car available to them [28], who may therefore have had less potential to reduce their emissions from motorised modes. Our findings are therefore consistent with an interpretation that the overall increase in walking and cycling attributable to Connect2 may have been brought about more by generating new trips than by prompting a modal shift from motorised to non-motorised travel modes.

In interpreting these findings it is worth reflecting on this study's statistical power to detect changes in CO_2 emissions. As shown in the post-hoc power calculations (Appendix D) this study had 80% power to detect differences of 6-7 $kgCO_2$/person/week or more in contrasts by distance ('live <2km', 'live >=2km') or Connect2 use ('yes', 'no'). This is comparable to a change in distance travelled by an average UK car (emitting 0.18 $kgCO_2$/km [43]) of about 36 km per week, which is comparable to the average distance travelled by car per day [9]. Similarly, it equates to about two-fifths the size of the difference between emissions from residents with no car available vs. those with at least one car available, or half the difference between those with at least one car available vs. those with two cars available to them (9 vs. 28 vs 42 $kgCO_2$/week in the baseline sample as shown in [17]). The study was therefore able to detect relatively moderate differences in travel CO_2 emissions, but lacking the power to detect smaller changes.

4.2 Strengths and limitations

The main strengths of this study include its cohort design, population-based sampling and use of a graded measure of exposure to enable controlled comparisons within the local populations. These represent important methodological advances on most previous studies on active travel and mode share (as potential precursors of CO_2 emissions) which used repeat cross-sectional designs [44-46], only sampled infrastructure users [47] or used control groups which were not comparable at baseline [48]. Crucially, no previous study of this kind has estimated the effects on CO_2 emissions. These study strengths allowed the examination of substantive questions such as those regarding the effects on CO_2 emissions from motorised travel by journey purpose and transport mode. The approach has therefore the potential to be used by other researchers attempting to design and execute CO_2 evaluations of complex infrastructural interventions in diverse contexts and circumstances.

Nevertheless, this study had several key limitations. Although the study sought to minimize measurement error by using seven-day recall instruments appropriate to the specific outcomes under investigation, the CO_2 emissions outcomes still had high standard deviations (mainly due to social variability) and this reduced statistical power. The study was therefore able to detect relatively moderate changes in CO_2 emissions, but lacked the power to detect smaller changes. Future evaluative research may address this limitation of small effect sizes by increasing the sample size and/or focussing solely on short trips below 8 kilometres where we would expect lower variability in the main outcomes. A second key limitation is the potential for selection bias: given the relatively low response rate, the study population cannot be assumed to be representative. Yet although older than the general population on average, participants generally appeared fairly similar in their demographic, socio-economic and travel-related characteristics (Appendix B). Moreover, we know of no reason to expect bias in the pattern of *associations* and, in particular, no reason to expect differential biases with respect to the primary exposure measure of distance from the intervention.

5 CONCLUSIONS

This paper set out to evaluate the population-wide impacts of new high-quality walking and cycling infrastructure in the UK on CO_2 emissions from motorized travel. While the new routes attracted walkers and cyclists [28] and were associated with population-level increases in walking, cycling and physical activity [29], there was no evidence that this success translated into sizeable decreases in CO_2 emissions from motorised travel across the study population. However, the findings to date cannot exclude the possibility of *small* effects of the new routes on CO_2 emissions that this study lacked the power to detect. Further research would be needed to detect small effect sizes, most likely by increasing the sample size due to the often observed high variability of CO_2 emissions from personal transport [17].

In the context of energy and climate policy, a more comprehensive approach of higher ‘doses’ of infrastructural interventions of the kind studied here, linked with ambitious active travel promotion and policies targeted at mode shift away from private motorized transport (e.g. CO_2-graded car pricing at point of use, car restraint and parking pricing in urban areas, commuter car sharing, Park-and-Bike) may be required to achieve the substantial carbon savings needed to meet climate change mitigation and energy security goals.

GLOSSARY

BMI=Body Mass Index
CI=Confidence interval
CO_2=carbon dioxide
UK=United Kingdom

AUTHORS' CONTRIBUTIONS

DO leads the iConnect work package that includes this survey, and DO and CB participated in the design of the survey. CB and AG defined the research question addressed in this paper, with CB calculating carbon emissions and AG performing statistical analyses. CB drafted the manuscript, and AG and DO revised it critically for important intellectual content. All authors read and approved the final manuscript.

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LIST OF APPENDICES

Appendix A. Maps of Connect2 intervention

This appendix contains three maps of the Connect2 intervention sites.

Appendix B. Comparison of study population versus the general population

This appendix contains a comparison of the study population versus the general population, including references.

Appendix C. Raw levels of and changes in CO_2 emissions

This appendix shows the distribution of Connect2 proximity and use at one- and two-year follow-up, and raw levels and changes in outcome variables. It also provides results on weekly CO_2 emissions at baseline and one-year follow-up, stratified by Connect2 exposure.

Appendix D. Post-hoc power calculations of effectiveness

This appendix contains a table showing observed data used in post-hoc calculations of our power to detect relative changes in our primary outcome measure in contrasts by a) distance and b) Connect2 use. It also contains a figure showing post-hoc calculations of our power to detect relative changes in total CO_2 emissions in contrasts by a) distance and b) Connect2 use.

Appendix A: Maps of Connect2 intervention

Figure A.1: Locations of UK case study sites

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Figure A.2: 'Core' and 'greater' Connect2 projects in the Southampton study site

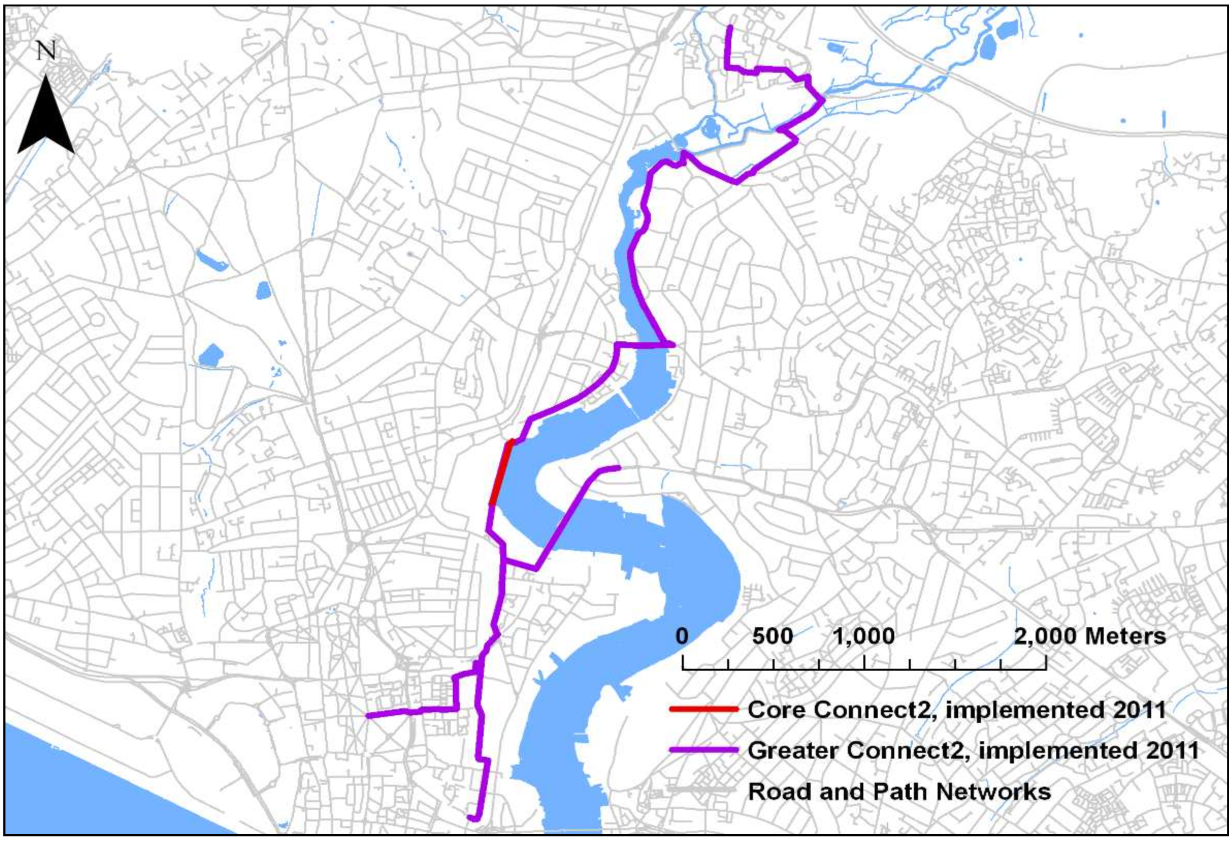
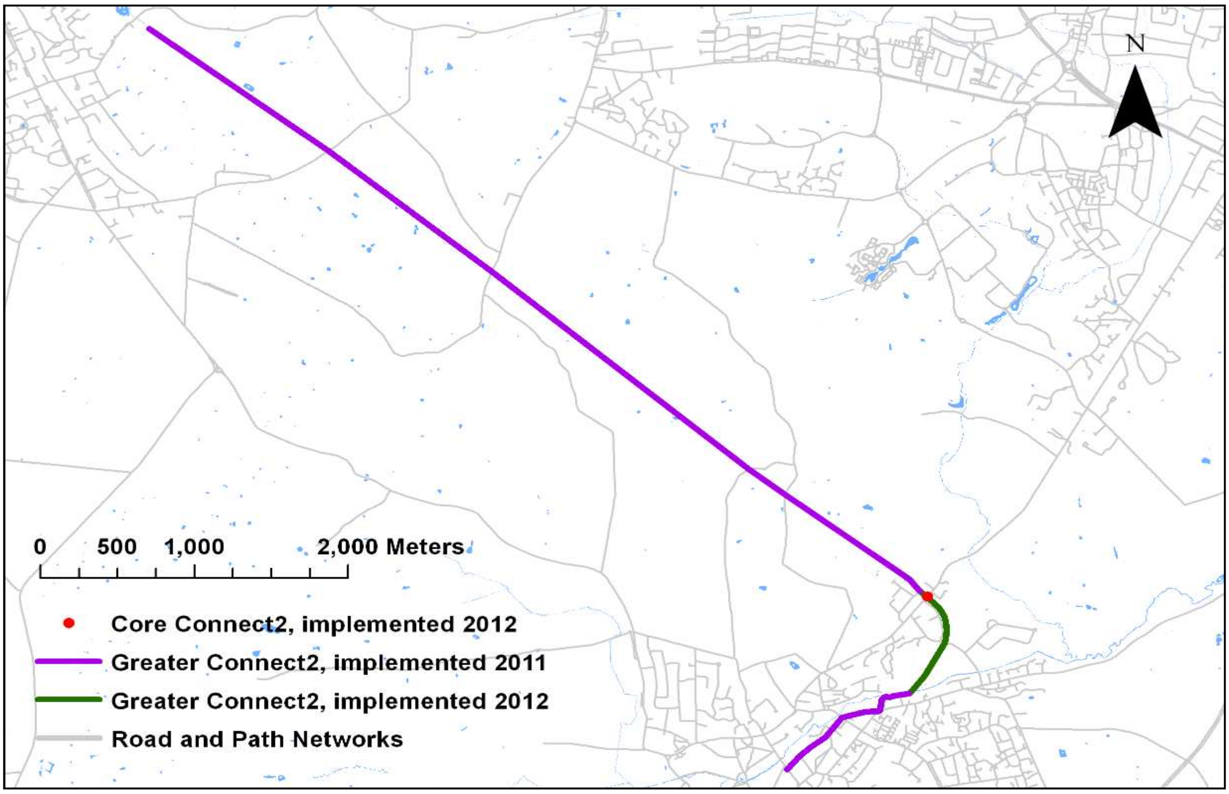


Figure A.3: 'Core' and 'greater' Connect2 projects in the Kenilworth study site



Appendix B. Comparison of study population cohorts versus the general population

Table B.1: Comparison of study population versus the general population

Domain	Baseline characteristics	Level	Study sample, *weighted by age & sex* (%)		General population (%)	Comparison population
			One year (N=1849)	Two year (N=1510)		
Demographic	Sex	Female	51	51	51	[a] Local: Office for National Statistics 2010
		Male	49	49	49	
	Age (years)	18-29	26	25	26	
		30-49	35	35	35	
		50-64	22	22	22	
		65+	17	18	17	
	Ethnicity	White	94	94	94	[b] Local: Census 2001
		Non-White	6	6	6	
	Any child under 16	No	78	77	60	
		Yes	22	23	40	
	Urban/rural status	Urban	96	96	94	
		Rural	4	5	6	
Socio-economic	Highest educational qualification	Degree	44	46	26	[b] Local: Census 2001
		A-level	20	21	11	
		GCSE	16	15	16	
		None or other	20	18	46	
	Tenure	Home owner	78	79	70	
		Renting	22	21	31	
	Employment status	Employed	64	62	64	
		Unemployed	2	2	3	
		Student	7	8	6	
		Other econ. inactive	27	28	27	
Health	Weight status	Normal/underweight	57	57	39	[c] National Health Survey for England 2009
		Overweight	32	32	38	
		Obese	11	11	23	
	General health	Excellent/good	79	77	63	[b] Local: Census 2001
		Fair/poor	21	23	37	
	Long-term limiting illness	No	82	83	79	
		Yes	18	17	21	
Travel	Cars per adult in household	No cars	15	15	20	[b] Local: Census 2001
		<1 car per adult	39	39	35	
		≥1 cars per adult	46	46	44	
	Main mode to work (mode involving the greatest dist.)	Car	70	72	73	
		Public transport	12	12	10	
		Walk	10	9	13	
		Cycle	9	7	4	
	Percentage travel distance covered by different modes	Car	75	77	78	[d] National: National Travel Survey, 2010
		Bus or train	17	15	14	
		Walk	4	4	3	
		Cycle	2	2	1	
		Other modes	2	2	4	

[a] ONS mid 2010 population estimates (Office for National Statistics 2011), percentages calculated by authors. We included all adult residents (aged ≥16 years) living in the three local authorities from which we drew our study samples, giving equal weighting to each local authority.

[b] Census 2001 5% sample in Small Area Microdata (Office for National Statistics 2004), percentages calculated by authors. We included all adult residents (aged >20 years) living in private households in the

three local authorities from which we drew our study samples, giving equal weighting to each local authority. To ensure comparability, we also restricted our study sample to those aged 20 or more (97% of sample) when making comparisons with the census data.
[c] Health Survey for England 2009, adult sample (NHS Information Centre 2010)
[d] National Travel Survey 2010 (Department for Transport 2009).

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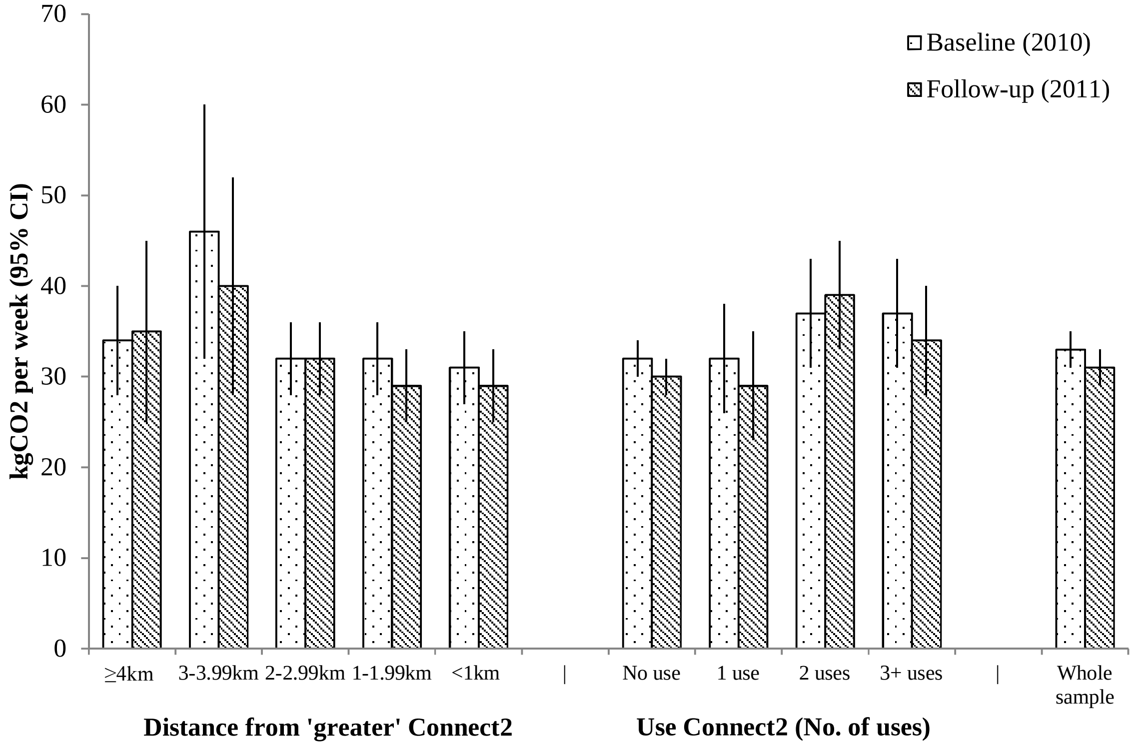
Appendix C. Raw levels of and changes in CO_2 emissions

Table C.1: Distribution of Connect2 proximity and use at one- and two-year follow-up, and raw levels and changes in outcome variables

Outcome behaviour	Exposure	Levels	One-year change in $kgCO_2$/week for CO_2 outcome, and min/week in all W&C				Two-year change in $kgCO_2$/week for CO_2 outcome, and min/week in all W&C			
			N (%)	2010 mean (SE)	2011 mean (SE)	Mean change (SE)	N (%)	2010 mean (SE)	2012 mean (SE)	Mean change (SE)
Transport CO_2 emissions (total)	Whole sample	-	1849	33 (1)	31 (1)	**-2 (1)**	1510	32 (1)	29 (1)	**-3 (1)**
	Proximity to greater Connect2	≥4km	178 (10%)	34 (3)	35 (3)	**1 (2)**	144 (10%)	34 (3)	33 (5)	**-1 (5)**
		3-3.99km	137 (7%)	46 (5)	40 (4)	**-6 (4)**	106 (7%)	53 (7)	47 (6)	**-7 (5)**
		2-2.99km	291 (16%)	32 (2)	32 (4)	**0 (3)**	229 (15%)	28 (2)	28 (2)	**-1 (2)**
		1-1.99km	631 (34%)	32 (2)	29 (2)	**-2 (2)**	490 (32%)	30 (2)	27 (2)	**-3 (2)**
		<1km	612 (33%)	31 (2)	29 (2)	**-1 (2)**	541 (36%)	30 (2)	26 (2)	**-4 (2)**
	Any Connect2 use	No	1251 (69%)	32 (1)	30 (1)	**-2 (1)**	933 (63%)	30 (1)	27 (1)	**-3 (1)**
		Yes, 1 type	266 (15%)	32 (2)	29 (2)	**-3 (2)**	254 (17%)	35 (3)	29 (3)	**-6 (3)**
		Yes, 2 types	186 (10%)	37 (4)	39 (6)	**2 (5)**	187 (13%)	41 (3)	37 (3)	**-4 (3)**
		Yes, 3-12 types	123 (7%)	37 (5)	34 (4)	**-3 (4)**	116 (8%)	27 (3)	26 (3)	**-1 (3)**
Transport CO_2 emissions (work/ business/ education)	Whole sample	-	1849	17 (1)	17 (1)	**0 (1)**	1510	15 (1)	14 (1)	**-1 (1)**
	Proximity to greater Connect2	≥4km	178 (10%)	18 (2)	19 (2)	**1 (2)**	144 (10%)	17 (2)	17 (4)	**0 (5)**
		3-3.99km	137 (7%)	25 (5)	23 (4)	**-2 (3)**	106 (7%)	31 (6)	29 (6)	**-3 (5)**
		2-2.99km	291 (16%)	17 (2)	19 (4)	**2 (3)**	229 (15%)	14 (2)	14 (2)	**0 (2)**
		1-1.99km	631 (34%)	15 (1)	14 (1)	**-1 (1)**	490 (32%)	12 (1)	11 (1)	**-1 (1)**
		<1km	612 (33%)	16 (2)	15 (2)	**-1 (2)**	541 (36%)	16 (1)	14 (1)	**-2 (1)**
	Use Connect2 for work/ business/ education)	No	1777 (97%)	17 (1)	17 (1)	**0 (1)**	1439 (97%)	15 (1)	14 (1)	**-1 (1)**
		Yes	49 (3%)	16 (4)	15 (3)	**-2 (3)**	51 (3%)	24 (5)	18 (4)	**-7 (4)**
Transport CO_2 emissions (personal business/ social/ leisure)	Whole sample	-	1849	16 (1)	15 (1)	**-1 (1)**	1510	17 (1)	15 (1)	**-2 (1)**
	Proximity to greater Connect2	≥4km	178 (10%)	16 (1)	17 (2)	**1 (2)**	144 (10%)	18 (2)	16 (2)	**-1 (2)**
		3-3.99km	137 (7%)	21 (2)	18 (2)	**-3 (2)**	106 (7%)	22 (2)	19 (2)	**-3 (3)**
		2-2.99km	291 (16%)	15 (1)	14 (1)	**-1 (2)**	229 (15%)	15 (1)	14 (1)	**-1 (2)**
		1-1.99km	631 (34%)	17 (1)	16 (1)	**-1 (1)**	490 (32%)	18 (2)	16 (1)	**-2 (1)**
		<1km	612 (33%)	15 (1)	14 (1)	**-1 (1)**	541 (36%)	15 (1)	12 (1)	**-3 (1)**
	Use Connect2 for personal business/social/ recreation)	No	1278 (69%)	16 (1)	15 (1)	**-1 (1)**	1042 (69%)	16 (1)	14 (1)	**-2 (1)**
		Yes, 1 type	380 (21%)	16 (1)	17 (1)	**1 (2)**	302 (20%)	19 (1)	16 (1)	**-3 (2)**
		Yes, 2-6 types	191 (10%)	18 (2)	16 (2)	**-2 (2)**	166 (11%)	15 (2)	14 (2)	**0 (2)**

Notes: $kgCO_2$=kilogram of carbon dioxide; SE=standard error of the mean; km=kilometres; all W&C=all walking and cycling.

Figure C.1: Weekly CO_2 emissions at baseline and one-year follow-up, stratified by Connect2 exposure (N=1849)



Appendix D. Post-hoc power calculations of effectiveness

Table D.1: Observed data used in post-hoc calculations of our power to detect relative changes in our primary outcome measure in contrasts by a) distance and b) Connect2 use

Outcome	SD of change score ($kgCO_2$/week) One-year follow-up (2010 to 2011)				SD of change score ($kgCO_2$/week) Two-year follow-up (2010 to 2012)			
	Distance from greater Connect2		Connect2 use		Distance from greater Connect2		Connect2 use	
	Live ≥2km (N=606)	Live <2km (N=1243)	Non-user (N=1240)	Users (N=586)	Live ≥2km (N=479)	Live <2km (N=1031)	Non-user (N=927)	Users (N=563)
Transport CO_2, total	46.5	45.0	41.5	53.0	48.7	40.3	44.2	42.0

Figure D.1: Post-hoc calculations of our power to detect relative changes in total CO_2 emissions in contrasts by a) distance and b) Connect2 use