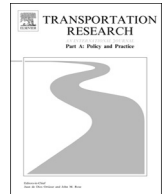




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Assessing the potential for carbon emissions savings from replacing short car trips with walking and cycling using a mixed GPS-travel diary approach

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ABSTRACT

There is a growing recognition of the role that walking and cycling can make in reducing greenhouse gas (GHG) emissions by substituting motorized travel, particularly on short trips. However, there is a lack of evidence at the micro level on the realistic, empirically derived potential of walking and cycling to displace motorized travel and thus reduce GHG emissions. The aim of this study was to investigate the potential for GHG emissions savings from replacing short car trips with walking and cycling and the extent to which high quality infrastructure for walking and cycling may influence day-to-day travel decisions, change the spatial and temporal nature of local journeys and impact on overall GHG emissions from motorised travel.

To achieve this aim this study conducted an in-depth observational study of a purposively selected cohort of 50 residents in Cardiff, Wales. Using a mixed-method approach detailed quantitative and qualitative data were collected for each participant using personal Global Position System (GPS) devices, 7-day travel diaries and contextual interviews over two seasonally matching 7-day time periods in 2011 and 2012. GHG emissions for motorized travel modes were derived using journey distance, vehicle technology details and average speeds obtained from the GPS data. The spatial and contextual data provided new insights into the complexities of walking behaviour and factors influencing cycling for everyday travel or recreation, including route choice decisions, activity destinations and the role of the new infrastructure to enable change.

We found significant potential of active travel to substitute short car trips, with sizeable impacts on carbon emissions from personal travel. Half of all car trips were less than 3 miles long. Taking into account individual travel patterns and constraints, walking or cycling could realistically substitute for 41% of short car trips, saving nearly 5% of CO₂e emissions from car travel. This was on top of 5% of 'avoided' emissions from cars due to existing walking and cycling. The evolving high quality walking and cycling infrastructure in the case study area was unlikely to promote a significant reduction in carbon emissions from (displaced) car journeys on its own.

The study contributes to the debate on how to achieve stringent low carbon targets in urban transport. The combination of methods for data collection developed and employed in this study also helps to inform future research on the wider environmental impacts of active travel, including 'co-benefits' of improved air quality, reduced noise and reduced fossil fuel use.

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1. Introduction

Policies and strategies focused on reducing greenhouse gas (or carbon dioxide equivalent, CO₂e) emissions from transport have primarily focused on techno-economic, regulatory and pricing measures such as improving vehicle efficiency through technological innovation and standards, fuel switching to low carbon fuels (electric vehicles, biofuels), and CO₂e-graded vehicle road taxation and fuel duties (Brand et al., 2013a; Santos et al., 2010). Walking and cycling for transport ('active travel') are widely assumed to substitute for at least some motorized travel and thereby reduce CO₂e emissions (de Nazelle et al., 2010; DfT, 2011; ECF, 2011; Goodman et al., 2012; Ogilvie et al., 2004; Sælensminde, 2004). This assumption is supported by the findings that bicycle access is negatively correlated with CO₂e emissions from motorized travel (Brand et al., 2013b), that energy expenditure from walking is negatively correlated with fossil fuel use from car driving (Frank et al., 2010a) and that individuals in more 'walkable' neighbourhoods make more walking trips and travel fewer vehicle kilometres (Frank et al., 2007). Although cycling cannot be considered a 'zero-carbon emissions' mode of transport, lifecycle emissions¹ from cycling can be more than ten times lower per passenger-km travelled than those from passenger cars (ECF, 2011). Also, due to so called 'cold start' excess emissions during the start phase of trips, short car trips have a higher impact per mile on air pollution and CO₂e emissions than longer journeys, especially in the winter (Beckx et al., 2010; Brand et al., 2013b; de Nazelle et al., 2010; Vagane, 2007). For these reasons, promoting active travel is increasingly recognised as a key element of low carbon strategies (de Nazelle et al., 2010; Kahn Ribeiro et al., 2007; Lindfeldt et al., 2010; Lovelace et al., 2011; Maibach et al., 2009; Pucher et al., 2011; Rabl and de Nazelle, 2012) with potential climate change, energy, air quality and health 'co-benefits' (Haines et al., 2009; Rabl and de Nazelle, 2012; Woodcock et al., 2009).

In many countries, the majority of trips made by car are short-distance journeys to work, education or shopping (Kahn Ribeiro et al., 2007; SIKA, 2007). In the United Kingdom (UK), for instance, about one fifth of CO₂e emissions and transport energy use come from car journeys of less than 8 km which could be made by foot or bicycle (DfT, 2009; Preston et al., 2013). As travel time and distance influence mode choice, people are less likely to walk or to cycle above certain thresholds (Bergström and Magnusson, 2003; Dill and Gliebe, 2008; Ellison and Greaves, 2011; Tilahun et al., 2007). The definition of what is a 'short trip' varies between studies, but it is commonly agreed that trips that are between 3 and 5 miles (8 km) can be defined as short (Beckx et al., 2013; Mackett, 2003). However, when considering potential of replacement of these same trips by walking and cycling, some suggest that the distance people are willing to walk or cycle can vary between 0.5 and 2 miles for walking (Vojnovic, 2006) and between 1.5 and 4.7 miles for cycling (Hartog et al., 2010). In a recent study on walking and cycling in the UK, Pooley et al. (2011) were more conservative and defined 0.5 miles (0.8 km) and 1.5 miles (2.4 km) as distances people would be willing to walk or to cycle, respectively, based on the assumption that this is the distance travelled by each mode of transport over an acceptable uninterrupted travel time of 10–15 min. In the UK, the National Travel Survey (ONS, 2015) reports that the average (not maximum) walking trip is 0.7 miles (1.1 km), and the average distance cycled is 2.9 miles (4.7 km). Arguably it would be feasible for most people to walk or cycle for up to 15–20 min, which translates into distances of 1 mile for walking and 3 miles for cycling. So, as there is no clear definition of what constitutes a 'short trip' we took a relatively conservative approach and defined short trips as all trips under 3 miles (5 km) in length.

The CO₂e emissions implications of a modal shift from motorized transport to walking and perhaps more significantly to cycling have received relatively little attention. The complex relationships between energy use, CO₂e emissions and transport have been investigated in general but active travel analysis is often based on analyses of the potential for emissions mitigation (Yang et al., 2018), based on the generation of scenarios (Lovelace et al., 2011; Tainio et al., 2017; Woodcock et al., 2007) or not able to detect small effect sizes (Brand et al., 2014). In particular, there is a limited understanding at the detailed micro level about the role of high quality infrastructure for pedestrians and cyclists on people's everyday travel behaviour and CO₂e emissions from personal travel (Brand et al., 2013b; Goodman et al., 2012). Much of the evidence suggests that a clear distinction between active modes (walking and cycling), journey purposes ('for recreation' or the various trip purposes 'for transport') alongside a better understanding of the social and environmental context in which travel takes place is crucial to provide good evidence (Frank et al., 2010b; Heinen et al., 2017; Song et al., 2017; Winters et al., 2017).

The use of GPS technology in studies of walking and cycling is a fairly recent if growing development. It has been recognized in the transport, mobility and health literatures that the methodology of combining tracking technology with more traditional (paper and pen) travel surveys is promising in order to obtain more reliable and accurate data, in particular for walking and cycling where under-reporting (e.g. walking) and over-reporting (e.g. cycling distance) have been a problem with travel surveys and diaries. Also, GPS based surveys enable researchers to collect data on trips and trip chaining, journeys distance, journey time and route taken at a level of detail not possible with traditional survey methods. In the context of evaluation of the impact of new infrastructure for walking and cycling, this methodology is promising for understanding and monitoring the temporal and spatial complexities of travel behaviour, which may be lost in frequency and/or distance-only based travel diaries. Although GPS-based surveys have distinct advantages they are (still) resource intensive, making it challenging to be applied to larger populations or samples, as for example explored with a traditional paper and pen survey instrument in the wider iConnect study (Ogilvie et al., 2012b; Ogilvie et al., 2011).

The purpose of this paper is to explore in detail the potential for CO₂e emissions reductions from substituting short car trips by walking and cycling in a real life setting. Using primary data collected in an observational study of 50 participants in the case study city of Cardiff, Wales, the paper provides detailed, spatially and temporarily explicit insights into people's travel behaviour and the potential for change based on those insights. In addition, this paper also explores the role of new walking and cycling infrastructure in

¹ There are energy losses associated with extraction and manufacturing of raw materials during bicycles and parts production, such as aluminium, steel and rubber. Additionally, dietary intake of cyclists is estimated to be 21 g of CO₂e energy per passenger kilometre travelled (ECF, 2011).

supporting modal shift and contributing to CO₂e emissions reductions at the local level, using a physical infrastructure intervention at Cardiff as a case study.

This paper first describes the overall approach, methods and data used. The first results section then presents the observed patterns of short car trips in Cardiff and the likely reasons influencing such modal choice. Following on from this, we assess the potential for replacement of short car trips with walking and cycling based on journeys distance, journey purpose and contextual factors (e.g. trip chaining involving a cycling stage). We then examine the CO₂e emissions impacts of short car trips based on observed travel activity data, followed by an assessment of the CO₂e emissions mitigation potential of walking and cycling. The paper concludes with a synthesis of the main findings and a discussion of how walking and cycling can contribute to the transition to a low carbon transport system within the spatial context of Cardiff.

2. Methodology

2.1. Case study site

We selected Cardiff as the natural experimental setting for this in-depth study, as the site was one of the larger *Connect2* projects (Ashden UK, 2013) set in an urban area and one of the three *iConnect* study (Ogilvie et al., 2011) core sites, which provided a unique opportunity to use the ‘core data’ collected through the *iConnect* baseline survey (Ogilvie et al., 2012a) and to receive support with participants’ recruitment.²

The Cardiff *Connect2* Scheme consisted of five elements, including a new traffic free bridge over the river Ely, opened in 2010, and improved link routes for pedestrians and cyclists (completed between 2011 and 2013) that increased connectivity between Penarth, Cardiff Bay Area facilities and Cardiff City Centre (Fig. 1). The aim of the scheme was to enable commuters to walk or cycle from Penarth into Cardiff (or the opposite way) and local residents to access the leisure and commercial facilities in the Bay and in Penarth without the need to travel by car. Further details on the geographical scope and timing of implementation are given in [Supplementary Material SM3](#).

2.2. Study approach

This study followed a mixed method (Bryman, 2006) quantitative driven approach with the quantitative measurement of travel behaviour using GPS devices and a 7-day travel diary at its core. Qualitative data collected in interviews were added to supplement and provide a deeper understanding of the quantitative data, including a more realistic assessment of the potential for change. These three measurement methods are outlined in [Table 1](#).

We further adopted an in-depth case study design by recruiting and observing a cohort of 50 residents over two waves in 2011 and 2012. Although the bridge was the first element of the scheme to be completed in 2010, further key elements linking the bridge to the walking and cycling network in Penarth and Cardiff as well as new pieces of infrastructure were completed only in the following three years up to 2013. The second wave therefore offered improved measurement accuracy and validation for the first wave as well as a year-on-year assessment of change while the scheme was being implemented. Overall, this approach was found as the most appropriate research design in meeting the objectives of this study within the timeframe of a 3-year research project, as it provided the opportunity to accurately measure detailed travel behaviour and CO₂e emissions at detailed individual as well as community levels.

2.3. Data and methods

The two main methods employed in this study for data collection were a GPS based 7-day travel survey (using a combination of GPS loggers and 7-day travel diary) and collection of contextual data (through an exit interview and qualitative observations).

2.3.1. 7-day GPS data

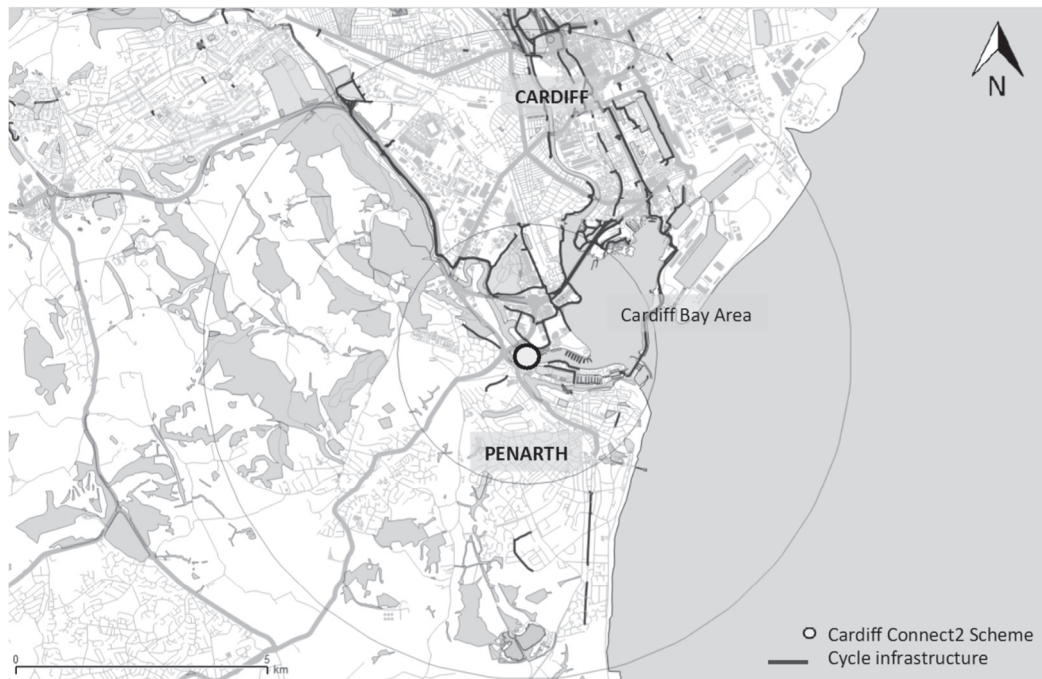
Traditional travel surveys or travel diaries are limited by poor data quality on journey distance and duration, underreporting of short trips and, more importantly for this study, lack of information on route choice. GPS devices can provide the ability to record accurate data on trip time and distance, speed and route taken. For this study, we used a personal GPS travel recorder (or GPS logger), the Qstarz BT – Q1000 XT device, made available by the funding body (EPSRC) through the *iConnect* project (grant agreement EP/G00059X/1). Further details are provided in the [Supplementary Material SM1](#).

2.3.2. 7-day travel diary

In order to overcome the issues with trip mode and trip purpose identification from GPS raw data,³ an adapted version of a seven-

² From the 84 available sites, the *iConnect* study selected three in-depth case studies sites using a combination of criteria such as accessibility to researchers, likelihood of measurable population impact, heterogeneity overall mix sites, risk that the project would not be implemented and expected timetable for implementation of the project. The three core study sites defined were Cardiff, Kenilworth and Southampton (Ogilvie et al., 2012a,b).

³ GPS devices can give very accurate information regarding trip route, distance, speed and duration; however, they do not record trip mode or purpose. Recent studies have been looking at potential ways of deriving this information from GPS raw data but it is still nowadays difficult to



Notes: The inner and outer circles denote respective 1.5 mile (2.4 km) and 4 mile (6.4 km) buffers around the ‘core’ element of the scheme, the bridge over the river Ely.

Fig. 1. Location of the Connect2 project, in relation to Cardiff city. Notes: The inner and outer circles denote respective 1.5 mile (2.4 km) and 4 mile (6.4 km) buffers around the ‘core’ element of the scheme, the bridge over the river Ely.

Table 1

Travel attributes recorded using mixed method approach developed in this study.

Attributes recorded	Measurement methods		
	GPS survey	Travel diary	Exit interview
Trip origin/destination	++	+	–
Trip route	++	–	–
Trip start/end time (duration =	++	+	–
Trip distance	++	–	–
Trip speed (average speed, maximum speed)	++	–	–
Trip purpose	*	+	–
Trip mode	*	+	–
Trip context	*	+	+
Reasons underlying changes in travel behaviour	–	–	+
Attitudes, motivations and perceived barriers towards walking and cycling in the local area	–	–	+
Perceived significance of new infrastructure for walking and cycling	–	–	+
		++	<i>objectively measured</i>
		+	<i>subjectively measured</i>
		–	<i>not provided</i>
		*	<i>attribute derived</i>

day travel diary was also developed for this study. This travel diary was designed with several important aspects in mind. Firstly, it focused on capturing only trip features required to validate GPS data: trip mode and trip purpose needed to be reported but not trip distance (the latter is a variable that participants usually struggle to fill-in traditional travel surveys). Secondly, this travel diary provided a dedicated section for recording contextual information that could enhance understanding of trips recorded, such as atypical conditions influencing journeys made. Thirdly, the design element of the travel diary aimed for clarity and minimization of written entry. For example, travel modes were recorded by marking a cross on a dedicated column of symbols representing different

(footnote continued)

process the enormous amount of data generated and to efficiently derive mode and purpose with total certainty relying exclusively on GPS data.

transport modes. Additionally, there was no need to repeatedly write the start point of the journey as it was assumed that the previous journey destination was also the origin of the journey that followed. Finally, the supplementary use of a travel diary also acted as a backup for the collection of data that the accompanying GPS failed to record. Further details are provided in the [Supplementary Material SM2](#).

2.3.3. Semi-structured interviews

A semi-structured exit interview was conducted with each participant on the last of four face-to-face meetings in order to provide context (the 'why') to the quantitative travel behaviour data. The exit interview was framed around the *iConnect* project evaluation framework (Ogilvie et al., 2011), which in turn was based on Pawson and Tilley's realist evaluation framework (Pawson and Tilley, 1997). This stipulates that context matters in explaining why change may happen (or may not happen), therefore providing important clues as to the potential for change. The interviews were guided with the intention to collect participants' views on the: a) perceived change in overall travel behaviour (and therefore CO₂e emissions) and the underlying barriers to and drivers for change; b) perceived role of walking and cycling in everyday travel (to gauge the potential for mode shift); c) perceptions and opinions on transport infrastructure and, in particular, walking and cycling facilities in the area. The qualitative data collected during the interviews was transcribed into a Word document and grouped into analytical categories to undertake content analysis.

2.3.4. Feasibility and reliability testing

A pilot study for testing the feasibility and reliability of the data collection methods was conducted with fourteen participants in Oxford during August 2010. Based on the feedback, some of the materials and protocol were adjusted, including confirmation of using a 7-day data collection period (as opposed to 4 days) and improvement of the legibility and scope of the travel diary.

2.3.5. Sample selection and size

The *iConnect* baseline survey in Cardiff generated a total of 1020 responses (Goodman et al., 2013; Goodman et al., 2014a). From this group, 659 respondents agreed to be contacted in the future for further research. The sampling frame was purposively selected by excluding those who had indicated to have no intention to do more journeys on foot or by bicycle in the future ($n = 129$) (the intention variable). The aim was therefore to focus on participants who were more likely to change travel behaviour in the short-term ('near-market') and explore mechanisms of change at the micro-level detail during the period of the study. From the 530 available respondents, 400 were randomly selected and an invitation sent to their household address. In 2011, 23% of the 400 respondents contacted confirmed their willingness to take part in this study. These people were contacted shortly after by phone or email to confirm their interest and to arrange an initial visit to their homes to commence the study. A total of 71 participants agreed to take part in the travel survey during 2011. In 2012, those participants that took part in the study in the previous year and from whom travel data records were valid ($n = 69$) were invited to take part in the study again. A positive response rate of 73.9% was achieved in this second year of the survey. The main reason for general dropout between waves was that participants had moved away from the case study site ($n = 5$) or were unwilling to take part in the follow up survey ($n = 11$). Therefore, the final panel sample size of this study was $n = 50$. The limitations of a purposively selected, non-representative sample are discussed later.

2.3.6. Data collection, preparation and identification

The collection of travel data in the case study site was conducted in two season-matching waves in the spring of 2011 and 2012. A total of 14 weeks was spent in the local area meeting participants, delivering and picking up devices and collecting contextual data. This meant that the researcher met each participant face-to-face on four different occasions, including the above mentioned exit interview.

An approximate total of 1,120,000 geo-coded points were recorded during the two survey periods. The level of detail in raw GPS



Fig. 2. Example of recorded car, walking and cycling tracks.

data was remarkable in most cases and a clear identification of particular trip routes, mode of travel or activity conducted at destination easily deduced (Fig. 2).

The procedure adopted for GPS data cleaning and processing used a hybrid approach based on trip identification and inference of trip mode and purpose validated by travel diary data. **Trips** were identified based on the concept that a trip is all travel between two activity nodes. Activity nodes were defined as clusters of points that were less than 50 m or more than 200 s from each other. For the ‘stay’ classification it was assumed that 7+ adjacent points within ± 2 min and 60 m distance were a stay. This is aligned with thresholds applied in other studies (Gong et al., 2012; Sorgenfri Jensen et al., 2009). Matching trips identified in GPS data with trips recorded in the travel diary was performed based on spatial (origin and destination) and temporal (time and date) features of trips. **Trip mode** was first deduced from the GPS file based on average speed, maximum speed and route taken, then validated with data from the travel diary. In case of conflict, other features were assessed, such as transport infrastructure network or past behaviour. **Trip purpose** was deduced from land use maps and visual checks and validated with travel diary data. More than 50 different expressions describing trip purpose were collected and mapped onto seven main categories based on National Travel Survey categorization (Taylor et al., 2012): commuting, business, escort and education, shopping or personal business, social and visiting friends or family, recreation and other leisure.

2.3.7. Deriving CO₂e emissions from travel activity data

CO₂e emissions from displaced motorised transport were calculated by multiplying mode, vehicle and speed specific carbon emissions factors (carbon dioxide, CO₂, methane, CH₄, and nitrous oxide, N₂O) with travel activity data (as distance travelled by mode) for each leg of a journey. In short, CO₂e emissions from passenger cars were calculated using distance travelled by trip purpose (obtained from the GPS and travel diary data) and converted into emissions by applying conversion factors that take into account car size (with engine size as a proxy), fuel type (petrol, diesel, hybrid electric, other), average vehicle speed (from GPS trip level data), vehicle age and the number of ‘cold starts’ (which causes excess emissions due to suboptimal fuel burn). The calculations applied in this study were based on road transport speed-emissions⁴ factors underlying the National Atmospheric Emissions Inventory⁵ (NAEI) and obtained from Defra (DEFRA, 2016). A similar approach was used for the core *iConnect* analyses reported elsewhere (Brand et al., 2014; Brand et al., 2013b; Goodman et al., 2012). Car technology details and age were obtained from the *iConnect* core survey datasets (Ogilvie et al., 2012a). For vans, motorcycles and public transport (bus and rail), average emissions factors for the specific regions were used, based on UK GHG reporting guidelines (DEFRA, 2016).

The CO₂e emission mitigation potential of utility walking and cycling was estimated by simulating a similar trip by car (origin and destination) and deriving associated CO₂e emissions, taking into account car details (engine size, fuel type, vehicle age) for each participant who had access to a car, average urban vehicle speeds of 40 km/h, and adding ‘cold start’ to ‘hot’ emissions based on the number of car trips, ambient temperature (annual mean of 11C) and average car trip lengths. For the estimation of annual CO₂e emissions levels, weekly totals were multiplied by 47 weeks instead of 52. As travel data collection took place between April and July in 2011 and 2012, the assumption of discounting 5 weeks ‘away from home’ (e.g. school holidays, public holidays) was in line with previous research (Brand et al., 2013b). The analytical software packages used to perform the calculations was Microsoft Excel v2016 (for computation of emissions) and SPSS v23 (for descriptive analysis).

3. Results

3.1. Sample characteristics

The purposively selected, non-representative sample was equally distributed in terms of gender (50%) and was diverse with respect to age (between 26 and 71 years old). Comparisons with local and national figures (see [Supplementary Materials, Table SM1](#)) suggest, however, that the sample showed bias towards younger people, higher levels of education, income, car ownership and home ownership. 17 participants had cycled at least once during the period of the study, either ‘for transport’ or ‘for recreational’ purposes. Most of the participants (90%) lived less than 1.5 miles (2.4 km) away from the *Connect2* infrastructures and those who were economically active 54% lived less than 5 miles away from their workplace. The most significant changes observed over the study period were related to change in jobs or economic activity ([Table SM2 in the Supplementary Materials](#)).

3.2. Overall travel activity

A total of 2664 trips were recorded during the two waves in 2011 and 2012. The 50 participants did an average of 3.8 trips (± 0.4 , 95% CI) per day, covering an average of 23.5 miles (± 6.9 , 95% CI) per day. This suggests that participants travelled slightly more frequently (1269 trips per year compared to 960 trips per year) and further (7722 miles compared to 6726 miles) than the national average (DfT, 2012). The majority of trips took place near the local case study site and were less than 5 miles long (77%).

⁴ The underlying speed-emissions curves are polynomial functions of emissions as a function of average speed, by vehicle type, fuel type, engine size and vehicle age. ‘Cold’ start emissions are dependent on the ambient air temperature, average trip lengths and the share of the trip length running ‘cold’ (Brand et al., 2013a,b).

⁵ These factors are usually used by local authorities for environmental impact assessments and by national government for reporting on national greenhouse gas emissions to the UNFCCC.

Table 2

Distribution and cumulative share of trips by mode and trip length (n = 2664).

	Walking	Cycling	Car	Public transport	Cumulative % by trip length
< 1 mile	18.3%	0.6%	7.5%	0.3%	26.7%
1–3 miles	7.1%	1.4%	22.4%	1.2%	58.8%
3–5 miles	1.4%	1.2%	11.2%	2.8%	75.4%
5–10 miles	0.0%	1.0%	12.5%	1.0%	90.3%
10–25 miles	0.0%	0.5%	4.2%	0.4%	95.4%
15–50 miles	0.0%	0.2%	1.5%	0.2%	97.2%
> 50 miles	0.0%	0.0%	2.1%	0.7%	100%

Travelling by car was the dominant mode of transport. Walking (29% mode share in this study vs. 22% national average) and cycling rates (6% in this study vs. 2% national average) were substantial above national average, and public transport mode share was lower (5% vs. 12%) (ONS, 2015).

As shown in Table 2, 59% of all trips recorded were less than 3 miles in length. Walking was the main method of travel for trips less than 1 mile (18.3%) and cycling trip frequency was relatively constant over short to medium trip lengths (between 1 and 10 miles). Car travel dominated journeys over 1 mile in length, with 30% of all trips recorded being car trips less than 3 miles long.

3.3. Existing patterns of short car trips

3.3.1. Total number of 'short trips'

We found that the average distance for utility walking and cycling trips was 1.0 miles (n = 770) and 4.1 miles (n = 103) respectively. As mentioned above, short trips were defined as trips of 3 miles or less, thus confirming our conservative approach in assessing potential shifts from car to cycling in particular. The total number of short trips recorded for all transport modes during the period of the study was 1566 (58.8%).

3.3.2. Short car trips: For what purpose, where and reasons for mode choice

Nearly half (47.7%; n = 798) of the car trips were shorter than 3 miles.⁶ The main purposes of these short car trips (46.6%) were for shopping and personal business (doctor, post office, etc). Other reasons to use the car over short distances included social purposes (17.4%) or accessing leisure activities (13.9%) (Fig. 3). Travelling to/from work or education totalled 19%.

The main destinations of short car trips in the local area are illustrated in Fig. 4. This included local shops in Penarth town centre, local leisure centres and schools on the South bank of the river Ely, and facilities on Cardiff Bay Retail Park, Cardiff City and Mermaid Quay.

The main reasons pointed out by the participants to use the car over short distances were usually related to time constraints, convenience, need to carry heavy goods, giving a lift to passengers, escorting children (to and from school, day care facilities or leisure activities) or due to lack of feasible transport alternatives (Box 1).

The participants stated a number of advantages of the car over walking or cycling: for some it was faster, for others it enabled them to carry passengers and goods, did not require any physical effort or was perceived to be safer.

Two examples are described and illustrated in Fig. 5. First, Jennifer (35 years old, three children) relied on her car to travel around on daily basis, including picking up/dropping their children at school or leisure activities or shopping. 80% of trips made by Jennifer (n = 60) were less than 3 miles long. Second, Jocelyne (54 years old) made many short car journeys to the local supermarket, while living less than 0.6 miles (1 km) away from the supermarket (if walking) but 1.5 mile (2.4 km) when driving.

3.4. Substitution potential for short car trips

In principle, short car trips are amenable to walking or cycling for most people and therefore, all of the 798 short car trips identified above could be replaced by active transport modes (up to 3 miles for cycling, and up to 1 mile for walking). However, it is acknowledged that trip characteristics (mainly trip purpose and complexity) influence mode choice to a great extent (alongside built environment, personal and household characteristics) (Beckx et al., 2013; de Nazelle et al., 2010; Song et al., 2017). We assessed the mode shift potential of short car trips by taking into account trip purpose and their complexity; for example, whether a short trip was part of a tour/home-based trip chain. This is presented next.

3.4.1. Short car trips: Trip chains matter

Understanding the setting of the trip and its stages is crucial to assess the journey transfer potential as trips are usually connected with other trips and travel mode choice is frequently made taking into account aspects of the whole chain. For example, if a one-mile car trip is only one element in a longer chain of several longer trips, car may be a more reasonable travel option. Tour or trip chains were defined in this study as a sequence of trips that start and finish at home.

⁶ The total number of short trips recorded varied little between the two waves, with 406 short car trips recorded in 2011 and 392 trips in 2012.

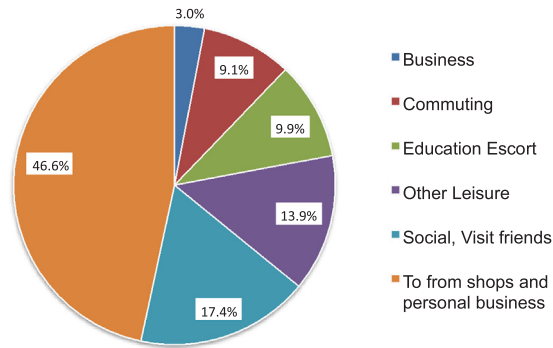


Fig. 3. Trip purpose of short car trips (n = 798).

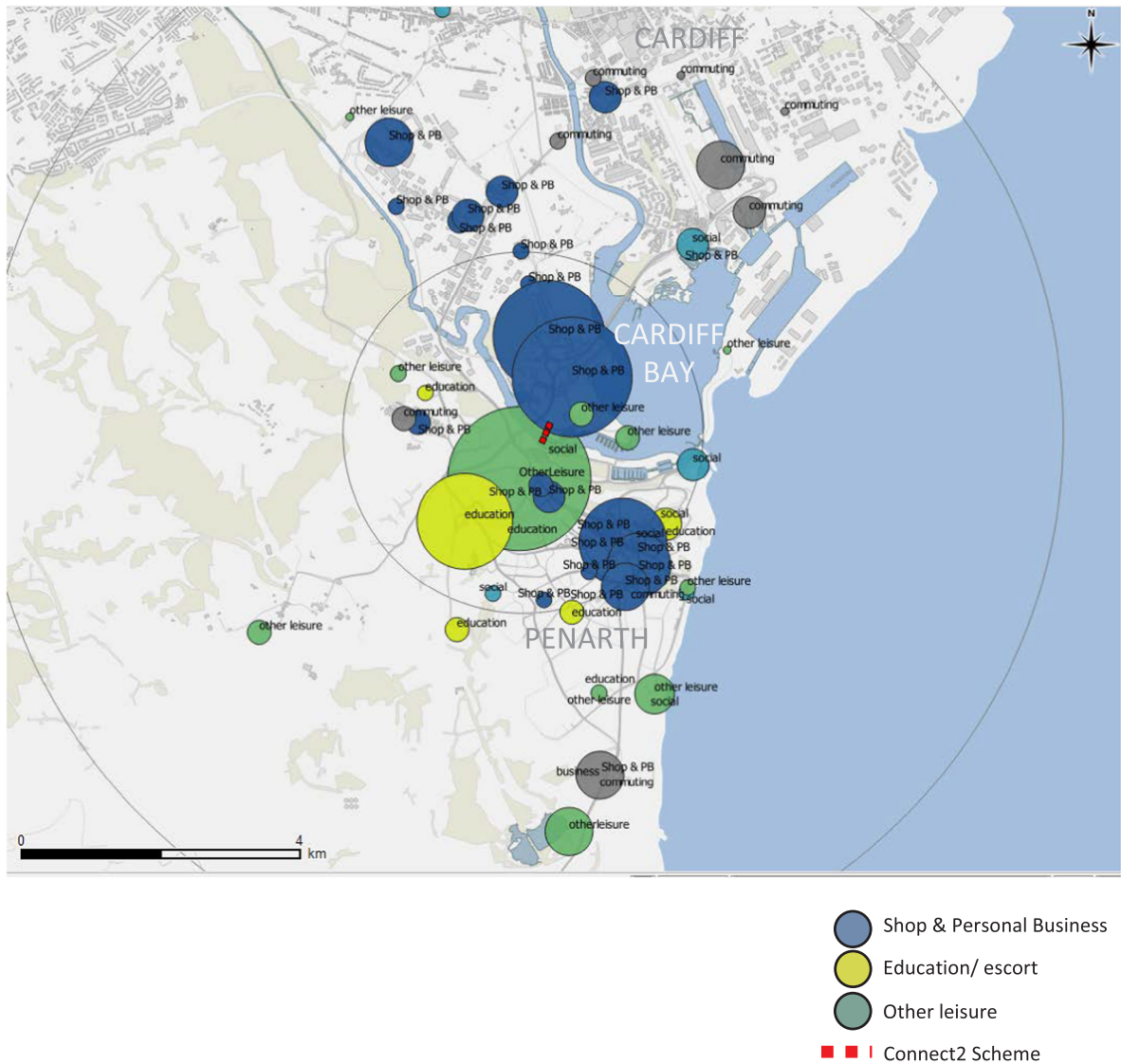


Fig. 4. Main destinations in the local area accessed by short car trips (< 3 miles).

A total of 1010 tours were recorded involving all the modes of transport. From those, 612 were car-based tours and 68.9% were shorter than 8 miles. The tours were on average 23.3 miles long and consisted of a number of different elements/stages (Table 3). Any trips that were not part of a home-based tour of up to 8 miles (12.8 km) and that were not longer than 3 miles were excluded from the

Box 1

I drop-off my children at school every day by car. The school is not far though and we could potentially walk but as I am on my way to work I found this way more practical and quicker. (Helen, 39 years old, two children)

Due to my heart condition, I cannot walk for more than 100 m, as I will get really short breath. Therefore, driving my car is the only I can afford to travel around and run errands in the local area. (Austin, 66 years old)

I usually drive my car when going to the local supermarket, as this is more convenient to carry shopping and groceries. However, I also drive my car even if I just need to buy a newspaper. I got used to travel around by car; and to be honest, I do not find the local environment very friendly for walking. (Jocelyne, 54 years old)

I go frequently for a bike ride with my children at Cosmeston Park or Cardiff Bay Area. That is not too far from our place [< 2 miles] and we could potentially cycle there instead of driving. However, I do not feel safe to cycle with my kids on the main road as therefore just prefer to put the bicycles in the car, driving and then cycling. (Paul, 38 years old, two children)

Since that I am on a career break and taking care of my three children, I end up driving our car all the time. My daily routines include dropping-off and picking-up the children from several locations across town, including nursery, school and activity centres.; and do shopping and run errands on the little time left. Travelling by car, even if most of the cases is for very short journeys, it still more convenient and efficient. (Jennifer, 35 years old, three children)

analysis as it would not be reasonable to expect a modal shift for short trips that were part of longer trips. Thus, a total of 550 short car trips were considered in scope for substitution.

3.4.2. Short car trips: Purpose matters

Trip purpose also plays an important role in mode choice over short distances. We filtered out short car trips where a participant was not the driver⁷ ($n = 83$), trips that involved escorting to and from a place ($n = 87$) or shopping trips to large retail areas⁸ ($n = 54$). Short car trips to local shops and personal business were however included, based on the assumption that when individuals shop locally they usually shop more frequently but lower quantities each time and, therefore, carrying lighter goods is more feasible when walking or cycling. Applying these criteria, our results suggest that 41% of short car trips had the realistic potential for mode substitution to walking and cycling (see also Table 5 below). Note that 25% of all short car trips recorded were less than 1 mile ($n = 198$) and therefore in walking range.

In sum, 59% of journeys recorded over the two waves were less than 3 miles, and 49% of all car trips were less than 3 miles. The main reasons to drive a car over short distances included time constraints, convenience, need to carry heavy goods, giving lift to passengers, escorting children or lack of feasible alternatives. Taking into account constraints around trip chains and trip purpose we found that walking or cycling could realistically substitute for 41% of short car trips, which is equivalent to 4.5% of all car trips.

3.5. CO₂e emissions from all surface transport and from short car trips

3.5.1. CO₂e emissions from surface transport

The travel activity of our 50 participants generated a total 2.86 tons of CO₂e over the two waves. This represents an average of 28.6 kgCO₂e (95% CI 21.1; 37.1)⁹ per participant per week (median 22.2 kgCO₂e), or 1.34 tons of CO₂e per participant per year. As expected, car travel was responsible for the largest share of CO₂e emissions, accounting for 90% (25.8 kgCO₂e per person per week) of total CO₂e emissions from surface transport. Given the small sample size, these figures were remarkably close to those reported elsewhere (Brand et al., 2013b; Brand and Preston, 2010).

In terms of trip purpose, trips for shopping and personal business activities (larger trip frequencies but lower trip distances) had lower average CO₂e emissions than trips to work and for social or leisure purposes (Table 4).

Furthermore, the emissions distributions were skewed towards a small minority of participants producing a larger share of the total. The top 20% of the sample were responsible for 55% of emissions while the bottom 20% for just 3%. Emissions from shopping and personal business trips were distributed most equally, and those from business and commuting trips least equally. This unequal distribution of transport emissions largely confirms the findings from previous studies (Brand and Boardman, 2008; Brand et al., 2014; Büchs and Schnepf, 2013; Susilo and Stead, 2009) and thus suggests validity of the findings.

3.5.2. CO₂e emissions from short car trips

Short car trips were 2.8 kgCO₂e per person per week, corresponding to 10.9% of all CO₂e emissions from car travel (Fig. 6). As expected, longer trips (> 50 miles) were responsible for a larger share of all CO₂e emissions (44%).

⁷ Trips as car passenger were not considered as car passengers usually get a lift in a car that is already on the road so their mode choice has a different basis.

⁸ It is assumed that participants are usually carrying heavy goods and groceries when travelling to these destinations and therefore, car travel is a more convenient alternative.

⁹ 27.0 kgCO₂e (95% CI: 17.93; 38.33) in 2011 and 30.24 kgCO₂e (95% CI: 22.66; 40.20) in 2012.

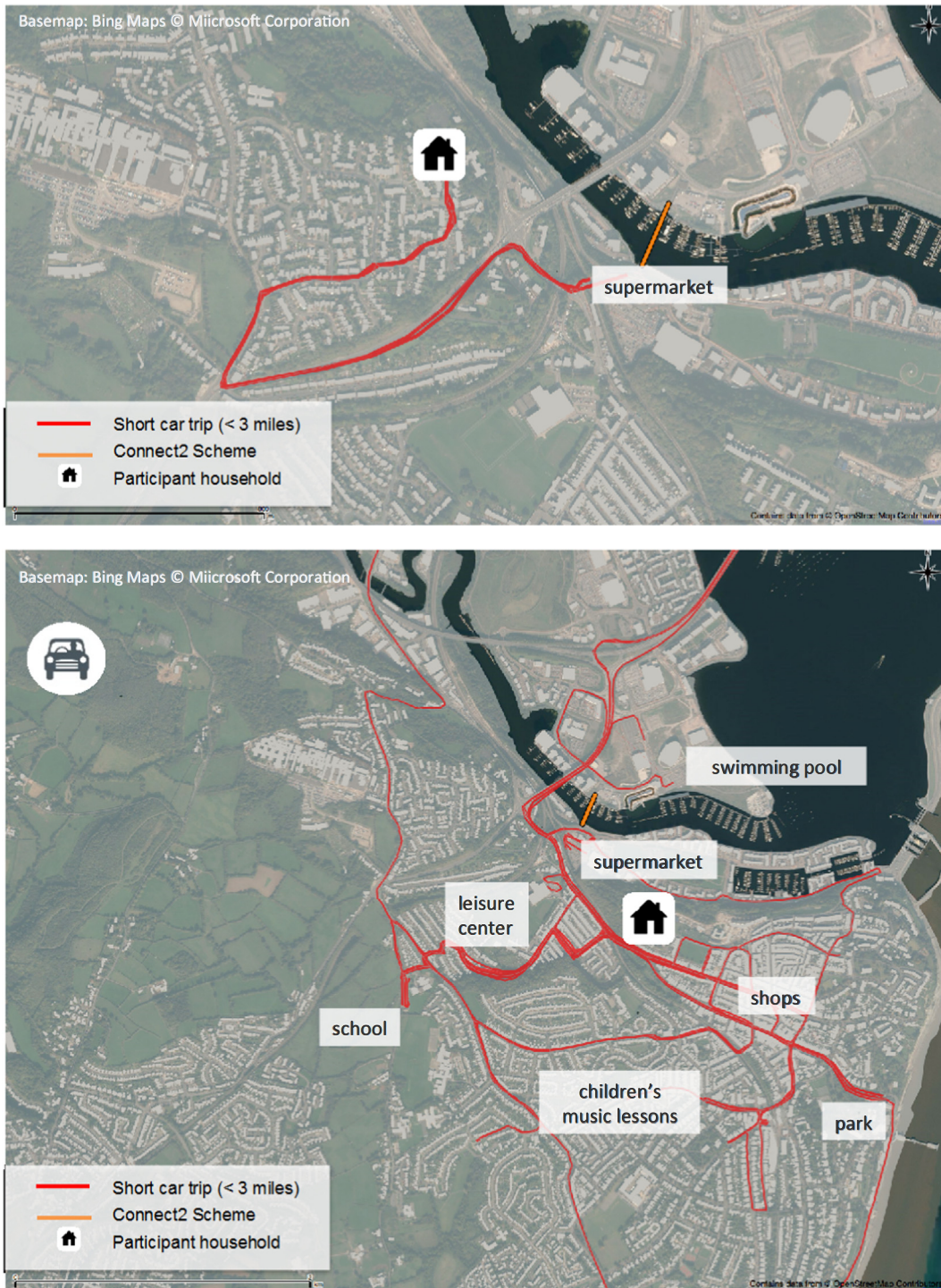


Fig. 5. Examples of short car trips (a) escorting children to school and running errands (top) and (b) shopping at the local supermarket (bottom).

Taking the realistic mode shift potential from the previous section we estimated that shifting 41% of short car trips to walking and cycling had the potential to mitigate carbon emissions *from car travel* by 4.5%, or 1.15 kgCO₂e per person per week (Table 5). This is equivalent to a mitigation potential *from all surface transport* of 4%.

The 41% potential for mode shift can be considered a realistic if conservative estimate for typical car drivers. In order to test for sensitivity of the results, Table 5 shows the different elements of filtering trips and emissions due to escorting, being a passenger in a car and shopping to large retail outlets. If those were not excluded, the mode shift potential would increase to 1.93 kgCO₂e per person

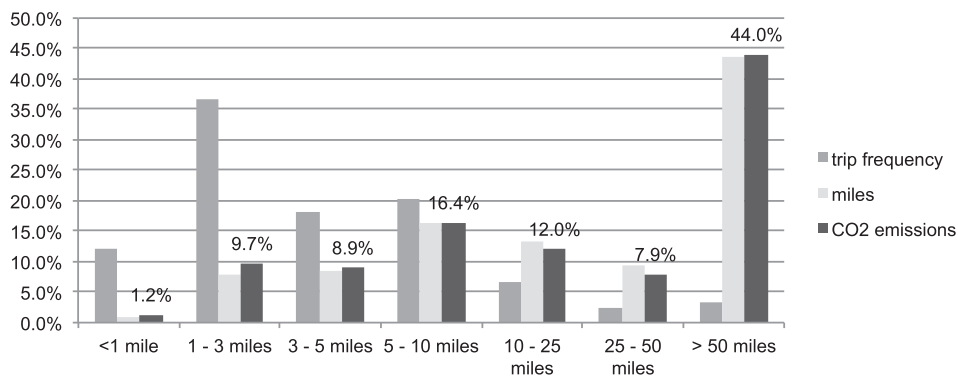
Table 3

Short car trip frequency by trip chain distance and number of stages (elements) within the tour.

	Car trip < 3 miles		Car trip > 3 miles	
	count	%	count	%
<i>Trip chain total distance</i>				
< 8 miles	550	68.9%	989	14.9%
8–20 miles	152	19.0%	291	44.2%
> 20 miles	96	12.0%	269	40.9%
<i>Number of tour elements</i>				
1	0	0.0%	0	0.0%
2	322	40.4%	296	45.0%
3	198	24.8%	139	21.1%
4	118	14.8%	74	11.2%
5 or more	160	20.1%	149	22.6%

Table 4Mean trip frequency, trip length and CO₂e emissions by trip purpose and year.

	2011			2012		
	Trip frequency	Mean trip distance	Mean CO ₂ e emissions	Trip frequency	Mean trip distance	Mean CO ₂ e emissions
Travel to work or education	27.5%	6.9	4.6	29.0%	9.7	7.2
Business trips	4.9%	20.5	2.5	4.8%	26.7	4.6
Shopping and personal business	35.1%	4.0	3.3	34.4%	4.7	3.7
Social and leisure	32.6%	10.3	6.0	31.9%	10.7	7.1

**Fig. 6.** Number of trips, distance travelled and CO₂e emissions from car travel by trip length (n = 1634).**Table 5**CO₂e emissions per person per week (n = 50, pooled dataset).

	n	CO ₂ e emissions per person per week (kgCO ₂ e)	Share of short car trips (%)
All surface transport (car, bus, taxi, motorcycle, rail)		28.70	
All car travel		25.80	
Short car trips (< 3 miles)	798	2.80	100
– Short car trips part of chain trip less than 8 miles	248	0.87	31
– Short car trip escorting people	84	0.29	10
– Short car trip as a passenger	83	0.29	10
– Short car trip for shopping purposes (large retail areas)	54	0.19	7
= Short car trips with potential to be replaced by active travel	329	1.15	41

per week, or 69% of short car trips.

3.6. Role of walking and cycling in a low carbon transport system

3.6.1. Avoided CO₂e emissions from existing utility walking and cycling

Eleven participants used their bicycles for everyday travel in at least 104 occasions and for a total of 410 miles. If these cycling trips had been done by car, total CO₂e emissions from cars would have been 4.1% higher (106.8 kgCO₂e). Walking for everyday travel (i.e. to the shops, personal business and social activities, or just commuting) represented the main purpose of 531 of the walking trips recorded (NB: walking stages not considered here). If these walking trips had been done by car, the total amount of CO₂e emissions from cars would have been 0.8% higher (20.7 kgCO₂e). In total, the observed walking and cycling may have avoided 4.9% of CO₂e emissions from cars.

3.6.2. Associations between CO₂e emissions from motorized travel and proximity to the Connect2 scheme

The flagship element of the Connect2 scheme, the bridge over the river Ely, provided a route for both utility cycling (n = 17) and walking (n = 20) for everyday travel. If these trips had been done by car, carbon emissions would have been 12.3 kgCO₂e (0.5% of car emissions) higher. An ANOVA test (p = .754) showed, however, that there was no significant difference in CO₂e emissions between participants living less than 0.5 mile, between 0.5 mile and 1 mile, or more than 1 mile away from the Connect2 scheme. This suggested that proximity to the infrastructure was not associated with CO₂e emissions.

3.6.3. The CO₂e impacts of the Connect2 scheme – Potential for further savings

Further to avoided CO₂e emissions, potential CO₂e emissions impacts of the Connect2 Scheme were estimated based on the following three assumptions. First, the Connect2 Scheme provided an ideal route for pedestrians and cyclists if car journeys that started on the South bank of the river Ely and finished on the North bank (or vice versa) were replaced by walking and cycling. Second, short car trips along the Spurt or Penarth Road are within this category. Third, trips that were part of a home-based tour up to 8 miles, trips whereas participant was not the driver (n = 83) or that involved escorting to and from a place (n = 87), and trips to large retail stores were not considered.

In total, 69 short car trips (out of 329 potentially replaceable by walking and cycling) met the above criteria, the new Connect2 scheme providing an 'optimal' route (Fig. 7). Therefore, we estimated that the new Connect2 scheme could have supported a further mitigation of 32.9 kgCO₂e (i.e. 1.2% of car emissions).

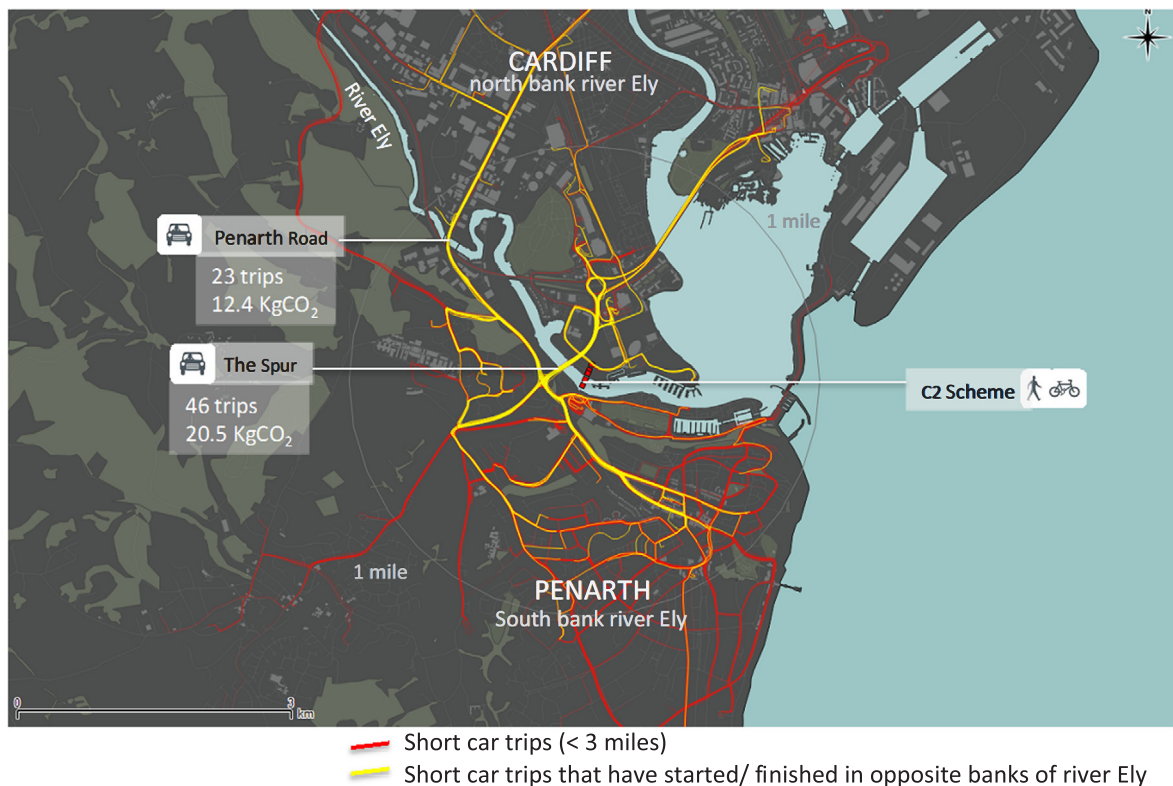


Fig. 7. Observed short car journeys (< 3 miles), colour coded by trip origin and destination.

3.6.4. Walking and cycling supporting public transport use

Detailed GPS records showed that over the two waves the participants travelled 2547 miles by public transport (182 journeys, average trip length 14 miles). While outside the main focus of the paper, results of how walking and cycling provided access to/from public transport and, therefore, contributed (indirectly) to reducing the need to travel by car are shown in [Supplementary Materials SM5](#).

4. Discussion

The main findings are discussed below, covering mode shift potential using GPS and travel diary data, observed and potential carbon emissions impacts of promoting such shift, and the role of the *Connect2* scheme in reducing carbon emissions.

4.1. Understanding short car trips and the potential of mode shift to walking and cycling

The finding that 49% of all recorded trips by the 50 participants were less than 3 miles is comparable to national figures. In Great Britain, 57% of trips less than 5 miles were made by car in 2012 ([ONS, 2015](#)), compared to 67% in this study. The main reasons given by participants to drive over short distances were related to habits, time constraints, convenience, the need to carry goods, the need to escort children and the lack of any suitable alternatives. Most of these reasons are supported by findings from previous studies ([Beckx et al., 2013](#); [Mackett, 2003](#); [Piatkowski et al., 2015](#); [Vagane, 2007](#); [Walton and Sunseri, 2010](#)).

The potential for replacing short car trips by walking or cycling was assessed using trip distance, trip purpose and trip context (i.e., the presence of the short trip within a tour/ home-based trip chain) as the main criteria. Rather than a trip based approach, where all trips are treated equally, a trip chain approach has the potential to provide a more accurate assessment ([Beckx et al., 2013](#); [Davidson et al., 2007](#); [Vagane, 2007](#)). The spatial detail contained in the original travel data set was crucial to perform this assessment.

The finding that about a fifth of all car trips (and two fifths of car trips under 3 miles in length) could feasibly be shifted to walking and cycling provides a realistic and reasonable assessment of local travel behaviour. One of the few studies to investigate the potential of active transportation based on GPS data suggested, however, that only 10% of car monitored trips could be replaced by walking and cycling ([Beckx et al., 2013](#)). This study was conducted in Belgium, had larger number of vehicle trips ($n = 20,634$ vehicle trips), a lower number of participants ($n = 20$), and the assessment methodology was different as, for example, trips to large retail shops or trips to local shops were not treated differently as was done in this study. Another study based on travel survey data only from the National Travel Survey in the UK put the mode shift figures higher at 31% of trips substitutable from car to walking and 78% to 'some alternative mode' ([Mackett, 2001](#); [Mackett, 2003](#)). However, that study applied a less detailed approach and little regard to the local context to estimate replacement potential. A study of the UK Sustainable Travel Demonstration Towns found that only subjective reasons prevented one third of all trips made by car to be made by walking, cycling or taking public transport ([Sustrans, 2005](#)). While the figures in these studies are diverging somewhat, they suggest significant potential for mode shift and provide a better understanding of the role walking and cycling can have in everyday travel.

It is widely acknowledged that several factors and conditions are necessary to support significant and sustained modal shift. First, the physical environment needs to be supportive and inviting for pedestrians and cyclists of all ages and skills. A network of high quality, safe and well connected routes for walking and cycling needs to be in place alongside policies that support a mix of uses and restrictions to car use. Cultural and individual factors are also playing a critical role as individuals' attitudes and preferences, including perceived convenience and flexibility, value of time and cost or environmental beliefs also influence modal choice and are likely to have an impact on decision to drive a car over short distances ([Beckx et al., 2013](#); [Buekers et al., 2015](#); [Vagane, 2007](#); [Vandenbulcke et al., 2011](#); [Vredin Johansson et al., 2006](#)). While shopping and escort trips were responsible for the largest share of short trips in this study, it can be argued that such activities may not necessarily exclude active travel as the choice of mode, as frequently perceived. As an example, the use of shopping trolleys, pushchairs, bike panniers, bicycle racks, bicycle children seats, cargo bicycles, bike trailers or electric bicycles could enable some of these journeys to be made entirely by bike or on foot. In Copenhagen, 25% of families with two or more children have a cargo bike and 50% of all Copenhageners with a cargo bike use it to transport children ([Copenhagenize, 2017](#)). E-bikes,¹⁰ on the other hand, can enable people of different ages and skills to comfortably cycle over longer distances, in hilly terrains or when carrying heavy loads.

4.2. CO₂e emissions from short car trips and their mitigation potential

The derived sample average of 28.6 kgCO₂e per person per week represents an estimated 1.35 tCO₂e for person per year, with car travel being responsible for the largest share of emissions, accounting for 90% of total CO₂e emissions from surface transport. These figures are unsurprisingly below national (1.89 tCO₂e per capita) and local (1.75 tCO₂e per capita) figures for all road transport in 2012 ([DECC, 2014](#)). They are also lower than the 1.6 tCO₂e per person per year reported in a related study ([Brand et al., 2013b](#)). The difference can be explained by the different scope (*passenger* surface transport vs. all road transport *incl. freight* in [DECC, 2014](#); and *passenger surface* transport vs. all passenger transport *incl. aviation* in [Brand et al., 2013a,b](#)), approaches used to record travel data

¹⁰ Emissions from e-bikes are found to be in the same range as ordinary bicycles, despite their electricity needs, because they allow for (56%) longer daily commutes and can substitute for cars on 39% of journeys.

(GPS based travel survey vs. self-reported surveys) and local context (national vs. local area). Interestingly, in both years of the survey, the mean was substantially higher than the derived median.¹¹ This suggests a skewed distribution of emissions, where a small proportion of individuals were responsible for a large share of emissions. The findings thus support the existing evidence on travel emissions inequalities (Bel and Rosell, 2017; Brand and Boardman, 2008; Büchs and Schnepf, 2013; Ko et al., 2011; Susilo and Stead, 2009), as the top quintile of the sample were responsible for 55% of carbon emissions while the bottom quintile for just 2.6%.

The finding that CO₂e emissions increased by 9% between 2011 and 2012 is somewhat against the secular trend of a marginal decrease in CO₂e emissions from road transport in Cardiff (DECC, 2014). While we made sure the same week of the year was measured, the difference may be explained by different weather (the period in 2012 was one of the wettest on record in Wales), the natural variability of travel activity within and between subjects as well as the small sample size and influence of outliers. Further analysis of the spatial and interview data (shown in SM4, including relevant changes for per participant) suggests that changes in life circumstances (such as getting a new job further away from home, starting to work from home, retiring, change in family responsibilities) and year-on-year variability were more likely to cause a significant change in travel behaviour over time (modal replacement and increase/decrease in distance travelled). Overall, however, our findings suggest that although the *Connect2* Scheme provided local residents with a new and well-used route for recreation, the scheme may not have provided most residents with practical new routes to the particular destinations they needed to reach.

By taken into account car technology details, trip speeds and excess emissions from ‘cold starts’ (which have a relatively higher impact on short trips) we obtained a better resolution and more accurate assessment of CO₂e emissions *per participant* than by simply using global or UK average car emissions factors. This is supported by the evidence that variability at the individual trip level can be between –50% and +100% (Brand and Boardman, 2008; Brand et al., 2013b).

The finding that short car trips (49% of all car trips recorded) were responsible for 10.9% of total car CO₂e emissions compares well with findings from national sources (DfT, 2015). The detailed and context-specific assessment of the potential for mode shift revealed that 41% of short car trips could realistically be made by walking and cycling. Modal shift could therefore realistically contribute to a mitigation of 4.5% of CO₂e emissions from car travel, or about 4% of CO₂e emissions from all surface passenger transport. This increased to 69% of short car trips (and 7.5% of CO₂e emissions from cars) if cycling and walking would further substitute escort and large-retail shopping trips normally done by car. This result therefore supports the argument that walking and cycling can play a significant if minor role in contributing to a lower carbon transport system, alongside other positive impacts on traffic congestion, reduced transport poverty, improved air pollution and personal health and wellbeing.

4.3. CO₂e emissions mitigation potential from walking and cycling

By assessing observed active travel behaviour we were able to put a carbon emissions value on the avoided motorised travel, suggesting that CO₂e emissions from cars would have been 4.9% higher if the walking and cycling had been done by car. Cycling contributed to the largest share of savings at 4.1%, which is comparable to estimates reported elsewhere that an increase in the cycling share in Britain to levels closer to northern Europe could reduce total emissions in the UK by around 6% (Gross et al., 2009). To put this into context, cycling represented 5% modal share in this study, which is above the national average of 1.5% but comparable to figures for larger urban areas (ONS, 2015). Also, this analysis provides an upper limit as some utility trips might not be made at all if not by walking or cycling, or made by other short distance modes such as urban bus (and rail).

4.4. Role of a *Connect2* scheme in promoting a modal shift away from car travel and CO₂e emissions mitigation potential

We found relatively low reductions of 0.5% of CO₂e emissions from avoided car travel due to the *Connect2* scheme, with a further potential of 1.2% of total CO₂e emissions if we included walking or cycling avoiding any short car trips running parallel to the scheme. To understand this result, it is important consider the local context of the scheme, type of services and facilities connected by the new scheme and the poor quality of the feeder routes. The scheme was likely to have a greater higher impact for recreational purposes rather than for utility travel (CO₂e emissions from recreational travel are not considered). This is supported by the finding that any relevant change in travel activity, and therefore CO₂e emissions, could be attributed to a shift away from the car motivated by an increase in walking and cycling and changes to local infrastructure. This is supported by results from the wider *iConnect* study that found that the extra walking and cycling trips generated by *Connect2* did not usually represent a modal shift away from motorized travel (Goodman et al., 2014a,b) or that these effects translated into sizeable CO₂e effects (Brand et al., 2014). In particular, our findings could not suggest that living near the infrastructure or using it resulted in lower CO₂e emissions from motorized travel, in line with results from parallel work (Brand et al., 2014). Other studies that have measured the effects of improving connectivity for cyclists (and pedestrians) have also found mixed findings with regards to change in modal share¹² (while not having considered changes in CO₂e emissions levels) (Ogilvie et al., 2004; Wilmsink and Hartman, 1987).

¹¹ Mean carbon emissions from all motorized surface passenger travel were 27.0 kgCO₂e (median 16.9 kgCO₂e) per person per week in 2011 and 30.24 kgCO₂e per week (median 21.4 kgCO₂e) in 2012.

¹² As an example, following extensive provision of cycle infrastructure in Delft (Netherlands) reported a 3% increase in the cycling mode share of all trips after three years with no change in the mode shares for walking or for car. But in Detmold and Rosenheim, households reported a negative modal shift of 5% of all trips (Detmold) and zero modal shift (Rosenheim) after five years.

4.5. Limitations to the study

The strength of the study lies in the development and use of a novel and detailed approach to measuring and evaluating changes in CO₂e emissions from walking and cycling activity and (displaced) motorized travel, using a combination of ‘objective’ (GPS) and ‘subjective’ (diary, interview) instruments. This provided a rich dataset of a purposively selected sample of 50 residents in Cardiff Bay Area. One of the limitations of the approach used is that the sample is not representative of the general population. Indeed, by selecting individuals who expressed an intention to cycle or walk more, we may have overestimated potential reductions in CO₂e emissions. On the other hand, by taking a relatively conservative approach to the definition of short car trips (under 3 miles) we may have underestimated both potential and avoided CO₂e emissions. For instance, if we had increased the threshold to 5 miles (which was well within the range of the study participants who cycled) the share of short car trips that could potentially be replaced would have increased by 11.2%.

It was originally intended to study causality between infrastructure provision and changes to cycling behaviour and CO₂e emissions. However, outright cancellation of the *Connect2 Banbury* (initial choice) and delays at *Connect2 Kenilworth* (field work started there in 2009) meant we had to switch sites at the last minute, with Cardiff/Penarth providing the best alternative at the time. It is worth noting that although data collection at t1 was after the ‘core’ element of the scheme (bridge) was opened, the scheme could not be considered ‘complete’ in 2010. In fact, the bridge was the first of five elements to be implemented, with the other four only being completed during 2011–2013. Therefore, we hypothesized that improvements to the local walking and cycling infrastructure and increased connectivity over time would support an increase in walking and cycling. The latter had been shown (Goodman et al., 2013, 2014b) not to happen instantly (e.g. just after opening the bridge or link-ways to Penarth) but rather slowly over the next 1–2 years. Generally, scheme implementation delays and reconfigurations are a limitation common to many natural experiments – particularly in times of austerity – and sadly out of control of the researcher.

5. Conclusions

This paper set out to investigate the potential of walking and cycling in replacing short car journeys, the CO₂e emissions impacts of such modal shift and the role of new high quality infrastructure for walking and cycling in supporting such change. The provision of high quality routes for pedestrians and cyclists in the local area, implemented as one of the flagship *Connect2* schemes, may have had a minimal impact in terms of CO₂e emissions. However, the finding that 41% of short car trips (and up to 69% when including escort, large-retail shopping and ‘as passenger’ car trips) could realistically be shifted to walking and cycling highlights the unexploited potential for policy and infrastructure investment to support such a shift and contributing towards a lower carbon transport system in urban areas. In the case of Cardiff, we estimated a potential reduction of about 4.5% of CO₂e emissions from car travel over and above the 4.9% of potentially avoided CO₂e emissions from existing walking and cycling activity. Walking trips under 1 mile provided 25% of the savings. Mitigating climate change is clearly only one argument for investing in measures for supporting modal shifts towards walking and cycling. Other, and often more significant, ‘co-benefits’ on traffic congestion, transport poverty, air pollution and improved health and wellbeing should be considered in a more comprehensive appraisal of active travel policies and measures. Although the reductions assessed here not insignificant, a comprehensive approach of more ambitious active travel promotion, policies and investments targeted at mode shift away from private motorized transport (e.g. car pricing at point of use, further car restraint and parking pricing in urban areas, commuter car sharing, Park-and-Bike, awareness raising of the relatively larger impact of short car trips) may be required to achieve the combined goals of climate change mitigation and its multiple ‘co benefits’ in urban areas.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.tra.2018.08.022>.

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