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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 considered the most sustainable and low carbon form of getting from A to B. 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, journey purpose, as well as personal and geospatial characteristics in seven European cities and derived mobility-related lifecycle CO_2 emissions over time and space. Statistical modelling of longitudinal panel ($n = 1849$) data was performed to assess how changes in active travel, the 'main mode' of daily travel, and cycling frequency influenced changes in mobility-related lifecycle CO_2 emissions.

We found that changes in active travel have significant lifecycle carbon emissions benefits, even in European urban contexts with already high walking and cycling shares. An increase in cycling or walking consistently and independently decreased mobility-related lifecycle CO_2 emissions, suggesting that active travel substituted for motorized travel – i.e. the increase was not just additional (induced) travel over and above motorized travel. 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 over a year, representing a substantial share of average per capita CO_2 emissions from transport. The largest benefits from shifts from car to active travel were for business purposes, followed by social and recreational trips, and commuting to work or place of education. Changes to commuting emissions were more pronounced for those who were younger, lived closer to work and further to a public transport station.

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Even if not all car trips could be substituted by active travel the potential for decreasing emissions is considerable and significant. The study gives policy and practice the empirical evidence needed to assess climate change mitigation impacts of urban transport measures and interventions aimed at mode shift to more sustainable modes of transport. Investing in and promoting active travel whilst 'demoting' private car ownership and use should be a cornerstone of strategies to meet 'net zero' carbon targets, particularly in urban areas, while also reducing inequalities and improving public health and quality of urban life in a post-COVID-19 world.

1. 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), cost (time cost, money cost), 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), infrastructure factors (density, diversity, design, transport system quantity and quality, which impact on trip 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). For instance, individuals drive for fewer trips if they live close to public transport, at higher population densities, and in areas with greater mix of residences and workplaces, and employed individuals with driver's license living in households with easy car access make a higher share of trips by car (Buehler, 2011). A recent review (Javaid et al., 2020) found that individuals are most motivated to shift modes, if they are well informed, if personal norms match low-carbon mode use, and, most importantly, if they perceive to have personal control over decisions. However, the review also found that the overall margin of shift as induced by individual and social settings remains limited. Instead, the infrastructure factors (such as the transport system and built environment) explains considerable differences in mode choice. Especially, accessibility metrics, such as distance to jobs, and street connectivity, an important measure of pedestrian access, as well as dedicated bike infrastructures play a crucial role in enabling modal shift.

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 2 km for walking, 5 km for cycling and 10 km 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).

A key consideration is thus to accurately assess the net mode substitution (or shift) away from one mode to another, as opposed to using alternative, more convenient routes (route substitution) or newly induced travel through intervention or policy. Route substitution tends to have little effect on carbon emissions. Induced demand for active travel (that is, demand that is in addition to previous demand) does not

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[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.

substitute for trips previously done by motorized modes of transport. Here, we use travel surveys to measure daily travel activity and mode choice at different time points and explore the changes in CO_2 emissions as a result of changes in travel activity. As cycling has some lifecycle CO_2 impact, any induced demand for cycling would increase emissions. Conversely, any increase in cycling that is substituting (or shifting away from) motorised modes would result in lower emissions. Our main hypothesis in this study is therefore: do increased levels of active modes decrease daily CO2 emissions, independent from other changes in motorised travel?

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 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.

2. Materials & 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 standardized guidance for all cities to reach a sufficient number of adult participants. To make use of the strengths and minimize weakness, a combination of different opportunistic recruitment methods was applied. This included press releases and editorials; common promotional materials following the same visual identity guidelines; direct targeting of local stakeholders and community groups to distribute survey information through their communication channels (like newsletters, intranet, and webpages); extensive use of social media (each city had its own Facebook and Twitter pages); and incentivizing for participation (e.g., prize). In addition, the random sampling approach was applied in the city of Örebro. To reduce the attrition rate and improve real-time monitoring, the Web-based platform featured a participant's and a researchers' user interface and dashboard. Facebook was one of the most effective approaches in reaching a high share of participants. Further details on the effectiveness and efficiency of the adopted 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 S3 in the Supplementary Information provides an excerpt of the PASTA BLQ, including travel diary data.

2.2. Key factors hypothesized to influence CO_2 emissions: Change in transport mode choice and use

For reasons given above, the primary factors hypothesized to influence CO_2 emissions 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. 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 (see Supplementary Table S2). The travel diary was based on the established KONTIV-Design (Brög et al., 2009; Socialdata, 2009), with some adaptations for online use. 5623 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 factors of interest 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, e.g. 'from car 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, e.g. 'more cycling' and 'from occasional cycling to frequent cycling'.

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 vehicle fleet composition, ambient temperatures (Supplementary Table S2) 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 CO_2 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 (doctor, post office, bank, etc.), escort trips[2] 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 ($n\ stations/km^2$), 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 in the main analysis.[3] 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'

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[2] In travel surveys escort trips are defined as those trips when the traveller has no purpose of his or her own, other than to escort or accompany another person; for example, taking a child to school.

[3] We used random effects for city in the main analysis (a) to take account of the fact that we observed only an incomplete, random subset of possible European/global cities and (b) to take account of correlation among responses from the same city. This assumed that there may be random variability across the cities, reflecting different 'starting points' (random intercepts) in terms of travel behaviour and CO_2 outcomes. The sensitivity analysis stratified by city provided further insights into this variability.

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 ('<10 km' 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, 2016b, 2014), time between t_0 and t_1 being greater than a year, and city. 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.

3. 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 Fig. 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%.

The travel diaries and questionnaires at t_0 and t_1 were completed on average 282 (SD: 203, min:14, max:728) days apart. 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 (see Fig. 2). 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 (Standard Deviation: 1.7) trips per day at baseline and 3.3 (SD: 1.7) trips per day at follow-up, ranging from 2.9 (SD: 1.5) trips per day in Rome at t_1 to 4.0 (SD: 2.1) trips per day in Antwerp at t_0. The observed cycling trip share at baseline was between 18% in Barcelona and 58% in Antwerp, i.e. significantly higher than cycling shares reported in Mueller et al. (2018) and a direct result of purposively oversampling cyclists (see Supplementary Table S5 for city-level values). Reported trip durations and distances were highly variable between subjects and cities, with respondents travelling on average 33.3 (SD: 58.1) km a day and for 90.5 (SD: 69) min a day at baseline. Daily travel distances at baseline across the cities were 0.8 (SD: 1.8) km for walking, 5.1 (SD: 9.7) km for cycling, 15.5 (SD: 40.7) km for public transport and 11.8 (SD: 39.9) km for driving a car or van (see Fig. 2).

3.2. Changes in mobility-related CO_2 emissions between baseline and follow-up

Mobility-related lifecycle CO_2 emissions totalled 2.8 (SD: 6.8) kilograms of CO_2 ($kgCO_2$) per day at baseline, with slightly higher emissions of 3.1 (SD: 7.2) $kgCO_2$/day at follow-up (Fig. 2). These higher emissions were largely due to an increase in emissions from driving. Driving a car or van made up the majority of these emissions averaging 1.9 (SD: 6.0) $kgCO_2$/day at t_0 and 2.2 (SD: 7.0) $kgCO_2$/day at t_1. Direct (i.e. operational, tailpipe) emissions from all travel activity made up 70% of mobility-related lifecycle emissions at 1.9 (SD: 4.9) $kgCO_2$/day at t_0 and 2.2 (SD: 5.4) $kgCO_2$/day at t_1. 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 due to the higher car use, while those in London and Vienna produced lower emissions due to a combination of lower car and higher public transport shares (Fig. 2 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

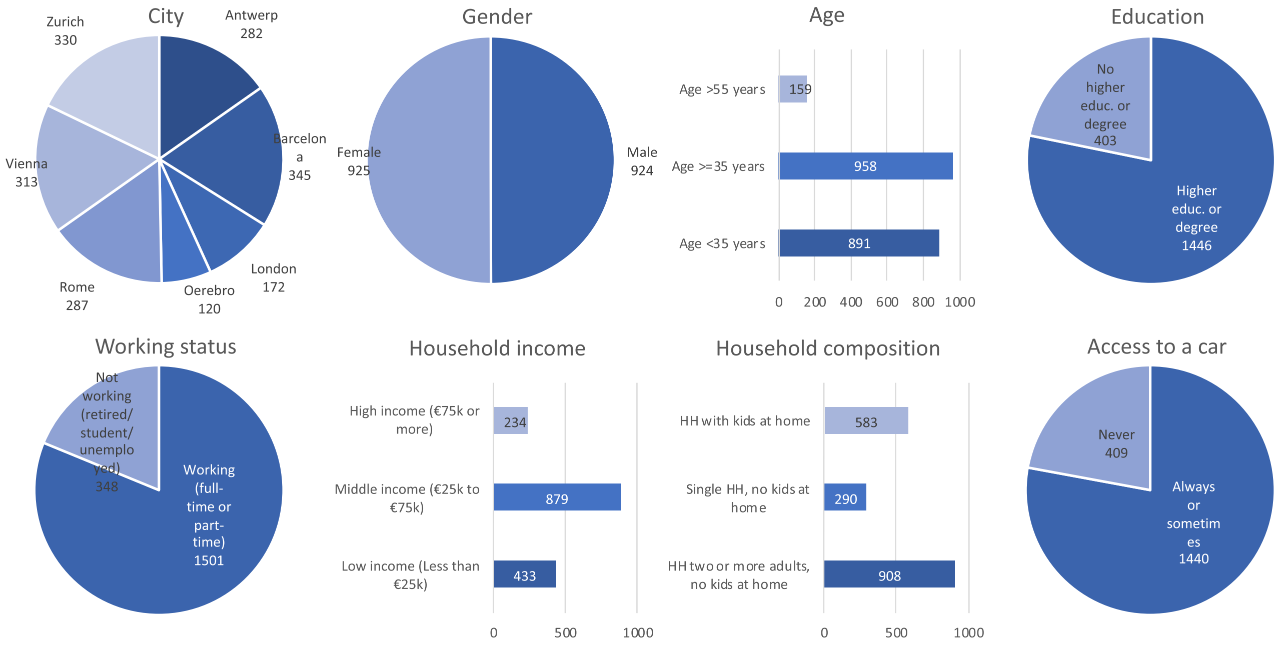

Fig. 1. Socio-demographic characteristics of study sample (n = 1849).

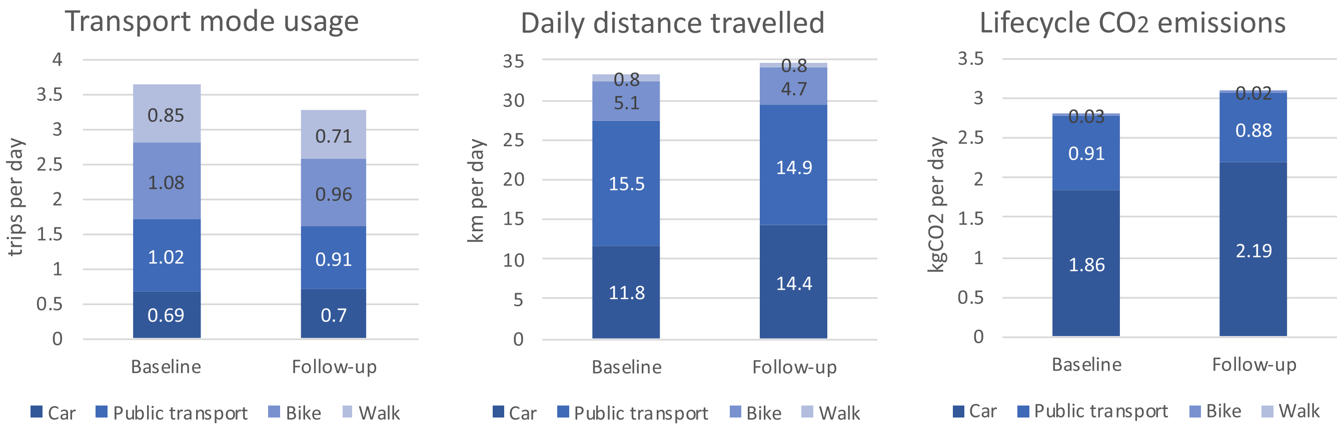

Fig. 2. Average transport mode usage, daily distance travelled and lifecycle CO_2 emisisons of the study sample at baseline and follow-up (n = 1849).

Table S5).

More than a third of respondents (36%) had changed their daily 'main mode of travel' at follow-up (Fig. 3, left), including 85 participants (5%) who changed from car/van to active travel, which decreased CO_2 emissions by −8.4 $kgCO_2$/day on average. About a third of respondents changed their daily cycling behaviour (Fig. 3, right).

3.3. The effects of changes in transport mode usage on lifecycle carbon emissions

3.3.1. All trip purposes

We found that more cycling or walking at follow-up significantly decreased daily mobility-related CO_2 emissions. This suggests a direct substitution effect of active travel away from motorized travel. If there had been no effect, emissions would not have changed as a result of changes in active travel activity. But they did, so this is a major finding. In the fully-adjusted model (Model 2 in Table 2a; also shown as dark blue dots and error bars in Fig. 4), 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, but 2.11 (95%CI 1.78 to 2.43) $kgCO_2$/day higher per additional car trip. It is important to highlight that the change effects were controlled for changes in trip rates of other modes of travel, therefore giving independent effects. Importantly, a negative effect for cycling trips means a decrease in total mobility-related CO2 emissions, independent of changes in travel by any of the other modes (car, PT, walking). 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.

Moving from left to right in Table 1, we see that adjusting for 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 S6).

The sensitivity analysis shown in Fig. 4 generally confirmed the main results, with some notable differences for subgroups of the study population. For participants living closer to work, for instance, the change estimates were marginally higher for motorized modes but lower for walking. Female and younger participants showed higher change effects

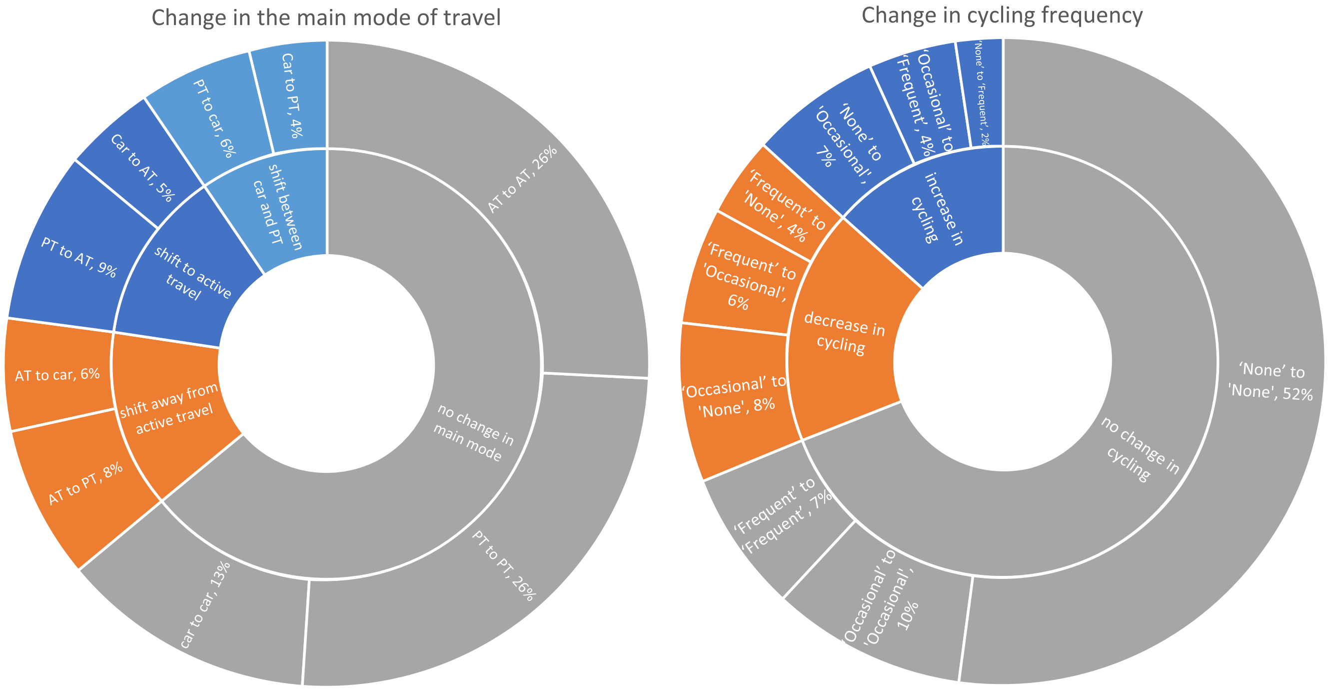

Fig. 3. Changes in main mode of transport and cycling frequency between baseline and follow-up.

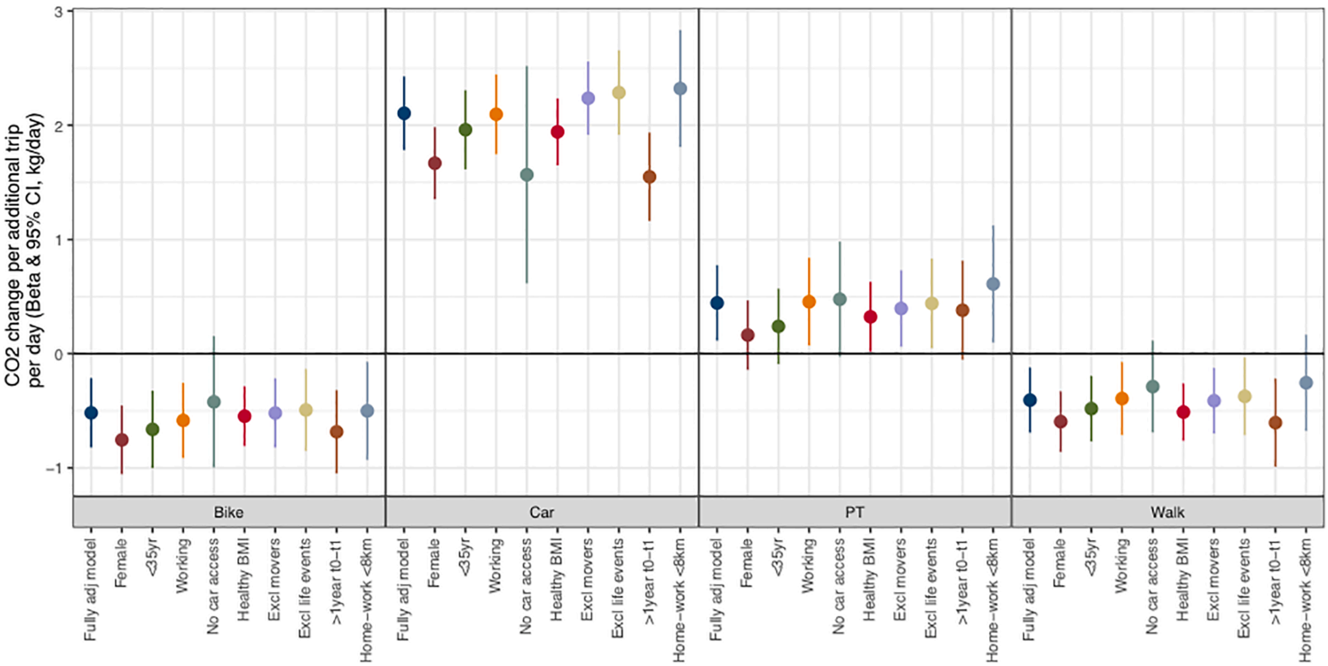

Fig. 4. Associations between change in mobility-related lifecycle CO_2 emissions (kg/day) and change in transport mode usage (trips/day) between t_0 and t_1. Fully adjusted models (Model 2) with sensitivity analyses (n = 1849). The dots are the beta coefficients, error bars are 95% CIs. AT = active travel, PT = public transport, BMI = body mass index.

for the active modes and lower change effects 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.

3.3.2. Focus on trip purpose

The associations between changes 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 (see Table 2a), which was due to relatively low counts (e.g. cycling for business was rare) and wider confidence intervals. An additional bike trip for social and recreational purposes lowered emissions by 0.27 $kgCO_2$; i.e. about half of the savings observed across all purposes (Table 1a). One less car trip lowered emissions by between 1.4 (travel for shopping, personal business, escort, other) and 3.3 (business travel) $kgCO_2$. These differences can be explained by the different trip lengths and car occupancy rates (close to 1 passenger per car for work and business, and close to 2 for social trips) observed for these purposes. 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 (Supplementary Table S10). Changes in emissions from business trips were lower for those without a degree and higher public transport journey times to the city center.

3.4. The effects of changes in the 'main mode' of transport on lifecycle carbon emissions

3.4.1. Main mode across all trip purposes

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 1b). 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 to active travel (*Car to AT*). On the other hand, emissions increased by 9.25 (95%CI 7.22 to 11.28) kg/day for changing from active travel to car or motorbike (*AT to car*). Those who changed their main mode from car to public transport (*Car to PT*) 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. Again, moving from left to right in Table 1b showed that adjusting for the covariates (models 1 and 2) slightly lowered the carbon effects for *AT to Car* and *AT to PT*, but increased them for *Car to AT* and *Car to PT*.

The sensitivity analysis shown in Fig. 5 again confirmed our main results. The largest difference to the fully adjusted model was for participants without access to a car, who showed a large (though with a wide CI) decrease in emissions for a shift in main mode from car to public transport (*Car to PT*). This was likely to be a shift away from being a *passenger in a car* to passenger on a bus or train. Interestingly, female participants had lower change scores for shifts away from motorized travel, but marginally higher change scores for shifts away from active modes. This may be because women tend to be more involved in escorting trips and 'mobility of care' (Sersli et al., 2020).

3.4.2. Main mode and trip purpose

Changes in the main mode of transport by trip purpose were also largely significant (Table 2b). For work or education, a shift from car or motorbike to active travel reduced commuting emissions by about 4 kg/day, while they increased by about 9 kg/day for a shift from active travel to car or motorbike. The apparent 'asymmetry' reflects the observation that those who changed main modes travelled further and perhaps with lower occupancy rates at follow-up than those who changed the other way around. It may also be explained by the recognition that the analysis by trip purpose took account of different car occupancy rates, speeds and other city-level factors influencing car CO_2 (see Supplementary Table S4 providing mean CO_2 emissions per passenger-km by city, emissions category and transport mode). 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 (about 1.1 passengers/car) for business travel by car.

Table 1
Associations between change in mobility-related lifecycle CO_2 emissions (kg/day) and change in the four key factors hypothesized to influence them.

n = 1849	Model 0: unadjusted (fixed effects)		Model 1: partly adjusted (mixed effects)[a]		Model 2: fully adjusted (mixed effects)[b]	
	Coefficient	Sig.	Coefficient	Sig.	Coefficient	Sig.
(a) Association between change in lifecycle CO_2 emissions (kg/day) and change in transport mode usage (trips/day) (full model with covariates, 95%CI and p-values in Table S6)						
Bike trip	−0.52	***	−0.52	**	−0.52	**
Car trip	2.13	***	2.12	***	2.11	***
Public transport trip	0.45	**	0.46	**	0.45	**
Walking trip	−0.41	**	−0.41	**	−0.41	**
(b) Association between change in lifecycle CO_2 emissions (kg/day) and change in main mode of transport (full model with covariates, 95%CI and p-values in Table S7)						
Stable: car[c]	0		0		0	
Active travel to car	9.73	***	9.63	***	9.25	***
Active travel to public transport	2.03	*	1.91	*	1.70	*
Car to active travel	−9.03	***	−9.08	***	−9.28	***
Car to public transport	−6.58	***	−6.64	***	−6.81	***
Public transport to active travel	−3.37	***	−3.56	***	−3.72	***
Public transport to car	4.93	***	4.83	***	4.88	***
Stable: active travel	−0.65	–	−0.70	–	−1.04	–
Stable: public transport	−0.63	–	−0.73	–	−0.77	–
(c) Association between change in lifecycle CO_2 emissions (kg/day) and change in cycling frequency categories (full model with covariates, 95%CI and p-values in Table S8)						
Stable: cycling trips[c]	0		0		0	
Fewer cycling trips	1.39	*	1.38	*	1.30	*
More cycling trips	−1.73	**	−1.78	**	−1.73	*
Far fewer cycling trips	4.18	***	4.18	***	4.09	***
Far more cycling trips	−2.19	.	−2.27	.	−2.43	*
(d) Association between change in lifecycle CO_2 emissions (kg/day) and change in cycling status (yes/no) (full model with covariates, 95%CI and p-values in Table S9)						
Stable: not cycling[c]	0		0		0	
Stable: cycling	−1.16	.	−1.17	.	−1.43	*
Less cycling	2.35	***	2.35	***	2.11	***
More cycling	−2.37	***	−2.44	***	−2.54	***

Significance: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, . $p < 0.1$, - $p>=0.1$.

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

[b] Model 2 adjusted for sex, age at baseline, baseline education level, baseline employment status, driving licence, car access, bike access, change in self-rated health, street-length density, building-area density, connectivity, facility richness index, home-work distance, travel distances by car from home to city center, nearest food store and nearest secondary school, public transport stations density, distance to nearest public transport station, time to travel by public transport from home to city center, number of different services and routes stopping at nearest public transit stop, time between t0 and t1; city as random effect.

[c] Reference category.

3.5. *The effects of changes in cycling frequency and changes between 'cyclists' and 'non-cyclists' on lifecycle carbon emissions*

Firstly, we found that the associations between changes in mobility-related lifecycle CO_2 emissions and changes in cycling frequency were all significant (see Table 1c): CO_2 emissions were −1.7 (95%CI −3.1 to −0.4) lower for those who cycled more (i.e. 1 to 2 times more per day) at follow-up than those who did not change cycling frequency (Cycling: stable, the reference group), and they were even lower for those who cycled far more (i.e. 3 times or more per day) at follow-up, reducing emission by −2.4 (95%CI −4.8 to −0.1) kg/day. Again, the sensitivity analysis (see Fig. 6) generally confirmed our results. A notable difference was 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, although the wide CI suggest this is inconclusive. 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 2c). Similar trends were observed for social and recreational trips but these were not significant due to low counts and wide CI.

Secondly, changes between daily 'cycling' and 'not cycling' showed similar effect sizes to the analysis of cycling frequency (Table 1d). More cycling reduced CO_2 emissions by −2.5 (95%CI −3.9 to −1.2) kg/day, less cycling increased emissions by 2.1 (95%CI 0.9 to 3.4) kg/day, and those who kept up their cycling had −1.4 (95%CI −2.7 to −0.1) kg/day lower emissions than those who did not cycle at either baseline or follow-up. The analysis by trip purpose showed statistically significant effects in the same directions for work and education trips only (Table 2d).

3.6. *City-specific effects*

Further sensitivity 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 Örebro and Zurich, and lower in London and Rome (Fig. 7). 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 Örebro, reflecting different trip distances and car occupancy rates. By comparison, changes in main mode of daily travel from car to active travel (*Car to AT*) showed the largest effect in Zurich, with the reverse (*AT to 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, which was likely to be due to those cities having good public transport services and longer trip distances.

4. 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 (induced) 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.

To illustrate this, an average person cycling 1 trip/day more and

Table 2

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).

n = 1849	Work or education[a]		Business[a]		Social or recreational[a]		Shopping, personal business, escort, or ‘other’[a]	
	Coefficient	Sig.	Coefficient	Sig.	Coefficient	Sig.	Coefficient	Sig.
(a) Association between change in lifecycle CO_2 emissions by purpose (kg/day) and change in transport mode usage (trips by purpose/day) (full model with covariates, 95%CI and p-values in Table S10)								
Bike trip	−0.11	–	−0.06	–	−0.27	*	−0.01	–
Car trip	3.14	***	3.32	***	3.01	***	1.37	***
Public transport trip	0.69	***	1.35	***	1.05	***	0.51	***
Walking trip	−0.23	*	−0.18	–	−0.20	.	−0.06	***
(b) Association between change in lifecycle CO_2 emissions by purpose (kg/day) and change in main mode of transport by trip purpose (full model with covariates, 95%CI and p-values in Table S11)								
Stable: car[b]	0		0		0		0	
Active travel to car	8.89	***	–	–	7.68	***	1.85	***
Active travel to PT	0.16	–	−4.52	*	0.91	–	−0.94	***
Car to active travel	−4.01	***	−6.56	–	−5.44	***	−4.67	***
Car to public transport	−6.13	***	−10.4	***	−5.54	***	−3.90	***
Public transport to active travel	−0.93	*	−4.84	*	0.002	–	−1.19	***
Public transport to car	5.08	***	4.68	.	8.67	***	1.94	***
Stable: active travel	−0.41	.	−4.94	.	0.09	–	−1.01	***
Stable: public transport	−0.29	–	−4.93	*	0.38	–	−1.16	***
(c) Association between change in lifecycle CO_2 emissions by purpose (kg/day) and change in daily cycling trips by trip purpose (full model with covariates, 95%CI and p-values in Table S12)								
Stable: bike trips[b]	0		0		0		0	
Fewer bike trips	0.25	–	0.43	–	0.33	–	−0.27	–
More bike trips	−0.45	–	0.33	–	−0.64	–	0.36	–
Far fewer bike trips	0.69	*	0.64	–	0.99	–	−0.10	–
Far more bike trips	−0.87	**	0.24	–	−0.54	–	−0.53	*
(d) Association between change in lifecycle CO_2 emissions by purpose (kg/day) and change in cycling frequency categories by trip purpose (full model with covariates, 95%CI and p-values in Table S13)								
Stable: not cycling[b]	0		0		0		0	
Stable: cycling	0.05	–	0.12	–	−0.19	–	−0.33	–
Less cycling	0.88	***	0.63	–	0.80	–	−0.10	–
More cycling	−0.65	*	0.26	–	−0.50	–	−0.22	–

AT = active travel, PT = public transport. Significance: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, . $p < 0.1$, - $p>=0.1$.

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

[b] Reference category.

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, 2013; Goodman et al., 2012) studies in the area of research of active travel and CO_2.

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).

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 largest benefits from shifts from car to active travel would be for business, then social/recreational followed by commuting to work or place of education. Shopping and personal business trips showed smaller mode shift benefits. Also, the changes to commuting emissions were more pronounced for those who were younger, lived closer to work and further to a public transport station. For business, those changes were higher for those living further away from the city centre, with lower public transport journey times to a city centre, and having a higher education degree. 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 shorter and more frequent, 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 factors of interest 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

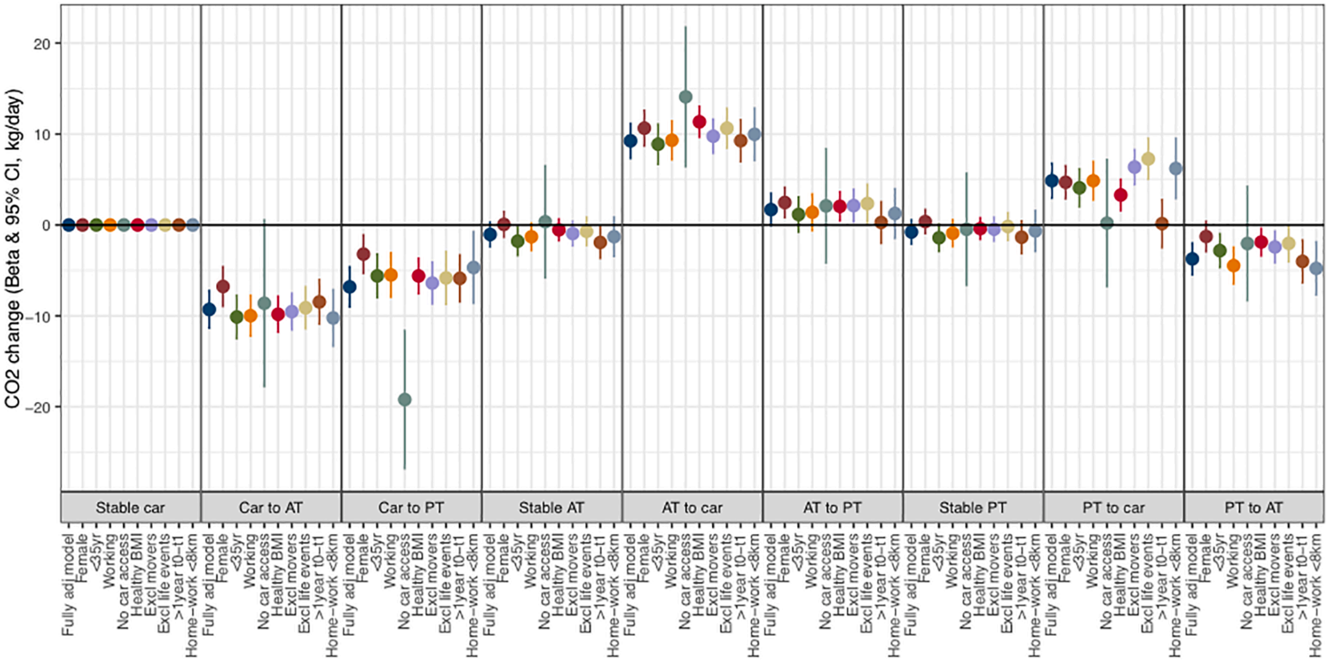

Fig. 5. Associations between change in mobility-related lifecycle CO_2 emissions (kg/day) and change in the main mode of transport between t_0 and t_1. Fully adjusted models (Model 2) with sensitivity analyses (n = 1849). The dots are the beta coefficients, error bars are 95% CIs. AT = active travel, PT = public transport, BMI = body mass index.

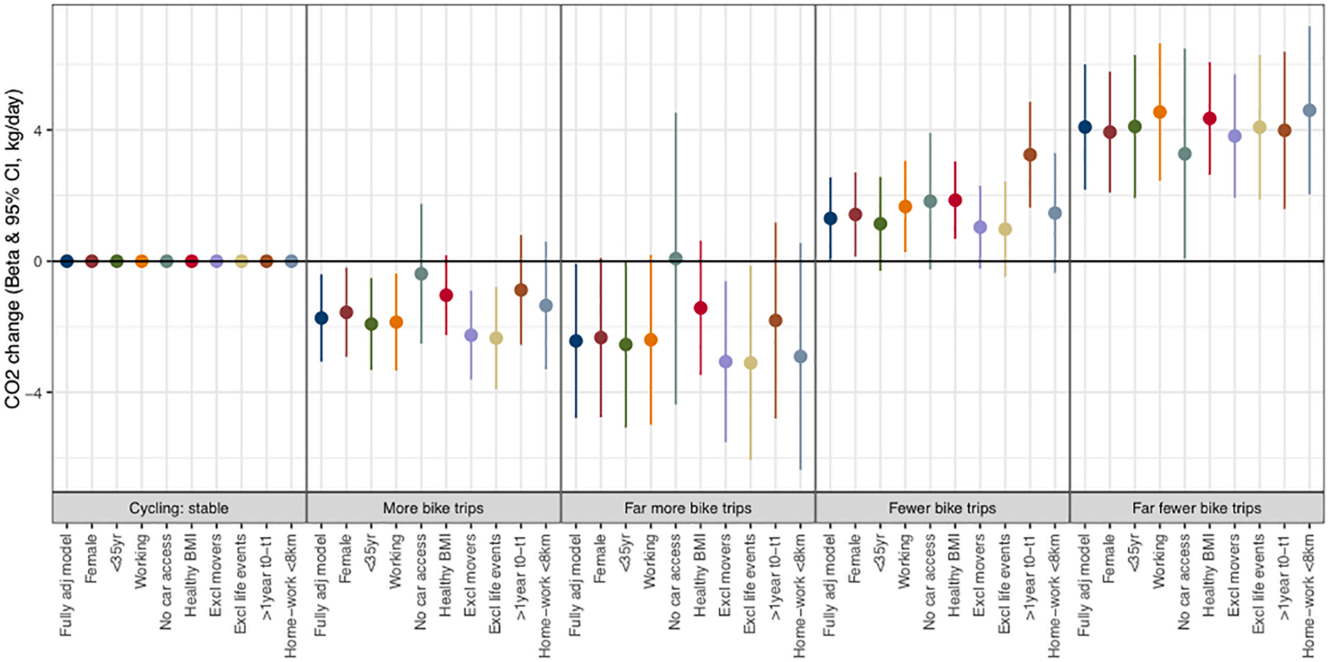

Fig. 6. Associations between change in mobility-related lifecycle CO_2 emissions (kg/day) and change in cycling frequency between t_0 and t_1. Fully adjusted models (Model 2) with sensitivity analyses (n = 1849). The dots are the beta coefficients, error bars are 95% CIs. BMI=body mass index.

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). 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); here, we covered all the main trip purposes. 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 factors or metrics 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

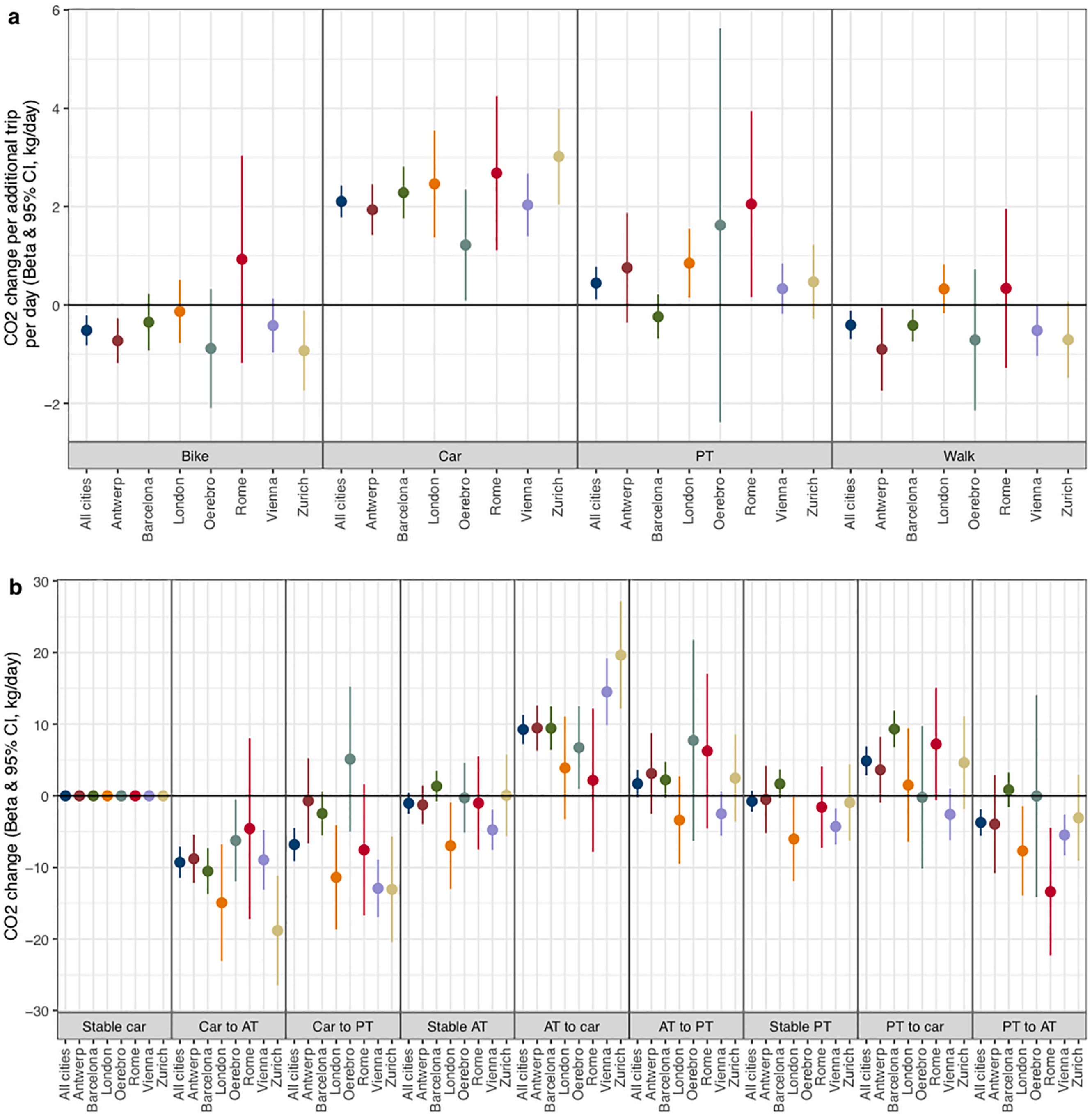

Fig. 7. City-stratified associations between change in mobility-related lifecycle CO_2 emissions (kg/day) and change in transport mode usage (panel a) and change in the main mode of transport (panel b). Fully adjusted models stratified by city (n = 1849). The dots are the beta coefficients, error bars are 95% CIs. AT = active travel, PT = public transport.

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 km 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. 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.

5. Conclusions

5.1. Key findings

There can be little doubt that active travel has many benefits, including net benefits on physical and mental health (in most settings), 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 *independently* lowered mobility-related lifecycle CO_2 emissions suggests that active travel indeed substitutes for 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.

5.2. Implications for policy and practice

The findings provide empirical evidence on converting 'mode shift to active travel' and 'levels of cycling and walking' into lifecycle carbon emission effects across a range of contexts, therefore offering researchers as well as policy and practice the opportunity to assess climate change mitigation impacts of urban transport measures and interventions aimed at mode shift to more sustainable modes of transport (see e.g. Brown et al., 2015; Scheepers et al., 2014; Winters et al., 2017). They can also provide much needed empirical (as opposed to modelled or assumed) evidence for exploring active travel scenarios at the global (Mason et al., 2015; Roelfsema et al., 2018), national (Goodman et al., 2019; Woodcock et al., 2018) and local (Zapata-Diomedi et al., 2017) levels.

There is a growing consensus that promoting active travel whilst 'demoting' private car ownership and use should 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). Comprehensive policy approaches operating at multiple levels (society, city, neighbourhood and individual) carry the most promise for substantial increases for this mode shift. At the level of the individual, personalized travel planning has shown modest increases in active travel and associated reductions in vehicle use and CO_2 emissions (Shaw et al., 2014). Highlighting potential health and air pollution 'co-benefits' of active travel can increase public acceptance of regulation of private car use to reduce an individual's carbon footprint (Amelung et al., 2019). At the population level, the most effective policies and policy packages operating relate to restricting car use, reducing the overall convenience and attractiveness of car use or promotion of public transport (Winters et al., 2017). Cities across the world that have followed a 'carrot-and-stick' approach of increasing investment in high-quality infrastructure for pedestrians and cyclists, increasing the cost of car ownership and use, limit car parking, limit car access to city centres or even ban cars altogether (Nieuwenhuijsen and Khreis, 2016) have seen significant mode shift to active (and public) transport (Pucher and Buehler, 2017). Urban design and land-use policies such as zoning regulations and building codes, addressing street layouts and increasing the density of development have shown to increase active travel by locating more jobs, schools, shops and retail within walking and cycling (incl. e-bikes) distance of where people live – one of the fundamental ideas behind the '15-minute city' (Sutcliffe, 2020; Whittle, 2020). In the future, the 15-minute city and other novel policy and planning concepts that follow an inverted transport policy pyramid (Fig. 8) will require a fairly radical rethink of our cities and is likely to reduce inequalities because the concepts involve mixing different population groups rather than maintaining the model of residential zoning by socioeconomic status currently used. They will also reduce the need for long distance travel and thereby reducing CO_2 emissions, air pollution and noise levels.

Cities are complex systems and to address their challenges we need systemic and holistic approaches that take into account many different factors and feedback loops and simultaneously address sustainability (the climate emergency, air pollution), livability, health and equity (Nieuwenhuijsen, 2020; Sallis et al., 2016). These ideas need support and investment. The European Green Deal and Green New Deal in the USA may be an opportunity, offering a comprehensive road map aimed at making us more resource-efficient and sustainable and represents a great opportunity for making our cities carbon neutral, more livable and healthier. As demonstrated in this study, active travel can play a key role in achieving these aims.

CRediT authorship contribution statement

Christian Brand: Conceptualization, Methodology, Data curation, Validation, Formal analysis, Writing - original draft, Writing - review & editing, Funding acquisition, Investigation, Visualization, Supervision, Project administration. **Thomas Götschi:** Conceptualization, Data curation, Writing - review & editing, Funding acquisition, Investigation. **Evi Dons:** Conceptualization, Data curation, Formal analysis, Writing - review & editing. **Regine Gerike:** Methodology, Writing - review & editing, Funding acquisition, Investigation. **Esther Anaya-Boig:** Data curation, Writing - review & editing. **Ione Avila-Palencia:** Data curation, Writing - review & editing. **Audrey de Nazelle:** Methodology, Writing - review & editing, Funding acquisition, Investigation. **Mireia Gascon:** Data curation, Writing - review & editing. **Mailin Gaupp-Berghausen:** Data curation, Writing - review & editing. **Francesco Iacorossi :** Data curation, Writing - review & editing. **Sonja Kahlmeier:** Data curation, Writing - review & editing, Funding acquisition, Investigation. **Luc Int Panis:** Methodology, Data curation, Writing - review & editing, Funding acquisition, Investigation. **Francesca Racioppi:** Methodology, Writing - review & editing, Funding acquisition, Investigation. **David Rojas-Rueda:** Methodology, Data curation, Writing - review & editing. **Arnout Standaert:** Data curation, Writing - review & editing. **Erik Stigell:** Writing - review & editing. **Simona Sulikova:** Methodology, Data curation, Writing - review & editing. **Sandra Wegener:** Methodology, Writing - review & editing. **Mark J. Nieuwenhuijsen:** Conceptualization, Methodology, Writing - review & editing, Funding acquisition, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

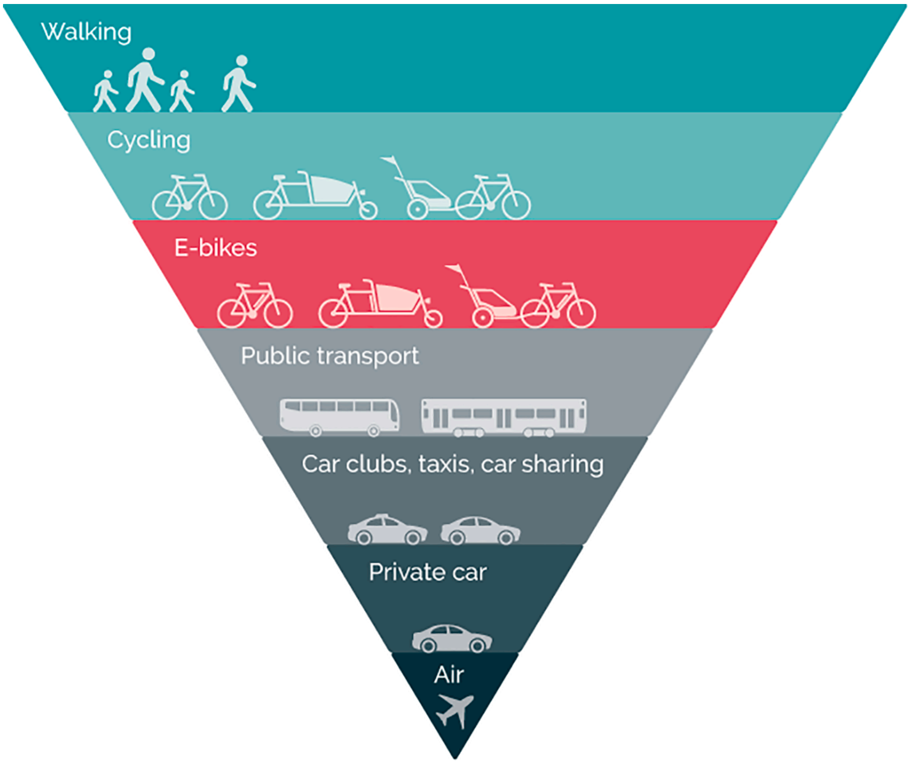

Fig. 8. Inverted and sustainable transport hierarchy. Source: taken from Philips et al. (2020).

the work reported in this paper. The authors alone are responsible for the views expressed in this article and they do not necessarily represent the views, decisions or policies of the institutions with which they are affiliated.

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Appendix A. Supplementary Information

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