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The cost of the wider impacts of road traffic on local communities: 1.6% of Great Britain's GDP

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ABSTRACT

This paper estimates the negative effects of motorised road traffic on the travel and walking behaviour of local residents in Great Britain and the cost of the wider negative impacts on local economic activity, external effects of motorised transport, social exclusion, neighbourhood social capital, self-rated health, and subjective wellbeing. We use the results of a survey (n = 3038) and models linking the characteristics of roads and pedestrian crossing facilities in each participant's local area, travel and walking behaviour, and the level and monetary value of the wider impacts of travel behaviour. The costs of road traffic borne by local communities were estimated as £31.9 billion per year, i.e. 1.6% of the Gross Domestic Product, or £631 per person. This value varies within the interval £569-£698/person/year, depending on the assumptions made. The highest estimated costs of motorised road traffic are reduced neighbourhood social capital (£236) and reduced subjective wellbeing (£196/person/year). The costs for some population segments, such as London residents, city residents, and people aged 25–34 are higher than the average. The characteristic of roads causing the highest costs is volume of motorised traffic above low (£264/person/year), followed by multiple lanes (£148), traffic speeds above low (£119), and absence of a median strip (£60). By quantifying for the first time, at the national level, the costs of the negative community effects of motor vehicles, this study provides evidence supporting policies to reduce traffic volumes and speeds and reallocate roadspace to pedestrians.

1. Introduction

Roads allow people to reach distant places, where they can access resources and opportunities not available in their local area. However, roads with large amounts of motorised traffic, or traffic moving at high speed, impact negatively on the quality of life of residents and other people using the local areas. The direct effects of road traffic on collision risk, noise, and local air pollution have been extensively quantified and valued monetarily (Friedrich and Bickel 2001, Delucchi and McCubbin 2010, Van Essen et al. 2020). However, road traffic also has indirect effects if, for example, residents avoid making trips (in particular walking trips) along or across busy roads, in order to reduce exposure to the direct effects (Kaczynski et al. 2014, Olabarria et al. 2014, Anciaes et al. 2017, Powers et al. 2019). Trip suppression may then have wider consequences for the affected individuals, including a reduction in physical activity; reduced accessibility (to jobs, education, goods, and services); lower levels of social interaction and support; poorer physical and

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mental health; and impaired wellbeing. Trip suppression may also have negative impacts for local communities as a whole, as it affects levels of neighbourhood social capital and local economic activity. If instead of suppressing trips, individuals shift trips from non-motorised to motorised modes, this may increase road congestion, reinforce the direct and indirect local impacts of motorised traffic, and contribute to global problems such as CO_2 emissions and the depletion of non-renewable resources.

This paper is the first study to estimate the cost of the wider negative impacts of motorised traffic on local communities at the national level in Great Britain (England, Scotland, and Wales). We use the results of a survey (n = 3038) to quantify the effects of road traffic on the travel behaviour of local residents, including the number of trips to specified local places, travel modes used, and total amount of time spent walking locally. We then quantify and value the costs of these travel behaviour effects on local economic activity, external effects of motorised transport, social exclusion, neighbourhood social capital, self-rated health, and subjective wellbeing. We also investigate differences in these costs in terms of region, type of settlement, demographics, characteristics of roads (number of lanes, presence of a median strip, traffic volume, traffic speed) and type of pedestrian crossing facilities (signalised, footbridge, underpass, or pedestrian platform).

The paper proceeds with a review of the wider negative impacts of road traffic on local communities, and their monetary value. Sections 3 and 4 present the survey data and methods, respectively. Section 5 presents models estimating the number of trips to local places, travel modes used, per-trip expenditure in four different types of local business, the amount of time spent walking, neighbourhood social capital, self-rated health, and subjective wellbeing. Section 6 uses the models to estimate the monetary value of the various impacts on local communities. Section 7 discusses the policy implications of the results and outlines the strengths and limitations of the data and methods used.

2. Literature review

The negative local impacts of busy roads can be valued as the willingness of residents to pay to change some road characteristics (e.g. reduce traffic volume or speed). This can be calculated from stated preference surveys in which participants choose among different road scenarios, linked with different monetary values (Gundlach et al 2018, Anciaes et al. 2018, Anciaes and Jones 2020), or by revealed preference models that estimate associations between house prices and the presence or the characteristics of busy roads (Kawamura and Mahajan 2005, Li and Saphores 2012, Allen et al. 2015). However, these methods do not capture the overall costs to residents of living close to busy roads, as the impacts of motorised traffic on quality of life (e.g. health and wellbeing) are not usually considered by participants in stated preference surveys and are not fully capitalised in housing markets.

An alternative method is to value the specific effects of busy roads on walking trips that are currently made, such as detours to walking routes and delays in crossing the road. In fact, in several countries, official guidance for appraising the barrier effect of traffic on pedestrian movements recommends multiplying time losses for pedestrians by a unit value of time (MIT, 2008, App3; Austroads, 2014, Ch.5.5.6; BMVI, 2016, Ch.III.3.3.11). This approach can be applied at the national level. For example, in a study in Switzerland, Ecoplan-INFRAS (2008) combined the daily number of times that people cross roads, the average time loss per crossing (considering road width and number of lanes), and a fixed value of time.

Again, these methods do not provide a complete picture. This is because motorised traffic constrains the travel behaviour of local residents, who may choose not to walk, and use motorised means of transport instead, or suppress some trips (Olabarria et al. 2014, Anciaes et al. 2017, Powers et al. 2019). For example, Mindell et al. (2017) found that some people avoid walking on busy roads even when the roads have many trip attractors, such as shops. Individuals may also choose alternative trip destinations or walking routes, to avoid busy roads. Even in this case, there is still a reduction in accessibility because these selected destinations and routes may be less attractive or less convenient, as they were not the individuals' first choice.

The impact of motorised traffic on the choice of modes of transport used by residents to reach local destinations has consequences on the local economy. Several studies have shown that although individuals who walk to high streets spend less per trip than those who arrive by car, they also make more trips (Bent and Singa, 2009, Jones et al., 2007, Clifton et al., 2013, TfL, 2016). On balance, the overall effect on local economic activity of shifting trips from walking to car tends to be negative. In addition, this shift increases congestion and the negative external effects associated with car travel, such as noise, air pollution, and collision risk.

Restrictions on the number of trips made locally also have adverse consequences on the way that individuals relate to society. There is consistent evidence that neighbourhood social interaction is negatively affected by high motorised traffic volumes (Appleyard et al. 1981, Bosselmann et al. 1999) and fast traffic speeds (Sauter and Huettenmoser 2008), due to reductions in short walking trips and the use of streets as social spaces. This affects neighbourhood social capital (i.e. the resources that individuals can access through others living nearby). Trip suppression also reduces the ability of individuals to participate in employment and to access goods and services, increasing the risk of social exclusion (Currie et al. 2010). Several studies have estimated models relating social capital or social inclusion with income and the number of trips made. In these studies, the monetary value of a suppressed trip was estimated as the increase in income required to maintain levels of social capital or social inclusion when individuals make one less trip (Stanley et al. 2011, 2012).

Busy roads may also have impacts on physical and mental health and on subjective wellbeing. This is due to reduced satisfaction with walking trips (Anciaes et al. 2019) and the consequences of less walking, including physical inactivity (Chiang et al. 2019), reduced use of parks (Kaczynski et al. 2014), reduced satisfaction with overall travel (Friman et al. 2013, 2017), and reduced social capital (Curl and Mason 2019). There is a fast-growing literature on the monetary value of the health benefits of active travel (Cavill et al. 2008, Brown et al. 2016) but almost no studies to date have measured the health impacts of reduced walking that is specifically caused by the presence of busy roads (i.e. roads with high volumes or speeds of motorised traffic). An exception is Sælensminde (2002 Ch.7, 2004 Ch.5), who valued the loss due to the non-realised benefit of a "natural amount" of walking and cycling due to motorised traffic, taking into account increased vulnerability to diseases (through lower levels of physical activity) and work absences.

In conclusion, there is growing evidence of the negative effects of local motorised traffic on travel behaviour, and walking in particular, and separate evidence on the associations between restrictions on travel behaviour and several individual and community impacts. There is also a range of established methods to estimate the monetary value of some of these impacts. However, there is no evidence to date linking motorised traffic, travel behaviour, wider impacts, and the monetary value of these impacts. This paper fills this gap in the evidence by developing a conceptual framework of the pathways linking motorised traffic and its wider impacts, estimating those pathways, and making a comprehensive economic assessment of the impacts at the national level.

3. Data

3.1. Survey details and variables collected

The data for this study comes from a nationally-representative online survey of 3038 individuals aged 18 and above living in Great Britain. This was a part of an omnibus survey (a regular survey conducted by a market research company, in which researchers can purchase extra questions). The survey was conducted in March 2017. Some variables were collected as core questionnaire items of the omnibus survey. These variables included: age, gender, ethnicity, marital status, household composition, household income, socio-economic group, number of cars in the household, highest formal educational qualification, employment status, housing tenure, region, type of settlement (city with population above 10,000, town, village, or hamlet), and whether the participant was personally responsible for selecting most of the items to be bought from supermarkets and food shops. The exact residential location was not collected to protect the privacy of participants.

Household income per year was collected in 13 bands (from "up to £7,000″ to "£83,001 or more"). Participants could choose not to answer this question. We converted income into a numerical variable using the midpoint of each band and then estimated income per person by dividing household income by the number of persons in the household. Missing data on income was integrated in the models as a separate dummy variable.

A set of weights was calculated by the survey provider in order to adjust the achieved sample to the profile of the National Readership Survey (a random probability face-to-face survey conducted annually with 34,000 UK adults). The profile was based on the core questionnaire items listed above. The weights were applied to all analyses in this paper.

A series of questions specific to the present study were added to the core questionnaire items, as described below.

Participants were asked about the characteristics of the busiest road near their home. This included: the number of lanes for motorised vehicles in each direction (1, 2, 3, "do not know"); the presence of a median strip where pedestrians could stop when crossing the road (yes, no, "do not know"); volume of traffic (light, average, heavy); and speed of traffic (slow, average, fast). Participants were also shown illustrations and descriptions of types of pedestrian crossing facilities: straight signalised, staggered signalised, unsignalised marked, footbridge, underpass, and pedestrian platform (i.e. where the road is lowered and goes through a tunnel so pedestrians can walk at ground level). They were then asked if each of those facilities was available on the busiest road near them. In the case of straight and staggered signalised crossings, participants were also asked how long they usually had to wait before crossing the road ("no wait", "half a minute", "1–2 min", "3 or more minutes", or "I never cross like this").

Travel behaviour was assessed in relation to 11 types of local places: 1) corner shop or newsagent; 2) supermarket; 3) pub, restaurant, or café (referred to as "café" hereafter); 4) high street or shopping centre with several shops; 5) park or playing field; 6) school or childcare facility; 7) community or leisure centre; 8) general practitioner or health centre; 9) chemist or pharmacy; 10) train or underground station; and 11) the home of a friend or relative. Four questions were asked about these places:

- Whether they are: 1) within walking distance and on the participants' side of the busiest road, 2) within walking distance on the other side of that road, or 3) not within walking distance. Participants could report that several places of the same type were within walking distance, both on their side and on the other side of the busiest road.
- Trip frequency, i.e. how often participants go to the places listed (response options: "most days", "2–3 times a week", "about once a week", "once or twice a month", "once every 2–3 months", "once or twice a year", and "seldom or never"). We converted this variable into the number of yearly (return) trips, using the midpoint of the intervals corresponding to each category.

- For those participants who visit the places listed at least once or twice a year, how they usually travel to get there (response options: walk, cycle, public transport, or car). Participants could report more than one option.
- Also for participants who visit the places listed at least once or twice a year, how much they usually spend each time they visit four types of places: corner shops; supermarkets; cafés; and high streets or shopping centres. In the case of high streets/shopping centres, participants were instructed to exclude the expenditure already accounted for by the three other types of places listed above.

Neighbourhood social capital was measured using an instrument that produces scores that have been found to correlate with physical functioning (Breeze and Laing 2008) and wellbeing (Toma et al. 2015). The instrument consists of nine pairs of contrasting statements about the participants' local area (for example: "I really feel part of this area"). Answers were scored from 1 (most negative) to 7 (most positive). As the scale had acceptable internal reliability in our sample (Cronbach's alpha $\alpha = 0.873$), we summed the scores from the nine questions to obtain an overall score (with a range of 9–63), where higher scores indicated higher neighbourhood social capital.

Subjective wellbeing was measured using the 7-item short version of the Warwick-Edinburgh Mental Well-Being Scale (SWEMWBS) (Stewart-Brown et al. 2009) (used with permission). This consists of seven statements about the participants' feelings and thoughts over the previous two weeks: "feeling optimistic about the future", "feeling useful", "feeling relaxed", "dealing with problems well", "thinking clearly", "feeling close to other people", and "been able to make up my own mind about things". The statements have a 5-point response scale: "none of the time" (scored 1), "rarely", "some of the time", "often", and "all of the time" (scored 5). As the scale had acceptable internal reliability in our sample (Cronbach's alpha $\alpha = 0.870$), we summed the scores from the seven questions to obtain an overall score (with a range of 7–35), where higher scores indicate higher wellbeing. The scores were transformed to metric scores, in order to be used as an interval scale in regression models (Stewart-Brown et al. 2009).

Participants were also asked how long they had lived in their local area; whether they had a disability that restricted their mobility; their self-rated health status ("very good", "good", "fair", "bad", or "very bad"); and the number of minutes spent walking, in a usual week, as a means of transport (such as going to and from work, walking to shops or to public transport) and for recreation, health, or fitness (referred to as "recreation" hereafter). To be compatible with the other variables included in our analyses, we converted these values from weekly to yearly.

3.2. Descriptive statistics

As shown in Table 1, the characteristics of participants and their residence location were well aligned with those of Great Britain's population, as given by 2011 census data. The characteristics of the roads reported as the busiest in the participants' local area, and the available pedestrian crossing facilities in those roads, were also consistent with previous expectations (for example, the majority of roads were classified as having average traffic volume and average speed). 5% of participants reported that the busiest road had three lanes for motorised traffic in each direction and 41% reported that the road had a median strip. 35% of participants perceived the busiest road to have a heavy volume of traffic and 25% reported the traffic speed as fast. The most common pedestrian crossing facilities were unsignalised marked (32%) and straight signalised (29%).

Means and standard deviations (SD) were calculated for the numerical variables. The neighbourhood social capital score had a mean value of 43.3 (SD = 10.0). The number of minutes usually walked locally per week for transport (mean = 206, SD = 188) and for recreation (mean = 140, SD = 174) were consistent with the results of the International Physical Activity and Environment Network project in the UK, as reported by Frank et al. (2017) (walking for transport: mean = 218, walking for recreation: mean = 129; no SD reported). The results for the wellbeing score (mean = 23.4, SD = 4.6) were close to those estimated using Health Survey for England data, as reported by Ng Fat et al. (2017) (mean = 23.7, SD = 3.9).

Table 2 shows descriptive statistics for location, trip frequency, travel mode, and average per-trip expenditure for the 11 types of local places. As an example, 64% of participants reported that a corner shop is within walking distance and on their side of the busiest road (regardless of whether there is also a shop within walking distance on the other side). 27% reported that a corner shop is within walking distance on the other side of the busiest road but that no shop is within walking distance on their side of the road. Only 9% of participants reported that no corner shop is within walking distance of where they lived (either on their side or on the other side of the busiest road). The places with the highest probability of being visited most days were corner shops (13%) and schools/childcare facilities (11%). Most participants walked to corner shops, cafés, parks/playing fields, schools, pharmacies, stations, and the home of friends or relatives. Most participants travelled by car to supermarkets, high streets/shopping centres, and general practitioners/health centres. Only small proportions of participants cycled to local places. The average per-trip expenditures were consistent with the values reported by previous studies (e.g. Jones et al., 2007, TfL, 2016).

Table 1
Demographics, residence location, and road characteristics: descriptive statistics.

Demographics		**% sample**	**% population**
Age	18–24	11	12
	25–34	15	17
	35–44	16	18
	45–54	18	18
	55–64	15	15
	65–74	22	11
	75+	4	10
Gender	Female	51	51
Ethnicity	Non-white	7	13
Marital status	Single	29	35
Household composition	With children	25	38
Household income ('000£/year)	<=21	38	–
	21–41	34	–
	>41	18	–
	Missing	10	–
Socio-economic group	A (Highest)	8	22
	B	21	
	C1 and C2	47	52
	D	12	25
	E (Lowest)	13	
Cars in the household	0	22	26
	1	52	42
	2 or more	27	32
Qualifications	Degree or equivalent	25	27
	Below degree	73	50
	None or primary	2	23
Employment status	Full-time work	36	45
	Part time work	15	17
	Unemployed	4	4
	Student	10	9
	Home*	8	4
	Retired	27	18
Shopper	Yes	91	–
Restricted mobility	Yes	21	–
Self-rated health status	Very good	17	48
	Good	44	34
	Fair	30	13
	Bad or very bad	9	5

Residence location		**% sample**	**% population**
Housing tenure	Owned home	62	66
	Privately rented	17	16
	Social housing	20	17
Region	North East	4	4
	North West	10	11
	Yorkshire	9	9
	East Midlands	7	7
	West Midlands	8	9
	East of England	11	10
	London	12	13
	South East	13	14
	South West	9	9
	Wales	6	5
	Scotland	9	9
Type of settlement	City	42	–
	Town	38	–
	Village/hamlet	20	–
Living in area	<1 year	4	–

Road characteristics		**% sample**	**% population**
Road lanes	1	48	–
	2	46	–
	3	5	–
Median strip	Yes	41	–
	No	56	–
Traffic volume	Light	8	–
	Average	57	–
	Heavy	35	–
Traffic speed	Slow	7	–
	Average	68	–
	Fast	25	–
Crossing facilities	Straight signalised	29	–
	Staggered signalised	19	–
	Unsignalised marked	32	–
	Footbridge	6	–
	Underpass	6	–
	Pedestrian platform	2	–

Notes: Sample proportions are unweighted. Population proportions were calculated from merged data from the 2011 England and Wales census and the Scotland census. Socio-economic group - A: Higher managerial/administrative/professional; B: Intermediate managerial/administrative/professional; C1: Supervisory/clerical and junior managerial/administrative and professional; C2: Skilled manual workers; D: Semi-skilled and unskilled manual workers; E: State pensioners/casual and lowest grade workers/unemployed with state benefits only. *Home: Looking after home or family

Table 2
Variables on places: descriptive statistics.

	Corner shop or newsagent	Supermarket	Pub, restaurant, or café	High street or shopping centre	Park or playing field	School or childcare facility	Community or leisure centre	General practitioner or health centre	Pharmacy	Station	Home of friend or relative
Location (%)											
On participant's side of road[1]	64	32	54	25	55	54	36	37	43	18	53
Only on other side of road[2]	27	36	32	28	31	31	27	34	34	25	20
Not within walking distance	9	32	14	47	14	15	36	29	22	57	27
Trip frequency (%)											
Most days	13	9	2	4	7	11	2	0	1	5	6
2–3 times a week	20	33	9	13	9	4	5	1	2	4	17
About once a week	24	43	20	33	15	5	8	3	6	6	26
Once or twice a month	17	10	25	29	19	3	8	16	31	11	23
Once every 2–3 months	7	2	17	10	12	3	6	29	28	14	11
Once or twice a year	5	1	11	4	12	3	9	35	19	17	6
Seldom or never	14	3	16	7	26	71	62	16	14	44	12
Travel mode (%)[3]											
Walk	82	38	56	37	78	53	46	46	56	51	61
Cycle	4	3	3	4	5	5	7	3	3	4	5
Public transport	1	9	13	19	3	7	7	10	7	21	11
Car	19	64	44	54	18	39	41	51	45	33	46
Average per-trip expenditure (£)[4]	6	39	24	29	–	–	–	–	–	–	–

Notes: [1] Type of place is within walking distance and exists on the participant's side of the busiest road (regardless of whether it also exists on the other side). [2] Type of place is within walking distance and exists only on other side of the busiest road (not on the participant's side). [3] Proportion of participants reporting using each mode to go to the specified place (among participants who go at least once/twice a year to that place). Participants could report more than one travel mode. [4] The average per-trip expenditure in high streets/shopping centres includes only expenditures in shops other than corner shops, supermarkets, and cafés.

4. Hypotheses and methods

4.1. Overview

Fig. 1 shows the conceptual framework used to structure the analyses that follow. We hypothesise that the characteristics of the busiest roads in the local area and the types of available pedestrian crossing facilities (e.g. footbridges, underpasses, etc.) create a barrier effect that leads to a reduction in the number of trips to local places (❶) and a higher probability of using motorised modes (car and public transport) rather than active modes (walking and cycling) (❷), compared with a scenario where the barrier effect of busy roads and crossing facilities is not present. We assume that even when crossing facilities for pedestrians exist, their use implies delay and inconvenience, contributing to the barrier effect (Anciaes and Jones 2018).

We then hypothesise that the number of trips and travel mode are associated with the average per-trip expenditure on local businesses (❸). The number of trips made to local places by active modes of travel (walking and cycling) is associated with the time spent walking for transport (❹) and the number of trips made to parks, by all modes, is associated with the time spent walking for recreation (❺). In addition, the barrier effect of the road directly influences the time spent walking for recreation (as it reduces the pleasure people derive from walking).

Finally, we hypothesise that the number of trips to different places (by all modes) and the time spent walking for transport and for recreation are associated with three outcomes: neighbourhood social capital, self-rated health, and subjective wellbeing (❻, ❼, and ❽). Self-rated health is assumed to depend on neighbourhood social capital, and subjective wellbeing is assumed to depend on neighbourhood social capital and self-rated health, plausible hypotheses from the literature (Mohnen et al. 2011, Clark and Lisowski 2018, Deeming 2013).

There are six types of monetary value that can be derived from the estimated relationships (green boxes in Fig. 1): the total expenditure on local businesses; the value of the external effects of trips made by motorised modes; the value of social exclusion associated with trips not made (by any mode); and the values of changes in neighbourhood social capital, self-rated health, and subjective wellbeing due to trips not made (by any mode or specifically by walking).

Some aspects are beyond the scope of this paper (white boxes in Fig. 1). Busy roads have direct impacts on local residents, including collision risk; exposure to noise and air pollution; and delays, inconvenience, and disamenity to walking trips that are currently made. These direct impacts may then be associated with number of trips and choice of travel mode. Both direct effects and barrier effects may also be associated with travel behaviour changes other than number of trips and choice of travel mode, including the choice of trip

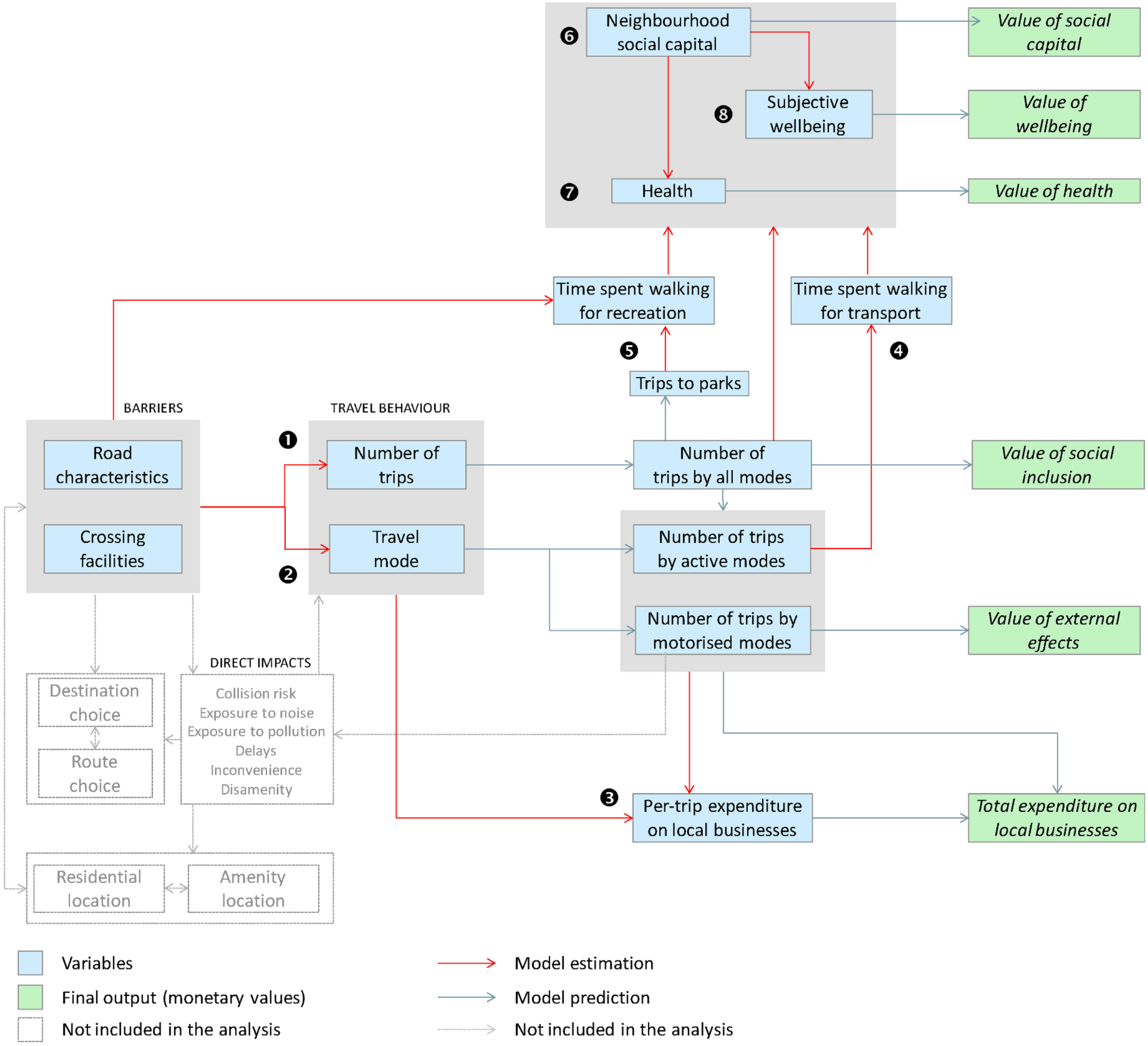

Fig. 1. Conceptual framework to estimate the wider costs of road traffic on local communities.

destinations and travel routes. There are also interrelationships between the location of roads, people, and amenities.

The subsections below describe how we use the data collected in the survey to measure the concepts and links that are the object of analysis in this paper.

4.2. *Barrier effects of roads and pedestrian crossing facilities*

The extent to which road characteristics and pedestrian crossing facilities are barriers to the movement of local residents is measured using two separate indices developed by Anciaes and Jones (2020), based on the choices (regarding crossing roads) that participants made in a stated preference survey.

The first index (road characteristics index) measures the barrier effect caused by the reported design and traffic characteristics of the busiest road near the participant's home. The index has a value for each possible combination of: 1) the number of lanes for motorised traffic (1, 2, or 3 in each direction), 2) presence of median strip (yes or no), 3) traffic volume (low, medium, or high), and 4) traffic speed (10, 20, 30, or 40mph). The combination of high traffic volume and 40mph speed was assumed not to occur, due to road congestion. The index varies from 0% (for a road with the best possible characteristics for pedestrians, i.e. 1 lane per direction, a median strip, and low traffic volume and speed) to 100% (for a road with the worst possible characteristics, i.e. 3 lanes, no median strip, medium traffic volume, and 40mph traffic speed).

In the present paper, the road characteristics index (I_{ROAD} in the equations that follow) was calculated for each survey participant from the answers to the aforementioned questions about the characteristics of the busiest road near where participants live. We assumed a correspondence between the traffic volume categories in the survey questionnaire ("light", "average", or "heavy") and the categories of the index ("low", medium", or "high"). We also assumed a correspondence between the traffic speed categories in the questionnaire ("slow", "average", or ”fast“) and the categories of the index (10, 20/30, 40mph). For the small minorities of participants who did not know the number of lanes (2%) or whether the road had a median strip (3%), we assumed that the road had 1 lane and no median strip, respectively.

The second index (crossing facilities index) measures the barrier effect caused by different types of pedestrian crossing facilities. The index was defined on the same scale as the road characteristics index. As calculated in Anciaes and Jones (2020), the values of the index for underpasses, footbridges, and pedestrian platforms were 13%, 5%, and 0%, respectively. The index for signalised crossings depends on waiting time for pedestrians.

In the present paper, the crossing facilities index (I_{FAC} in the equations that follow) was calculated for each survey participant as the index of the type of facility existing in the local area that has the lowest barrier effect. As vehicles on Great Britain's roads are required to stop for pedestrians at unsignalised marked crossings, we assumed that the barrier effect of these crossings is the same as the one of signalised crossings with no waiting time. We also assumed that where no crossing facilities are present, the crossing facilities index is equal to the road characteristics index. In addition, the value of the index of crossing facilities was truncated at the value of the road characteristics index: that is, we assumed that pedestrians do not use crossing facilities if these are perceived to have a larger barrier effect than the road itself.

We assumed that these two indices of the barrier effects of roads are associated with travel behaviour when visiting places on foot requires crossing the busiest road in the participant's local area. Therefore, in the models described in the next two sub-sections, the two indices were interacted with 11 dummy variables representing the cases where the 11 local places listed earlier (e.g. corner shop, etc.) were reported to be within walking distance on the other side of the busiest road but not on the participant's side, i.e. where the participant needs to cross the road to access the place on foot.

4.3. Number of trips

The model of number of trips (❶ in Fig. 1) was fitted using an expanded dataset where each record contained a value for the number of trips made by each participant each year to each of the 11 types of local places (amounting to 33,418 individual- and place-specific observations). The model estimates the number of trips T_{ip} to a given type of place p in the local area of participant i as a function of: 1) dummy variables D_p representing each type of place (with home of friend/relative as the omitted reference category); 2) a dummy variable N_{ip} representing the case where the place is not within walking distance (irrespective of the side of the road); 3) the characteristics X_i of participants and their residence location; 4) interactions between those characteristics and the type of place (X_iD_p); and 5) the two indices of the barrier effect described in Section 4.2, i.e. I_{ROADi} (road characteristics index) and I_{FACi} (crossing facilities index). As previously noted, the index is applied only when the type of place exists only on the other side of the busiest road (and not on the participants' side). As each participant is represented in the expanded dataset with 11 place-specific records, the error terms were assumed to be correlated within the same participant.

$$T_{ip} = f(D_p, N_{ip}, X_i, X_iD_p, I_{ROADi}, I_{FACi}) \quad (1)$$

The model was specified as a zero-inflated negative binomial model (Greene 1994), as the dependent variable (number of trips per year) is an overdispersed count variable with many zeros (26% of the 33,418 records), and the zeros can be understood as being generated by a separate process from the one that generates the number of trips (for example, some people may not need to go to some types of local places). The model has two equations, one for the probability that the number of trips is zero and another for the number of trips among the subset of participants making at least one trip. For a unit change in the explanatory variables, after exponential transformation, the coefficients in the first equation represent the odds ratio for the number of trips being zero, and the coefficients in the second equation represent the change in the number of trips, expressed as a ratio (Hilbe 2011).

We used the parameters from the estimated model to predict the number of trips that each participant would make to each place over a period of one year in the current situation (i.e. with the current values of the road characteristics and crossing facilities indices) and in an alternative scenario where the road does not represent a barrier to movement (i.e. the road characteristics and crossing facilities indices are both equal to 0). The predicted number of trips was obtained by multiplying the predicted number of trips from the second equation of the model by the probability that this number is non-zero (from the first equation).

4.4. Travel mode

The model of travel mode choice (❷ in Fig. 1) was fitted using an expanded dataset where each record represented a travel mode, or combination of travel modes, potentially used to access each of the 11 types of local places, conditional on the number of trips to that place being non-zero. The dataset for modelling contained 24,165 individual-, place-, and mode-specific observations. The model was used to estimate the probability M_{imp} of participant i using the mode or combination of modes m to go to place p as a function of: 1) dummy variables D_p representing each type of place; 2) dummy variables N_{ip} for places not within walking distance (irrespective of the side of the road); 3) the characteristics of participants and their residence location (X_i); and 4) the two indices of the barrier effect (I_{ROADi} and I_{FACi}). The error terms were assumed to be correlated within the same participant.

$$M_{imp} = f(D_p, N_{ip}, X_i, I_{ROADi}, I_{FACi}) \quad (2)$$

The model was specified as a multinomial logit model with six possible outcomes. Three outcomes represented single travel modes: (1) public transport; (2) car; and (3) active travel (including walking and cycling). The other three outcomes were combinations of travel modes: (4) car and public transport; (5) public transport and active travel; and (6) car and active travel. The reference outcome was active travel.

Walking and cycling were aggregated into the outcome category of active travel because cycling represented a small proportion of all choices (2.3% of all choices, plus 0.8% in combination with other modes). Assuming separate outcomes for cycling and its combinations with other modes would lead to problems in the estimation of standard errors due to the variance matrix being nonsymmetric. For the same reason, choices for the combination of three travel modes (car, public transport, and active travel) were integrated with the ones for car and public transport, as they represented only 0.6% of all choices.

We used the parameters from the estimated model to predict the probabilities of each participant using each mode, or combination of modes, to travel to each place in the current situation (with the current values of the road characteristics and crossing indices) and in the alternative "no-barriers" scenario with values of zero for the barrier effect of roads and crossing facilities.

These travel mode probabilities were then multiplied by the predicted number of trips to each place per year made in the current situation and the no-barriers scenario, obtained from the model of number of trips (❶ in Fig. 1), to derive the predicted number of trips to each place per year by each mode or combination of modes. The predicted number of trips made by combinations of modes was then distributed equally among those modes, in order to derive, for each participant and local place, the predicted number of trips per year made by car, public transport, and active travel.

4.5. Per-trip expenditure on local businesses

Four separate models (❸ in Fig. 1) were used to estimate each participant's per-trip expenditure in four types of local businesses: corner shops; supermarkets; cafés; and shops in high streets or shopping centres. The model was fitted on the subset of participants who reported going to those places at least once or twice a year. A log-linear specification was used. The log transformation was needed to ensure normality of the dependent variables, as the distribution of expenditures was skewed (positively). The model was used to estimate the logged expenditure $E_{i,p}$ of participant i on each type of local business p as a function of: 1) the observed yearly number of trips to that business ($T_{i,p}$); 2) dummy variables D_m representing the travel mode or combination of modes used to access the business; and 3) the characteristics of the participants and their residence locations (X_i).

$$E_{i,p} = f(T_{ip}, D_m, X_i) \quad (3)$$

The values of the two barrier effect indices (road characteristics and crossing facilities) were not entered into the models directly. As outlined in the conceptual framework set out in Fig. 1, our hypothesis is that the per-trip expenditure on the four types of local businesses depends on the barrier effect of the road characteristics and pedestrian crossing facilities **through the intermediate effects** on the number of trips made by local residents (T_{ip} in the equation above) and on the mode (or combination of modes) of travel they use to go there (D_m in the equation above).

4.6. Amount of time spent walking

Two separate models of the amount of time spent walking per year were fitted, one estimating the number of minutes walked for transport (❹ in Fig. 1) and the other estimating the number of minutes walked for recreation (❺). The two models were specified as zero-inflated negative binomial models, as the number of minutes spent walking locally for transport and for recreation were overdispersed count variables with many zeros (22% and 32% of the 3038 participants, respectively) and the zeros can be understood as being generated by a separate process (for example some people may not be able to walk).

According to our conceptual framework (Fig. 1), the amount of time spent walking for transport (W_{TRi}) is indirectly influenced by the barrier effect of the road and pedestrian crossing facilities via an impact on the overall number of trips by active modes made to all of the 11 types of local places ($T_{i,active,all}$). The amount of time spent walking for recreation (W_{RECi}) is influenced by the barrier effect both directly (as measured by the two indices of the barrier effect I_{ROAD} and I_{FACi}) and indirectly via an impact on the number of trips made by any travel mode to parks ($T_{i,all,park}$). Both models control for the characteristics of the participants and residence locations (X_i).

$$W_{TRi} = f(T_{i,active,all}, X_i) \quad (4)$$

$$W_{RECi} = f(T_{i,park}, I_{ROADi}, I_{FACi}, X_i) \quad (5)$$

4.7. Neighbourhood social capital, self-rated health, and subjective wellbeing

The last set of models estimate the wider impacts of travel behaviour on individuals (❻, ❼, and ❽ in Fig. 1). The models for neighbourhood social capital (SC_i in equation 6 below) and subjective wellbeing (WB_i in equation 8) are linear regressions. The model for self-rated health (H_i in equation 7) is a logistic regression of the probability of reporting a self-rated health status of good or very good.

The explanatory variables for the three models are: 1) the logged number of minutes walked for transport and for recreation over a year (W_{TRi} and W_{RECi}); 2) the observed number of trips T_{ip} to each type of place over a year, by all modes; 3) logged yearly income (Y_i); 4) dummy variable for the cases where income is missing ($Y_{i,no}$); and 5) the characteristics of participants and their residence location (X_i). Minutes walked and income were entered as logs to account for a possible positive but decreasing effect on the dependent variables. In accordance with our conceptual framework (Fig. 1), self-rated health depends on neighbourhood social capital, and subjective wellbeing depends on neighbourhood social capital and self-rated health.

$$SC_i = f(W_{TRi}, W_{RECi}, T_{ip}, Y_i, Y_{i,no} X_i) \quad (6)$$

$$H_i = f(W_{TRi}, W_{RECi}, T_{ip}, Y_i, Y_{i,no}, X_i, SC_i) \tag{7}$$

$$WB_i = f(W_{TRi}, W_{RECi}, T_{ip}, Y_i, Y_{i,no}, X_i, SC_i, H_i) \tag{8}$$

The values of the road characteristics and crossing facilities indices were not entered into the models directly. As outlined in Fig. 1, we hypothesise that the three outcomes depend on the barrier effect of the road and crossing facilities **through the intermediate effects** of the number of trips made to different places and of the total number of minutes walked for transport and for recreation.

4.8. Valuation

We used the parameters from the estimated models to make predictions for two scenarios: the current situation (with the two indices of barrier effect calculated from the survey participants' answers about the characteristics of the busiest road and pedestrian crossing facilities in their local area), and a "no-barriers scenario" where the two indices of barrier effect are equal to zero.

4.8.1. Per-trip expenditure on local businesses

For each participant and type of local place, we used the models of the per-trip expenditure (❸ in Fig. 1) to predict the per-trip expenditure in the current situation and in the no-barriers scenario. We then multiplied the predicted per-trip expenditures by the predicted yearly number of trips in each case, to derive the yearly expenditure. Finally, we calculated the impact of the barrier effect of roads on local businesses as the difference in the yearly expenditure between the current situation and the no-barriers scenario.

4.8.2. External effects of motorised transport

We first calculated the number of car and public transport trips made by each participant as the difference between the predicted number of trips by these modes in the current and no-barriers scenario. We then assumed that the length of each trip is 1.61 km, which corresponds to a return trip to a point halfway to the limits of the "local area" as defined in the survey questionnaire (i.e. area within 1 mile or 1.61 km). We also assumed that trips by public transport are made by bus. The length of all trips made by each participant by car and bus was then multiplied by unit values of the external effects of car and bus passenger trips per km, respectively. These unit values were taken from the Country Data spreadsheet included in the Van Essen et al. (2020) study. This study includes estimates for two types of costs: congestion and non-congestion (including collisions, noise, air pollution, and effects on climate, energy, and habitats). For the United Kingdom, for cars and buses respectively, the congestion costs per passenger-km in 2016 were €0.0675 and €0.0816 and the non-congestion costs were €0.062 and €0.0405. For each mode, we added the values for non-congestion and congestion costs and converted the sum to pound sterling using the March 2017 average exchange rate.

4.8.3. Social exclusion

The unit value of an additional trip in reducing the probability of social exclusion for individuals currently at risk of being socially excluded was taken from the study of Stanley et al. (2012) in Australia. This unit value, equal to AUS$20, was converted to pound sterling using the March 2017 average exchange rate. We classified unemployed individuals (4% of participants in our study) as being at risk of social exclusion. We then multiplied the unit value by the difference in the predicted number of trips made by unemployed participants in the current situation and the no-barriers scenario.

4.8.4. Neighbourhood social capital, self-rated health, and subjective wellbeing

The models of neighbourhood social capital, self-rated health, and subjective wellbeing, include as explanatory variables the participants' income and variables that depend on the barrier effect of the busiest road (i.e. number of trips to local places and amount of time spent walking). We can estimate the value of the barrier effect as the substitution between income and changes in those variables. In other words, the costs imposed by the barrier effect of busy roads on neighbourhood social capital, self-rated health, and subjective wellbeing are estimated, for each participant, as the change in income that is necessary to maintain levels of neighbourhood social capital and subjective wellbeing, and a good or very good health status, when moving from the no-barriers scenario to the current situation. The interrelationships between the three outcomes (see equations 7 and 8) were not included in the accounting of the costs, to avoid double counting.

This approach is not grounded in the usual economic reasoning of rational individuals maximizing expected utility through choices that satisfy preferences (for example, preferences regarding trips). Instead, our approach assumes that there is a substitution between income and other factors (e.g. trips) in determining experienced utility (expressed as social capital, health, or subjective wellbeing) (Fujiwara 2019, Ch.3). In other words, an individual is equally well-off (in terms of social capital, health, or subjective wellbeing) with a certain amount of extra income or with a certain change in other factors (e.g. number of trips). This approach has been increasingly applied in valuations of non-market goods through changes in subjective wellbeing (Frey et al. 2009), and has been included in official guidance for valuation of public policies in the UK (HMT and SITF 2021). As mentioned in Section 2, the method has also been used in the transport literature to value trips based on statistical models of social capital and social inclusion (Stanley et al. 2011, 2012).

In practice, we predicted the number of trips, minutes spent walking, and the three outcomes (neighbourhood social capital, self-rated health, subjective wellbeing) for the 'no barriers' scenario (i.e. I_{ROAD} and I_{FAC} both equal to zero) and the current scenario (with the current values of I_{ROAD} and I_{FAC} as calculated from survey data). We then calculated the difference between the predicted values in the two scenarios. Using the models described above, we then calculated, for each participant, the change in income that would make the difference equal to zero when moving from the no-barriers to the current scenario.

5. Model results

5.1. Number of trips

Table 3 shows the two equations (number of trips and probability that the number of trips is zero) of Model ❶. Tests (reported in the table notes) confirmed that the zero-inflated negative binomial specification is more suitable than a standard binomial or a

Table 3
Model ❶: Number of trips per year to a given place in the local area.

	Number of trips (if > 0)			Number of trips = 0		
	Coefficient	*S.E*		*Coefficient*	*S.E*	
Constant	4.26	0.06	***	−2.64	0.11	***
Type of place						
Corner shop or newsagent	0.25	0.03	***	0.75	0.11	***
Supermarket	0.32	0.06	***	−3.54	0.88	***
Pub, restaurant, or café	−0.56	0.04	***	0.51	0.12	***
High street or shopping centre	−0.36	0.07	***	−1.54	0.20	***
Park or playing field	−0.18	0.04	***	1.66	0.10	***
School or childcare facility	0.32	0.06	***	4.25	0.11	***
Community or leisure centre	−0.28	0.06	***	3.33	0.10	***
General practitioner or health centre	−1.91	0.05	***	−17.26	0.27	***
Pharmacy	−1.44	0.04	***	−3.85	3.22	
Station	−0.84	0.08	***	1.90	0.10	***
Place not within walking distance[1]	−0.49	0.03	***	1.51	0.07	***
Age group						
18–24	0.15	0.06	***	−0.69	0.12	***
25–34	0.08	0.05	*	−0.68	0.11	***
65–74	0.11	0.03	***			
75+	0.09	0.05	**			
Other individual characteristics						
Female	−0.12	0.03	***			
Ethnicity: non-white	0.22	0.06	***	−0.54	0.15	***
Restricted mobility	0.10	0.04	***	0.33	0.08	***
Household with children < 18	0.20	0.04	***	−1.58	0.11	***
Socio-economic group: A (highest)				−0.22	0.12	*
Socio-economic group: B				−0.26	0.08	***
Socio-economic group: E (lowest)				0.37	0.10	***
Cars in household: 1	−0.07	0.04	*			
Cars in household: 2 or more	−0.12	0.04	***	−0.16	0.07	**
Residence location characteristics						
City	0.07	0.03	**			
Owned home	−0.09	0.03	***	−0.21	0.07	***
Living in area < 1 year	−0.19	0.07	**			
Region: Scotland	−0.06	0.04	*			
Region: Yorkshire	−0.10	0.05	*			
Region: West Midlands	−0.09	0.05	*			
Interactions demographics-place						
Shopper * Supermarket	0.16	0.06	***			
Shopper * High street or shopping centre	0.34	0.07	***			
Female * School or childcare facility	0.47	0.08	***			
Full-time work * Station	0.71	0.10	***			
Health = bad or very bad * general practitioner or health centre	0.55	0.11	***	−16.29	0.72	***
Index of barrier effect of road						
Road characteristics * place only on other side	−0.12	0.03	***			
Crossing facilities * place only on other side				0.22	0.13	*
Dispersion parameter	1.51 (S.E. = 0.02)					
Number of observations	33,418					
Observations where number of trips = 0	8,735					
Number of participants	3,038					

Notes: Model ❶ in Fig. 1. Zero-inflated negative binomial model with clustered standard errors and sample weights. Significance levels: ***<1%, **<5%, *<10%. [1]:Irrespective of side of busiest road. S.E: Standard error. Likelihood ratio test: $p < 0.001$. Vuong test (zero-inflated vs. standard binomial): $p < 0.001$. Likelihood ratio test of dispersion = 0: $p < 0.001$. Reference categories: place = home of friend/relative; place within walking distance; age = 35–64; male; ethnicity = white; not restricted mobility; no children; socio-economic group = C or D; cars = 0; type of settlement = not city; housing tenure = does not own home; living in area for one year or more: region: not Scotland, Yorkshire, or West Midlands.

Poisson specification. The index of the barrier effect of road characteristics is significant and negative in the equation of the number of trips and the index of the barrier effect of crossing facilities is significant and positive in the equation of the probability of making zero trips. This shows that when places are only within walking distance on the other side of the road (and individuals have to cross the road to access the places on foot), then: 1) individuals living in areas where the reported busiest road conditions are more adverse for pedestrians tend to make fewer trips than average; and 2) individuals living in areas where the pedestrian crossing facilities are less convenient have a higher than average probability of making zero trips. These results confirm the hypothesis that busy roads are a barrier to local mobility (both due to the characteristics of the roads themselves, and to the characteristics of crossing facilities).

Given the logistic specification for the probability that the number of trips is zero, a unit change in the crossing facilities index (i.e. from 0 to 1, representing the best to worst facilities) is estimated to increase the odds of making zero trips by a factor of 1.24 (i.e. exp (0.22) = 1.24). Given the negative binomial specification for the number of trips, a unit change in the road characteristics index (i.e. from 0 to 1, representing the best to worst characteristics) would decrease the number of trips by 11.3% (i.e. exp(-0.12) = 0.887 = 1-0.113).

The other results are also consistent with prior expectations. Corner shops, supermarkets, school/childcare facilities, and places within walking distance tend to be visited more often than other local places. Compared with the reference categories (see notes to Table 3), individuals younger than 35 or aged 65 or over, those identifying as non-white, with restricted mobility, in households with children, and living in cities, tend to make more local trips. Women, individuals in households with cars, homeowners, and those living in the local area for less than a year make fewer local trips. As expected, participants who are responsible for shopping make more trips to supermarkets and high streets, those in full time work make more trips to stations, and those reporting bad or very bad health make more trips to a general practitioner or health centre. Women make more trips to schools.

The local places with the highest probability of attracting zero trips are school/childcare facilities, community/leisure centres, stations, parks, and places that are not within walking distance. The probability of making zero trips to a given place is higher for individuals with restricted mobility and in the lowest socio-economic group. The probability is lower for individuals younger than 35, identifying their ethnicity as non-white, in households with children or with two or more cars, in the two highest socio-economic groups, and homeowners.

5.2. Travel mode

Table 4 shows the estimated multinomial logit model of travel mode choice (conditional on the number of trips to the relevant place being non-zero) (model ❷ in Fig. 1). The reference outcome is active travel only. The index of the barrier effect of road characteristics is significant and positive in the equations for car only and public transport only. This shows that when places are only within walking distance on the other side of the road, individuals living in areas where the reported busiest road conditions are more adverse for pedestrians have a higher than average probability of using car only or public transport only, rather than using active modes only. The index of the barrier effect of crossing facilities is positive in the equations for car and for the combination of car and active modes. This shows that individuals living in areas where the crossing facilities are less convenient have a higher than average probability of travelling only by car or by using both car and active modes, rather than by using only active modes. These results confirm the hypothesis that busy roads are a barrier to making trips to local places by active modes of travel.

Given the results of the multinomial logistic regression for the six-category outcome variable (with active travel only as reference), a unit change in the road characteristics index (i.e. from 0 to 1, representing the best to worst characteristics) would increase the relative risk of using public transport vs. active modes by a factor of 2.01 (exp(0.70) = 2.01). Likewise, a unit change in the crossing facilities index would increase the relative risk of using car vs. active modes by a factor of 1.72 (exp(0.54) = 1.72).

The other results are consistent with prior expectations. In particular, the probability of making a trip by active travel modes only, rather than by another mode or combination of modes, is higher for trips to corner shops and parks/playing fields, as shown by the negative coefficients for the dummy variables identifying these places across all outcomes modelled. The probability of using active travel modes to go to a given type of place is lower when the place is not within walking distance or when the individuals have restricted mobility, as shown by the positive coefficients of the respective variables across all outcomes.

Table 4
Model ❷: Mode choice.

	Public transport only			Car only			Car + public transport			Public transport + active travel			Car + active travel		
	Coefficient	*S.E*		*Coefficient*	*S.E*		*Coefficient*	*S.E*		*Coefficient*	*S.E*		*Coefficient*	*S.E*	
Constant	−3.94	0.26	***	−3.96	0.21	***	−5.48	0.41	***	−3.60	0.42	***	−3.71	0.31	***
Type of place															
Corner shop or newsagent	−1.72	0.26	***	−1.16	0.08	***	−3.88	0.59	***	−2.31	0.40	***	−1.75	0.12	***
Supermarket	0.42	0.14	***	1.28	0.07	***	−0.10	0.18		0.08	0.18		0.16	0.10	
Pub, restaurant, or café	0.84	0.13	***	0.44	0.07	***	0.19	0.16		0.66	0.14	***	−0.35	0.09	***
High street/shopping centre	1.08	0.12	***	0.53	0.08	***	0.24	0.15		0.57	0.16	***	−0.53	0.11	***
Park or playing field	−1.28	0.21	***	−1.27	0.09	***	−2.66	0.36	***	−1.46	0.27	***	−1.59	0.12	***
School or childcare facility	0.51	0.21	**	0.16	0.11		−0.99	0.38	***	−1.21	0.45	***	−0.80	0.15	***
Community/leisure centre	0.10	0.21		0.12	0.10		−1.01	0.28	***	−0.86	0.30	***	−1.08	0.16	***
GP or health centre	0.28	0.14	**	0.47	0.07	***	−0.66	0.19	***	−0.20	0.20		−0.54	0.11	***
Pharmacy	−0.22	0.14		0.14	0.07	*	−1.02	0.19	***	−0.47	0.20	**	−0.72	0.10	***
Station	0.72	0.13	***	−0.68	0.09	***	−0.51	0.18	***	0.01	0.17		−1.28	0.15	***
Place not within walking distance	3.41	0.13	***	3.23	0.10	***	2.97	0.16	***	1.31	0.23	***	0.66	0.16	***
Age group															
18–24	−0.13	0.20		−0.64	0.16	***	0.52	0.26	**	0.74	0.27	***	−0.13	0.19	
25–34	0.01	0.15		0.01	0.11		0.58	0.27	**	0.12	0.23		0.23	0.14	
65–74	0.54	0.16	***	0.25	0.10	**	0.07	0.27		0.26	0.32		−0.26	0.16	*
75+	0.78	0.26	***	0.56	0.17	***	0.56	0.49		0.06	0.49		−0.66	0.30	**
Other individual characteristics															
Female	0.38	0.12	***	0.27	0.08	***	0.23	0.17		−0.18	0.18		0.14	0.11	
Ethnicity: non-white	0.35	0.18	*	−0.09	0.17		0.34	0.27		0.35	0.25		−0.02	0.25	
Restricted mobility	0.54	0.15	***	0.82	0.11	***	0.57	0.28	**	0.39	0.21	*	0.03	0.16	
Household with children < 18	−0.01	0.15		0.16	0.10	*	0.28	0.22		−0.04	0.23		0.27	0.12	**
Socio-economic group: A (Highest)	−0.22	0.21		−0.26	0.14	*	−0.06	0.31		−0.36	0.44		−0.04	0.20	
Socio-economic group: B	0.07	0.15		−0.16	0.10	*	−0.03	0.21		−0.11	0.23		0.08	0.13	
Socio-economic group: E (Lowest)	0.34	0.17	**	0.43	0.14	***	0.52	0.34		−0.22	0.28		0.37	0.21	*
Cars in household: 1	−0.65	0.14	***	2.63	0.16	***	1.59	0.26	***	−1.03	0.21	***	2.26	0.24	***
Cars in household: 2 or more	−0.93	0.16	***	3.27	0.17	***	1.59	0.31	***	−1.34	0.28	***	2.85	0.26	***
Full-time work	0.15	0.14		0.18	0.09	*	−0.14	0.19		0.06	0.21		0.01	0.12	
Unemployed	−0.02	0.22		−0.83	0.32	**	0.03	0.48		0.71	0.34	**	−0.24	0.35	
Residence location characteristics															
City	0.71	0.20	***	−0.18	0.10	*	0.47	0.28	*	0.72	0.32	**	−0.01	0.15	
Town	0.54	0.18	***	0.02	0.10		0.17	0.25		0.88	0.31	***	0.14	0.15	
Region: London	0.12	0.17		−0.69	0.13	***	0.24	0.26		0.87	0.22	***	−0.57	0.19	***
Region: Scotland	0.45	0.18	**	0.11	0.13		0.57	0.26	**	−0.04	0.32		0.47	0.17	***
Region: North East	0.45	0.24	*	0.39	0.21	*	0.46	0.39		0.41	0.40		0.47	0.25	*
Region: South East	−0.30	0.17	*	−0.24	0.12	**	−0.25	0.30		−0.06	0.28		−0.09	0.15	
Region: South West	−0.45	0.22	**	−0.08	0.13		0.09	0.30		0.45	0.31		−0.09	0.18	
Index of barrier effect of road															
Road characteristics * place only on other side	0.70	0.13	***	0.32	0.08	***	0.30	0.22		0.06	0.18		−0.01	0.12	
Crossing facilities * place only on other side	−0.19	0.26		0.54	0.17	***	−0.23	0.63		0.30	0.41		0.65	0.22	***
Number of observations	24,165														
Number of participants	3,022														

Notes: Model ❷ in Fig. 1. Multinomial logit model with clustered standard errors and sample weights. Omitted travel mode category: active travel only (walk and/or cycle). Significance levels: ***<1%, **<5%, *<10%. S.E: Standard error. Likelihood ratio test: $p < 0.001$. Mc Fadden's $R^2 = 0.27$; Count $R^2 = 0.68$; Adjusted Count $R^2 = 0.36$. Reference categories: place = home of friend/relative; place within walking distance; age = 35–64; male; ethnicity = white, not restricted mobility; no children; Socio-economic group = C or D; cars = 0; employment status = not full-time work or unemployed; type of settlement = village or hamlet; region: not London, Scotland, North East, South East, or South West.

5.3. Per-trip expenditure on local businesses

Table 5 shows the estimated log-linear models of the per-trip expenditure on four types of local businesses (among subset of participants with non-zero trips) (model ❸ in Fig. 1). The number of trips is significantly positive in the model of expenditure on corner shops (i.e. the more frequently individuals go to these shops, the higher the per-trip expenditure) and negatively significant in the model of expenditure in supermarkets (the more frequently individuals go to supermarkets, the lower the per-trip expenditure). All else being equal, the trips generating the highest per-trip expenditures are those made by public transport only or car only (in the case of corner shops); public transport only, car only, or car and another mode (in supermarkets); car only or car and active travel (in cafés); and all modes or combinations of modes other than active travel only (in high streets/shopping centres). The results for the control variables are consistent with previous expectations.

These results suggest that the barrier effect of busy roads is positively associated with the per-trip expenditure on supermarkets,

Table 5
Models ❸: Logged per-trip expenditure on local businesses.

	Model A Corner shop			Model B Supermarket			Model C Pub, restaurant, café			Model D High street/ shopping centre		
	Coefficient	*S.E*		*Coefficient*	*S.E*		*Coefficient*	*S.E*		*Coefficient*	*S.E*	
Constant	1.48	0.06	***	3.03	0.08	***	2.87	0.04	***	2.55	0.06	***
Number of trips (year) (100 s)	0.09	0.02	***	−0.27	0.03	***						
Travel mode												
Public transport only	0.52	0.19	***	0.17	0.08	**				0.41	0.06	***
Car only	0.19	0.04	***	0.60	0.04	***	0.22	0.03	***	0.42	0.04	***
Car + public transport				0.43	0.16	***				0.58	0.10	***
Public transport + active travel										0.19	0.10	**
Car + active travel				0.30	0.06	***	0.18	0.06	***	0.23	0.09	**
Age group												
<25				−0.22	0.07	***						
25–34				−0.09	0.04	**						
45–54	−0.17	0.04	***							−0.11	0.05	**
55–64	−0.30	0.05	***				−0.08	0.05	*	−0.13	0.06	**
65–74	−0.34	0.05	***	−0.08	0.04	**	−0.21	0.05	***	−0.25	0.05	***
75+	−0.35	0.08	***	−0.16	0.06	**	−0.35	0.08	***	−0.36	0.09	***
Other individual characteristics												
Female										0.11	0.04	***
Ethnicity: non-white	0.14	0.07	**							0.17	0.08	**
Single				−0.15	0.04	***	−0.31	0.04	***			
Household with children	0.13	0.04	***	0.22	0.04	***				0.20	0.05	***
Income/person/year (1000 s)				0.01	0.002	***	0.01	0.002	***	0.01	0.002	***
Income: missing				0.11	0.06	**	0.13	0.05	**	0.09	0.06	
Full-time work	0.11	0.04	***				0.09	0.04	**	0.09	0.04	**
Unemployed												
Student	−0.13	0.08	*									
Responsible for shopping				0.16	0.06	***						
Residence location characteristics												
Social housing	0.11	0.05	**							0.11	0.06	*
City	−0.11	0.04	**									
Town	−0.09	0.04	**									
Region: London										0.13	0.06	**
Region: Scotland							0.12	0.05	**	0.17	0.06	***
Region: Wales	−0.12	0.07	*									
Region: North West				0.09	0.04	**						
Region: West Midlands	0.11	0.06	*									
Region: East Midlands	−0.18	0.06	***									
Region: South West												
Region: South East	0.08	0.05	*	0.10	0.04	**						
Number of participants	2,716			2,975			2,569			2,741		
R^2	0.09			0.24			0.08			0.10		
F-Test	$p < 0.001$			$p < 0.001$			$p < 0.001$			$p < 0.001$		

Note: Models ❸ in Fig. 1. Log-linear models with sample weights, for participants reporting at least one or two trips per year. Significance levels: ***<1%, **<5%, *<10%. S.E: Standard error. Reference categories: mode = active travel only (walking and/or cycling); age = 35–44; male; ethnicity = white; marital status = not single; no children; income not missing; employment status = not in full-time work, unemployed, or student; participant is not personally responsible for most of shopping in supermarkets and food shops; housing tenure = not social housing; type of settlement = village or helmet; region = North East, Yorkshire, or East of England.

cafés, and high streets, via the effect on the number of trips by car or public transport (which is positive as found in Model ❷ in Table 4). In the case of supermarkets, the barrier effect of busy roads is also positively associated with per-trip expenditure via the effect on number of trips by all modes (which is negative as found in Model ❶ in Table 3).

In the case of corner shops, the net effect on per-trip expenditure is less clear, because the positive effect of the additional trips by public transport and car is balanced by the negative effect of the reduced number of trips by all modes, since the coefficient of the number of trips is positive.

Further analysis (not reported in Table 5) found that when combining the predicted impact of the barrier effect of the busiest road on per-trip expenditure (as described above) with the predicted impact on the yearly number of trips (which is negative, as derived in Model ❶ in Table 3), the overall impact of the barrier effect on **yearly expenditure** on the four types of businesses is negative for all participants.

5.4. Amount of time spent walking locally

Table 6 shows the estimated models of the yearly minutes spent walking locally for transport and for recreation (models ❹ and ❺ in Fig. 1). Tests (reported in the bottom rows of the table) confirmed that the zero-inflated negative binomial specification is more

Table 6
Models ❹ (minutes walked for transport) and ❺ (minutes walked for recreation).

	Model ❹ Minutes walked/year for transport						Model ❺ Minutes walked/year for recreation					
	Minutes			Minutes = 0			Minutes			Minutes = 0		
	Coefficient	*S.E*		*Coefficient*	*S.E*		*Coefficient*	*S.E*		*Coefficient*	*S.E*	
Constant	8.99	0.04	***	−0.51	0.22	**	9.21	0.04	***	−0.26	0.09	***
Number of trips by active mode (year) (100 s)	0.09	0.01	***	−0.58	0.05	***						
Number of trips (by all modes) to parks (year) (100 s)							0.30	0.02	***	−1.07	0.15	***
Individual characteristics												
Age: 18–24				−0.61	0.25	**	−0.25	0.07	***			
Age: 25–34							−0.20	0.06	***			
Age: 35–44							−0.16	0.07	**			
Ethnicity: non-white	−0.13	0.07	*									
Restricted mobility	−0.09	0.06	*	0.69	0.12	***	−0.14	0.06	**	0.69	0.11	***
Single				−0.29	0.15	**						
Household with children							−0.12	0.06	**			
Socio-economic group: E (Lowest)										0.27	0.14	**
Cars: 1				0.85	0.18	***						
Cars: 2 or more				1.19	0.19	***						
Qualifications: degree										−0.34	0.11	***
Residence location characteristics												
City				−0.56	0.14	***	−0.08	0.05	*			
Town				−0.36	0.14	***						
Homeowner										−0.37	0.09	***
Living in area < 1 year	−0.18	0.08	**									
Region: London				−0.75	0.24	***	−0.10	0.06	*			
Region: Yorkshire				−0.66	0.20	***				−0.33	0.16	**
Region: East				−0.29	0.17	*						
Region: South East				−0.37	0.16	**						
Index of barrier effect of road												
Road characteristics	–			–			n.s.			n.s.		
Crossing facilities	–			–			n.s.			n.s.		
Dispersion parameter	0.66 (S.E = 0.02)						0.60 (S.E. = 0.02)					
Number of participants	3,038						3,038					
Number of participants reporting zero minutes	676						970					
Likelihood ratio (LR) test	$p < 0.001$						$p < 0.001$					
Vuong test (zero-inflated vs. standard binomial)	$p < 0.001$						$p < 0.001$					
LR test of dispersion = 0	$p < 0.001$						$p < 0.001$					

Notes: Models ❹ and ❺ in Fig. 1. Zero-inflated negative binomial models with sample weights. Index of barrier effect of road: "-": not included in the model specification, "n.s.": not included in final model because of statistical insignificance. Significance levels: ***<1%, **<5%, *<10%. S.E: Standard error. Reference categories: age 45+; ethnicity = white; not restricted mobility; marital status = not single; no children; Socio-economic group: above E; cars = 0; qualifications < degree; type of settlement = village or hamlet; housing tenure = not owned home; living in area for one year or more; region = not London, Yorkshire, East, or South East.

suitable than a standard binomial or a Poisson specification, in both models.

The higher the number of trips by active modes made to the places specified in the survey, the higher the number of minutes spent walking for transport, and the lower the probability of spending zero minutes. These results confirm the hypothesis that the barrier effect of roads influences the amount of time spent walking for transport via an intermediate impact on the number of walking trips to local places. Compared with the reference categories (see notes to Table 6), the estimated amount of time walked for transport is lower for individuals identifying as non-white, with restricted mobility, and living in their local area for less than a year. The probability of spending zero minutes is higher for individuals with restricted mobility and in households with cars, and lower for individuals aged 18–24 years, single, and living in cities or towns. These results are consistent with expectations.

Also as hypothesised, the higher the number of trips (by all modes) to parks or playing fields, the higher the amount of time spent walking for recreation, and the lower the probability of spending zero minutes. Compared with the reference categories, the estimated minutes spent walking for recreation is lower for individuals aged 18–44, with restricted mobility, in households with children, and living in cities. The probability of spending zero minutes is higher for individuals with restricted mobility and in the lowest socio-economic group (E), and lower for individuals with a university degree, and homeowners. These results are also plausible.

Given the logistic specification for the probability that the number of minutes is zero, making 100 extra trips by active modes of travel is estimated to decrease the odds of walking zero minutes for transport by a factor of 0.56 (i.e. exp(-0.58) = 0.56). Likewise, making 100 extra trips (by any mode) to parks would decrease the odds of walking zero minutes for recreation by a factor of 0.34 (i.e. exp(-1.07) = 0.34). Given the negative binomial specification for the minutes spent walking, making 100 extra trips by active modes would increase the minutes walked per year for transport by 9% (i.e. exp(0.09) = 1.09). Likewise, making 100 extra trips to parks would increase minutes walked per year for recreation by 35% (i.e. exp(0.30) = 1.35).

The indices of the road characteristics and crossing facilities barrier effects were not statistically significant in the models for walking for recreation (and so they were not included in the final model reported in Table 6). This suggests that the barrier effect only influences walking for recreation through the intermediate impact on the number of trips made to parks or playing fields.

5.5. Neighbourhood social capital, self-rated health, and subjective wellbeing

Table 7 shows the estimated models of neighbourhood social capital, self-rated health, and subjective wellbeing. The coefficients of the logged minutes walked for recreation are significant and positive in the three models. This suggests that the impact of the amount of time spent walking for recreation is positive but progressively smaller. In the model of self-rated health, the amount of time spent walking for transport is also statistically significant, again in a non-linear association. Levels of neighbourhood social capital are also positively associated with the number of trips to corner shops and to the home of friends or relatives. Subjective wellbeing is positively associated with the number of trips to cafés and to the home of friends or relatives.

Given the linear specifications for neighbourhood social capital and subjective wellbeing and the log specification for minutes walked for recreation, a 1% increase in minutes spent walking for recreation would increase the neighbourhood social capital score by approximately 0.16 (on a 9–63 scale) and increase the wellbeing score by 0.06 (on a 7–35 scale). Given the results of a binary logit regression model for self-rated health, a 1% increase in the minutes walked per year for recreation would increase the odds of reporting good or very good health (vs. reporting fair, bad, or very bad health) by a factor of approximately 1.09 (exp (0.09) = 1.09). A 1% increase in the minutes walked per year for transport would increase these odds by a factor of 1.05 (exp (0.05) = 1.05).

These results confirm the existence of several significant pathways linking the barrier effect of roads with the three outcomes. The barrier effect of roads reduces levels of neighbourhood social capital via a reduction of the number of trips made to corner shops and homes of friends and relatives. The barrier effect also reduces the odds of reporting good or very good health via a lower amount of time spent walking for transport. Finally, the barrier effect of roads reduces subjective wellbeing via reduced number of trips to cafés and homes of friends and relatives. The barrier effect is related to all three outcomes via a lower amount of time spent walking for recreation (due to reduced number of trips to parks or playing fields),

All three outcomes depend positively on logged income per person, confirming a non-linear association. Above the age of 44, increasing age is associated with higher levels of neighbourhood social capital and wellbeing, and with a lower probability of reporting good or very good health. Compared with the reference categories (see notes to Table 7), levels of neighbourhood social capital are higher for women and lower for individuals living in social housing, and in cities or towns. The probability of reporting good or very good health is higher for women and individuals with a university degree and living in cities, and lower for those who are unemployed and live in social housing. Wellbeing scores are higher for individuals in households with children and living in cities. As expected, the probability of reporting good or very good self-rated health is positively associated with neighbourhood social capital. Subjective wellbeing is positively associated with neighbourhood social capital and with having good or very good health.

Table 7
Models ❻, ❼, ❽ (Neighbourhood social capital, self-rated health, and subjective wellbeing).

Specification	Model ❻ Neighbourhood social capital			Model ❼ Self-rated health = good or very good			Model ❽ Subjective wellbeing		
	Linear			Logit			Linear		
	Coefficient	*S.E*		*Coefficient*	*S.E*		*Coefficient*	*S.E*	
Constant	25.8	2.67	***	−3.96	0.69	***	8.88	0.99	***
Walking									
Log(minutes/year for transport)				0.05	0.01	***			
Log(minutes/year for recreation)	0.16	0.04	***	0.09	0.01	***	0.06	0.02	***
Number of trips per year									
Corner shop	0.004	0.002	*						
Pub, café, or restaurant							0.003	0.001	**
Home of friend/relative	0.02	0.003	***				0.004	0.001	***
Income									
Log (income/person/year)	1.81	0.28	***	0.28	0.07	***	0.54	0.10	***
Income: missing	16.1	2.68	***	2.61	0.68	***	4.59	0.95	***
Age group									
35–44				−0.34	0.15	**			
45–54	2.16	0.53	***	−0.75	0.14	***	0.64	0.19	***
55–64	2.34	0.56	***	−1.08	0.15	***	1.18	0.21	***
65–74	4.48	0.50	***	−1.10	0.14	***	2.02	0.19	***
75+	4.54	0.80	***	−1.35	0.20	***	2.13	0.32	***
Other individual characteristics									
Female	0.81	0.37	**	0.26	0.09	***			
Household with children							0.33	0.18	*
Qualifications: degree				0.24	0.12	**			
Unemployed				−0.83	0.25	***			
Residence location characteristics									
Social housing	−1.36	0.65	**	−0.54	0.15	***			
City	−4.76	0.53	***	0.20	0.09	**	0.42	0.14	***
Town	−4.25	0.52	***						
Region: London	−1.17	0.63	*						
Region: Scotland	1.47	0.65	**						
Region: South West	1.59	0.64	**						
Neighbourhood social capital				0.03	0.004	***	0.10	0.008	***
Health = good or very good							2.19	0.14	***
R^2	0.13						0.28		
F-Test	$p < 0.001$						$p < 0.001$		
Log pseudolikelihood				−1776.1					
Likelihood ratio test				$p < 0.001$					
Mc Fadden's R^2				0.12					
Count R^2				0.68					
Adjusted Count R				0.20					
Number of participants	3038			3038			3038		

Notes: Models ❻, ❼, and ❽ in Fig. 1. Models with sample weights. Significance levels: ***<1%, **<5%, *<10%. S.E: Standard error. Reference categories: income not missing; age 18–34; male; no children; qualifications < degree; employment status = not unemployed; housing tenure = not social housing: type of settlement = village or hamlet; region = not London, Scotland, or South West; health: fair, bad, or very bad.

6. Monetary values

6.1. Main values

Table 8 shows the monetary values of the barrier effect of roads, derived from the models in Section 5 and using the methods presented in Section 4.8. The values are per-person and per-year and are shown for the whole of Great Britain and disaggregated by region, type of settlement, gender, age, and socio-economic group. The average overall per-person cost of the barrier effect is **£631/year**. Applying this value to the whole adult population of Great Britain results in a total cost of **£31.9 billion**, i.e. **1.6% of Great Britain's GDP** in 2017.

The highest costs of the barrier effect of the road per person are reduced neighbourhood social capital (£236/person/year), reduced wellbeing (£196), increased probability of less than good health (£127), and reduced expenditure on local businesses (£64). The values of social exclusion (£7.1/person/year) and external effects of motorised transport (£0.8) are of a smaller magnitude. In the case of

Table 8
Average per-person value of the barrier effect of roads (£/year).

	Expenditure on local businesses	External effects of motorised transport	Social exclusion	Neighbourhood social capital	Self-rated health	Subjective wellbeing	Total
Overall (Great Britain)	64	0.8	7.1	236	127	196	631
Region							
Scotland	59	0.8	4.4	205	109	170	548
North East	66	0.8	7.9	209	112	177	573
North West	75	0.8	15.9	273	131	230	726
Yorkshire & Humber	57	0.7	7.5	235	91	201	593
West Midlands	66	0.7	6.9	198	114	166	551
East Midlands	60	0.9	7.4	251	125	218	662
Wales	52	0.7	17.2	204	107	159	539
East of England	49	0.7	4.4	222	116	184	577
London	87	1.1	3.3	317	167	265	839
South East	70	0.7	5.8	230	137	187	631
South West	50	0.7	2.9	195	158	155	562
Type of settlement							
City	78	0.9	5.9	286	146	244	761
Town	65	0.8	9.8	226	131	189	621
Village	35	0.6	5.2	155	84	117	397
Hamlet	18	0.4	0	118	73	75	285
Gender							
Male	65	0.8	8.1	260	135	215	684
Female	64	0.8	6.2	213	119	178	580
Age							
18–24	60	0.9	11.5	292	130	265	759
25–34	82	1.0	11.5	371	167	300	933
35–44	81	0.9	7.9	231	118	192	630
45–54	72	0.8	10.2	200	127	171	580
55–64	59	0.7	7.1	200	121	162	550
65–74	43	0.6	0	186	108	150	487
75+	45	0.6	0	155	124	125	450
Socio-economic group							
A (highest)	56	0.7	1.2	337	162	284	840
B	69	0.8	0.2	339	173	274	856
C1	58	0.8	1.5	211	114	178	563
C2	69	0.8	4.6	243	138	205	661
D	72	0.9	8.2	173	104	150	508
E (lowest)	61	0.7	36.8	115	68	91	372

social exclusion, this is because the value of suppressed trips in this study applies only to individuals identified at a current risk of social exclusion because of being unemployed. Our estimates are therefore conservative, as other groups (for example, some older people) are also at risk of social exclusion through an inability to travel in the local areas. In the case of the external effects, the small value occurs because the trips shifted from active modes to motorised modes due to the barrier effect of the road are local trips, defined as trips within 1 mile. As such, the overall increase in miles travelled by motorised modes, compared with a scenario where there is no barrier effect, is small.

Cities and the London region have the highest per-person costs of all types except social exclusion, which are higher in towns and in Wales and the North West. Men and individuals in the 25–34 age groups have higher costs than women and other age groups.

6.2. *Values by characteristics of roads and crossing facilities*

The values in the previous table measure the overall cost of the barrier effect, compared with a hypothetical scenario where the barrier effect is completely removed from all the roads in the country that have two or more lanes per direction, or no median strip, or medium or high traffic volumes or speeds, or crossing facilities causing some delay or inconvenience to walking trips. Table 9 shows the costs associated with specific characteristics of the roads and crossing facilities, compared with scenarios where those characteristics are improved by one level (e.g. from 3 to 2 or from 2 to 1 lanes) or two levels (e.g. from 3 to 1 lane), with the other characteristics remaining the same. The values were obtained by re-running all analyses for the specified scenarios.

The per-person yearly costs of the current situation, compared with a scenario where all roads have 1 lane, a median strip, low traffic volumes, and low speeds are £148, £60, £264, and £119 respectively. The costs in comparison with improvements by only one

Table 9
Average per-person value of the barrier effect of characteristics of roads and crossing facilities (£/year).

	Expenditure on local businesses	External effects of motorised transport	Social exclusion	Neighbourhood social capital	Self-rated health	Subjective wellbeing	Total
Lanes = 2 or 3 (vs. 1)	19	0.11	1.9	54	27	47	148
Lanes = 3 (vs.2)	3	0.03	0.3	11	5	10	30
Lanes = 2 (vs.1)	15	0.08	1.6	43	22	37	118
Median strip = No (vs. Yes)	7	0.04	0.6	23	11	19	60
Volume = medium or high (vs. low)	33	0.18	2.6	97	49	82	264
Volume = high (vs. med)	12	0.07	0.9	32	19	28	92
Volume = med (vs. low)	19	0.10	1.5	60	28	50	158
Speed = medium or high (vs. low)	15	0.08	1.3	44	22	37	119
Speed = high (vs. med)	7	0.04	0.5	19	10	16	51
Speed = med (vs. low)	9	0.05	0.9	25	13	21	68
Underpass (vs. platform)	−0.4	0.01	0.02	0.1	0.4	0.1	0.2
Underpass (vs. straight signalised.)	−0.3	0.01	0.02	0.1	0.3	0.1	0.1
Footbridge (vs. platform)	−0.3	0.01	<0.01	0.06	0.3	0.02	0.1
Footbridge (vs. straight signalised)	−0.1	<0.01	<0.01	0.02	0.1	0.01	0.03
Staggered signalised (vs. platform)	−0.4	0.01	0.03	0.1	0.4	0.1	0.2

level (for example, from three to two lanes or from two to one lane) are smaller. The costs of the existing crossing facilities, compared with facilities less inconvenient for pedestrians, are of a smaller magnitude than the costs of the road characteristics.

6.3. Sensitivity to assumptions

All analyses were rerun to test the sensitivity of the results to alternative assumptions. Converting trip frequencies to number of trips using the lower or upper limit of the intervals provided in the survey, rather than the midpoint (see Section 3.1), would result in a per-person cost of the barrier effect of £698 and £569, respectively. Converting income categories into income values using the lower or upper limit of the intervals, rather than the midpoint (see Section 3.1), would result in a per-person cost of the barrier effect of £654 and £619, respectively. Converting the number of trips made by combinations of modes to individual modes assigning 75% to active travel modes, car, and public transport (rather splitting the numbers equally as described in Section 4.4.) would result in a per-person cost of the barrier effect of £632, £631, and £631, respectively. These results show that the cost estimates in Table 8 are robust to changes in the assumptions in the methods used to derive them.

7. Discussion

This paper estimated the costs of busy roads on the quality of life of residents in the surrounding areas, considering the wider impacts caused by changes in travel behaviour, and walking in particular. The analysis developed a conceptual framework and then used statistical models relating the conditions of local roads and pedestrian crossing facilities with aspects of travel behaviour, expenditure on local businesses, and three types of outcomes: neighbourhood social capital, self-rated health, and subjective wellbeing.

The models confirmed the hypothesis that the barrier effect of roads affects local travel behaviour: worse road characteristics for pedestrians reduce the number of trips to local places and increase the propensity to use motorised modes rather than active modes of travel. Worse crossing facilities increase the propensity to make zero trips and increase the propensity to use a car. We have also found evidence of several impacts stemming from the changes in travel behaviour:

- Per-trip expenditures on local businesses were associated with number of trips (with the sign depending on the type of business) and positively associated with the use of motorised modes.

- Walking for transport was positively associated with walking/cycling trips to local places. Walking for recreation was positively associated with number of trips made to parks, but not directly associated with the barrier effect, as hypothesized.
- Neighbourhood social capital, self-rated health, and subjective wellbeing were positively associated with walking for recreation. Self-rated health was also positively associated with walking for transport, and neighbourhood social capital and subjective wellbeing were positively associated with the number of trips to some local places. The lack of a significant association between walking for transport and neighbourhood social capital and subjective wellbeing is plausible. People walking for transport are likely to be more sensitive to travel time and so may make fewer stops to socialize and may not perceive walking time as an opportunity to relax (which tends to increase wellbeing).

Monetary values were then attached to these impacts, using model parameters and predictions. Monetary values were also attached to the impacts on social exclusion and on the external effects of motorised transport, using unit monetary values from the literature. The overall wider costs of road traffic were estimated to be £31.9 billion per year, i.e. 1.6% of Great Britain's GDP, or £631 per person. The analysis also revealed differences between the costs obtained for different regions and segments of the population.

Our study has three main strengths. The first is to provide evidence on the costs of the effects of roads that are borne by local communities and are caused by the mediating impacts on travel behaviour. This is in contrast with previous research which has focused on the direct effects of roads on exposure to noise and air pollution, or measured the barrier effect of roads using stated or revealed preference studies, which cannot fully capture the impacts on travel behaviour of living close to busy roads. The second strength is to estimate the impact of a variety of characteristics of roads and pedestrian crossing facilities. Previous studies considered only traffic volumes or speeds. The third strength is to use a representative sample covering the whole of Great Britain, thus including both urban and rural areas, with and without major roads, as the majority of previous studies have focused on specific urban areas near major roads.

The analysis has some caveats, which could be considered in future research. Our questionnaire was delivered only to adults, although there is evidence that busy roads affect the independent mobility of children (Shaw et al. 2015). As with other online surveys, our sample may also underrepresent some individuals with no access to the internet, some of them possibly at risk of social exclusion. We looked only at two types of effects on travel behaviour: number of trips and travel mode, but it is likely there are also effects on trip destinations and walking routes. In addition, the number of trips made to a given type of place also depends on travel mode (in our analysis, these aspects were modelled separately) and individuals usually visit more than one place in the same trip and make trips to places other than the 11 places listed in the survey.

Aggregating trips made by walking and cycling in some of the models is another limitation, which can be addressed by using larger samples or restricting studies to areas where cycling represents a higher proportion of all trips. The models of neighbourhood social capital, self-rated health, and subjective wellbeing also did not consider physical activity other than walking (e.g. cycling, sports, gym exercise). In addition, we cannot rule out the possibility of reverse causation. For example, lower levels of walking can be a consequence of poor health or low neighbourhood social capital and wellbeing. There are also several wider costs of roads that we did not account for, such as the social cost of increased crime in areas with few pedestrians.

Other modelling approaches are possible. A structural equation model could specify social capital and wellbeing as latent variables and specify paths linking all impacts. This would require simplifications, as keeping the current zero-inflated negative binomial and multinomial logit specifications would lead to convergence problems. The models of number of trips and modal choice could also be extended by interacting demographics, location, and type of place with the barrier effect indicator and with the "not within walking distance" variable.

The method to value neighbourhood social capital, self-rated health, and subjective wellbeing has some caveats. The hypothesis is that income and other factors (including trips) influence neighbourhood social capital, self-rated health, and subjective wellbeing. However, the effects estimated in the models may be explained by unobserved variables. Some authors have also argued that valuations of non-market goods and services through wellbeing tend to produce large values because of under-estimated income coefficients (which are the denominator in the formula estimating the values) (Atkinson et al. 2018, Ch.7.3.1). This is because it is difficult to model all the pathways through which income is linked to wellbeing. This issue also applies to our method to value neighbourhood social capital and self-rated health.

Despite these caveats, accounting for the wider costs of busy roads in residential areas provides useful information for the appraisal of road projects, which in most countries tends to be skewed towards the benefits from time savings for users of motorised modes of transport, without considering the full consequences for local communities. In particular, the barrier effects of roads on pedestrians are currently treated as a non-quantifiable impact in transport appraisal guidance documents in most countries (including England, Scotland, and Wales). The values developed in this study could fill this gap as they are disaggregated by individual characteristics of roads and crossing facilities (see Table 9). The assessment of projects to change these characteristics on a particular road or corridor could make direct use of these values or, after further analysis, disaggregate them further by region, type of area, and population profile, to better fit the context of the project.

Integrating barrier effect costs in transport project appraisal does not "double count" the costs of other negative local effects of high traffic volumes and speeds, such as noise. The estimation of noise costs usually assumes exposure at home, and account for annoyance, sleep disturbance, and other direct health impacts, not impacts that arise via changes in walking behaviour. We have also minimized double counting among the impacts estimated in this paper. We modelled the associations between three outcomes (neighbourhood social capital, health, and subjective wellbeing), excluding the changes in each of these outcomes that are directly explained by changes in the other two. There are also no problems of separability between those three outcomes and expenditure on local businesses and external costs of motorised transport, because the latter two are impacts on other people, not on the person changing travel behaviour. Separability is harder to solve for social exclusion, which is probably associated with the three outcomes mentioned above. We have not modelled these associations due to lack of data to measure social exclusion. Instead, we related number of trips directly with the value of social exclusion, using data from a previous study. Future research could solve this issue by measuring social exclusion and estimate its associations with neighbourhood social capital, self-rated health, and subjective wellbeing.

Other possible extensions could be to incorporate the aspects shown in Fig. 1 but not included in the current analysis. An example is the role of noise and other traffic-related local environmental aspects as barriers to the movement of pedestrians. A more complex extension would be to estimate the long-term relationships between the location of roads with different characteristics and the location of people and amenities. This would require models of household residential choice and business location choice.

Apart from the estimation of costs for project appraisal, the results of this paper produced evidence that support policies that reduce the barrier effect caused by busy roads on pedestrian movement, especially policies that reduce traffic volumes (for example, through pricing or traffic restriction policies). The evidence on imbalances in the costs borne by different individuals and regions in the country also highlights the need to consider spatial and social equity when planning investments in the road network.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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