The climate change mitigation impacts of active travel: Evidence from a longitudinal panel study in seven European cities

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Abstract

Active travel (walking or cycling for transport) is generally good for health, the environment and the economy. Yet the net effects of changes in active travel on changes in mobility-related CO_2 emissions are complex and under-researched. Here we collected longitudinal data on daily travel behavior, mode choice, as well as personal and geospatial characteristics in seven European cities and derived mobility-related lifecycle CO_2 emissions from daily travel activity over time and space. Fixed- and mixed-effects modelling of longitudinal panel data (n=1849) was performed to assess the associations between changes in lifecycle CO_2 emissions and changes in transport mode use (primary exposure), main mode of travel, and cycling frequency (secondary exposures).

Daily mobility-related lifecycle CO_2 emissions were 2.8 $kgCO_2$ per person at baseline, with car travel contributing 69% and cycling 1%. At follow-up, mobility-related lifecycle CO_2 emissions were -0.52 (95%CI -0.82 to -0.21) $kgCO_2$/day lower per additional cycling trip, -0.41 (95%CI -0.69 to -0.12) $kgCO_2$/day lower per additional walking trip, and -2.11 (95%CI -1.78 to -2.43) $kgCO_2$/day lower per 'avoided' car trip. An average person cycling 1 trip/day more and driving 1 trip/day less for 200 days a year would decrease mobility-related lifecycle CO_2 emissions by about 0.5 tonnes over a year. Those who changed from 'not cycling' to 'cycling' decreased daily CO_2 emissions by -2.54 (95%CI -3.90 to -1.17) $kgCO_2$/day. Mobility-related CO_2 emissions decreased by -9.28 (95%CI -11.46 to -7.11) kg/day for those who changed their 'main mode' from car, van or motorbike to active travel. Extensive sensitivity analyses by city, journey purpose and key personal characteristics largely confirmed our results.

Active travel is shown to substitute for motorized travel, with significant climate change mitigation effects. Even if not all car trips could be substituted by active travel the potential for decreasing emissions is considerable and significant. Investing in and promoting active travel should therefore be a cornerstone of strategies to meet net zero carbon targets, particularly in urban areas, while also improving public health and quality of urban life.

Introduction

The transport sector remains at the center of any debates around energy conservation, exaggerated by the stubborn and overwhelming reliance on fossil fuels by its motorized forms, whether passenger and freight, road, rail, sea and air. The very slow transition to alternative fuel sources and propulsion systems to date has resulted in this sector being increasingly and convincingly held responsible for the likely failure of individual countries to meet their obligations under consecutive international climate change agreements (Sims et al., 2014). In Europe, greenhouse gas (GHG) emissions decreased in the majority of sectors between 1990 and 2017, with the exception of transport (EEA, 2019). Modal shifts away from carbon-intensive to low-carbon modes of travel hold considerable potential to mitigate carbon emissions (Cuenot et al., 2012). There is growing consensus that technological substitution via electrification will not be sufficient or fast enough to transform the transport system (Creutzig et al., 2018; IPCC, 2018).

Investing in and promoting 'active travel' (i.e. walking, cycling, e-biking) is one of the more promising ways to reduce transport carbon dioxide (CO_2) emissions[1] (Amelung et al., 2019; Bearman and Singleton, 2014; Castro et al., 2019; de Nazelle et al., 2010; ECF, 2011; Elliot et al., 2018; Frank et al., 2010; Goodman et al., 2012; Keall et al., 2018; Neves and Brand, 2019; Quarmby et al., 2019; Sælensminde, 2004; Scheepers et al., 2014; Tainio et al., 2017; Woodcock et al., 2018). As the temporary shift in travel behaviors due to the COVID-19 pandemic has shown, mode shift could reduce CO_2 emissions from road transport more quickly than technological measures alone, particularly in urban areas (Beckx et al., 2013; Creutzig et al., 2018; Graham-Rowe et al., 2011; Neves and Brand, 2019). This may become even more relevant considering the vast economic effects of the COVID-19 pandemic, which may result in reduced capacities of individuals and organizations to renew the rolling stock of road vehicles in the short and medium term, and of governments to provide incentives to fleet renewal.

The net effects of changes in active travel on changes in mobility-related CO_2 emissions are complex and under-researched. Previous research has shown that travel carbon emissions are determined by transport mode choice and usage, which in turn are influenced by journey purpose (e.g. commuting, visiting friends and family, shopping), individual and household characteristics (e.g. location, socio-economic status, car ownership, type of car, bike access, perceptions related to the safety, convenience and social status associated with active travel), land use and built environment factors (which impact journey lengths and trip rates), accessibility to public transport, jobs and services, and metereological conditions (Adams, 2010; Alvanides, 2014; Anable and Brand, 2019; Bearman and Singleton, 2014; Brand and Boardman, 2008; Brand and Preston, 2010; Cameron et al., 2003; Carlsson-Kanyama and Linden, 1999; Ko et al., 2011; Nicolas and David, 2009; Stead, 1999; Timmermans et al., 2003). Yet active travel studies are often based on analyses of the potential for emissions mitigation (Yang et al., 2018), the generation of scenarios (Goodman et al., 2019; Lovelace et al., 2011; Mason et al., 2015; Tainio et al., 2017; Woodcock et al., 2018) or smaller scale studies focusing on a single city, region or country (Brand et al., 2014; Neves and Brand, 2019). Many of the latter are cross-sectional, so the direction of causality remains unclear. Longitudinal studies are needed to investigate change in CO_2 emissions as a result of changes in active travel activity; however, longitudinal panel studies (with or without controls) are scarce. A small number of intervention studies have been reported, for instance by Keall et al (2018) who in a case study in New Zealand found modest associations between new cycling and walking infrastructure and reduced transport CO_2 emissions.

To better understand the carbon-reduction impacts of active travel, it is important to assess (and adjust for) the key determinants of travel carbon emissions across a wide range of contexts and include a detailed, comparative analysis of the distribution and composition of emissions by transport mode (e.g. bike, car, van, public transport, e-bike) and emissions source (e.g. vehicle use, energy supply, vehicle manufacturing). While cycling cannot be considered a 'zero-carbon emissions' mode of transport,

lifecycle emissions from cycling can be more than ten times lower per passenger-km travelled than those from passenger cars (ECF, 2011). For most journey purposes active travel covers short to medium trips – typically 2km for walking, 5km for cycling and 10km for e-biking (Castro et al., 2019). Typically, the majority of trips in this range is made by car (Beckx et al., 2013; JRC, 2013; Keall et al., 2018; Neves and Brand, 2019; U.S. Department of Transportation, 2017), with short trips contributing disproportionately to emissions because of 'cold starts', especially in colder climates (Beckx et al., 2010; de Nazelle et al., 2010). On the other hand, these short trips, which represent the majority of trips undertaken by car within cities, would be amenable to at least a partial modal shift towards active travel (Beckx et al., 2013; Carse et al., 2013; de Nazelle et al., 2010; Goodman et al., 2014; Keall et al., 2018; Mason et al., 2015; Neves and Brand, 2019; Vagane, 2007).

To address these needs, this paper aimed to investigate to what extent *changes* in active travel are associated with *changes* in mobility-related carbon emissions from daily travel activity across a wide range of urban contexts. To achieve this aim, we included seven European cities with different travel activity patterns, transport mode shares, infrastructure provisions, climates, mobility cultures and socio-economic makeups. We also addressed a number of practical needs. First, as the most common metric used by local and national administrations across the world is mode share (or split) by trip frequency, not by distance (EPOMM, 2020; U.S. Department of Transportation, 2017), we based the main exposure analysis on changes in trip frequencies by mode and purpose. Second, there is a lack of standardized definitions and measurements (self-reported or measured) to identify groups within a population who changed their 'main mode' of transport (e.g. based on distance, duration or frequency over a given time period), or who changed from being a 'frequent cyclist' to 'occasional cyclists', or simply from 'not cycling' to 'cycling'. These should be split as much as possible as there may be different effects on net CO_2 emissions. Third, instead of focusing on the commute journey only, as with many studies that rely on Census data, trips for a wider range of journey purposes were considered in this study, including travel for business, shopping, social and recreational purposes.

Using primary data collected in a large European multicenter study of transport, environment and health, the paper first describes how lifecycle CO_2 emissions from daily travel activity were derived at the individual and population levels across time and space, considering urban transport modes, trip stages, trip purposes and emissions categories. The core analysis then identifies the main contributing factors and models the effects of changes in mode choice and usage over time on changes in mobility-related lifecycle carbon emissions. Further analysis models changes in lifecycle carbon emissions from switching between 'groups of transport users', including by 'main' mode of transport and different categories of cycling frequency. By doing so, the paper provides a detailed and nuanced assessment of the climate change mitigation effects of changes in active travel in cities.

[1] For transport, CO_2 is by far the most important greenhouse gas, comprising approximately 99% of direct greenhouse gas emissions. Surface transport is still dominated by vehicles with internal combustion engines running on petrol (gasoline) and diesel fuels. These propulsion systems emit relatively small amounts of the non-CO_2 greenhouse gases methane (CH_4) and nitrous oxide (N_2O), adding approximately 1% to total greenhouse gas emissions over and above CO_2.

Materials And Methods

2.1 Study design and population

This study used longitudinal panel data from the 'Physical Activity through Sustainable Transport Approaches' (PASTA) project (Dons et al., 2015; Gerike et al., 2016). The study design, protocol and evaluation framework have been published previously (Dons et al., 2015; Götschi et al., 2017). Briefly, the analytical framework distinguished hierarchical levels for various factors (i.e. city, individual, and trips), and four main domains that influence mobility behavior, namely factors relating to transport mode choice and use, socio-demographic factors, socio-geographical factors, and socio-psychological factors. Seven European cities (Antwerp, Belgium; Barcelona, Spain; London, United Kingdom; Orebro, Sweden; Rome, Italy; Vienna, Austria; Zurich, Switzerland) were selected to provide a good representativeness of urban environments in terms of size, built environment, transport provision, modal split and ambition to increase levels of active travel (Raser et al., 2018). To ensure sufficiently large sample sizes for different transport modes, users of less common transport modes such as cycling were oversampled (Raser et al., 2018). Participants were recruited opportunistically on a rolling basis following a standardized guidance for all cities and also some city-specific approaches. A comprehensive user engagement strategy was applied to minimize attrition over the two-year timeframe. Further details on the recruitment strategy are given elsewhere (Gaupp-Berghausen et al., 2019).

In total, 10,722 participants entered the study on a rolling basis between November 2014 and November 2016 by completing a baseline questionnaire (BLQ) at t_0. Participants provided detailed information on their weekly travel behavior (frequency by mode), daily travel activity (one-day travel diary), geolocations (home, work, education), vehicle ownership (private motorized, bicycle, etc.), public transport accessibility and socio-demographic characteristics. Follow-up questionnaires were distributed every two weeks: every third of these follow-up questionnaires also included a one-day travel diary (Dons et al., 2015), with the final of these classified as the final questionnaire at t_1. Participants had to be 18 years of age (16 years in Zurich) or older and had to give informed consent at registration. Data handling and ethical considerations regarding confidentiality and privacy of the information collected were reported in the study protocol (Dons et al., 2015). Table S2 in the Supplementary Information provides an excerpt of the PASTA BLQ, including travel diary data.

2.2 Exposure: change in transport mode choice and use

For reasons given above, the primary exposure variables were changes in daily trip frequencies between t_0 and t_1, by transport mode and trip purpose. Due to low counts of e-biking and motorcycle trips, e-biking was merged with cycling, with indirect emissions derived from observed bike/e-bike shares (see also footnote of **Error! Reference source not found.**). Also, motorcycle was merged with car as reported CO_2 emission rates for motorcycles are comparable to cars *on a per passenger-km basis* (BEIS, 2019). Participants provided information on each trip made on the previous day, including start time, location of origin, transport mode, trip purpose, location of destination, end time and duration (Table S2). The travel diary was based on the established KONTIV-Design (Brög et al., 2009; Socialdata, 2009), with some adaptations for online use. 5,623 participants provided a valid travel diary in either the BLQ or the long FUQ; out of those 1849 participants completed valid surveys and travel diaries at both t_0 and t_1. In the travel diary, trip purpose, duration and location were self-reported. Trip distance was obtained retrospectively feeding origin and destination coordinates to the Google Maps Application Programming Interfaces (API), which returned the fastest route per mode between origin and destination.

To explore changes between groups of individuals three secondary exposure variables were used. First, participants were categorized as using a 'main mode' of travel based on furthest daily distance (levels: walking, cycling, car, public transport) at both t_0 and t_1. From this, nine categories of 'change in main mode' were derived as: stable active travel, stable car, stable public transport, from car to active travel, from car to public transport, from active travel to car, from active travel to public transport, from public transport to car, and from public transport to active travel. Further categorizations based on cycling frequency included a dichotomous variable of 'cycling' on the diary day (yes/no) as well as a trichotomous variable characterizing participants as 'frequent cyclist' (three or more times a day), 'occasional cyclist' (once or twice a day), or 'non-cyclist' (none). From these, several categories of change were derived: stable cycling, stable not cycling, stable 'occasional' cycling, stable 'frequent' cycling, less cycling, more cycling, from not cycling to 'occasional' cycling, from not cycling to 'frequent' cycling, from 'occasional' cycling to 'frequent' cycling, from 'occasional' cycling to not cycling, from 'frequent' cycling to 'occasional' cycling, and from 'frequent' cycling to not cycling. Table 1 below shows sample sizes and mean (SD) values of the primary outcome variable for each group.

2.3 Outcome variables: carbon dioxide emissions

The primary outcome of interest was daily lifecycle CO_2 emissions (mass of carbon dioxide in gram or kilogram per day) attributable to passenger travel. Lifecycle CO_2 emissions categories considered were *operational* emissions, *energy supply* emissions and *vehicle production* emissions. First, operational emissions were derived *for each trip* based on trip distance (computed from travel diary data), 'hot' carbon emissions factors, emissions from 'cold starts' (for cars only) and vehicle occupancy rates (passengers/vehicle) that varied by trip purpose. The method for cars and vans considered mean trip

speeds (derived from the travel diaries), location-specific vehicle fleet compositions (taking into account the types of vehicle operating in the vehicle fleets during the study period) and the effect of 'real world driving' (adding 22% to carbon emissions derived from 'real world' test data based on BEIS (2019) and ICCT (ICCT, 2017)) to calculate the so called 'hot' emission of CO_2 emitted per car-km. For motorcycle, bus and rail, fuel type shares and occupancy rates were based on BEIS (2019). Buses were mainly powered by diesel powertrains; motorcycles were 100% gasoline; and urban rail was assumed to be all electric. For cars, 'cold start' excess emissions were added to 'hot' emissions based on the vehcile fleet composition, ambient temperatures (see Table S13 in the Supplemntary Information) and trip distances observed in each city: across the seven cities, cold start emissions averaged 126 (SD 42) gCO_2 per car *trip*, with the trip share of a car operating with a 'cold' engine averaging 13 (SD 8) percent. Derived cold start emissions were higher-than-average in Orebro and Zurich, and lower in Barcelona. Second, carbon emissions from energy supply considered upstream emissions from the extraction, production, generation and distribution of energy supply, with values taken from international databases for fossil fuel emissions (2016; JEC, 2014; Odeh et al., 2013) and emissions from electricity generation and supply (Ecometrica, 2011). Third, vehicle lifecycle emissions considered emissions from the manufacture of vehicles, with aggregate carbon values per vehicle type (cars, motorcycles, bikes and public transport vehicles) derived assuming typical lifetime mileages, mass body weights, material composition and material-specific emissions and energy use factors. The main functional relationships and data are provided in the Supplementary Information. The derived emissions rates (in grams of CO2 per passenger-km) for each city are given in Supplementary Table S4, disaggregated by emissions category and transport mode and averaged over the study period (2014-2017).

Total daily emissions were calculated as the sum of emissions for each trip, mode and purpose (e.g. the sum of 4 trips on a given day = trip 1: home to work by car, trip 2: work to shop by bike, trip 3: shop to work by bike; and trip 4: work to home by car). Secondary outcomes of interest were mobility-related lifecycle CO_2 emissions for four aggregated journey purposes: (1) work or education/school trips; (2) business trips; (3) social or recreational trips; and (4) shopping, personal business, escort or 'other' trips.

2.4 Covariates

Based on previous research we hypothesized a number of key covariates that have been shown to confound the association between changes in mobility-related carbon emissions and changes in transport mode choice and use (e.g. Brand et al., 2013; Büchs and Schnepf, 2013; Cervero, 2002; Goodman et al., 2019; Stevenson et al., 2016; Zahabi et al., 2016). Demographic and socio-economic covariates considered in the analyses were age, sex, employment status, household income, educational level, and household composition (e.g. single occupancy, or having children or not). Vehicle ownership covariates considered were car accessibility, having a valid driving license, and bicycle accessibility. The only health covariate was self-rated health status, which has been shown to influence motorized travel and transport CO_2 emissions (Goodman et al., 2012). In addition to these self-reported variables, the 'objective' built environment characteristics included here were (see Gascon et al., 2019 for how these

were derived): street-length density (m/km^2), building-area density (m^2/km^2), connectivity (intersection density, n/km^2), facility richness index (number of different facility types (POIs) present, divided by the maximum potential number of facility types specified, *n facility types/74*), home-work distance (Euclidean distance from home to main work/study address, if applicable), and travel distances by car from home to city center, nearest food store and nearest secondary school. Public transport accessibility variables were public transport stations density (*n stations/km²*), distance to nearest public transport station (*m*), time to travel by public transport from home to city center, and number of different services and routes stopping at nearest public transit stop to the home location. The number of days between t_0 and t_1 was included as a covariate to test temporal changes of any effects.

2.5 Statistical analysis

Firstly, bivariate analyses were performed to assess the association between mobility-related lifecycle CO_2 emissions, the exposure variables, and the potential covariates. Secondly, a longitudinal analysis was performed to assess the change in mobility-related lifecycle CO_2 emissions that results from a change in daily travel behavior between t_0 and t_1. We used mixed-effects linear regression models with city as a random effect (to take account of correlation among responses from the same city). Three regression models were fitted: (0) unadjusted (exposure only); (1) adjusted by socio-demographic covariates: sex, age, education level, employment status; and (2) adjusted by all covariates from model 1 and additionally other covariates that either explained some of the variability in CO_2 emissions or had previously been shown to influence emissions (Section 1): access to a car or van, holding a valid driving license, bicycle ownership, self-rated health, street density, building density, connectivity, richness of facilities, travel distances by car from home to city center, nearest food store and nearest secondary school, home-work distance, public transport stations density, distance to nearest public transport station, time to travel by public transport from home to city center, and number of different services and routes stopping at nearest public transit stop. All built environment and accessibility variables were standardized. Sex, age at baseline, baseline education level and city were hypothesized time-invariant covariates. The same set of models were fitted for mobility-related lifecycle CO_2 emissions for the four aggregated journey purposes.

Possible interaction by sex, age, level of education, employment status, car access, home-work distance, and city were investigated with Type II Wald chisquare tests in the fully-adjusted models. We observed significant interactions for changes in use for some transport modes (e.g., change in car use with gender, car access, home-work distance, or city; change in walking with level of education or baseline BMI) and changes in the main mode of transport (e.g., with age, level of education, employment status, car access, life event, or city). Therefore, all models' sensitivity to different levels of the above factors were tested. Specifically, we tested the models' sensitivity with respect to: sex ('female'), participant age ('<35 years'), working status ('working'), home-work distance ('<10km' and 'working'), car access ('not having access to a car'), body weight ('healthy BMI'), excluding participants who had moved during follow-up (Clark et al.,

2014), excluding participants with a life changing event (moved house, new job or new job location, birth or adoption of a child in the household, stopped working, married, child/someone has left the household, gained/lost access to a car) (Clark et al., 2016a, b; Clark et al., 2014; Giles-Corti et al., 2016), time between t_0 and t_1 being greater than a year, and city (Table 1). The effect of potentially influential observations was tested in a sensitivity that excluded 'extreme' change values (n=54, or 2.9%) based on a cutoff value of *4*mean(Cook's distance)*. Only observations without missing data were included. R statistical software v3.6.1 was used for all analyses.

Results

3.1 Summary statistics and sample description

The final longitudinal sample included 1,849 participants completing 3,698 travel diaries reporting 12,793 trips in total. As shown in Table 1, the sample was well balanced between male and female, and between the seven cities. Participants were highly educated with 78% of the participants having at least a secondary or higher education degree. Aged between 16 and 79 at baseline, the majority of participants were employed full-time (63%), with 72% on middle to high household incomes (i.e. >€25,000) and 32% reported to have children living at home. The share of participants without access to a car was 22%.

While cycling and public transport were the most frequent transport modes among our participants at both baseline and follow-up, people travelled furthest by public transport and car (Table 1). Transport mode usage was similar between sexes, with a slightly higher prevalence of male cyclists and drivers vs. female walkers and public transport users. Our sample travelled an average of 3.6 (±1.7) trips per day at baseline and 3.3 (±1.7) trips per day at follow-up, ranging from 2.9 (±1.5) trips per day in Rome at t_1 to 4.0 (±2.1) trips per day in Antwerp at t_0 (see Supplementary Table S5 for city-level values). The observed cycling trip share at baseline was between 18% in Barcelona and 58% in Antwerp (see Supplementary Table S5 for city-level values), i.e. significantly higher than cycling shares reported in Mueller et al. (2018) and a direct result of purposively oversampling cyclists. Reported trip durations and distances were highly variable between subjects and cities, with respondents travelling on average 33.3 (±58.1) km a day and for 90.5 (±69) min a day at baseline. Average trip lengths at baseline across the cities were 0.8 (±1.8) km for walking, 5.1 (±9.7) km for cycling, 15.5 (±40.7) km for public transport and 11.8 (±39.9) km for driving a car or van.

Table 1: Summary statistics of outcomes, exposures and other covariates

Longitudinal sample (n=1849) and mean (SD) lifecycle CO_2 emissions

		Baseline (t_0)	Follow-up (t_1)
CO_2 emissions	**All modes, lifecycle**	**2.80 (6.81)**	**3.10 (7.22)**
(kg per day)	Car, lifecycle	1.86 (5.98)	2.19 (7.02)
	Public transport, lifecycle	0.91 (2.56)	0.88 (2.32)
	Bike, lifecycle	0.03 (0.05)	0.02 (0.05)
	Walk, lifecycle	0 (--)	0 (--)
	Al modes, direct only ^	*1.94 (4.89)*	*2.17 (5.37)*
	All modes, indirect only ^	*0.86 (2.02)*	*0.93 (1.93)*
Transport mode usage	Car	0.69 (1.31)	0.70 (1.31)
(trips per day)	Public transport	1.02 (1.30)	0.91 (1.23)
	Bike	1.08 (1.61)	0.96 (1.52)
	Walk	0.85 (1.32)	0.71 (1.26)
	All modes	**3.63 (1.75)**	**3.29 (1.74)**
Average distance travelled	Car	11.8 (39.9)	14.4 (50.4)
(km per day)	Public transport	15.5 (40.7)	14.9 (38.0)
	Bike	5.1 (9.7)	4.7 (9.4)
	Walk	0.8 (1.8)	0.8 (2.1)
	All modes	**33.3 (58.1)**	**35.9 (59.5)**
Average travel time (min/day)	All modes	90.5 (69.0)	89.0 (71.6)
Participant age (years)	All	37.8 (11.4)	38.6 (11.5)

Sub samples/groups and mean (SD) lifecycle CO_2 emissions

		Baseline (t_0)		Follow-up (t_1)	
Exposures		Lifecycle CO_2, kg/day	n (%)	Lifecycle CO_2, kg/day	n (%)
Main mode	Car	7.94 (9.30)	392 (21)	8.85 (12.2)	444 (24)
(based on distance)	Public transport	2.64 (7.03)	735 (40)	2.49 (3.60)	687 (37)
	Bike	0.21 (0.63)	559 (30)	0.15 (0.37)	538 (29)
	Walk	0.04 (0.19)	163 (9)	0.05 (0.21)	180 (10)
Cycling category	Non-cyclist (none)	3.64 (6.29)	1129 (61)	4.26 (8.39)	1185 (64)
(based on trips per day)	Occasional cyclist (once or twice)	2.14 (9.6)	409 (22)	1.27 (4.26)	409 (22)
	Frequent cyclist (thrice or more)	0.63 (1.84)	311 (17)	0.63 (2.03)	255 (14)
Cycling (yes/no)	Not cycling on the day	3.64 (6.29)	1129 (61)	4.26 (8.39)	1185 (64)
	Cycling on the day	1.49 (7.37)	720 (39)	1.02 (3.58)	664 (36)
City	Antwerp	3.03 (5.5)	282 (15)	3.77 (6.92)	282 (15)
	Barcelona	2.22 (4.56)	345 (19)	2.31 (4.58)	345 (19)
	London	1.96 (3.73)	172 (9)	2.61 (4.98)	172 (9)
	Oerebro	4.23 (6.49)	120 (6)	4.75 (7.82)	120 (6)
	Rome	3.72 (11.1)	287 (16)	3.63 (10.9)	287 (16)
	Vienna	2.08 (3.92)	313 (17)	2.59 (6.68)	313 (17)
	Zurich	3.02 (8.15)	330 (18)	3.02 (6.86)	330 (18)
Sex	Male	3.20 (8.56)	924 (50)	3.38 (8.44)	924 (50)
	Female	2.40 (4.38)	925 (50)	2.82 (5.74)	925 (50)
Age (for sensitivity analysis)	Age <35 years	2.42 (4.59)	891 (48)	3.00 (6.17)	891 (48)
	Age >=35 years	3.15 (8.35)	958 (52)	3.19 (8.08)	958 (52)
	Age >55 years	3.49 (10.6)	159 (9)	2.81 (6.73)	159 (9)
Self-rated health	Excellent	2.89 (5.38)	179 (10)	2.98 (6.29)	179 (10)
	Very good	2.61 (5.36)	790 (43)	3.14 (8.57)	790 (43)

	Good	3.06 (8.83)	715 (39)	3.02 (5.80)	715 (39)
	Fair or poor	2.48 (3.55)	165 (9)	3.39 (6.67)	165 (9)
BMI (for sensitivity analysis)	Healthy BMI (18.5<=BMI<25)	2.50 (5.22)	1239 (67)	2.85 (5.83)	1239 (67)
	Overweight (BMI>=25)	3.61 (9.83)	524 (28)	3.59 (9.75)	524 (28)
Household income	Low income (Less than €25k)	2.7 (9.4)	433 (23)	3.09 (9.81)	433 (23)
	Middle income (€25k to €75k)	2.88 (6.22)	879 (48)	3.08 (6.19)	879 (48)
	High income (€75k or more)	2.67 (4.36)	234 (13)	3.16 (7.03)	234 (13)
Employment status	Working (full-time or part-time)	2.86 (6.67)	1501 (81)	3.14 (7.44)	1501 (81)
	Not working (retired/student/etc.)	2.55 (7.39)	348 (19)	2.93 (6.21)	348 (19)
Education level	Higher education or degree	2.55 (4.85)	1446 (78)	3.0 (6.12)	1446 (78)
	No higher education or degree	3.7 (11.3)	403 (22)	3.46 (10.2)	403 (22)
Household composition	HH two or more adults, no kids	2.64 (5.74)	908 (49)	3.06 (6.41)	908 (49)
	Single HH, no kids	2.56 (5.61)	290 (16)	3.17 (7.29)	290 (16)
	HH with kids	3.28 (8.81)	583 (32)	3.24 (8.52)	583 (32)
Car accessibility	Always or sometimes	3.16 (6.88)	1440 (78)	3.54 (7.95)	1440 (78)
	Never	1.52 (6.4)	409 (22)	1.55 (3.21)	409 (22)
Time between t_0 and t_1	<= 365 days	2.84 (5.21)	1210 (65)	3.11 (7.71)	1210 (65)
	> 365 days	2.72 (5.21)	639 (35)	3.08 (6.2)	639 (35)
Home-work distance	<= 8km	2.17 (7.38)	1319 (71)	2.63 (7.75)	1319 (71)
	>8km	4.36 (4.76)	530 (29)	4.27 (5.52)	530 (29)

^ Direct: tailpipe emissions. ^ Indirect: well-to-tank (fuel/energy production) plus vehicle manufacture. BMI: body mass index.

3.2 Changes in outcomes and exposures

The travel diaries and questionnaires at t_0 and t_1 were completed 282 (±203, min:14, max:728) days apart. Changes in mobility-related lifecycle CO_2 emissions were normally distributed, with a mean change of 0.3 (±9.4) $kgCO_2$/day between baseline and follow-up, largely due to an increase in emissions from driving (Table 1). At baseline, lifecycle CO_2 emissions were 2.8 (±6.8) kilograms of CO_2 ($kgCO_2$) per day, with slightly higher emissions of 3.1 (±7.2) $kgCO_2$/day at follow-up. Driving a car or van made up the majority of these emissions averaging 1.9 (±6.0) $kgCO_2$/day at t_0 and 2.2 (±7.0) $kgCO_2$/day at t_1. Direct (i.e. operational, tailpipe) emissions from all travel activity made up the majority (70%) of mobility-related lifecycle emissions. While travel to work or place of education produced the largest share of CO_2 emissions (43% at t_0, 40% at t_1), there were also considerable contributions from social and recreational trips (29% at t_0, 38% at t_1), followed by shopping or personal business trips (15% at t_0, 14% at t_1) and business trips (13% at t_0, 8% at t_1). The means were significantly higher than the respective medians, suggesting positively skewed distributions of emissions. Thus, a small proportion of individuals were responsible for most of the emissions.

In our sample, respondents in Orebro and Rome produced significantly higher-than-average CO_2 emissions (mean 4.2 $kgCO_2$/day and 3.7 $kgCO_2$/day at baseline) due to the higher car mode shares, while

those in London and Vienna produced lower emissions (mean 2.0 kgCO$_2$/day and 2.1 kgCO$_2$/day, respectively) due to a combination of lower car and higher public transport shares (Table 1 and Supplementary Table S4). At follow-up, mobility-related CO$_2$ emissions had increased in Antwerp, London, Orebro and Vienna, with a slight fall in Rome. Differences between cities can partially be explained by differences in sample demographics, socio-economics, private and public transport provisions, and observed mode shares (Supplementary Table S5).

More than a third of respondents (36%) had changed their daily 'main mode of travel' at follow-up, including 85 participants (5%) who changed from car/van to active travel, 158 participants (9%) who changed from public transport to active travel, and 209 participants (11%) who changed to car, van or motorbike. The largest increase in mean emissions was for a change in 'main mode' from active travel to car/van at 10.3 kgCO$_2$/day, with the largest decrease for a change from active travel to car/van at -8.4 kgCO$_2$/day. The prevalence of changing between cycling frequency categories was 31%: 327 participants reported less cycling, 246 reported more cycling, and 1,276 participants did not change their cycling behaviour (Supplementary Table S6). Similarly, the prevalence of changing between driving frequency categories was 29%.

3.3 Change in transport mode usage (trips/day)

We found that more cycling or walking at follow-up significantly decreased daily mobility-related CO$_2$ emissions (Table 2a), implying a substitution effect of active travel away from motorized travel as opposed to additional, induced active travel. In the fully-adjusted model, mobility-related lifecycle CO$_2$ emissions were -0.52 (-0.82 to -0.21) kgCO$_2$/day lower per additional cycling trip, -0.41 (-0.69 to -0.12) kgCO$_2$/day lower per additional walking trip, but 2.11 (95%CI 1.78 to 2.43) kgCO$_2$/day higher per additional car trip (while controlling for changes in trip rates of other modes of travel). While an additional public transport trip increased mobility-related CO$_2$ emission, the effect was only about a fifth of the increase from an additional car trip. Adjusting for the time-invariant and time-varying covariates slightly reduced the estimates in the adjusted models (models 1 and 2): older participants had lower changes in lifecycle CO$_2$ emissions, whereas those with shorter public transport travel times between home and the city center had marginally higher changes in CO$_2$ emissions (see Supplementary Table S7).

The sensitivity analysis (Figure 1a) generally confirmed our results: the change estimates were marginally higher for motorized modes and lower for walking for those participants living closer to work, while differences between those working and not working were negligible. Female and younger participants showed higher change scores for the active modes and lower change scores for the motorized modes. Excluding those with less than one year between t_0 and t_1 resulted in a slightly larger change in carbon emissions per trip for the active modes and smaller change in car emissions per trip. Excluding 'extreme' change values resulted in slightly smaller change scores across all modes (not shown).

The associations between change in mobility-related lifecycle CO_2 emissions for the four trip purposes and changes in the associated transport mode usage were highly significant for the motorized modes but only marginally significant for changes in active travel trips due to relatively low counts (e.g. cycling for business was rare) and wider confidence intervals (Table 3a). A change in cycling frequency for social and recreational trips had the largest effect on emission changes. Changes in car trips showed significantly larger effects on changes in lifecycle CO_2 emissions for commuting, business, social and recreational trips than for shopping, personal business and escort trips. For public transport, the effect sizes were larger-than sample-average for business, social and recreational trips, reflecting longer trip distances for these purposes. For commuting, changes in carbon emissions were lower for older participants and those living further away from work or closer to the nearest public transport station (Table S11). Changes in emissions from business trips were lower for those without a degree and higher public transport journey times to the city center.

Table 2: Associations between change in mobility-related lifecycle CO_2 emissions (kg/day) and change in the four main exposures. Full results in the Supplementary Information.

n=1849	Model 0: unadjusted (fixed effects)		Model 1: partly adjusted (mixed effects) [†]		Model 2: fully adjusted (mixed effects) [#]	
	Coefficient (95% CI)	p-value	Coefficient (95% CI)	p-value	Coefficient (95% CI)	p-value
(a) Association between change in lifecycle CO_2 emissions (kg/day) and change in transport mode usage (trips/day) (full model in Table S7)						
Bike	-0.516 (-0.818 to -0.215)	< 0.0001	-0.524 (-0.826 to -0.222)	0.001	-0.517 (-0.821 to -0.214)	0.001
Car	2.127 (1.808 to 2.445)	< 0.0001	2.117 (1.799 to 2.436)	< 0.0001	2.105 (1.783 to 2.427)	< 0.0001
Public transport	0.448 (0.121 to 0.776)	0.007	0.461 (0.134 to 0.789)	0.006	0.445 (0.114 to 0.776)	0.008
Walk	-0.409 (-0.691 to -0.127)	0.005	-0.406 (-0.688 to -0.123)	0.005	-0.406 (-0.691 to -0.121)	0.005
(b) Association between change in lifecycle CO2 emissions (kg/day) and change in main mode of transport (full model in Table S8)						
Stable: car	0	--	0	--	0	--
Active travel to car	9.726 (7.729 to 11.723)	< 0.0001	9.626 (7.626 to 11.626)	< 0.0001	9.251 (7.223 to 11.279)	< 0.0001
Active travel to PT	2.034 (0.236 to 3.833)	0.027	1.907 (0.101 to 3.713)	0.038	1.697 (-0.204 to 3.599)	0.05
Car to active travel	-9.032 (-11.178 to -6.886)	< 0.0001	-9.081 (-11.229 to -6.932)	< 0.0001	-9.283 (-11.459 to -7.107)	< 0.0001
Car to PT	-6.583 (-8.867 to -4.299)	< 0.0001	-6.638 (-8.922 to -4.354)	< 0.0001	-6.805 (-9.117 to -4.493)	< 0.0001
PT to active travel	-3.37 (-5.114 to -1.625)	< 0.0001	-3.558 (-5.317 to -1.8)	< 0.0001	-3.724 (-5.573 to -1.875)	< 0.0001
PT to car	4.927 (2.937 to 6.918)	< 0.0001	4.826 (2.829 to 6.822)	< 0.0001	4.875 (2.858 to 6.893)	< 0.0001
Stable: active travel	-0.646 (-1.999 to 0.706)	0.349	-0.702 (-2.06 to 0.656)	0.311	-1.041 (-2.508 to 0.426)	0.164
Stable: PT	-0.631 (-1.985 to 0.723)	0.36	-0.727 (-2.087 to 0.634)	0.295	-0.768 (-2.207 to 0.671)	0.295
(c) Association between change in lifecycle CO2 emissions (kg/day) and change in daily cycling trips (full model in Table S9)						
Stable cycling trips	0	--	0	--	0	--
Fewer cycling trips	1.387 (0.189 to 2.585)	0.023	1.383 (0.184 to 2.583)	0.024	1.303 (0.048 to 2.558)	0.042
More cycling trips	-1.73 (-3.019 to -0.441)	0.008	-1.781 (-3.071 to -0.49)	0.007	-1.733 (-3.068 to -0.398)	0.011
Far fewer cycling trips	4.176 (2.318 to 6.034)	< 0.0001	4.179 (2.317 to 6.04)	< 0.0001	4.088 (2.176 to 5.999)	< 0.0001
Far more cycling trips	-2.191 (-4.498 to 0.116)	0.063	-2.272 (-4.584 to 0.04)	0.054	-2.433 (-4.784 to -0.083)	0.042
(d) Association between change in lifecycle CO2 emissions (kg/day) and change in cycling frequency categories (full model in Table S10)						
Stable: not cycling	0	--	0	--	0	--
Stable: cycling	-1.162 (-2.348 to 0.024)	0.055	-1.171 (-2.368 to 0.026)	0.055	-1.429 (-2.714 to -0.143)	0.029
Less cycling	2.348 (1.183 to 3.513)	< 0.0001	2.353 (1.183 to 3.522)	< 0.0001	2.11 (0.86 to 3.359)	0.001
More cycling	-2.366 (-3.667 to -1.066)	< 0.0001	-2.44 (-3.745 to -1.134)	< 0.0001	-2.535 (-3.904 to -1.166)	< 0.0001

[†]Model 1 adjusted for sex, age at baseline, baseline education level, baseline employment status; city as random effect

3.4 Change in main mode of transport

We also observed statistically significant associations between changes in mobility-related lifecycle CO_2 emissions and changes in the 'main mode' of transport, as defined by daily distance travelled (Table 2b). In the fully adjusted model (model 2), CO_2 emissions decreased by -9.28 (95%CI -11.46 to -7.11) kg/day for those who changed main mode from car or motorbike to active travel (CaràAT); conversely emissions increased by 9.25 (95%CI 7.22 to 11.28) kg/day for changing from active travel to car or motorbike (ATàCar). Those who changed their main mode from car or motorbike to public transport (CaràPT) reduced CO_2 emissions by -6.81 (95%CI -9.12 to -4.49) kg/day, while a shift from public transport to active travel decreased emissions by -3.72 (95%CI -5.57 to -1.88) kg/day. Adjusting for the covariates (models 1 and 2) slightly lowered the carbon effects for ATàCar and ATàPT, but increased them for CaràAT and CaràPT. The sensitivity analysis (Figure 1b) again largely confirmed our results. Female participants had lower change scores for shifts away from motorized travel, but marginally higher change scores for shifts away from active modes. Those without access to a car showed a large (though with a wide CI) decrease in emissions for a shift in main mode from car to public transport; likely to be a shift away from being a *passenger in a car* to passenger on a bus or train.

Changes in the main mode of transport by trip purpose were also largely significant (Table 3b). For work or education, a shift from car or motorbike to active travel reduced commuting emissions by -4.01 (95%CI -5.63 to -2.40) kg/day, while they increased by 8.89 (95%CI 7.36 to 10.43) kg/day for a shift from active travel to car or motorbike. The largest change was observed for a change in main mode from car to public transport for business purposes, reflecting longer trip distances and low occupancy rates for business travel by car.

Table 3: Associations between changes in mobility-related lifecycle CO_2 emissions for each trip purpose and changes in the four main exposures by purpose (fully adjusted models).

=1849	Work or education #		Business #		Social or recreational #		Shopping, personal business, escort, or 'other' #	
	Coefficient (95% CI)	p-value	Coefficient (95% CI)	p-value	Coefficient (95% CI)	p-value	Coefficient (95% CI)	p-value

Association between change in lifecycle CO_2 emissions by purpose (kg/day) and change in <u>transport mode usage</u> (trips by ...ose/day) (full model in Table S10)

...ke	-0.114 (-0.262 to 0.034)	0.131	-0.058 (-0.418 to 0.303)	0.754	-0.265 (-0.594 to 0.063)	0.113	-0.004 (-0.087 to 0.078)	0.919
...r	3.138 (2.918 to 3.359)	< 0.001	3.318 (2.872 to 3.764)	< 0.001	3.005 (2.693 to 3.316)	< 0.001	1.374 (1.296 to 1.453)	< 0.001
	0.694 (0.548 to 0.84)	< 0.001	1.349 (0.959 to 1.739)	< 0.001	1.049 (0.73 to 1.368)	< 0.001	0.505 (0.397 to 0.614)	< 0.001
...lk	-0.234 (-0.432 to -0.035)	0.021	-0.183 (-0.665 to 0.299)	0.456	-0.204 (-0.506 to 0.099)	0.187	-0.061 (-0.137 to 0.015)	0.118

Association between change in lifecycle CO_2 emissions by purpose (kg/day) and change in <u>main mode of transport by trip ...ose</u> (full model in Table S11)

...able: car	0	--	0	--	0	--	0	--
...' to car	8.893 (7.357 to 10.429)	< 0.001	--	--	7.676 (4.811 to 10.54)	< 0.001	1.845 (1.07 to 2.619)	< 0.001
...' to PT	0.157 (-0.602 to 0.916)	0.686	-4.515 (-9.003 to -0.027)	0.049	0.914 (-0.876 to 2.703)	0.317	-0.939 (-1.483 to -0.396)	0.001
...r to AT	-4.014 (-5.633 to -2.396)	< 0.001	-6.556 (-16.307 to 3.195)	0.188	-5.444 (-8.316 to -2.572)	< 0.001	-4.672 (-5.518 to -3.826)	< 0.001
...r to PT	-6.133 (-7.099 to -5.167)	< 0.001	-10.41 (-15.02 to -5.79)	< 0.001	-5.537 (-7.499 to -3.576)	< 0.001	-3.898 (-4.504 to -3.293)	< 0.001
...to AT	-0.928 (-1.728 to -0.128)	0.023	-4.844 (-9.429 to -0.259)	0.038	0.002 (-1.822 to 1.825)	0.999	-1.191 (-1.754 to -0.628)	< 0.001
...to car	5.083 (4.131 to 6.036)	< 0.001	4.684 (-0.126 to 9.493)	0.056	8.671 (6.722 to 10.62)	< 0.001	1.936 (1.312 to 2.561)	< 0.001
...able: AT	-0.408 (-1.156 to 0.339)	0.284	-4.943 (-10.219 to 0.333)	0.066	0.085 (-1.862 to 2.032)	0.932	-1.014 (-1.593 to -0.435)	0.001
...able: PT	-0.292 (-0.975 to 0.391)	0.402	-4.929 (-9.332 to -0.526)	0.028	0.377 (-1.271 to 2.025)	0.654	-1.156 (-1.666 to -0.645)	< 0.001

Association between change in lifecycle CO_2 emissions by purpose (kg/day) and change in daily <u>cycling trips by trip purpose</u> ... model in Table S12)

...able bike	0	--	0	--	0	--	0	--
...wer trips	0.252 (-0.434 to 0.938)	0.471	0.426 (-1.864 to 2.715)	0.716	0.325 (-1.459 to 2.108)	0.721	-0.271 (-0.784 to 0.242)	0.3
...ore trips	-0.45 (-1.149 to 0.249)	0.207	0.333 (-3.105 to 3.77)	0.849	-0.639 (-2.591 to 1.312)	0.521	0.362 (-0.215 to 0.939)	0.218
...r fewer ...ps	0.686 (0.126 to 1.246)	0.016	0.637 (-0.674 to 1.949)	0.341	0.985 (-0.255 to 2.224)	0.119	-0.1 (-0.49 to 0.289)	0.614
...r more ...ps	-0.872 (-1.514 to -0.231)	0.008	0.239 (-1.494 to 1.972)	0.787	-0.537 (-1.786 to 0.712)	0.399	-0.527 (-0.944 to -0.11)	0.013

Association between change in lifecycle CO_2 emissions by purpose (kg/day) and change in <u>cycling frequency categories by trip purpose</u> (full model in Table S13)

...able not ...cling	0	--	0	--	0	--	0	--
...able ...cling	0.05 (-0.478 to 0.578)	0.853	0.12 (-3.949 to 4.189)	0.954	-0.191 (-1.785 to 1.403)	0.815	-0.334 (-0.902 to 0.234)	0.249
...ss cycling	0.883 (0.355 to 1.411)	0.001	0.626 (-0.616 to 1.869)	0.323	0.804 (-0.359 to 1.967)	0.175	-0.101 (-0.445 to 0.242)	0.564
...ore ...cling	-0.654 (-1.247 to -0.061)	0.031	0.264 (-1.335 to 1.862)	0.746	-0.5 (-1.653 to 0.653)	0.395	-0.22 (-0.607 to 0.167)	0.266

...odels adjusted for sex, age at baseline, baseline education level, baseline employment status, driving license, car access, bike ...ss, change in self-rated health, street-length density, building-area density, connectivity, facility richness index, home-work ...nce, travel distances by car from home to city center, nearest food store and nearest secondary school, public transport ...ons density, distance to nearest public transport station, time to travel by public transport from home to city center, number of ...rent services and routes stopping at nearest public transit stop, time between t_0 and t_1; city as random effect.

...active travel, PT=public transport.

3.5 Change in cycling frequency and change between 'cyclists' and 'non-cyclists'

Firstly, we found that the associations between changes in mobility-related lifecycle CO_2 emissions and changes in cycling frequency were all significant (Table 2c): in the fully adjusted model (model 2) CO_2 emissions were -1.73 (95%CI -3.07 to -0.40) lower for those who cycled more (1 to 2 times more) per day at follow-up than those who did not change cycling frequency, and they were even lower for those who cycled far more (3 times or more) at t_1, reducing emission by -2.43 (95%CI -4.78 to -0.08) kg/day. Again, the sensitivity analysis (Figure 1c) generally confirmed our results, with a notable difference for participants without access to a car whose emissions did not drop significantly after an increase in cycling frequency at t_1, suggesting that those trips were not substituting for private motorized travel. We also observed slightly lower effects for increased cycling for those with a healthy weight/BMI. Cycling far more at t_1 was also associated with significantly reduced lifecycle CO_2 emissions for commuting to work or place of education and for shopping, personal business and escort trips (Table 3c and Supplementary Table S13). Similar trends were observed for social and recreational trips but these were not significant due to low counts and wide CI.

Secondly, changes between the binary cyclist/non-cyclist groups showed similar effect sizes to the analysis of cycling frequency. Associations between mobility-related lifecycle CO_2 emissions and changes between 'non-cyclists' and 'cyclists' were all significant (Table 2d): less cycling increased emissions by 2.11 (95%CI 0.86 to 3.36) kg/day, more cycling reduced them by -2.54 (95%CI -3.90 to -1.17)

kg/day, and those who kept up their cycling had -1.43 (95%CI -2.71 to -0.14) kg/day lower emissions than those who did not cycle at either t_0 or t_1. While the sensitivity analysis (Figure 1d) generally confirmed our results, the analysis by trip purpose showed significant effects in the same directions for work and education trips only (Table 3c and Supplementary Table S14).

3.6 Further sensitivity by city

Further analysis stratified by city revealed that the effects of changes in daily cycling trips on changes in mobility-related CO_2 emissions were marginally higher in Oerebro and Zurich, and lower in London and Rome (Figure 2). In Rome emissions *increased* slightly, but this was not significant due to low counts and wide CI. Additional car trips increased emissions more in Rome and Zurich, and less in Oerebro, reflecting different trip distances and car occupancy rates. By comparison, changes in main mode of daily travel from car to active travel (car→AT) showed the largest effect in Zurich, with the reverse (AT→car) showing largest effects in Zurich and Vienna, possibly reflecting longer trip distances in these cities. A shift in main mode from car to public transport showed marginally higher effects in London, Vienna and Zurich (i.e. cities with good public transport services and longer trip distances).

Discussion

4.1 Summary of results and comparison with previous studies

In our panel of 1,849 participants from seven European cities of different sizes, built environments, socio-demographic make-ups and mobility cultures, we found highly significant associations between changes in daily transport mode use and changes in mobility-related lifecycle CO_2 emissions. The finding that an increase in cycling or walking at follow-up (including those who already cycled at baseline) decreased mobility-related lifecycle CO_2 emissions suggests that active travel substitutes for motorized travel – i.e. this was not just additional travel over and above motorized travel. Similarly, our finding that changing from 'not cycling' at baseline to 'cycling' at follow-up significantly decreased mobility-related lifecycle CO_2 emissions provides further evidence of mode substitution away from motorized travel. This also suggests that even if not all car trips could be substituted by bicycle trips the potential for decreasing emissions is considerable and significant.

To illustrate this, an average person cycling 1 trip/day more and driving 1 trip/day less for 200 days a year would decrease mobility-related lifecycle CO_2 emissions by about 0.5 tonnes of CO_2 (tCO_2) over a year, representing a sizeable chunk of annual per capita lifecycle CO_2 emissions from driving (which e.g. in the UK amount to about 1.4 tCO_2 per person per year). The potential savings also represent a substantial share of average per capita CO_2 emissions from transport (excl. international aviation and shipping), which for the cities in this study ranged between 1.8 tCO_2/person/year in the UK to 2.7

tCO$_2$/person/year in Austria (CAIT and Climate Watch, 2020: 2016 data). A change in 'main mode' of transport from car to active travel for a day a week would have similar effects, decreasing emissions by about 0.5 tCO$_2$/year. So, if 10% of the population were to change travel behaviour this was the emissions savings would be around 4% of lifecycle CO$_2$ emissions from car travel. The size and direction of emissions changes are in line with some of the scenario/modelling (Goodman et al., 2019; Rabl and de Nazelle, 2012; Tainio et al., 2017; Woodcock et al., 2018) and empirical (Brand et al., 2014; Brand et al., 2013; Goodman et al., 2012) studies in the area of research of active travel and CO$_2$. More broadly, the findings provide empirical evidence on converting 'mode shift to active travel' into carbon effects, therefore offering researchers and policy makers the opportunity to assess climate change mitigation impacts of policy measures and interventions aimed at mode shift (see e.g. Brown et al., 2015; Scheepers et al., 2014).

The sensitivity analyses generally confirmed our main results, with differences for some subgroups as expected (e.g. those who increased cycling but had no access to a car did not decrease CO$_2$ emissions at follow-up) or inconclusive due to low counts. The differences in mean emissions and effect sizes in the seven cities may be explained by observed and contextual factors such as differences in modal shares (Supplementary Table S5), trip lengths (larger effects in larger cities), and the provision (or not) of good public transport services and active travel infrastructure (Supplementary Table S2) as well as differences in sampling for each city (Raser et al., 2018).

As a result of limited data availability, often relying on census data, active travel research has often focused on travel activity from commuting only (Bearman and Singleton, 2014; Clark et al., 2016b). In our study, commuting and business travel was responsible for about half of mobility-related CO$_2$ emissions, followed by social and recreational trips (29% at t_0, 38% at t_1) and shopping or personal business trips (15% at t_0, 14% at t_1). The finding that changes in emissions were larger for business and social/recreational trips by car and public transport may partially be explained by longer trip distances (and lower occupancy rates for business travel). These longer trips may therefore be less conducive to mode shift. In contrast, shopping and personal business trips were found to be significantly shorter, therefore increasing the potential for mode shift to active travel.

4.2 Strengths and limitations

The main strengths of this study include its longitudinal panel design, international coverage of urban locations and use of different measures of exposure to enable controlled comparisons within the sample populations. These represent important methodological advances on previous studies on the links between active travel, transport mode use and associated CO$_2$ emissions, which largely used cross-sectional designs (Brand et al., 2013; Sloman et al., 2009; Troelsen et al., 2004; Wilmink and Hartman, 1987). Very few studies have provided empirical evidence of changes in transport CO$_2$ emissions as a result of changes in active travel using panel data (Brand et al., 2014). These study strengths allowed the

investigation of substantive questions such as those regarding the effects on mobility-related CO_2 emissions from changes in transport mode use, journey purpose and city. The approach of using measures of exposure that are commonly used by local and national administrations across the world (trips as the main unit of assessment for mode shares; a measure of 'main mode'; different groups of 'cyclists') has therefore the potential to be used by policy and practice in diverse contexts and circumstances (EPOMM, 2020; U.S. Department of Transportation, 2017).

However, the study had several limitations. First, the CO_2 emissions outcomes had high standard deviations (mainly due to social and temporal variability of daily travel activity) and this reduced statistical power. Nevertheless, the analysis could detect highly significant changes for the majority of outcomes under investigation. Future research may address this limitation by increasing the sample size, measurement period and/or focussing solely on short trips below 8 kilometres where we would expect lower variability in the main outcomes. Second, recall bias and participant burden of a substantive survey instrument may have impacted the travel diary reporting, which may have reduced the number of reported trips. However, the observed trip frequencies (e.g. 3.6 trips per person per day on average at baseline) and mode shares (e.g. significantly higher cycling shares in Antwerp, lower cycling shares in Barcelona, higher public transport shares in London, Vienna and Zurich) were in line with figures reported for the cities (Raser et al., 2018). Third, the recruitment and sampling strategy means that our sample cannot be assumed to be representative of the general population, especially for education level and age. Orebro was the lone city that made a concerted effort for random sampling, whereas in other cities an opportunistic recruitment strategy was followed (Dons et al., 2015). However, by oversampling some of the less frequent transport modes, we had a sufficiently large sample of cyclists and public transport users in all cities to find statistically significant associations. Fourth, we excluded carbon emissions from dietary intake in the lifecycle analysis as the evidence is inconclusive on whether day-to-day active travel (as opposed to performance/sport activity) significantly increases overall dietary intake when compared to motorized travel (Tainio et al., 2017). For instance, a study using consumption data obtained from a consumer survey found that a 10% rise in active transport share was associated with a 1% *drop* in food-related emissions, which may be related to overall health awareness or concerns as well as impacts on well-being and mental health (Ivanova et al., 2018). Another recent study by Mizdrak et al. (2020) assumed that increased energy expenditure is directly compensated with increased energy intake, while acknowledging that this is an unproven assumption. Finally, while we accounted for several influencing factors that were often not available in previous studies, such as trip data by mode and purpose, public transport accessibility and a suite of built environment variables, our regression models did not account for more than 41% of the variation in the population. This suggests that changes in mobility-related CO_2 emissions are also influenced by other factors such as lifestyle and socio-cultural factors (Brand et al., 2019; Panter et al., 2013; Weber and Perrels, 2000), as well as the social and temporal variability of daily travel mentioned earlier.

4.3 Conclusion

There can be little doubt that active travel has many benefits, including net benefits on physical and mental health (in most settings), providing access to jobs and services as well as being low cost and reliable (Mindell, 2015). This paper started by asking a question that keeps coming up, namely whether more cycling or walking actually reduces mobility-related carbon emissions – as opposed to representing added or induced demand that does not substitute for motorised travel. Using longitudinal panel data from seven European cities we found highly significant associations between changes in mobility-related lifecycle CO_2 emissions and changes in daily transport mode use, changes in cycling frequency and changes in the 'main mode' of daily travel. Importantly, the finding that an increase in cycling or walking at follow-up decreased mobility-related lifecycle CO_2 emissions suggests that active travel indeed substitutes for motorized travel. Promoting active travel in urban areas should therefore be a cornerstone of strategies to meet 'net zero' carbon targets that are unlikely to be met without significant mode shift away from motorized transport (Creutzig et al., 2018).

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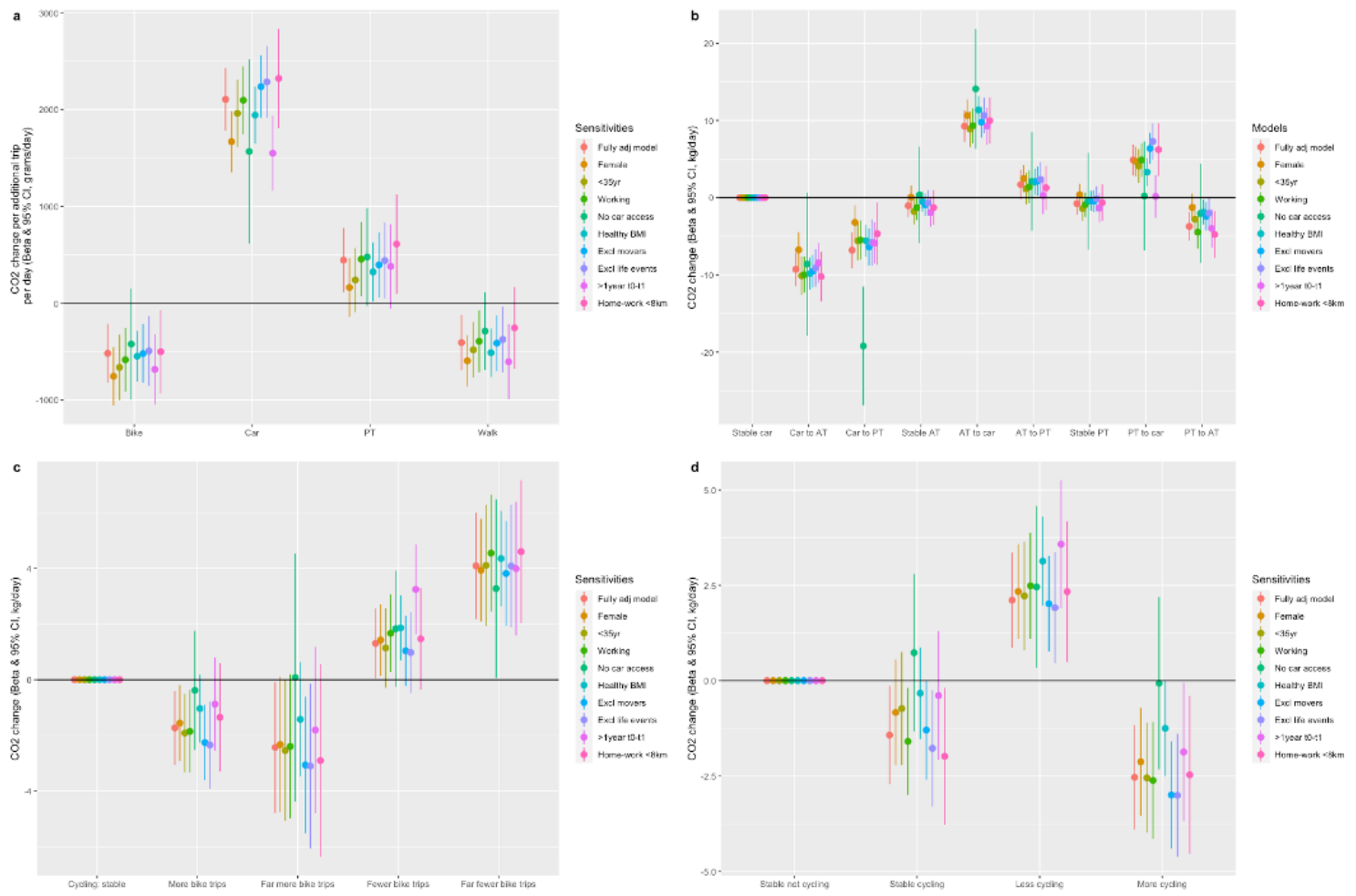
Figures

Figure 1

Effect sizes from the fully adjusted models with sensitivity analyses (n=1849). Panel a shows change in transport mode usage (trips per day) as the exposure variable, panel b change in the main mode of transport, panel c change in daily cycling frequency, and panel d change in cyclist categories. The dots are the beta coefficients and indicate changes in daily mobility-related lifecycle CO2 emissions between t0 and t1 (error bars are 95% CIs).
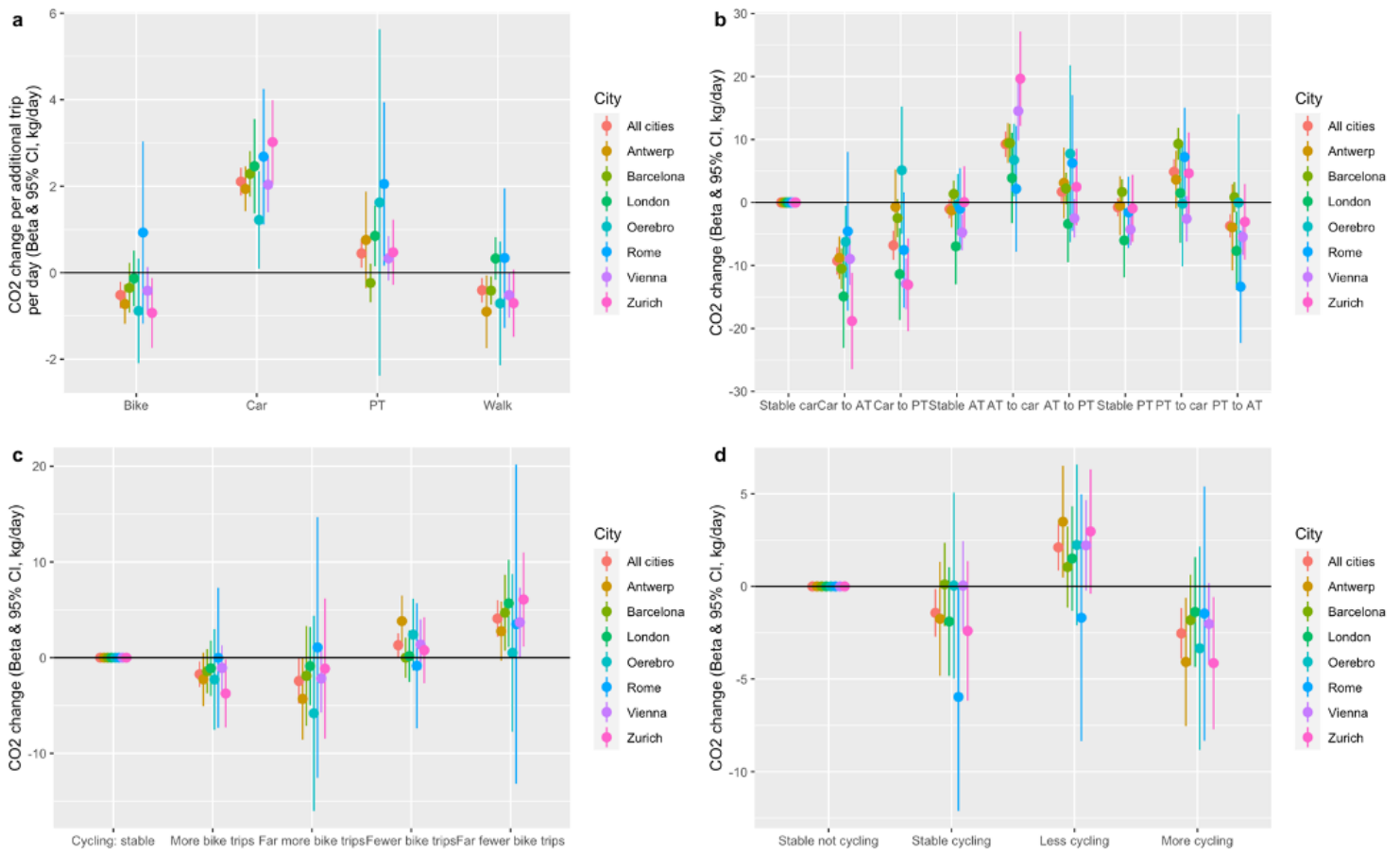

Figure 2

Effect sizes from the fully adjusted models stratified by city (n=1849). Panel a shows change in transport mode usage (trips per day) as the exposure variable, panel b change in the main mode of transport, panel c change in daily cycling frequency, and panel d change in cyclist categories. The dots are the beta coefficients and indicate changes in daily mobility-related lifecycle CO2 emissions between t0 and t1 (error bars are 95% CIs).

Supplementary Files

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