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Satisfying transport needs with low carbon emissions: Exploring individual, social, and built environmental factors

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ABSTRACT

The article studies the relationships between daily travel greenhouse gas (GHG) emissions and self-rated satisfaction with transport needs. It also investigates the conditions that satisfy one's transport needs at emission levels compatible with internationally agreed reduction targets by 2030 to keep warming below 1.5 degrees. It uses a representative geo-questionnaire survey from Poznan, a functional urban area in Poland (ca 800 thousand inhabitants), with 550 study participants answering questions used in the study. Four built environmental (BE) and accessibility measures are calculated using geospatial methods and used as predictors of low/high emission levels, low/high need satisfaction levels, and their combinations (i.e., *social-ecological quadrants*), along with socio-demographic characteristics and transport-related resources, competences, and responsibilities. The relationship between transport need satisfaction and GHG emissions is positive but weak and non-linear. In line with previous studies on well-being and energy or carbon footprints, the relationship appears to saturate (i.e., need satisfaction most steeply increasing at low emission levels). The saturation point is at the emission level lower than the 2030 1.5-degree compatible target (~300 kg CO_2/year/person). A sizeable group (~30 %) satisfies their transport needs at low emission levels (i.e., sufficiency condition). Exploratory spatial data analysis reveals that members of this group cluster in Poznan city center. All BE characteristics significantly and strongly influence the outcome variables, with central, densely populated, and walkable locations increasing the odds of having one's needs met at low emission levels. Retirees comprise about half of the sufficiency group, but there are also many workers. Specific transport needs that negatively impact the ability to meet one's needs at low emission levels, including multiple locations and doing errands on the way from or to work. The results support land use policies that reduce travel distances (i.e., densification, preventing sprawl, promoting walkable street designs) as they support low-carbon access to necessary activities for all social groups. Suburban residential locations, in turn, are associated with low need satisfaction and high emissions. The results also highlight that the ability to meet one's transport needs within the emission threshold is spatially and individually differentiated, with implications for climate policies in the mobility domain.

1. Introduction

Transportation is a major source of greenhouse gas (GHG) emissions, generating about 14 % of all emissions and about ¼ of energy-related CO_2 emissions, with emission levels growing in most regions (Lamb et al., 2021). Ground passenger transport makes up about half of these emissions, with a high share generated within urban areas and by urban dwellers. Urban mobility thus significantly contributes to climate change, which has become a major threat to human livelihoods in many parts of the world now and in the future. To mitigate these risks and keep global warming within a relatively safe range of 1.5 degrees, global emissions from the transportation sector must be reduced by about 60 % in 2050 (Jaramillo et al., 2022).

Reducing emissions by shortening travel distances raises the question of potential social injustice if human needs cannot be satisfied with reduced mobility. The sustainable mobility paradigm promotes the

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ability to achieve access to valuable destinations without traveling long distances (Banister, 2008). Some definitions of sustainable mobility explicitly promote ecological and social goals (Næss, 2020). However, research and policy practice often consider them separately and contradict each other. Studies that focus on emission reductions sometimes disregard policies' social outcomes. Transport poverty studies tend to focus only on improving access and, sometimes, promoting higher car ownership. Similar tensions in research and political discourse have led to calls for approaches that reconcile the social and the ecological (Grossmann et al., 2021; Rode, 2023).

1.1. Social-ecological approaches to mobility

Multiple approaches in literature address the dual challenge of providing good living conditions without transgressing ecological limits, including *safe and just space* (Raworth, 2012), *consumption corridors* (Fuchs et al., 2021), and *sufficiency* (Toulouse et al., 2019). No country provides a sufficient level of well-being without exerting unsustainable ecological pressures, but countries differ in the environmental costs of living standards (Fanning et al., 2021; Roberts et al., 2020). Meeting human needs may require vastly different levels of resources and emission levels depending on *how* the needs are satisfied (i.e., what are the *need satisfiers*) and how well the *provisioning systems* translate resources into human need satisfaction (Brand-Correa et al., 2020; Fanning et al., 2020). Baltruszewicz et al. (2023) illustrate empirically that high well-being is possible at low energy uses when measured at the household level. Living in urban areas and not relying on cars makes this scenario more likely.

Several studies have started to apply similar perspectives to mobility and accessibility. Virág et al. (2022) used various socio-economic indicators at a national scale to measure the impact of material stocks and mobility infrastructure on both GHG emissions and the provision of well-being. Dillman, Czepkiewicz, et al. (2023) provided a global assessment of the social-ecological performance of a mobility system aggregated at national levels, with similar conclusions to the abovementioned studies. Arnz and Krumm (2023) calculate models of sufficiency futures for mobility in Germany. They use travel distances and modes to estimate energy demand and treat them as a proxy for decent mobility levels. Such studies tend to be concentrated on high levels of spatial aggregation. However, ongoing efforts translate them into *fair mobility budgets* differentiated by spatial location and individual mobility requirements (e.g., Millonig et al., 2022).

At the urban scale, the Doughnut Economics Action Lab provides guidelines for breaking down the *safe and just space* to a city or neighborhood scale and creating locally relevant indicators, including those on mobility and accessibility (Fanning et al., 2022). Dillman et al. (2021) propose a *safe and just space* approach to urban mobility derived from planetary boundaries, human need theories, and transport poverty literature. Similarly, Willberg et al. (2023) relate urban accessibility and its indicators to the safe and just framework. By substituting the notion of accessibility based on time and distance with emissions, Kinigadner et al. (2021) highlight that the level of access within a given carbon budget is higher in city centers and when traveling by public transport rather than by car.

So far, few disaggregated studies have investigated the conditions for satisfying transport needs with low ecological costs. In particular, the impact of the BE characteristics and differences in people's life circumstances, abilities, and transport needs on *both* emissions and transport poverty has not been studied in detail.

1.2. Studies on transport-related GHG emissions and transport disadvantage

GHG emissions depend primarily on the proportion of trips made and distances traveled by car. Existing meta-analyses, focused on US studies, confirm that living in densely populated and densely built areas with mixed land uses, walkable street design, locally accessible services, and public transport is associated with reduced car use and shorter travel distances (Ewing & Cervero, 2010; Stevens, 2017). Research in the Nordic countries further emphasizes the influence of regional accessibility on car driving and travel distances (Næss, 2012; Næss et al., 2017).

Studies that explicitly measure GHG emissions from daily travel and their systematic reviews largely confirm these findings and associate the abovementioned built environmental characteristics with lower emission levels (Boeing et al., 2024; Des Rosiers et al., 2017; Wang et al., 2023). Many studies also find a positive influence of income, employment, and being a male on driving distances and GHG emissions (Leroutier & Quirion, 2022; Wang et al., 2023). Some studies find a positive association between education level and daily travel emissions (Wu et al., 2019), although others differ (Bel & Rosell, 2017). The relationships between the BE characteristics and emissions are complicated by the spatial sorting of relevant socio-economic attributes within a given urban region (e.g., whether high-income households tend to reside in central or suburban locations). The studies also emphasize a highly unequal distribution of travel emissions, with a highly mobile minority generating the vast majority of GHGs (Bel & Rosell, 2017; Czepkiewicz et al., 2019; Leroutier & Quirion, 2022; Wang et al., 2023).

Existing studies also suggest that central residential location, local accessibility, walkable street design, high population density, and public transport access also reduce the risk of transport poverty, transport disadvantage, and social exclusion, particularly for low-income and carless households (Allen & Farber, 2020; Lucas et al., 2018; Ma et al., 2018). Lucas et al. (2018) also note that trip frequencies and travel distances do not necessarily lead to better social inclusion and may be associated with travel burdens. Mattioli (2014) further illustrated how car dependence in peripheral and rural areas amplifies contradictions between mobility's social and ecological outcomes, leading to car deprivation or burdens to car owners (e.g., high monetary cost or travel time).

Few empirical studies explicitly connect GHG emissions and transport disadvantage. Kamruzzaman et al. (2015) analyzed a small sample from rural Northern Ireland. They concluded that low emission levels and social inclusion are not necessarily conflicting and may be reconciled since short travel distances enhance both. Kilian et al. (2022) explored transport emissions in London and their relation to social factors and well-being, concluding that "it is possible to have reduced emissions without negatively impacting well-being". Kinigadner et al. (2020, 2021) investigated accessibility within trip-based carbon budgets and illustrated how public transportation provides better access to destinations than cars under such constraints. Other studies do not measure or model emissions directly but note how some of the intensive car users (who typically have high GHG emission levels) are highly vulnerable to transport poverty (e.g., Blandin et al., 2024). To our knowledge, no study has explicitly investigated the conditions for satisfying one's transport needs with emission levels compatible with emission reduction targets.

1.3. Objectives and research questions

The current article adds to the literature on transport-related GHG emissions, transport poverty literature, and the emerging field that combines the two. It does so by applying survey data, geospatial data, and statistical and spatial statistical analyses to study the intersection between transport need satisfaction and transport-related GHG emissions in an urban region in Poland. Specifically, the article investigates:

1. The relationship between GHG emissions and transport needs satisfaction;
2. The spatial patterns of transport need satisfaction and GHG emissions;

3. The role of accessibility and other BE characteristics in influencing the satisfaction of transport needs, GHG emission levels, and the ability to meet transport needs at low emission levels;
4. The influence of individually differing resources, competencies, and needs related to daily travel on the satisfaction of transport needs and the ability to do so at low emission levels.

We study the various configurations of emissions and need satisfaction by dividing study participants into *social-ecological quadrants* based on two thresholds: personal GHG emissions compatible with climate policy targets and the level of self-rated satisfaction of transport needs. Before going into empirical details, we introduce the concept of mobility as a need satisfier and its relevance for sufficiency considerations.

2. Mobility as a need satisfier: a conceptual framework

In this article, we primarily treat mobility as a means to satisfy human needs by providing access to activities and social interactions at destinations. It is thus a *need satisfier* rather than a basic need or good (Mattioli, 2016). Some degree of mobility is usually required for participation in key social interactions, such as working, studying, shopping, visiting people, caring for someone, or resting. These activities are necessary within contemporary societies to meet basic human needs, such as subsistence, physical health, social relatedness, or leisure (Gough, 2015; Max-Neef et al., 1991).[1] The inability to reach destinations where vital social interactions and activities happen may result in resigning from participating, not satisfying one's essential needs, and eventually causing *social exclusion* or other significant harm.

How much and what kind of mobility is required to participate in these activities effectively and without much burden depends on other socially organized *need satisfiers*, such as the distribution of activities in time and space or the customary and habitual ways of doing things (Brand-Correa et al., 2020; Dillman et al., 2021; Fanning et al., 2020). Such conditions are highly context-specific, historically shaped, and mutable by policy and social change. They shape requirements for mobility stemming from need-satisfying activities, which we call *transport needs*. For example, the separation of work and leisure in time and space, the opening hours and location of childcare facilities, or the convention of doing large shopping in malls all influence the need to travel in a highly context-specific and differentiated way.

Characteristics of the built environment (BE) are particularly important in structuring transport needs (Næss et al., 2019). The spatial distribution of land uses and facilities, transport infrastructures, urban form, street design characteristics, and so on influence distances between trip origins and destinations and the conditions and costs of using travel modes (i.e., *accessibility*). Most vital services, such as healthcare, education, housing, or employment, as well as professional and personal activities (e.g., work, childcare, leisure), are organized in space and time, creating spatiotemporal constraints for users (Cascetta et al., 2016; Hägerstrand, 1970).

People's ability to travel and access activities are further shaped by various characteristics of individuals and households (Geurs & van Wee, 2004; Kaufmann et al., 2004, 2010; van Wee, 2022). Following Kaufmann et al. (2004), we refer to this capacity as *motility* and propose to recognize its multiple facets, such as *competencies* (i.e., abilities and skills required to find out about opportunities and rules for movement and to move), *resources* (including the financial, material, and social, such as being able to afford tickets, owning a car, or having someone who can provide lifts), specific *needs and responsibilities* that result from social roles and relationships that require movement (e.g., being a worker or student or taking care of someone), and as *norms, attitudes, and values* (including those related to travel modes and lifestyles). These characteristics vary at the individual and household level but reflect the socially structured and amenable ways practices are performed.

Together with the BE and organizational constraints, these characteristics differentiate the capacity for being mobile, accessing destinations, and participating in society in a highly contextual and dynamic manner (Flamm & Kaufmann, 2006; Hamidi & Zhao, 2020). Given the importance of being able to choose how to travel (De Vos, 2019) and where to live (Schwanen & Mokhtarian, 2005) for travel patterns and travel satisfaction, and the fact that being able to avoid travel can also be an asset (Ferreira et al., 2017) we propose to distinguish between: the *ability to be mobile*, which is typically the focus of motility analyses, the *ability to choose how to be mobile* (e.g., travel modes), *ability to substitute or avoid mobility* (e.g., with proximity or remote access), and *ability to redefine the situation* (e.g., change the place of residence). The ability to choose modes and avoid mobility (and still participate in key activities) is particularly important for this article since it enables one to meet one's transport needs with low emissions.

3. Materials and methods

3.1. Survey data

The study is set in the Poznan functional urban area (FUA), which hosts around 800 k inhabitants, more than 500 k of which live in the core city of Poznan. It is located in Western Poland and has a monocentric structure with suburban towns concentrically arranged around the core city. The FUA has good public transportation provision, particularly in the core city. The central part of the core city and some suburban town centers have high population densities and walkable distances to services and street designs. The modal share of trips in 2017 was 20 % by public transport, 56 % by car, 19 % by walking, and 3 % by bicycle (Thiem et al., 2018). The share of walking and public transport was higher in the core city (21 % and 29 %, respectively) and, particularly, its downtown area (30 % and 37 %) than in other parts of the region.

The survey data were collected from November 2022 to April 2023 specifically for a research project on travel behaviour, greenhouse gas emissions, and the role of built environmental and social factors in shaping them. The data collection used a geo-questionnaire, which included conventional survey questions and an interactive map that allowed participants to mark locations and answer questions about them (Czepkiewicz et al., 2018). The survey had several thematic modules, some presented to all participants and some shown only to a randomly selected subsample. Professional pollsters administered the survey using tablets in a Computer-Assisted Personal Interview (CAPI) setting. The pollsters visited households using a random route procedure with starting points distributed proportionally to residential distribution in census areas. Only one person from each drawn household could take part in the survey. The socio-demographic characteristics of the sample were controlled to obtain a representative structure in terms of age, gender, education level, and residential area (the proportion between the core city and the rest of the region). The control was done by ceasing to collect data from socio-demographic categories that reached the maximum quota. The resulting composition of the sample thus closely follows that of the study area. The total sample size after data cleaning was 1845. Some of the questions used in this article were presented to a random subset of participants, which reduced the sample to roughly one-third of this number. Furthermore, some answers were missing, and the sample size (N) for the analyses presented in the article varies from 521 observations with a full set of variables in regression models, to 551 observations with emission estimations and transport need satisfaction variables. The sample size difference did not influence the results.

[1] Human need theories both overlap and differ in what they consider the core or basic human needs. Describing these differences is, however, outside of this paper's scope.

3.2. Greenhouse gas emissions

The study considers direct and indirect GHG emissions associated with travel activity within the urban area of residence (excluding long-distance travel). The emissions include direct fuel combustion in vehicles (Scope 1), electric energy generation, and fuel extraction, refinement, and transport (Scope 2). We report scopes 1 and 2 together as well-to-wheel emissions (WTW). The emissions were estimated based on reported travel activity, vehicle type, occupancies, and driving distances between origins and destinations. Trip data were collected using an interactive map tool by marking locations most frequently visited by the study participants during the last three months in four categories ("Working, studying, picking up children", "Shopping, services, errands", "Culture, entertainment, religion, meetings", "Sport, rest, recreation"), and answering questions about details of activities done at the location, visiting frequency, usual trip origin, the frequency of using travel modes, and typical vehicle occupancy (if traveling by car). The distances were modeled with ArcGIS Network Analyst and OpenStreetMap road data, assuming car driving, using hierarchy attributes and one-way restrictions, and optimizing travel time. Yearly distances by travel were estimated for each visited location based on numerically coded answers about travel frequency and the frequency of using travel modes when visiting a location. Distance modeling considered varying trip origins (i.e., trips made from work or between work and home).

Emission coefficients of travel modes and vehicle types were based on secondary sources and vehicle characteristics (i.e., fuel use, energy use, drive type) and per-trip vehicle occupancies from the survey. The coefficients are summarised in Table A4 in the Appendix. The formula for calculating the GHG emissions from travel activity is:

$$E_{WTW} = \sum_i TD \times MS_i \times EF_i,$$

where E_{WTW} is the sum of well-to-wheel emissions from a person's travel activity within the period (here, one year), and TD is the distance traveled by all modes. MS is the share of distance traveled by mode i (such as private car, bicycle, train, bus, tram, plane, or ferry), EF is an emission factor of mode i expressed in CO_2 equivalent per passenger kilometer (kg CO_2eq / pkm).

We based the per capita GHG emissions threshold on the European Effort Sharing Regulation (ESR) target by 2030 in sectors not covered by the EU Emissions Trading System (non-ETS). The current target for Poland is a 17.7 % reduction from the 2005 level (European Commission, 2023). Emissions from the transportation sector in Poland in 2005, including international bunkers, amounted to 38.2 Mt. CO_2eq (1 t CO_2eq per capita) (European Commission, 2021). The target for 2030 is thus 31.4 Mt. CO_2eq (**0.85 t CO_2eq** per capita, after dividing by the projected 37 million inhabitants). Assuming that about 20 % of the sectoral emissions come from freight, outside[2] of scope here, we take **0.68 t CO_2eq** per capita per year as the threshold value. It aligns with mobility-related per capita 2030 targets compatible with 1.5-degree warming reduction pathways suggested elsewhere (0.45–0.83 t CO_2eq, Akenji et al., 2021; Dillman, Heinonen, & Davíðsdóttir, 2023). The targets include all personal mobility for short and long distances. Due to the high share of long-distance travel in urban dwellers' transport emissions (Czepkiewicz et al., 2019, 2024), we allocate half the limit to short-distance travel (**0.34 t CO_2eq** for each scope). We mark each study participant with a variable denoting whether their travel emissions fall below or above the threshold.

The distribution of emission levels is highly skewed, with 10 % of top-emitting participants contributing 45 % of emissions and 20 % of top emitters contributing 67 %. The average is 0.56 t CO_2eq, and the median is 0.22 t CO_2eq; 5.6 % of participants reported zero emissions, and 58.6 % fell below the emission threshold.

3.3. Satisfaction with transport needs

We measured the satisfaction of transport needs with respondents' self-assessment based on the question, "How well do your mobility options allow you to comfortably meet the following needs?" with six items referring to trip purposes:

- Getting to your place of work or study
- Reaching a doctor or other health services
- Getting to places of recreation
- Visiting friends or relatives living in or around Poznań
- Doing your daily shopping
- Making larger purchases (e.g., furniture, household appliances, electronics).

The question was accompanied by an explanation: "By 'mobility options, ' we mean access to vehicles, ability to purchase tickets, available public transport connections, physical abilities, skills, etc.". The question was loosely inspired by the perceived accessibility measure in Lättman et al. (2018) and the measure of transport difficulties from the UK National Travel Survey 2020. Transport need satisfaction differs from the more commonly applied notion of travel satisfaction (De Vos et al., 2013) by focusing on reaching activities rather than trips and travel behavior. Still, the question refers to comfort, which accounts for the importance of ease and convenience in satisfying one's transport needs. It also differs from commonly applied measures of activity participation, trip numbers, or travel distances, which often assume that a higher number of visits or longer distance equals a better social outcome, which may not always be true.

The answers were provided on a five-step scale (i.e., "Not at all", "Only a little", "To some extent", "To a large extent", "Completely") and coded numerically from 1 to 5. The option "No such need" was coded as 5. The indicator used in the calculations is an average of the numeric values. Average values above four represented high satisfaction and were used as a threshold. The question was presented to 551 valid

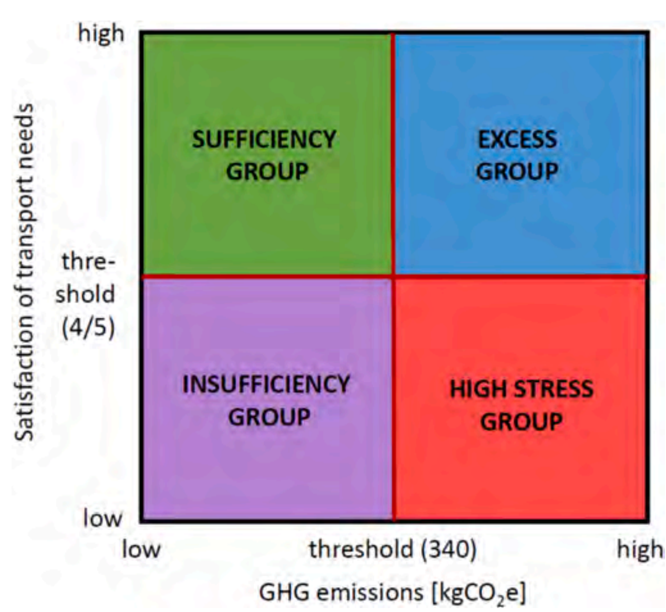

Fig. 1. Social-ecological performance quadrants and threshold values.

[2] The current share of transport emissions from freight is higher, around 40% (Rabiega & Sikora, 2020). The figure is reduced here to accommodate the higher share of aviation emissions in the studied population due to higher travel volumes than in the whole country (Czepkiewicz et al., 2024). The targets presented here are illustrative and their division into domains requires further research.

survey participants in the Poznan area, of whom 317 (58 %) exceeded the threshold.

3.4. Social-ecological quadrants

The chart area is divided into four quadrants of a "social-ecological matrix" (Fig. 1) using indicators' thresholds, and study participants are assigned to quadrants based on indicator values. The four quadrants signify:

A. **"Sufficiency" group** (30 % of the sample). This group satisfies their transport needs at low carbon emission levels. It is a desirable situation from the social-ecological perspective, in which transport needs are met with low burden on the climate.
B. **"Excess" group** (27 %**).** This group satisfies their transport needs at high carbon emission levels. Members of this group achieve good living conditions in terms of mobility and accessibility but at an unsustainably high ecological cost.
C. **"Insufficiency group"** (28 %). This group has unsatisfied transport needs at low carbon emission levels. Local mobility of its members does not incur a dangerously high burden on the climate, but their mobility and access needs are somewhat frustrated.
D. **"High stress" group** (14 %**).** This group has unsatisfied transport needs at high carbon emission levels. It is the least desirable situation from the social-ecological perspective since poor living conditions are achieved at a high ecological cost.

3.5. Socio-demographic characteristics

The survey included several key socio-demographic characteristics. Gender was captured in three categories: Man (47 % of the sample), Woman (53 %), and Other (no answers). Age was measured in years, with an additional binary variable distinguishing people aged 60 or more (26 %). Households with children under 18 (40 %) were marked with a binary variable. Education level was measured in six levels, recoded into four categories: Primary (10 %), Vocational (20 %), High school (35 %), and University (35 %). Life situation was captured with a multiple-response question with eleven options, recoded into three categories: Employed (66 %), Student (7 %), and Other (28 %). The latter group comprises retirees (25 % of the sample) and a few unemployed and homemakers. Job types were captured with 14 categories collapsed into six groups ('Professionals and managers', 'Office workers', 'Qualified manual workers', 'Service or retail workers', 'Unskilled manual workers', and 'Students').

3.6. Transport-related resources, competencies, and needs

To measure financial resources, we asked about the net monthly household income. Due to a high share of missing answers (~40 %), we used a multiple imputation method (Graham 2012), in which missing values are replaced by plausible regression estimates based on other complete cases with values closest to the predicted value for the missing entry. We carried out ten imputations using regression models fitted with occupational status, gender, level of education, number of adults in the household, and existing income data.

We measured car ownership (83 % of households had at least one vehicle) and access to the car as a driver or passenger. We coded the two variables into levels described in Table 1.

Mobility competencies were measured with the question, "Would you be able to perform any of these activities?" with eight items ("Walk several hundred meters by yourself", "Ride a bicycle", "Drive a car somewhere", "Get on a bus or tram", "Find a public transport connection to another part of the city or urban region", "Rent an e-scooter or a city bike", "Buy the right ticket for a bus, tram or suburban train", "Haul a ride on Uber, Bolt or a similar service"), and an ordered answer scale ("No, or probably not", "Yes, but only with the support of another person", "Yes, but with great difficulty", "Yes, but with little difficulty", "Yes, with great ease"). Due to a highly skewed distribution, we coded the answers into dummy variables for regression analyses, with only the top answer taking a positive value. We also averaged and reversed the items about walking and getting on the bus or tram to create a mobility impairment index.

Specific transport needs (i.e., responsibilities requiring travel) were captured with a question about frequency ("In a typical month, how often do you have to...") of six activities ("Visit someone who requires care or help", "Move between locations during work", "Go to a doctor or a therapist or to get a medical procedure", "Run errands on the way to or from work/school", "Take a child or a dependent person somewhere", "Buy everyday products for your household") with ordered answers ("Never", "Rarely", "Sometimes", "Often", "Very often") coded from 1 to 5.

3.7. Built environment characteristics

The BE characteristics are inspired by the 5D model (Ewing & Cervero, 2010; Næss et al., 2017) and include four GIS-based measures calculated relative to the residential location reported in the survey.

Distance to the city center describes the residential location relative to the closest main concentration of jobs and services, and refers to "regional destination accessibility" in the 5D model (Ewing and Cervero, 2010). Locations of the main centers were determined based on the combination of 1) the density of workplaces and services derived from the REGON (National Business Registry) database, 2) the density of services derived from OpenStreetMap, and 3) the density of visited locations marked in the geo-questionnaire. We estimated driving distances in kilometers from residences to the closest main city center using a Network Dataset based on OpenStreetMap road data and the Closest Facility tool in ArcMap. Note that the values range from nearly zero to about 37 km.

Three BE measures are captured in 1 km buffers around residential locations. Local service density is a cumulative accessibility measure calculated as the number of basic services derived from the REGON database within the buffer. It reflects the proximity and walking access to services in the local residential neighbourhood and refers to "local destination accessibility" domain of the 5D model (Ewing and Cervero, 2010). Basic service categories included ATMs, post boxes and offices, stores, beauty and hairdresser salons, laundry and cleaning services, churches, social centers, healthcare and childcare facilities, and sports and recreation facilities. Local population density is measured as the sum of residents within the buffer. It represents the proximity to other residents and the potential for social interactions, and refers to the "Density" domain in the 5D model (Ewing and Cervero, 2010). Local intersection density is measured as the density of intersections from the Topographic Objects Database (BDOT10k) street data layer calculated in the buffer. It approximates the characteristics of local street design that are conducive to walking and refers to the "Design" dimension of the 5D model (Ewing and Cervero, 2010).

All the BE characteristics are strongly correlated ($0.82 < |\rho| < 0.96$, Table A1). Distance to the city center negatively correlates with other factors. Due to the correlations and causal links between the variables (Næss, 2019), we do not include them all in single regression models.

Table 1
Car ownership and access variables.

Car ownership in the household	Access to the car by the respondent	Coded level of car access
No	–	None
Yes	Never or very rarely	
	Only in some situations	Low
	Sometimes yes, sometimes no	
	In most situations	High
	Freely – whenever I want	

3.8. Statistical analyses

The article employs a combination of exploratory data analysis of spatial and aspatial data with binomial logistic regression. Spearman's rank correlations (ρ) explore relationships between continuous and ordinal variables. Relationships between transport need satisfaction and GHG emissions are visualized using scatterplots with point densities and trend lines fitted with a locally estimated scatterplot smoothing (LOESS) function to highlight non-linearity. Due to the highly skewed emission distribution, the scatterplots are presented in two versions, with untransformed and log-transformed emission data.

The spatial clustering of continuous and ordinal variables is analyzed using the Getis-Ord Gi* statistic, highlighting where observations with high or low values cluster spatially (Anselin, 2020). Spatial clustering of membership in the four quadrants of the social-ecological matrix is explored with local join count statistic (Anselin & Li, 2019). The statistic involves counting occurrences of the same values (in this case, membership in a social-ecological quadrant) in pairs of neighboring locations (in this case, residences of study participants). A residential location is identified as a spatial cluster when it has a positive value (is a member of the quadrant) and the share of positive values among its neighbors is high. We define the neighborhood of each observation as 30 nearest neighbors for all local spatial autocorrelation analyses presented here. The variable density of observations in the study area and the need to avoid isolated observations led us to choose the k-nearest neighbors definition. The choice of 30 neighbors was based on data exploration and is a compromise between the ability to produce statistically significant results and avoiding too large sizes of neighborhoods. We used GeoDa software, which assesses the statistical significance of clusters using pseudo-*p*-values based on permutations.

Differences in interval and ordinal variables between the quadrants are assessed with the Kruskal-Wallis test and a post-hoc Dunn's test with Bonferroni correction, reported in Appendix B. We employ boxplots to show the descriptive statistics of predictors in the social-ecological quadrants and density distribution plots to show quadrant membership across the predictors' values. We report them in Appendix A. We then fit a series of logistic regressions using a *glm* package in R with a logit link. The models predict the membership of the following groups against the rest of the sample: "Low emissions", "High satisfaction", "Sufficiency", "Insufficiency", "Excess", and "High stress". The inclusion of variables was based on theory and data availability. However, due to collinearity and small sample size, we removed several variables whose influence was difficult to disentangle from other predictors. The excluded variables included age and education level (correlated with occupation categories) and built environment characteristics correlated with the distance to the city center. Due to the high statistical and theoretical importance of commuting, we also perform similar models on the sub-sample restricted to those in the "Employed" and "Student" categories.

4. Results

4.1. Transport needs satisfaction and GHG emissions

Transport needs satisfaction is weakly positively correlated with local travel emissions (ρ = 0.19). The relationship is positive primarily in the low range of emissions (below ca. 300 kgCO_2 per year), and then it levels off in the higher levels (Fig. 2). It also turns negative at very high emission levels, although it is highly uncertain due to few observations in this range. The upper-left quadrant of high need satisfaction and low emissions (i.e., the "Sufficiency" group) appears small in the untransformed chart (Fig. 2, left panel). However, this is mostly due to the highly skewed distribution of emissions, and the quadrant hosts ~30 % of the sample.

4.2. Transport needs satisfaction, GHG emissions, and the residential location

The spatial pattern of satisfaction with local transport needs shows strong clusters of high values in the central and northern parts of Poznań (Fig. 3, left panel). Clusters of low satisfaction are found in suburban municipalities, mostly in the eastern and southern parts of the region. Low emission values cluster in the central part of Poznan and Swarzędz municipality east of Poznan (Fig. 3, right panel). The BE characteristics correlate weakly with the self-rated satisfaction scores and CO2 emission levels (Table 2), and all correlations are statistically significant. The more central, densely populated, and walkable areas tend to have higher perceived need satisfaction and lower carbon emissions (Figs. 5 and 6). However, the relationships are weak to moderate, highlighting the importance of individual characteristics.

4.3. Characteristics and predictors of the socio-ecological quadrants

4.3.1. Summary

In a nutshell, three defining characteristics of 'Sufficiency' are related to the built environment, life stage, and gender, i.e., living in a densely populated, central location, being older, and being a woman rather than a man. Together, they tend to reduce the need to be mobile so that average access to a car and not particularly high skills are sufficient to get by comfortably with low emissions. As the distance to the center increases, similar living conditions may lead to a lower level of transport need satisfaction at the low emission level ("Insufficiency"), especially if the mobility competencies are low and if one is a retiree or an unskilled manual worker.

At the other end of the spectrum, 'High stress' is most likely a combination of a peripheral location (long distances, low density) with a

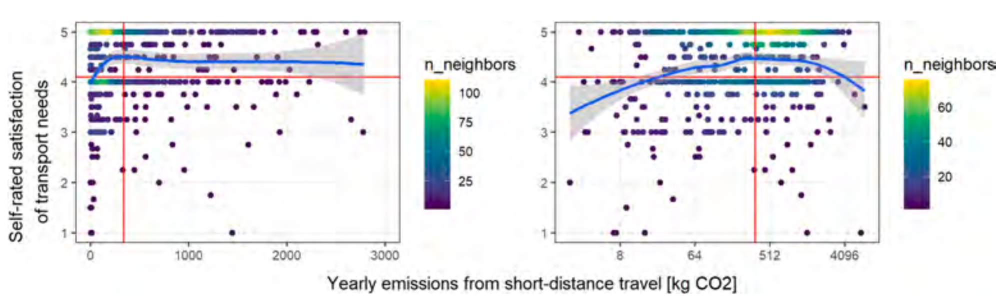

Fig. 2. Scatterplot of the relationship between the self-rated satisfaction of local transport needs and yearly emissions from local travel. The vertical red line signifies the 340 kg CO2 emission ecological threshold, and the horizontal red line represents the 4/5 self-rated satisfaction level. The emission values are untransformed in the left panel and log-transformed in the right panel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

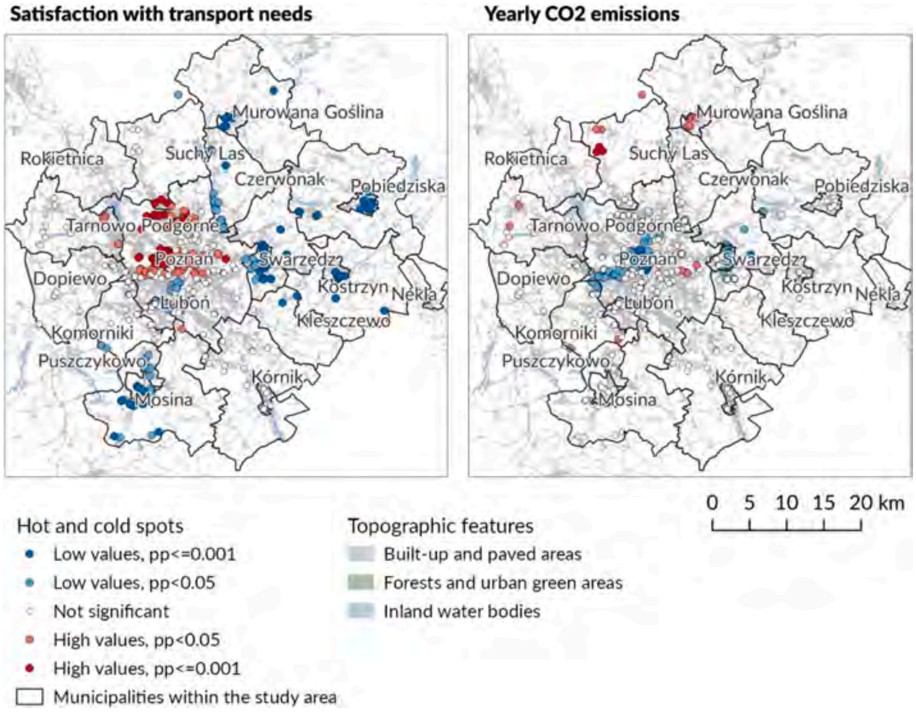

Fig. 3. Hotspot map (Getis-Ord Gi*) of self-rated satisfaction with local transport needs (left) and yearly CO_2 emissions from local travel. Weights are based on the 30 nearest neighbors.

Table 2
Spearman correlations between the BE characteristics, self-rated satisfaction with transport needs, and yearly CO_2 emissions.

	Distance to the main city center	Local population density	Local service density	Local intersection density
Satisfaction of transport needs	−0.27	0.17	0.21	0.23
Yearly CO_2 emissions	0.20	−0.26	−0.26	−0.24

high level of transport needs, which may be partly due to the location itself. Longer distances and lower density may not lead to lower need satisfaction if financial resources, skills, and car access are high enough, and transport needs and obligations are not too high. However, this combination leads to satisfying one's needs at unsustainable emission levels ('Excess').

The variability within each group is quite high, suggesting that particular combinations of individual and group characteristics with built environmental and organizational constraints may lead to higher or lower than expected satisfaction of needs and emissions and that achieving mobility sufficiency is possible in various circumstances.

4.3.2. *Low emission levels*

Being employed or studying, being a man, having a higher income, better access to a car, and the ability to drive or haul a ride with an app all *decrease* the odds of meeting the emission threshold (Fig. 7). Being able to cycle *increases* the odds of meeting the threshold. Among the specific transport needs, only those associated with errands on the way from or to work significantly reduce the odds of low emissions. The further the distance from the residence to the city center, the higher the odds of emissions exceeding the target level (each kilometer further decreases the probability of meeting the threshold by 7.5 %). Models with other BE characteristics show similar results (i.e., a higher population density, services, and intersections increase the probability of meeting the threshold). The "Low emissions" model fits well (Tjur $R^2 = 0.40$). The relationships are mostly similar when only considering those in employment or training (Table A3).

4.3.3. *High satisfaction with transport needs*

The model predicting high levels of transport need satisfaction has a poorer fit (Tjur $R^2 = 0.19$) but still provides meaningful and statistically significant results (Fig. 8). A higher ability to drive a car and being a man increase the odds of satisfying one's transport needs. Two transport needs particularly decrease the likelihood of satisfaction: the requirement to be mobile at work and to travel to take care of someone. A higher frequency of escorting a child or a dependent person somewhere *increases* the odds of satisfying one's transport needs. Importantly, a longer distance from residence to the city center decreases the odds of high satisfaction. The model computed only on those in employment or training shows that service and retail workers and manual workers have lower odds of satisfying their transport needs than professionals and managers (Table A3). The ability to rent micro-mobility tools increases the need satisfaction odds in this sub-sample.

4.3.4. *"Sufficiency" group*

Study participants belonging to the "Sufficiency" group (i.e., the "Low emissions – High satisfaction" group) predominantly cluster in centrally located parts of Poznan (Fig. 4A). Members of the group are significantly older than members of the "Excess" and "High stress" groups and younger than those in the "Insufficiency" group. Together with the "Insufficiency" group, it is common among people aged over 60 and retirees. Still, it is also present among the younger groups (~20–25 %) and employees (~25 %) (Fig. A4, Fig. A10, Fig. A11). Members of the "Sufficiency" group tend to have lower incomes, lower car ownership and access levels, and lower car-related competencies than the "Excess" and "High stress" groups. Compared to these two groups, they travel much more often on foot and less often by car.

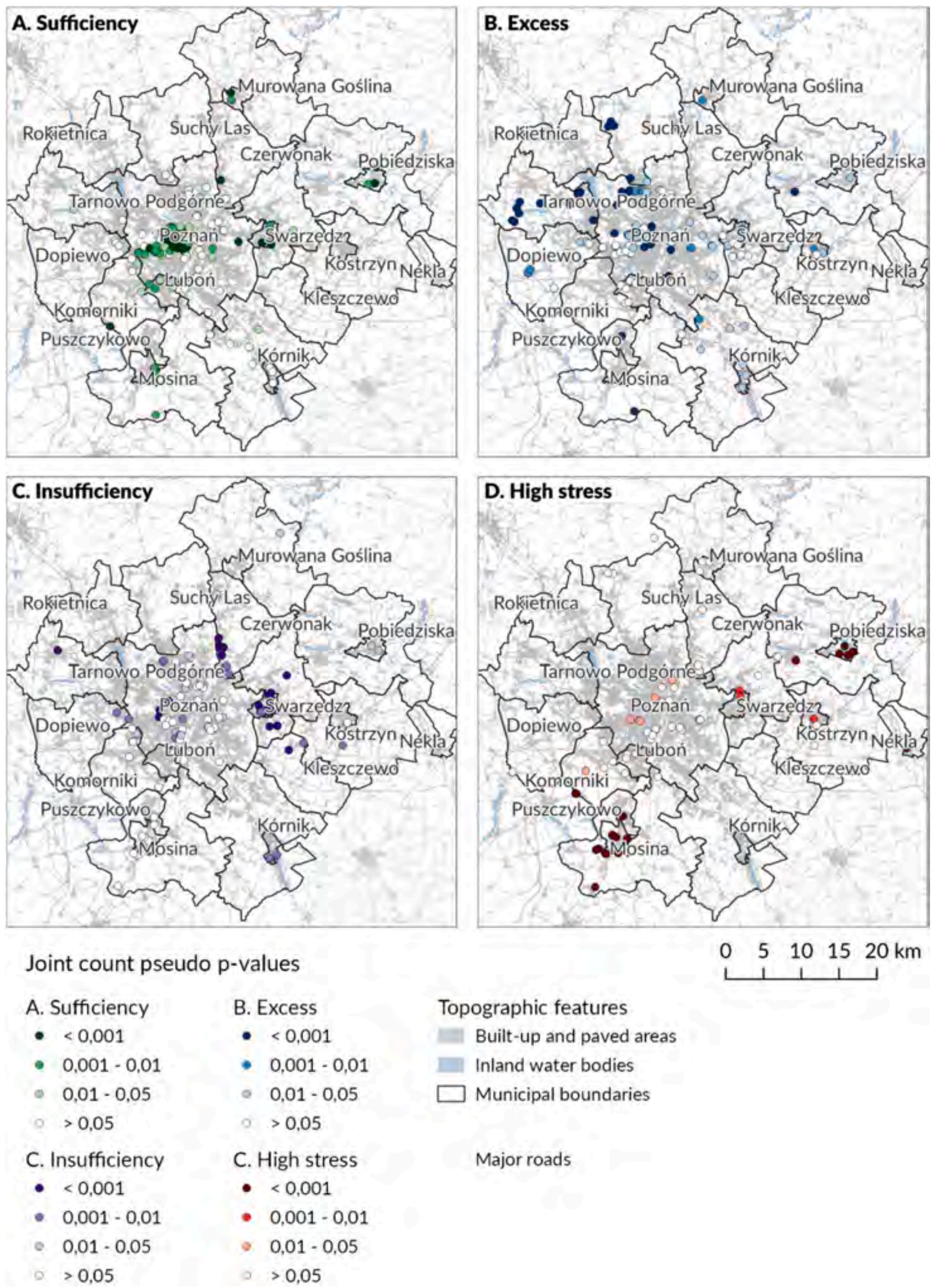

Fig. 4. The significance value of the join-count statistic of residents' membership in the social-ecological quadrants based on GHG emission levels and self-rated satisfaction of local transport needs. Low *p*-values depicted with dark colors mean the location is surrounded by a higher-than-expected share of neighbors in the same group.

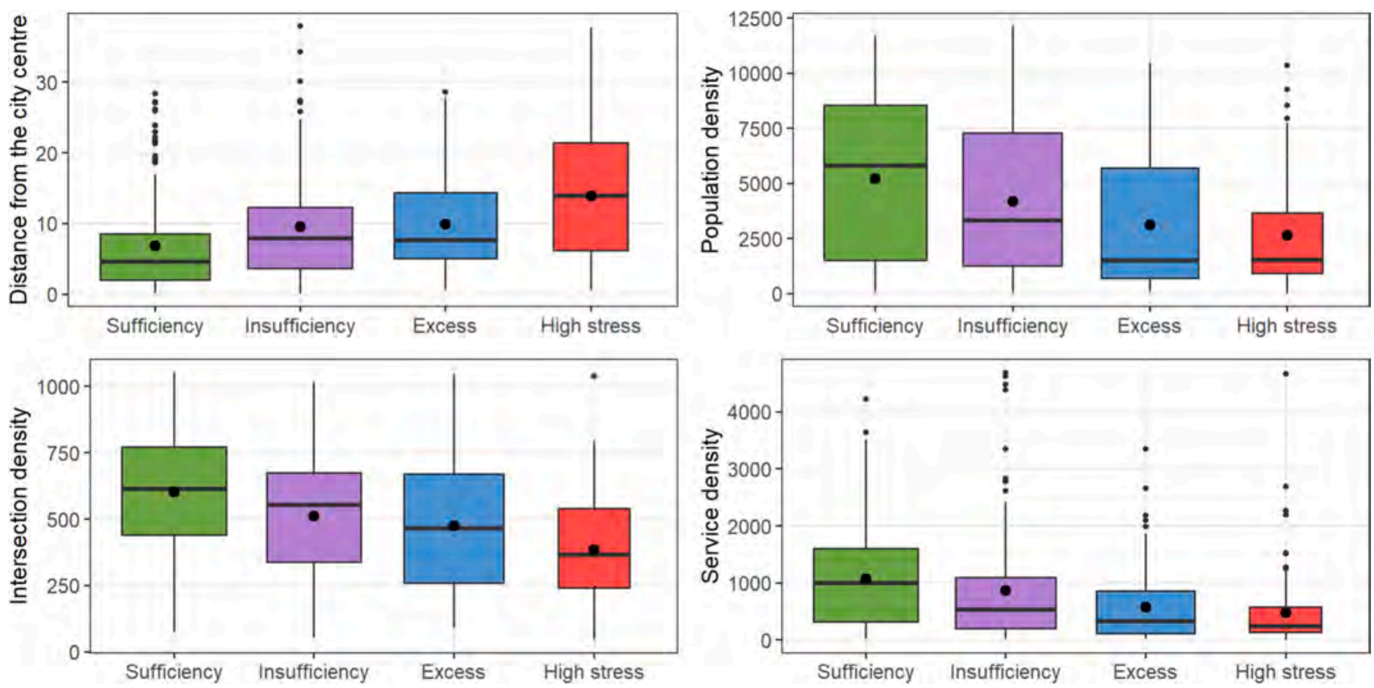

Fig. 5. Boxplots with the distribution of the BE characteristics in social-ecological quadrants.

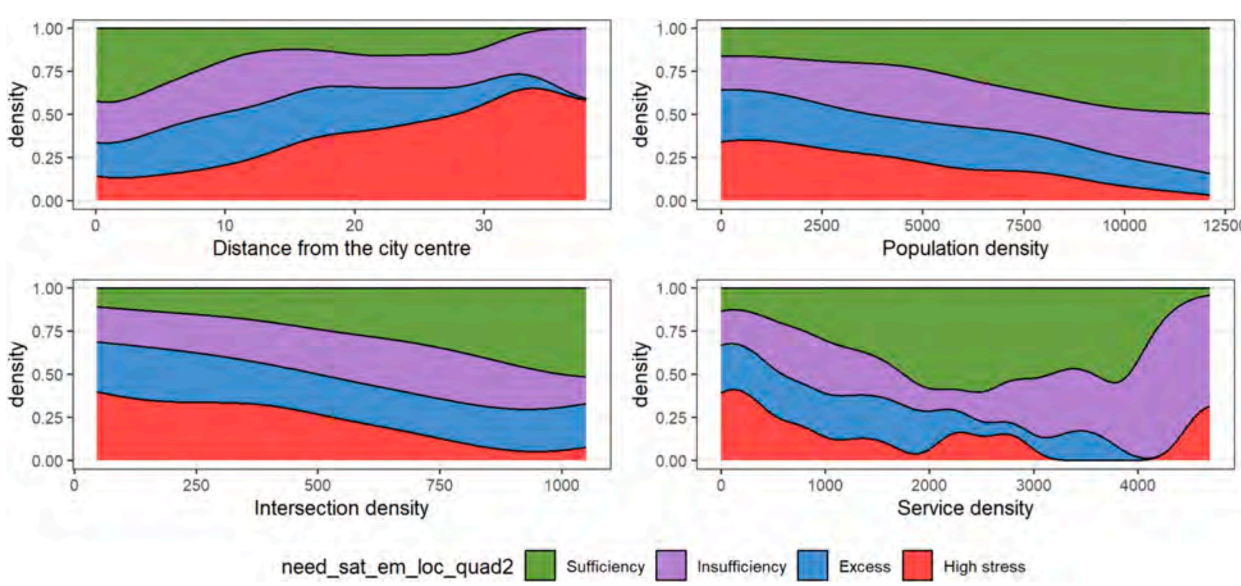

Fig. 6. Stacked density plots with social-ecological quadrant membership across the values of BE measures.

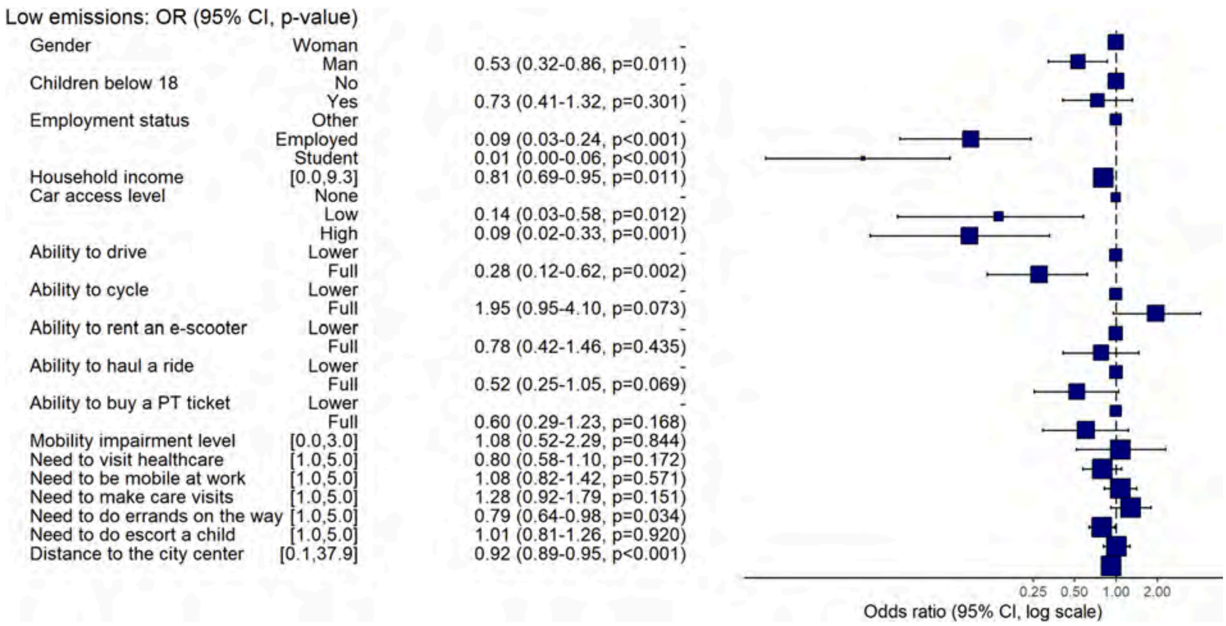

Fig. 7. Logistic regression on the "Low emissions" group performed on the whole sample.

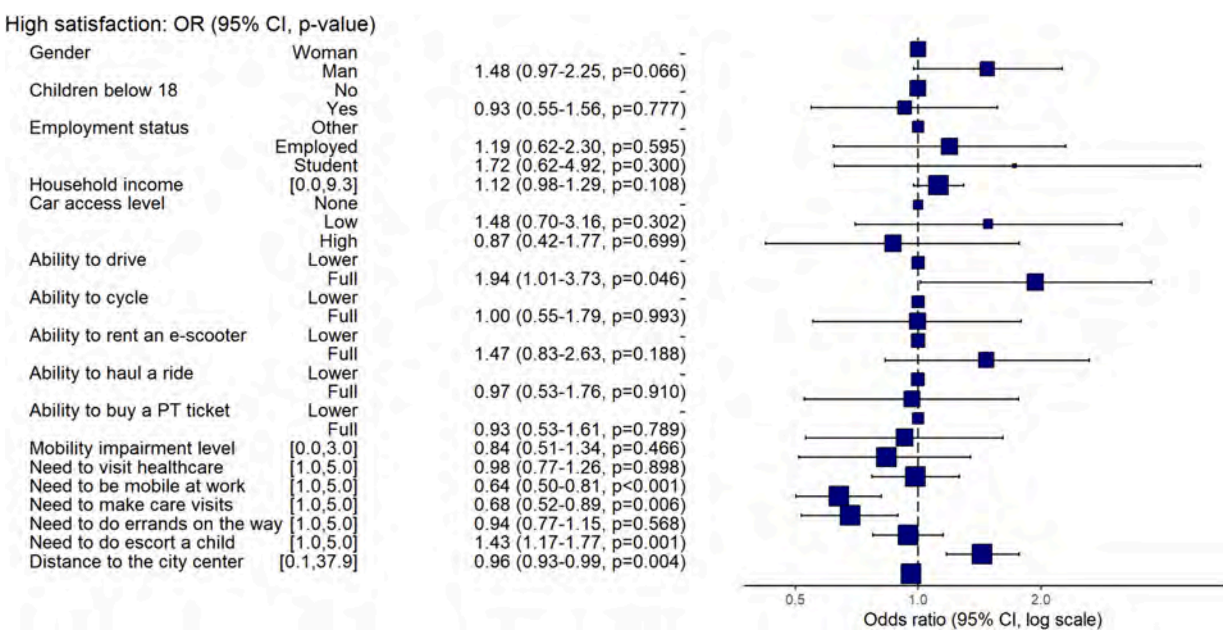

Fig. 8. Logistic regression on the "High satisfaction" group performed on the whole sample.

Modeling the membership in the "Sufficiency" group when controlling for other factors also emphasizes the role of BE characteristics in satisfying transport needs at low carbon cost: the closer one lives to the city center, the higher the odds they are in this group (Figs. 9 and 6). Being a student decreases the odds of being in the group. Having children decreases the odds of being in the "Sufficiency" group, but having to take a child or a dependent person somewhere *increases* these odds. Having a mobility impairment decreases the odds of being in the group. Being able to cycle increases the odds, but it is significant at $p < 0.1$ only when the model does not include mobility impairment. Frequent errands on the way to or from work decrease the odds of being in this group. When considering only workers and students, income level is associated with lower odds of being in the group, and the negative effects of having children and living farther from the center are amplified (Table A3).

4.3.5. "Insufficiency" group

Members of the "Insufficiency" group (i.e., "Low emissions – Low satisfaction") tend to cluster in the western part of Poznan and suburban towns east of Poznan (Fig. 4C). They tend to live farther from the city centers than the "Sufficiency" group but closer than those in the "High stress" group (Figs. 5 and 6). Being in the group is common among retirees and people aged over 60 but also happens among younger people (~20 %) and workers (~20 %) (Fig. A4, Fig. A10, Fig. A11). The group is the most common among people with primary and vocational education (Figure A8) and households with low incomes but the differences are not large. Many members of this group assess their financial situation positively (Fig. A4). Group members also report significantly higher transport needs related to visiting healthcare facilities and traveling to take care of someone than the "Excess" and "Sufficiency" groups. Their needs associated with being mobile at work are lower than those of the

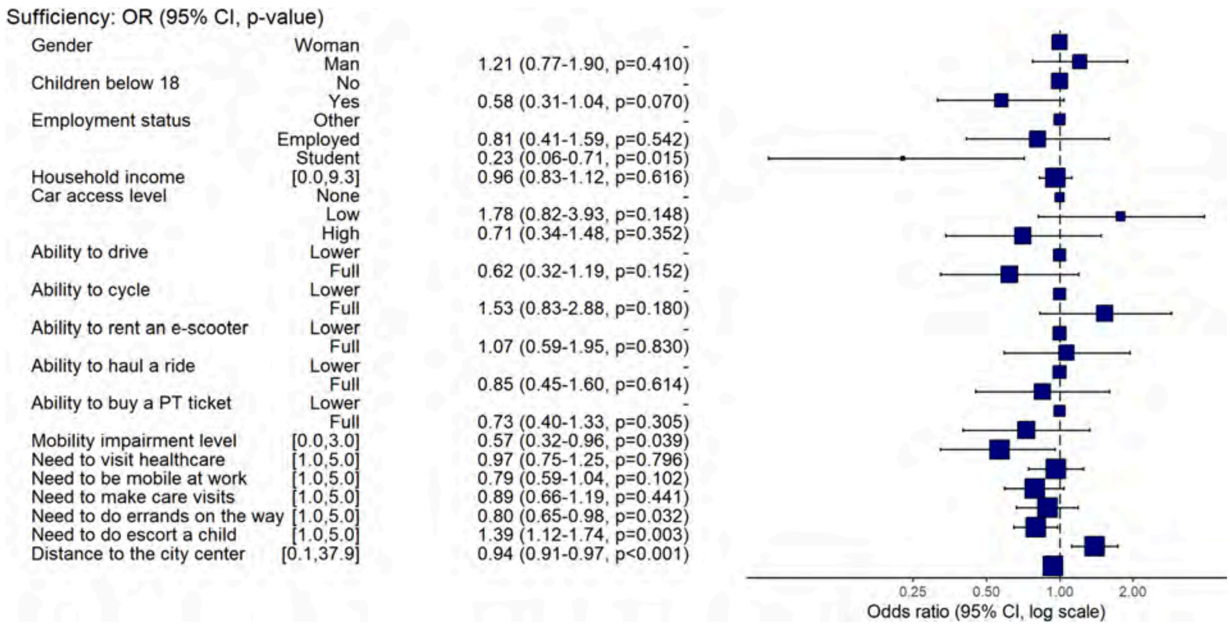

Fig. 9. Logistic regression on the “Sufficiency” group performed on the whole sample.

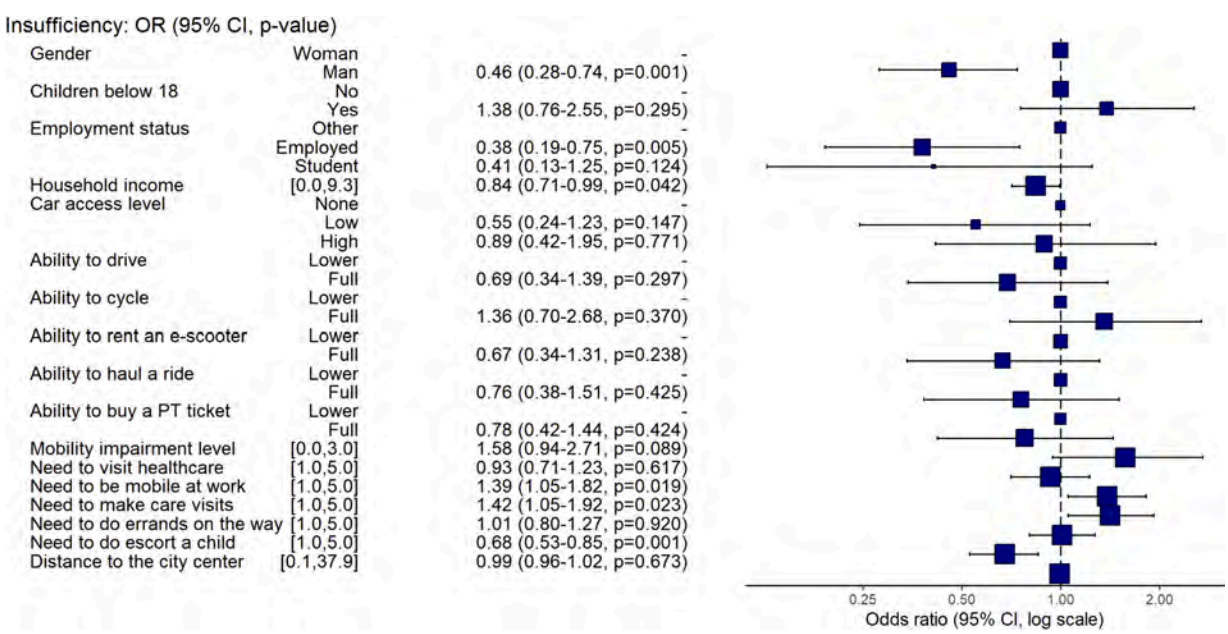

Fig. 10. Logistic regression on the “Insufficiency” group performed on the whole sample.

“High stress” groups. They have significantly lower mobility competencies than all the other groups.

When controlling for other variables, being a man, employed or studying, and with higher income *decreases* the odds of falling into the “Insufficiency” group (Fig. 10). The ability to drive a car also reduces the odds of being in this group. There is no significant association with the BE characteristics when predicting membership in this group compared to the rest of the sample. The frequency of having to visit multiple locations during a working day and travel to care for someone increases the odds of being in the “Insufficiency” group. Conversely, taking a child or a dependent person somewhere decreases these odds. When considering only employed or studying participants, unskilled manual workers, women, and those who need to travel to care for someone are particularly likely to fall into the group (Table A3).

4.3.6. *“Excess” group*

People in the “Excess” group cluster in the northwest part of Poznan and neighboring communes (Fig. 4B). They tend to reside farther from the city centers than those in the “Sufficiency” group but more centrally than those in the “High stress” group (Figs. 5 and 6). The group is the most common among people with university education (Fig. A8), men (Fig. A6), and households with children (Fig. A7). The group is almost entirely composed of employees (86 %) and students (12 %). There are virtually no people from car-less households and people who cannot drive in this group. Group members also report other mobility competencies, such as hauling a ride or riding a bicycle (Fig. A18). They have significantly lower transport needs related to visiting healthcare facilities, traveling to care for someone, and being mobile at work than those in the “High stress” group.

In the regression model, membership in the “Excess” group is

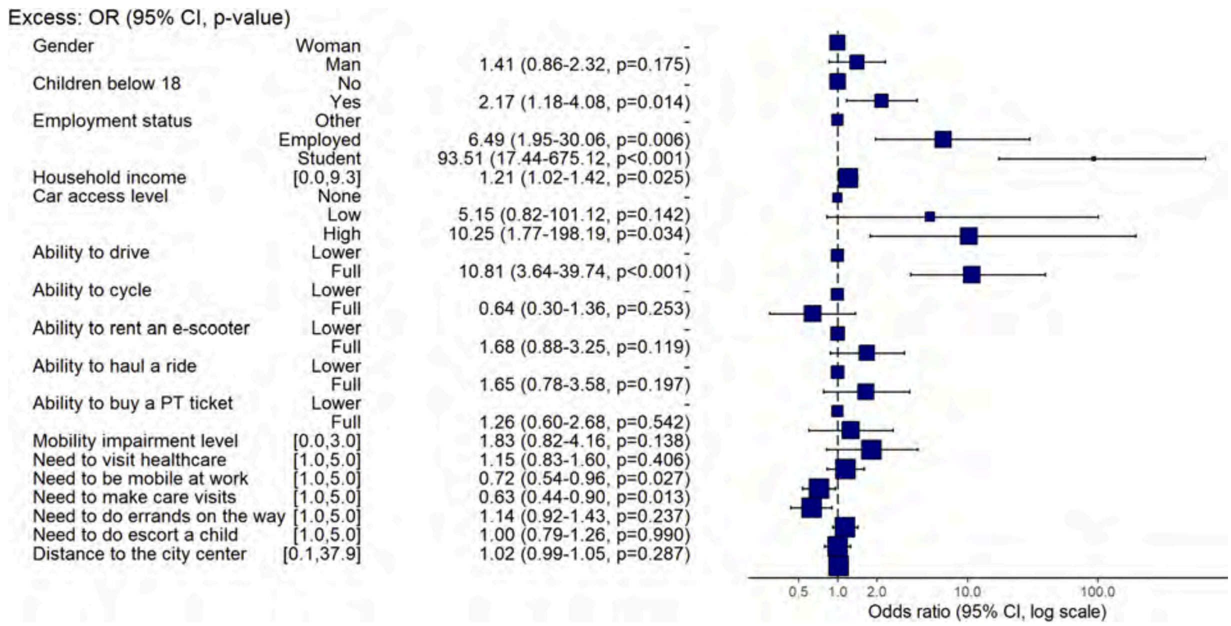

Fig. 11. Logistic regression on the "Excess" group performed on the whole sample.

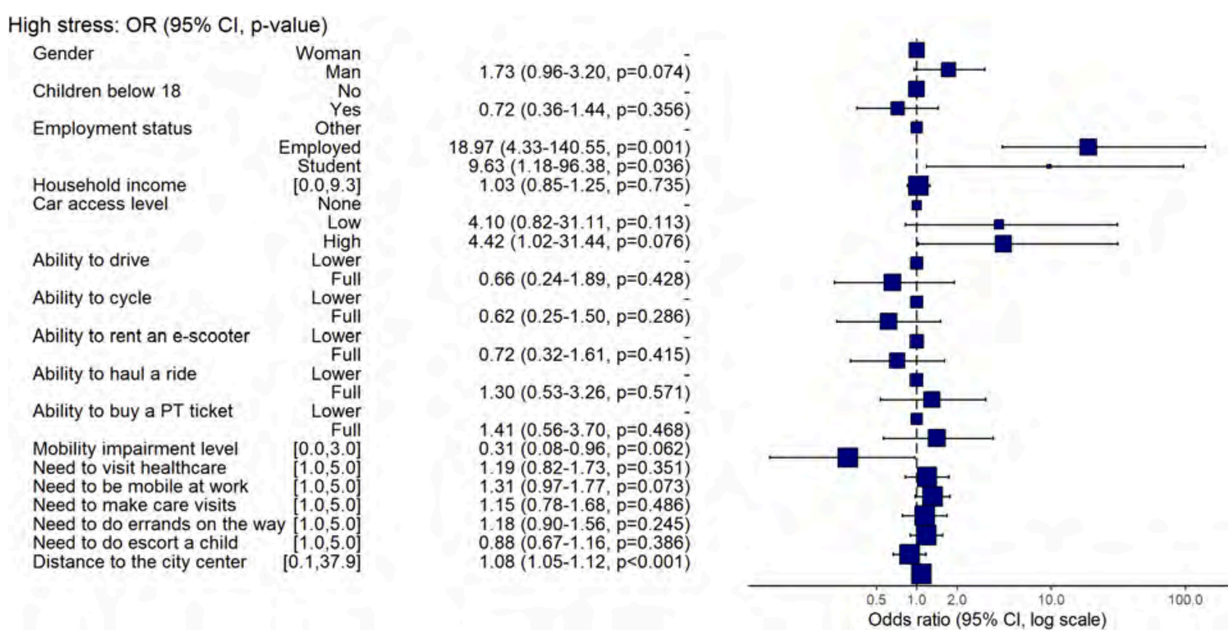

Fig. 12. Logistic regression on the "High stress" group performed on the whole sample.

positively influenced by living with children, being employed or a student, having a higher income, and having a higher ability to drive a car (Fig. 11). Having transport needs related to visiting multiple locations during a working day and traveling to care for someone decreases the odds of being in the group. There is no significant association with the BE characteristics when predicting membership in this group. The model fitted only on those in education or training shows that unskilled manual workers and those who work in service or retail jobs are unlikely to be in the "Excess" group (Table A3).

4.3.7. "High stress" group

People in the "High stress" group cluster in a few suburban towns (Fig. 4D). They tend to live far from the city center (Figs. 5 and 6). Few people over 60 belong to this group, predominantly composed of employees (93 %). They report higher incomes than people in the "Sufficiency" and "Insufficiency" groups, high mobility competencies, and a lack of mobility impairments. There are virtually no people from car-less households, and very few in this group cannot drive (Fig. A20). "High stress" have significantly higher transport needs related to visiting healthcare facilities, traveling to care for someone, and visiting multiple places at work than those in the "Excess" and "Sufficiency" groups.

When controlling for other variables, membership in the "High stress" group (i.e., having high emissions and low satisfaction with transport needs) is positively influenced by being employed and living farther from the city center (Fig. 12). When considering only workers and students, being a manual worker and having to be mobile while working increases the odds of falling into the group, and having a mobility impairment decreases the odds (Table A3).

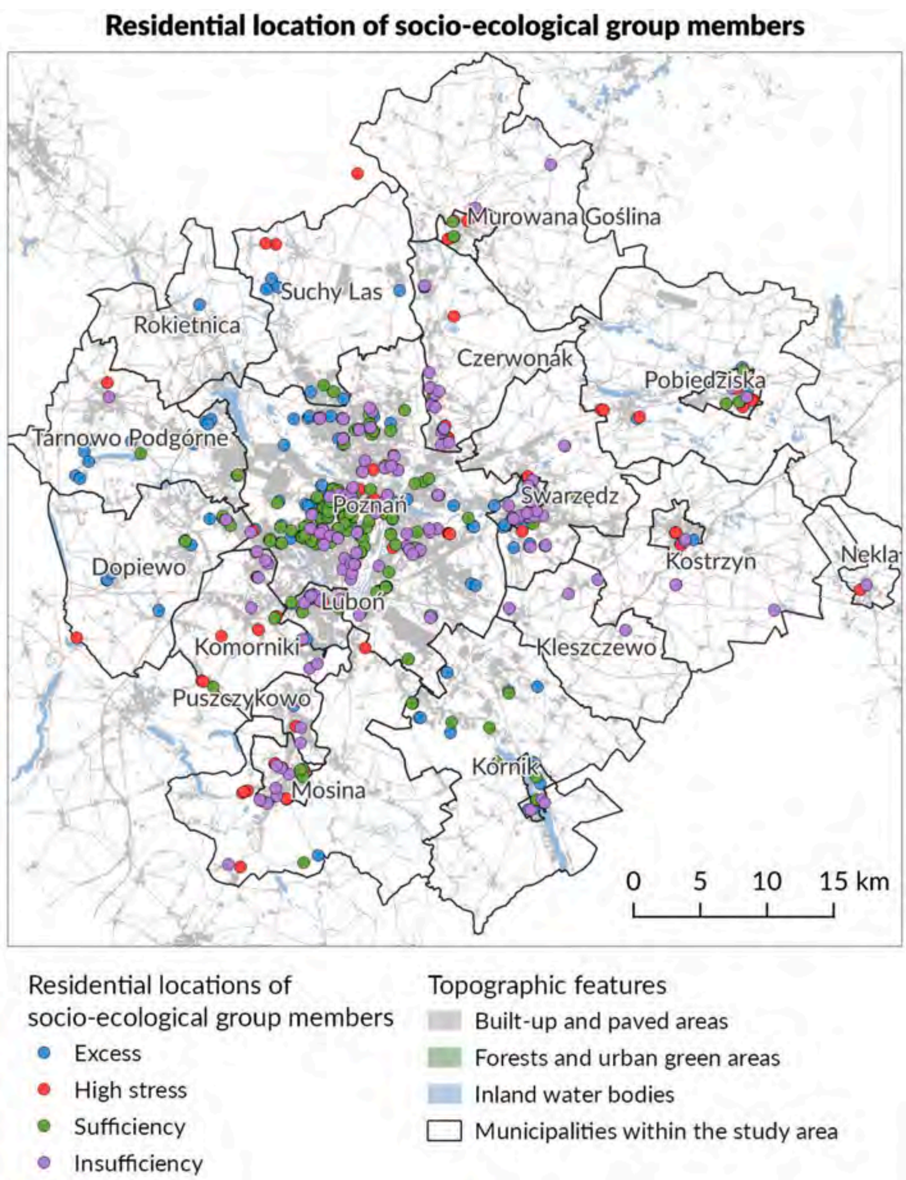

Fig. A1. Residential locations of socio-ecological group members in Poznań FUA.

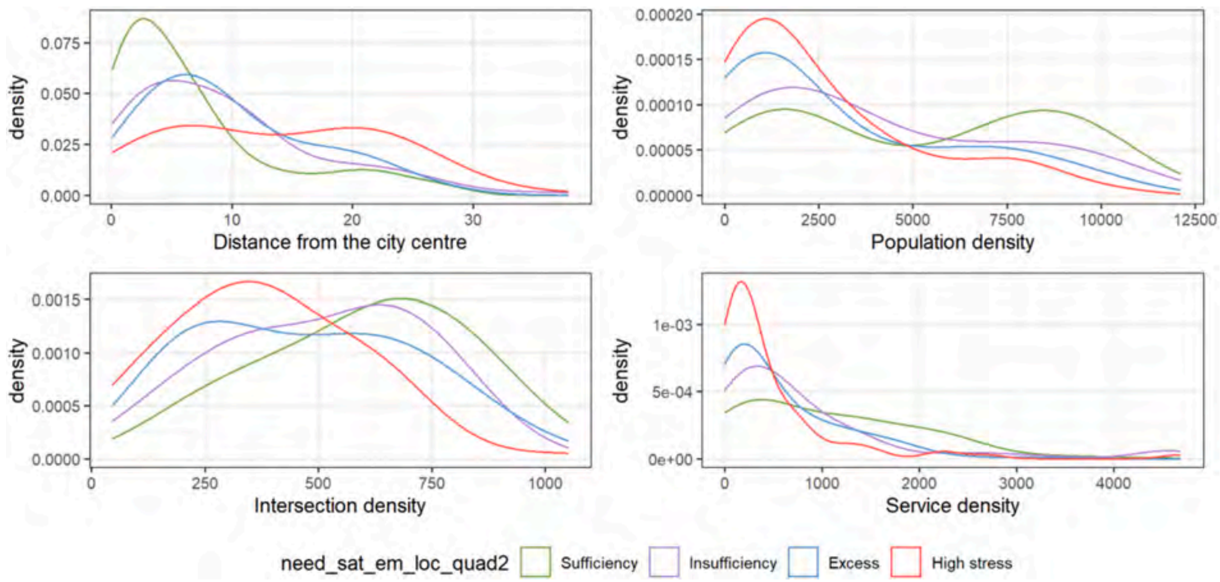

Fig. A2. Density plots with social-ecological quadrant membership across the values of BE measures.

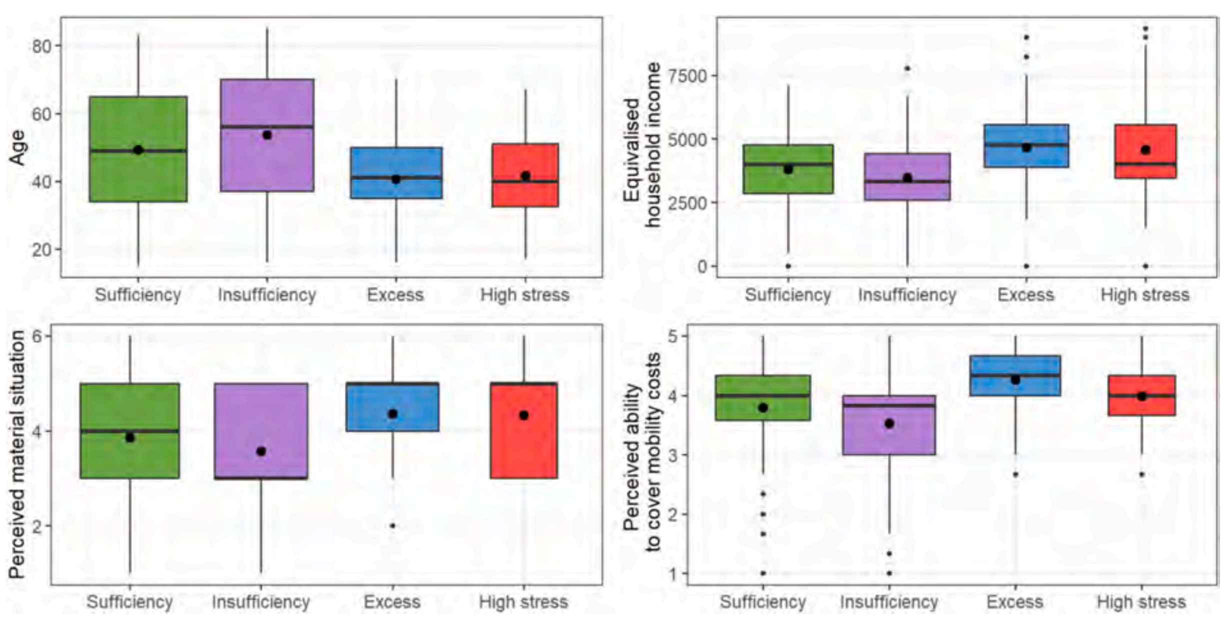

Fig. A3. Boxplots with the distribution of the age, income and perceived material situation variables in social-ecological quadrants.

5. Discussion

The study is one of the first to explicitly connect transport-related CO_2 emissions with the satisfaction of transport needs using disaggregated measurements at an urban scale. The results illustrate that transport needs are often satisfied at low emission levels. The increase in emissions has the strongest contribution to satisfaction in low emission ranges. Such *saturation effect* has also been described in aggregate studies about energy use and well-being, particularly in developed countries (tho Pesch, Einarsdóttir, Dillman, & Heinonen, 2023). However, we also show that the ability to satisfy one's needs at a low emission level is highly differentiated by residential location and individual characteristics. The exact shape of the relationship might also be different in other study areas.

The results on the role of BE characteristics in enabling low emissions and transport need satisfaction and emissions align with previous studies that separately considered their role in shaping GHG emissions (Des Rosiers et al., 2017; Wang et al., 2023; Wu et al., 2019) and social outcomes, such as activity participation and social inclusion (Allen & Farber, 2020; Ma et al., 2018). Our studies also confirm previous results on the association of being a man and having a high income with travel patterns that generate high GHG emission levels. In line with previous studies, we also emphasize the importance of proximity for low-income and older households to attain access at low mobility levels. Following Mattioli (2014), we highlight the role of suburban and car-dependent locations in creating various aspects of transport poverty. Even though we did not explicitly distinguish between car dependence and forced car ownership, our results regarding the "High stress" group illustrate how transport needs may be frustrated even with high *motility* in the sense of the ability to be mobile (i.e., good access to the car, high mobility competencies, and financial resources not below the sample's average).

The frustration of needs despite car access also stems from everyday life and professional demands, such as visiting multiple places during work and errands. Manual, retail, and service workers have particularly

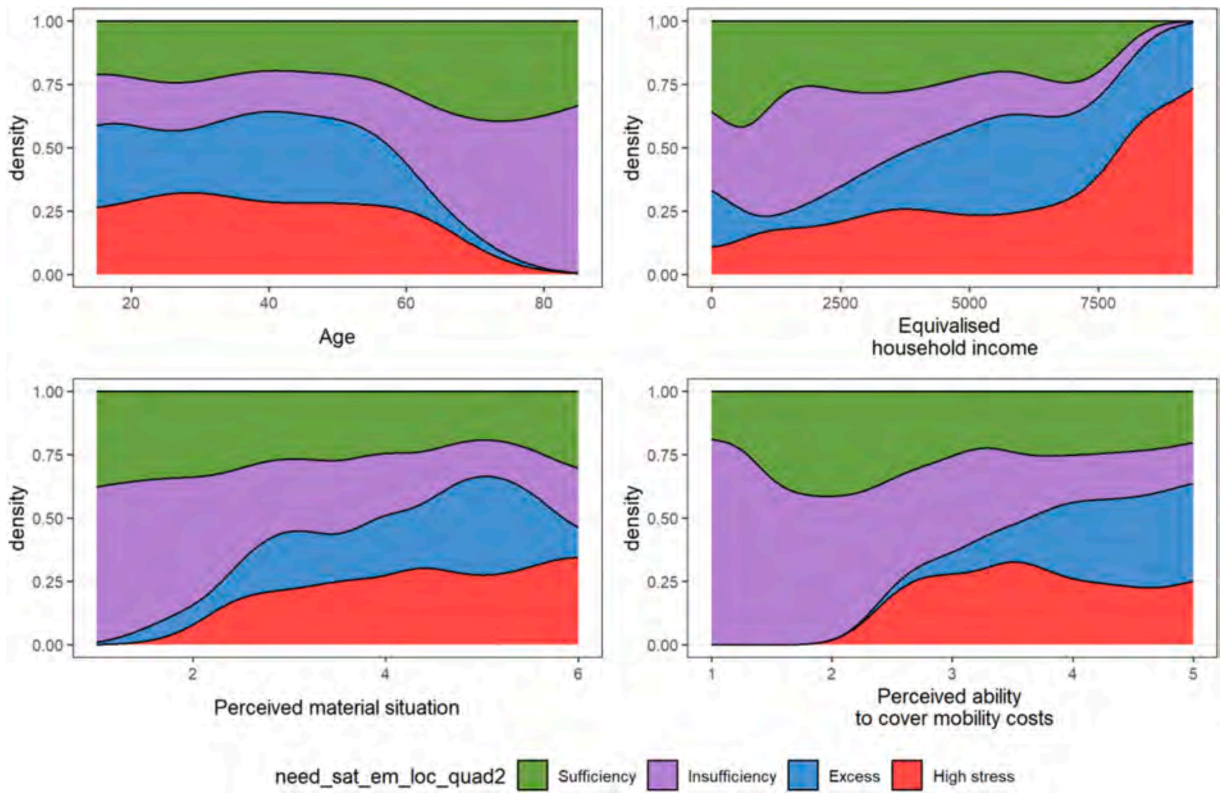

Fig. A4. Stacked density plots with social-ecological quadrant membership across the age, income, and perceived material situation variables.

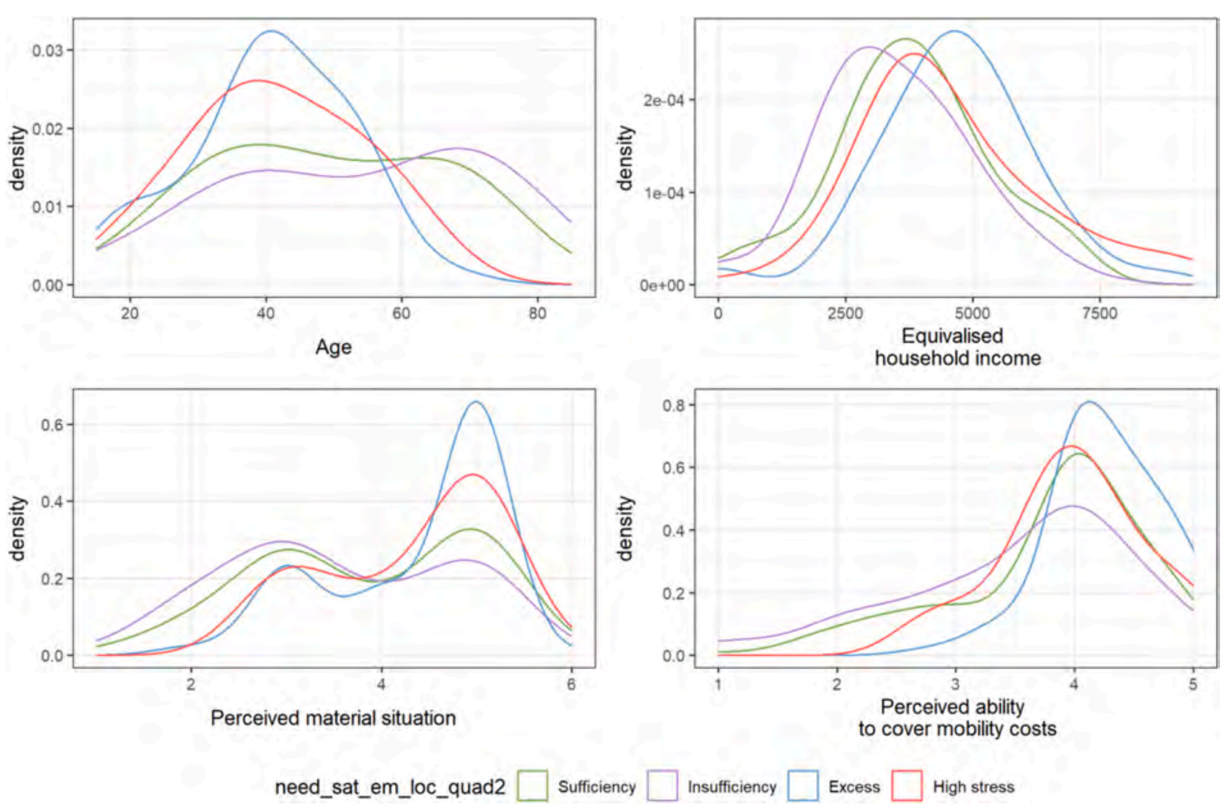

Fig. A5. Density plots with social-ecological quadrant membership across the age, income, and perceived material situation variables.

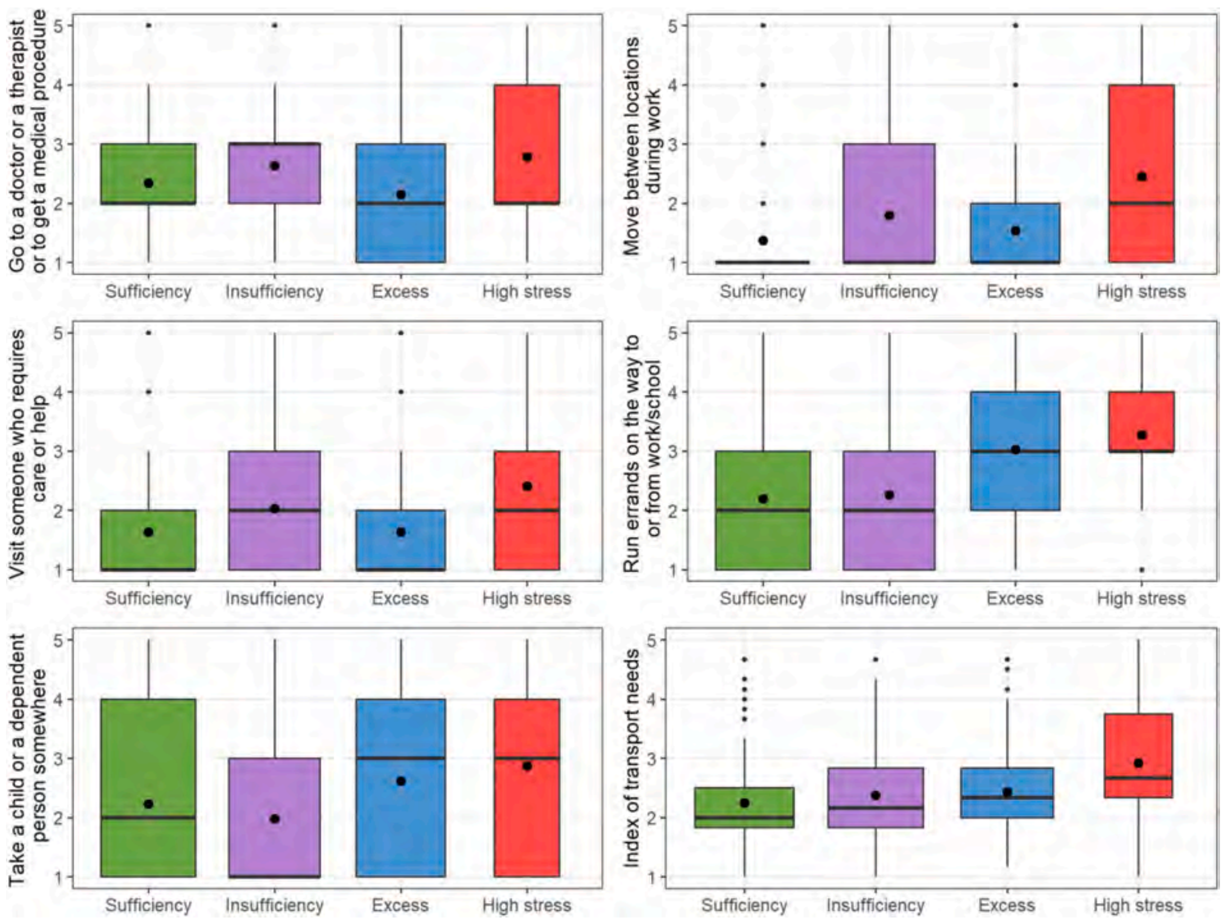

Fig. A13. Boxplots with distribution of the level of transport needs (i.e., the frequency of having to travel to perform activities) in social-ecological quadrants.

lower odds of having their transport needs satisfied at both low and high emission levels. It suggests that improving the sufficiency conditions requires improvement in low-carbon mobility options for those worker categories and must consider the risk for these usually low-paying jobs associated with potential mobility restrictions or the inability to live close to workplaces.

Furthermore, unraveling the pathways that make people regard certain trips as necessary to fulfill their needs is important. For example, our data suggests that doing errands during commutes correlates with having access to a car and living in places with scarce access to services. Our quantitative material cannot reveal whether the mobility-requiring practices precede mobility, result from car ownership, or are a product of a society organized around high mobility expectations. Qualitative studies and mixed methods analyses seem necessary to disentangle possible causalities behind the correlations.

Furthermore, the results highlight gender differences, as women are more likely than men to have their transport needs poorly satisfied at low emission levels ("Insufficiency" group). Two groups of women are particularly at risk of being in this group: older women and those with children. The need to visit to care for someone also positively predicts membership in the "Insufficiency" group, likely resulting from gender differences in care responsibilities. It highlights it as another sensitive area of transport policy that is mindful of social-ecological tensions.

Having children is positively associated with the "Excess" group and negatively with the "Sufficiency" group. It highlights the need to study the conditions that facilitate child-rearing without relying on private cars and high mobility levels. Finally, the association between high incomes, gender, car use, and high emissions raises the issue of the car as a status symbol and its association with masculine gender roles, potentially preventing sufficiency in the mobility domain.

Although our results reveal clear patterns regarding residential location, life situation, car access, and socio-economic status, they also highlight considerable variation within each group. It suggests that mobility sufficiency (as well as other conditions) is possible in various situations. It also supports the usefulness of the *motility* concept to socio-ecological mobility studies. Specific combinations of individual and group characteristics with BE and organizational constraints may lead to higher or lower satisfaction of needs and emissions than expected. Examples include car-less parents, low-emission professionals living in the suburbs, or high-emission car drivers living in city centers. Identifying the specific ways and conditions by which people achieve high levels of transport need satisfaction with low emissions can be useful for policy.

Regarding policy implications, our results support land use and transport policies that aim to shorten distances, maintain compact urban forms, and improve accessibility by walking and public transport. These BE characteristics are synergistic in reducing car use and emission levels and enabling transport needs satisfaction with low mobility. It is particularly important for low-income or otherwise disadvantaged people who often cannot afford to own and use a private car or do not have relevant mobility competencies. However, it comes with a caveat related to housing affordability. For historical and cultural reasons, residential mobility in Poland is relatively low, and homeownership rates are high. There is still a high proportion of low-income and older-age homeowners in central locations with good access. Such condition reduces the risk of *low-carbon gentrification* (i.e., forcing low-income households to relocate to peripheral locations with low accessibility due to price increases in the central, walkable areas) that might result from densification policies in more residentially mobile societies, such as Germany or the US (Bouzarovski et al., 2018). Reducing such risks requires accompanying land use and transport policies with housing

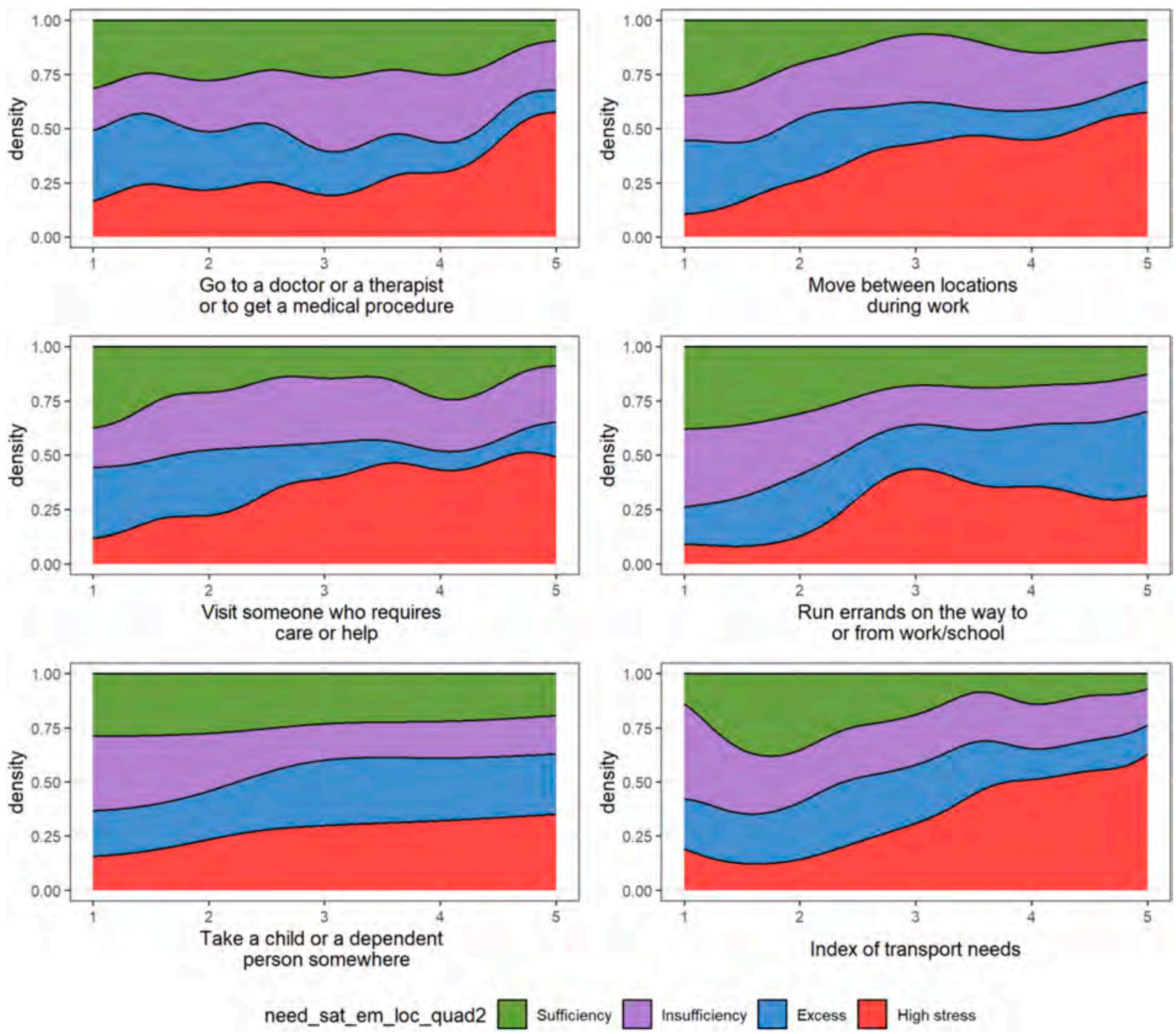

Fig. A14. Stacked density plots with social-ecological quadrant membership across the variables describing the level of transport needs (i.e., the frequency of having to travel to perform activities).

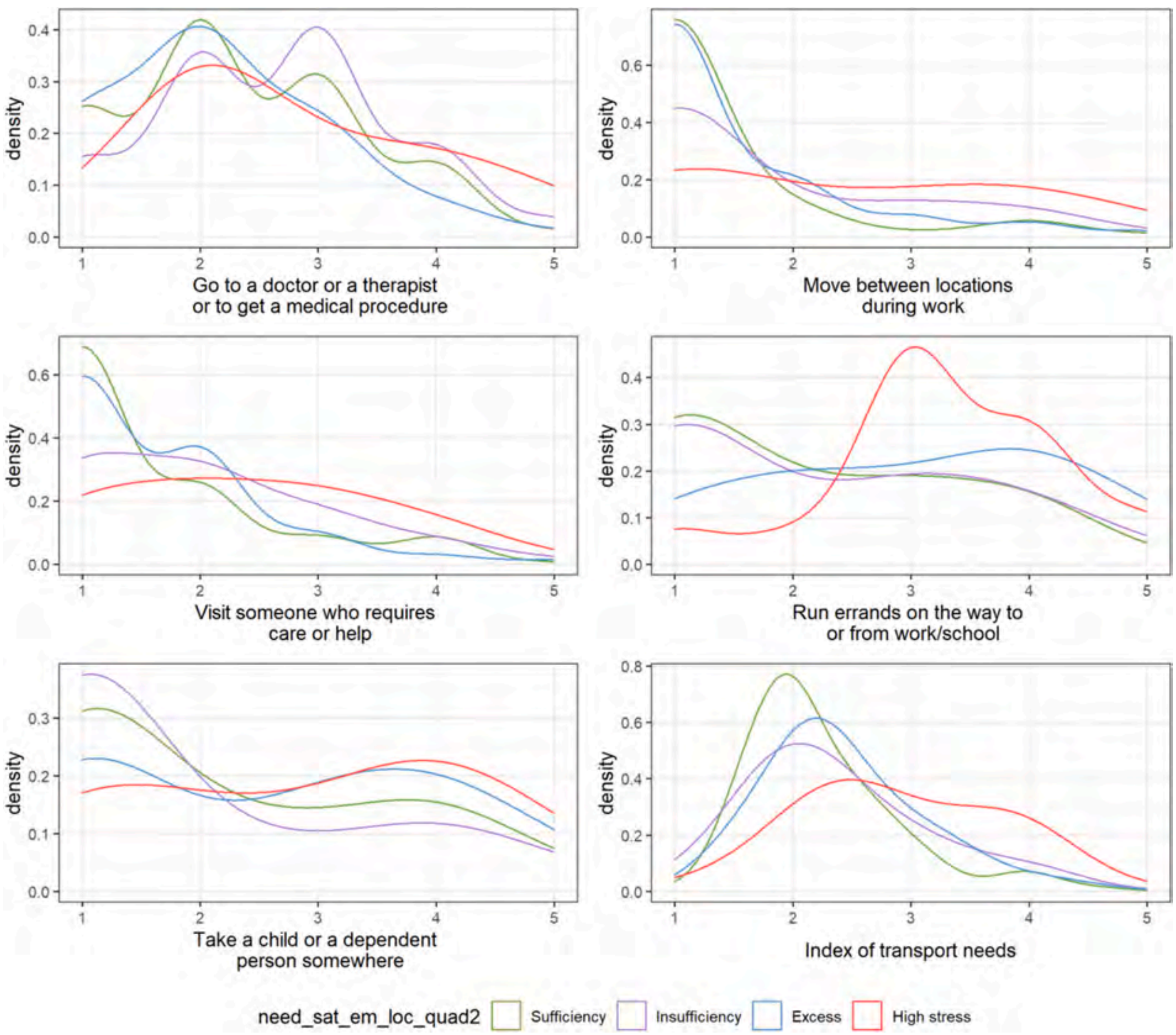

Fig. A15. Density plots with social-ecological quadrant membership across the variables describing the level of transport needs (i.e., the frequency of having to travel to perform activities).

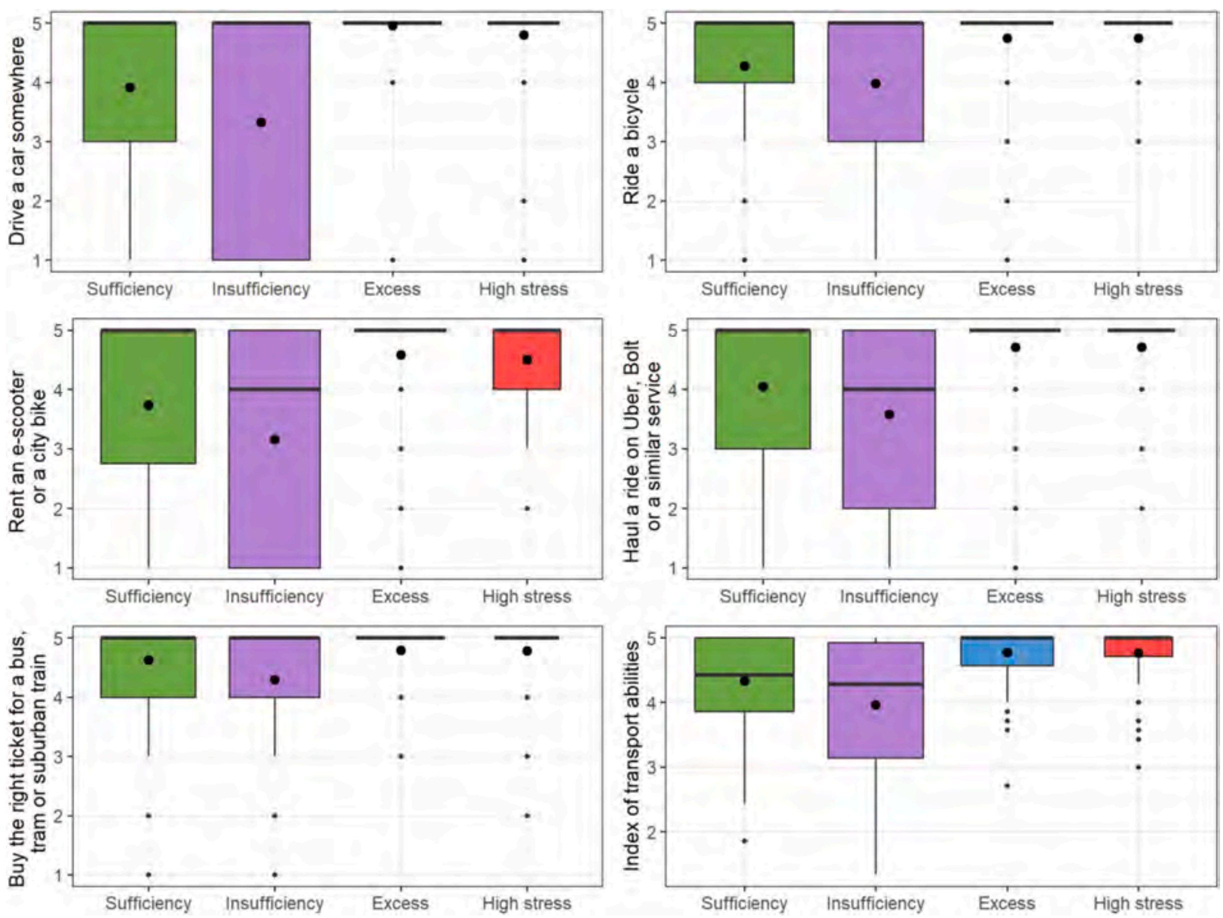

Fig. A18. Boxplots describing the level of mobility competencies and abilities in social-ecological quadrants.

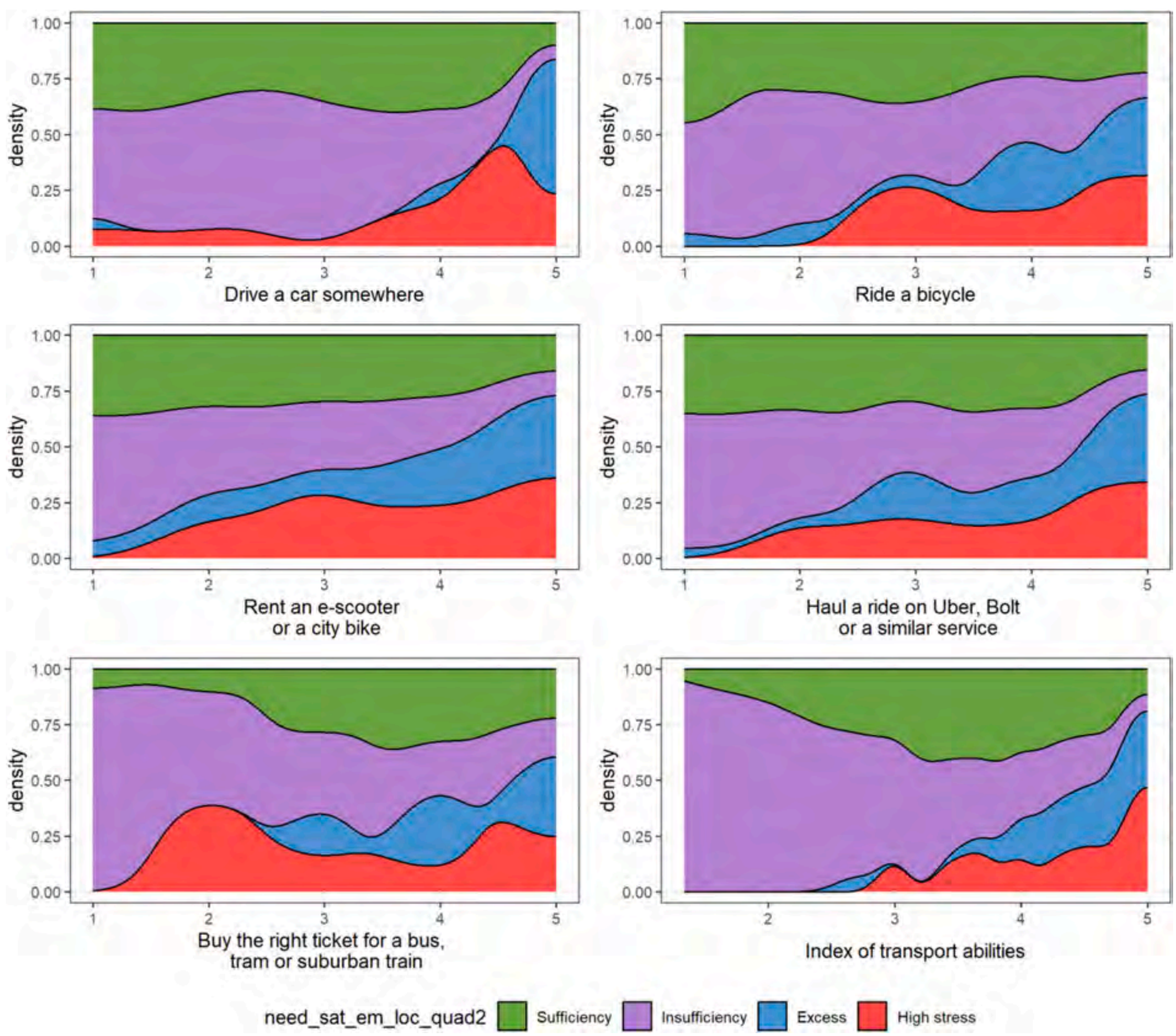

Fig. A19. Stacked density plots with social-ecological quadrant membership across the variables describing the level of mobility competencies and abilities.

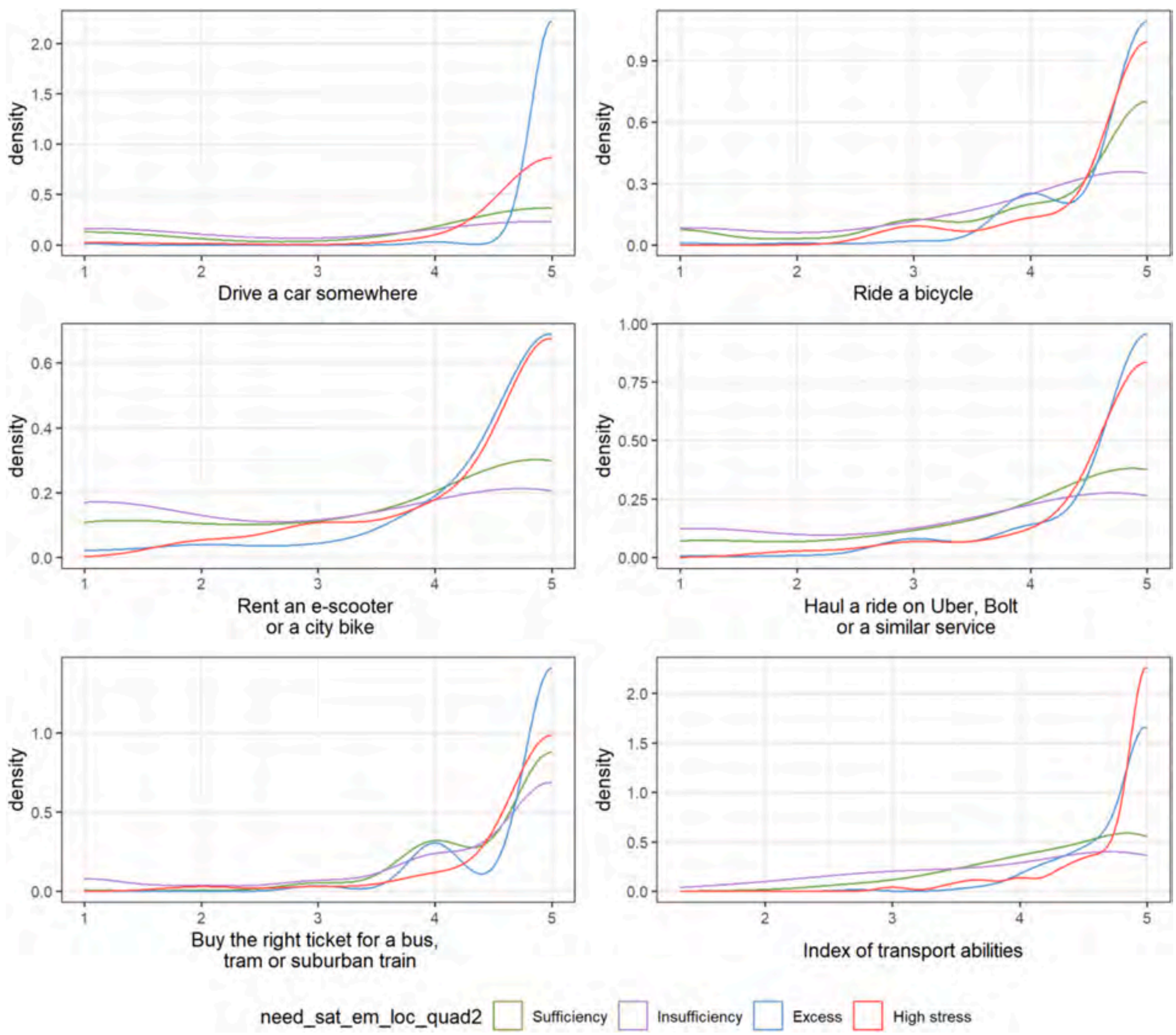

Fig. A20. Density plots with social-ecological quadrant membership across the variables describing the level of mobility competencies and abilities.

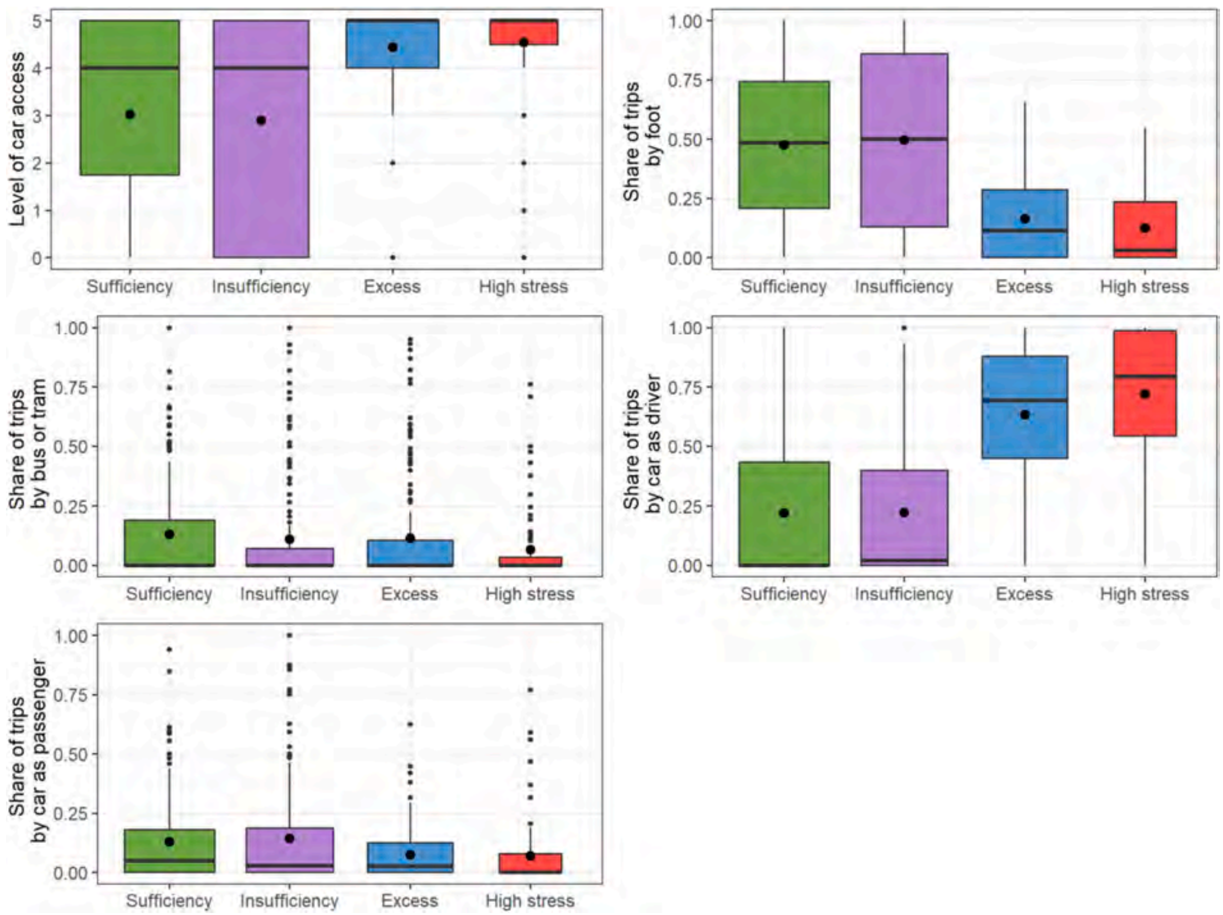

Fig. A21. Boxplots describing the level of car access and share of modes in reported trips in social-ecological quadrants.

policies that provide affordable and public housing in centrally located and walkable locations.

The results also highlight the need to spatially and individually differentiate the ability to reduce one's emissions from travel, with higher emission allowances necessary for people living in peripheral locations and with high mobility requirements related to their jobs, with implications for setting *fair mobility budgets* (Millonig et al., 2022; Rode, 2023).

The study is not without limitations. It is based on a relatively small sub-sample of a survey conducted in one urban area in Poland. Poznan FAU has relatively high levels of accessibility and public transport provision, its urban structure is monocentric, and its socio-spatial composition differs from many other European cities. Thus, the results may not be generalizable to rural areas, highly car-dependent cities, or polycentric urban regions. More similar studies in diverse locations are needed.

Our indicator of transport need satisfaction is self-rated, which allowed us to capture individual differences in the assessment in ways that trip frequency measures cannot. However, it also makes it challenging to use as a basis for a sufficiency threshold since people differ in their cognitive assessments of satisfaction due to, for example, response style or personality (OECD, 2013). The measure we used was tailor-made, limiting direct comparisons with other studies, and more studies are needed to replicate the results. The satisfaction measure could also be refined to include more trip purposes and align them better with human need theories. The treatment of options signifying a lack of need require consideration in future studies. Here, "No such need" was coded as a complete need satisfaction, due to potential biases and a sample size reduction that would result from coding it as missing. It was also consistent with out theoretical framework, which considers the ability to avoid mobility as an asset. The "No such need" option accounted for around 1 % of the answers in items related to daily shopping, visiting friends and family, and recreation, 5 % in shopping for large items, and 11 % in reaching places of work or study. Coding these answers as missing would unnecessarily exclude certain social groups (e.g., a large portion of retirees) and practices (e.g., fully remote work, always shopping online for large items) from the analysis. To account for differences in transport needs between commuters and non-commuters, we conducted regressions reported in Table A3.

Finally, we used a crude division into social-ecological quadrants, even though some might be misclassified due to measurement errors. Discrete thresholds of satisfaction and emission levels are also necessarily arbitrary and laden with assumptions. Our aim here was to simplify the interpretation and illustration of the method and to use explicit social and ecological thresholds. Future studies could explore the sensitivity of relationships to various threshold levels based on different assumptions, explore measures of social shortfall (i.e., the degree of transport poverty) and ecological overshoot (i.e., the degree to which ecological limits are transgressed) to study continuous relationships between the two or employ a fuzzy set theory to study group membership.

CRediT authorship contribution statement

Michał Czepkiewicz: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Filip Schmidt:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Dawid Krysiński:** Writing – review & editing, Data curation,

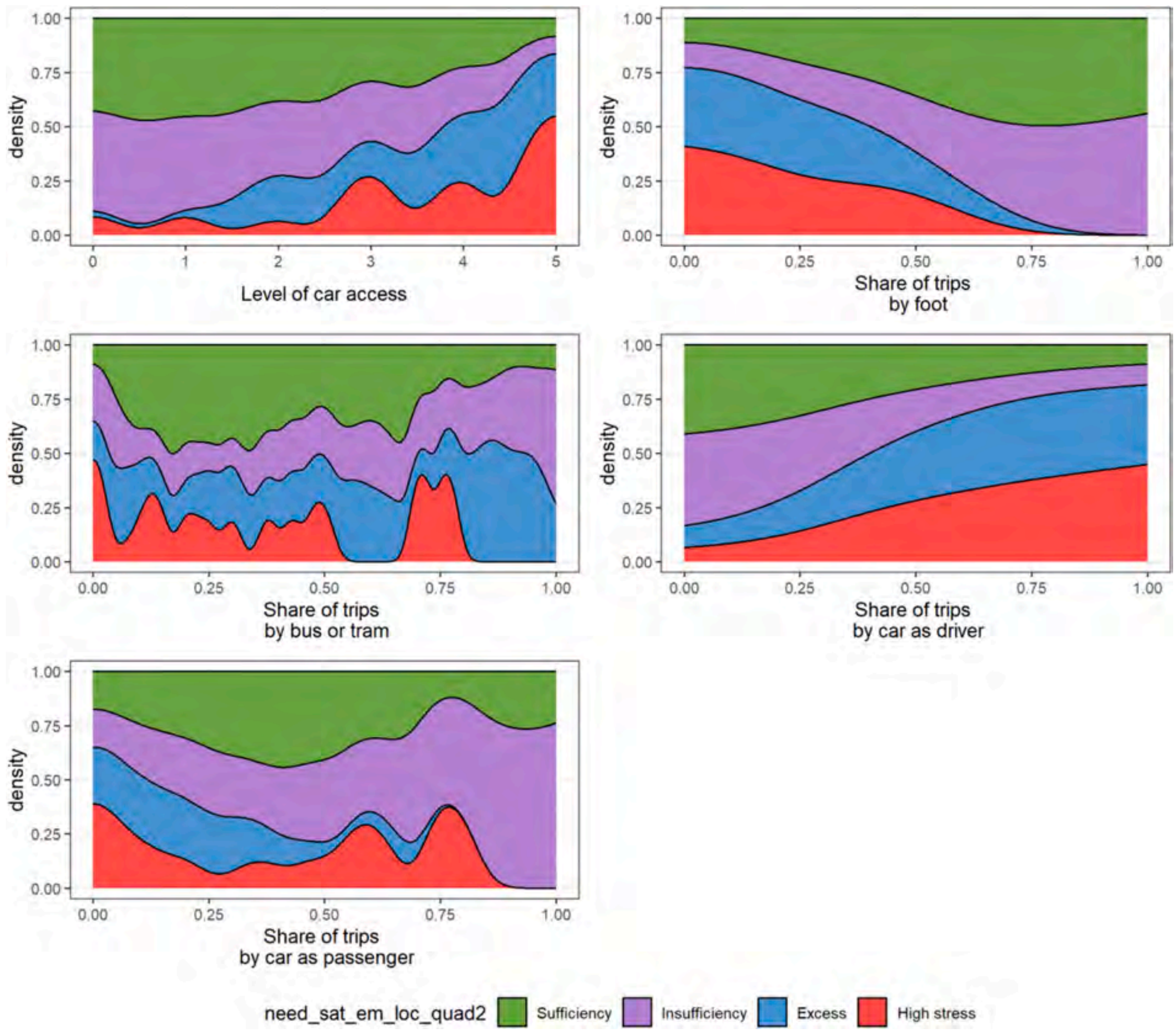

Fig. A22. Stacked density plots with social-ecological quadrant membership across the variables describing the level of car access and the share of travel modes in reported trips.

Conceptualization. **Cezary Brudka:** Writing – review & editing, Data curation, Conceptualization.

Data availability

Data will be made available on request.

Acknowledgements

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Table A1
Spearman correlations between built environment (BE) variables.

	Distance to the city centre	Local population density	Local intersection density	Local service density
Distance to the city centre	1.00	−0.85	−0.82	−0.89
Local population density	−0.85	1.00	0.89	0.96
Local intersection density	−0.82	0.89	1.00	0.92
Local service density	−0.89	0.96	0.92	1.00

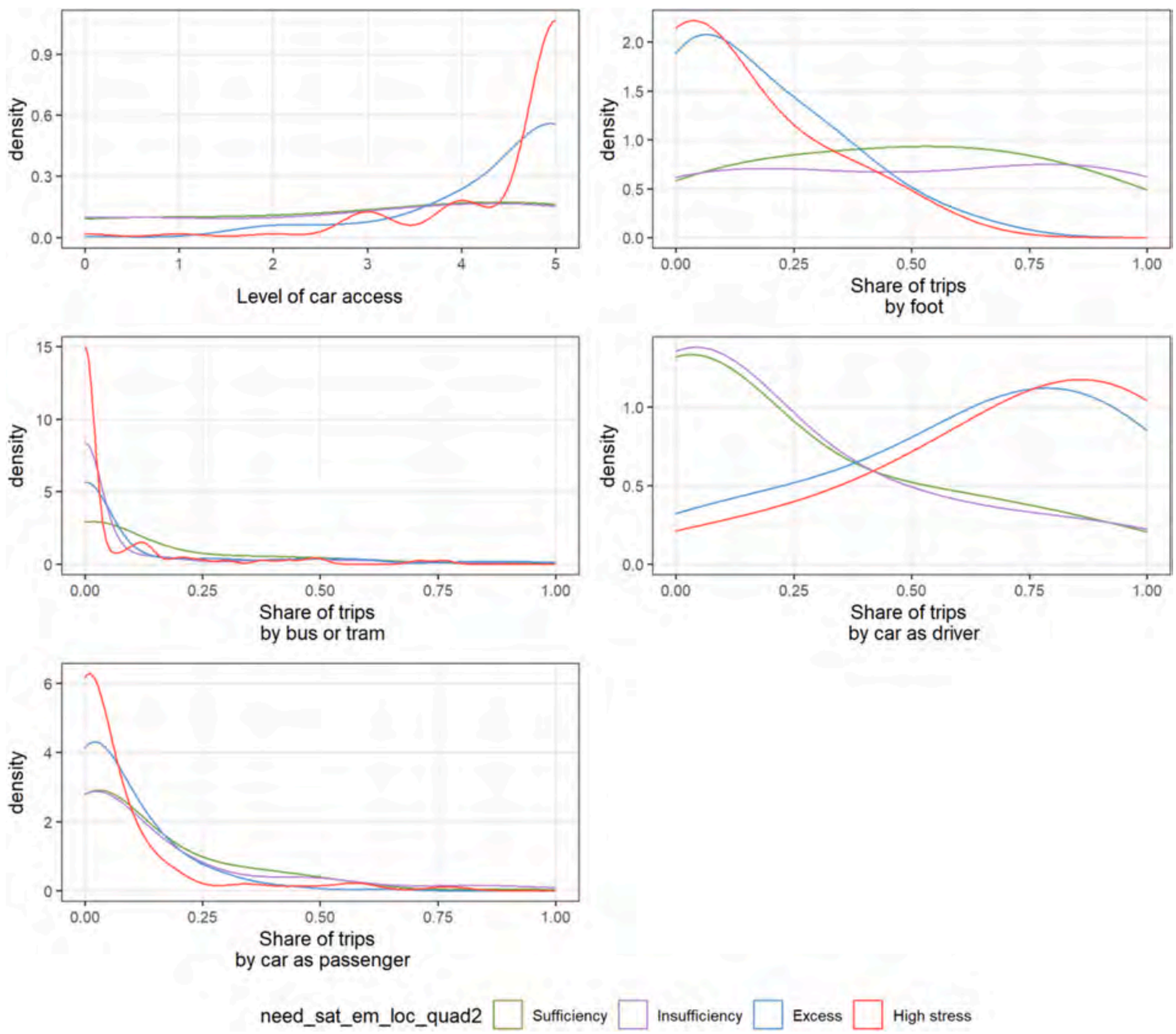

Fig. A23. Density plots with social-ecological quadrant membership across the variables describing the level of car access and the share of travel modes in reported trips.

Fig. A6. Socio-economic quadrants in gender groups.

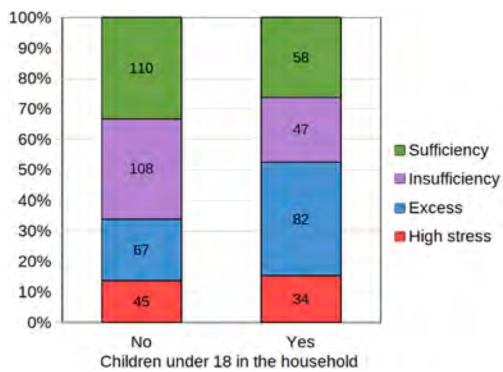

Fig. A7. Socio-economic quadrants in households with and without children under 18.

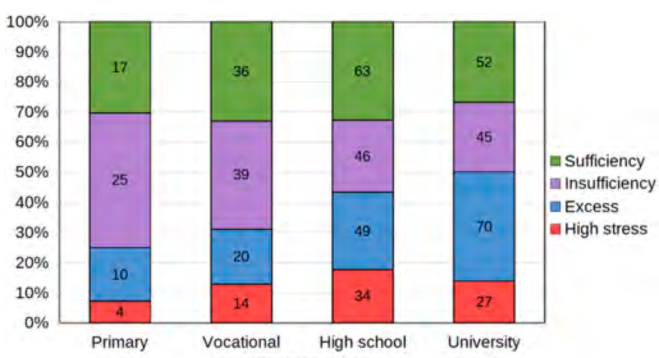

Fig. A8. Socio-economic quadrants in education levels.

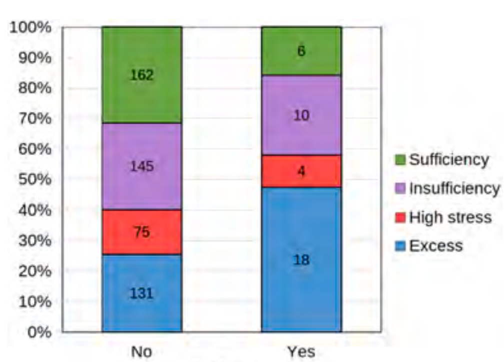

Fig. A9. Socio-economic quadrants in students and non-students.

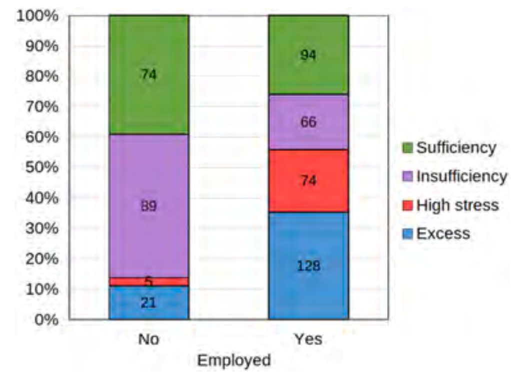

Fig. A10. Socio-economic quadrants in the employed and not employed.

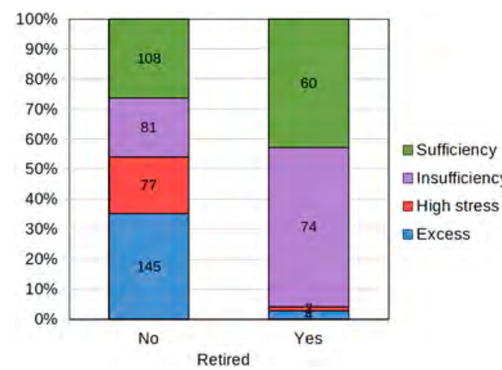

Fig. A11. Socio-economic quadrants in retired vs. not retired participants.

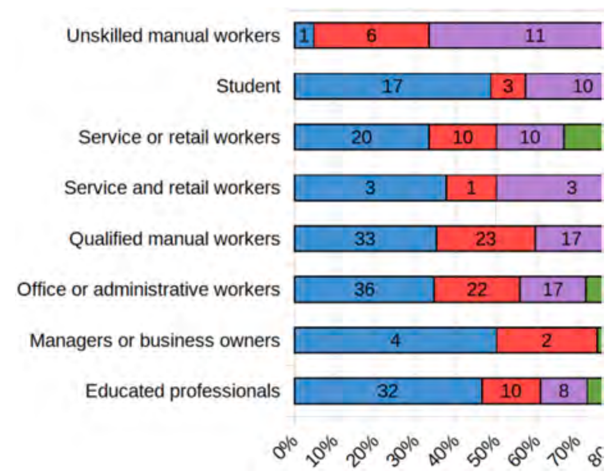

Fig. A12. Social-ecological quadrants in job types. A subsample of employees and students ($N = 399$).

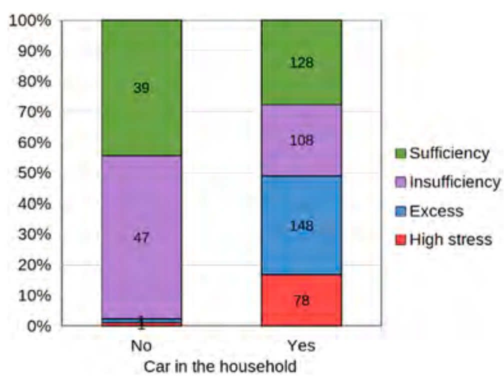

Fig. A16. Social-ecological quadrants in households with and without a car.

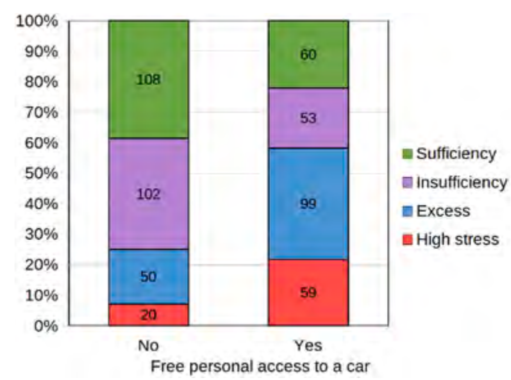

Fig. A17. Social-ecological quadrants in people with free access to a car or without it.

Table A2
Logistic regression results predicting membership in the groups of interest against the rest of the sample, performed on the whole sample used in the study. Provided coefficients are exponentiated (i.e., they represent odds ratios and their standards errors).

	Low emissions	High satisfaction	Sufficiency	Insufficiency	Excess	High stress
(Intercept)	3417.217***	1.491	4.303**	2.373	0.000***	0.001***
	(3356.001)	(0.748)	(2.350)	(1.355)	(0.000)	(0.001)
Man vs. Woman	0.581*	1.401	1.094	0.486**	1.358	1.622
	(0.140)	(0.294)	(0.245)	(0.118)	(0.336)	(0.486)
Kids in the household vs. No kids	0.705	0.955	0.618	1.350	2.242*	0.734
	(0.209)	(0.254)	(0.186)	(0.416)	(0.705)	(0.261)
Employed vs. Other	0.089***	1.231	0.857	0.367**	6.632**	19.088***
	(0.049)	(0.409)	(0.293)	(0.127)	(4.493)	(16.297)
Student vs. Other	0.012***	2.084	0.324+	0.330*	106.008***	11.188*
	(0.010)	(1.059)	(0.189)	(0.185)	(96.466)	(11.961)
Equivalised household income	0.817*	1.118	0.963	0.845*	1.205*	1.031
	(0.067)	(0.080)	(0.074)	(0.072)	(0.101)	(0.101)
Level of car access	0.398***	0.897	0.776	0.974	2.489*	1.702
	(0.111)	(0.161)	(0.142)	(0.189)	(0.897)	(0.571)
Ability to drive a car	0.277**	1.822+	0.581	0.756	11.042***	0.648
	(0.117)	(0.596)	(0.192)	(0.264)	(6.662)	(0.340)
Ability to cycle	1.941+	1.002	1.554	1.351	0.644	0.629
	(0.724)	(0.299)	(0.489)	(0.460)	(0.248)	(0.284)
Ability to haul an Uber, Bolt, etc.	0.518+	0.941	0.819	0.794	1.670	1.270
	(0.187)	(0.290)	(0.260)	(0.276)	(0.648)	(0.581)
Ability to rent an e-scooter or a bike	0.755	1.557	1.140	0.611	1.715	0.736
	(0.241)	(0.453)	(0.339)	(0.207)	(0.569)	(0.298)
Ability to buy an appropriate PT ticket	0.635	0.876	0.664	0.842	1.237	1.336
	(0.232)	(0.246)	(0.200)	(0.260)	(0.470)	(0.635)
Mobility disability level	1.040	0.847	0.578*	1.538	1.864	0.315+
	(0.390)	(0.206)	(0.157)	(0.404)	(0.758)	(0.199)
Needs: Healthcare	0.815	0.971	0.954	0.950	1.147	1.162
	(0.133)	(0.121)	(0.125)	(0.133)	(0.191)	(0.218)
Needs: Being mobile at work	1.093	0.629***	0.770+	1.422*	0.717*	1.303+
	(0.150)	(0.077)	(0.109)	(0.196)	(0.105)	(0.198)
Needs: Visiting to care for someone	1.249	0.704**	0.937	1.371*	0.638*	1.177
	(0.213)	(0.096)	(0.137)	(0.205)	(0.118)	(0.230)
Needs: Errands	0.795*	0.954	0.813*	0.997	1.138	1.184
	(0.087)	(0.095)	(0.085)	(0.117)	(0.128)	(0.166)
Needs: Escort a child or dependent person	1.016	1.437***	1.390**	0.671***	0.993	0.884
	(0.116)	(0.150)	(0.154)	(0.081)	(0.117)	(0.126)
Distance to the city centre	0.925***	0.961**	0.940***	0.992	1.017	1.082***
	(0.016)	(0.013)	(0.016)	(0.016)	(0.016)	(0.020)
N	521	521	521	521	521	521
AIC	495	645	594	529	471	369
Tjur R2	0.403	0.186	0.145	0.227	0.305	0.225
Log.Lik.	−228	−304	−278	−246	−216	−165

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table A3
Logistic regression results predicting membership in the groups of interest against the rest of the sample, performed on participants reporting being employed or studying. Provided coefficients are exponentiated (i.e., they represent odds ratios and their standards errors).

	Low emissions	High satisfaction	Sufficiency	Insufficiency	Excess	High stress
(Intercept)	278.695*** (291.332)	23.783*** (22.290)	179.028*** (205.493)	0.221 (0.245)	0.007*** (0.008)	0.005*** (0.006)
Man vs. Woman	0.669 (0.174)	1.561 (0.424)	1.388 (0.441)	0.386** (0.126)	1.215 (0.330)	1.551 (0.509)
Kids in the household vs. No kids	0.725 (0.230)	0.815 (0.254)	0.402* (0.159)	1.730 (0.653)	1.993* (0.651)	0.794 (0.292)
Equivalised household income	0.814* (0.072)	0.980 (0.087)	0.800* (0.086)	0.921 (0.098)	1.132 (0.102)	1.112 (0.116)
Level of car access	0.414** (0.116)	0.460** (0.129)	0.271*** (0.077)	1.734+ (0.572)	2.342* (0.839)	1.718 (0.600)
Ability to drive a car	0.297** (0.131)	1.949 (0.838)	0.326* (0.150)	0.895 (0.427)	10.278*** (6.302)	0.506 (0.279)
Ability to cycle	2.132+ (0.859)	1.173 (0.457)	2.120 (0.990)	1.199 (0.552)	0.574 (0.231)	0.641 (0.315)
Ability to haul an Uber, Bolt, etc.	0.457* (0.177)	0.763 (0.294)	0.581 (0.253)	0.920 (0.417)	1.701 (0.683)	1.595 (0.794)
Ability to rent an e-scooter or a bike	0.766 (0.253)	2.078* (0.718)	1.377 (0.531)	0.454+ (0.185)	1.644 (0.555)	0.673 (0.288)
Ability to buy an appropriate PT ticket	0.587 (0.228)	0.915 (0.347)	0.775 (0.363)	0.693 (0.302)	1.280 (0.503)	1.499 (0.763)
Mobility disability level	1.324 (0.542)	1.393 (0.547)	0.968 (0.484)	1.550 (0.684)	1.455 (0.614)	0.262+ (0.182)
Needs: Healthcare	0.845 (0.148)	0.851 (0.148)	0.791 (0.167)	1.104 (0.238)	1.088 (0.191)	1.188 (0.236)
Needs: Being mobile at work	0.964 (0.142)	0.684** (0.096)	0.769 (0.149)	1.191 (0.200)	0.783 (0.118)	1.383* (0.218)
Needs: Visiting to care for someone	1.405+ (0.259)	0.592** (0.107)	0.940 (0.207)	1.586* (0.334)	0.552** (0.108)	1.173 (0.241)
Needs: Errands	0.763* (0.089)	0.887 (0.110)	0.670** (0.095)	1.009 (0.151)	1.178 (0.139)	1.178 (0.177)
Needs: Escort a child or dependent person	0.993 (0.121)	1.605*** (0.213)	1.647** (0.256)	0.552*** (0.091)	1.023 (0.127)	0.910 (0.137)
Office workers	1.127 (0.423)	0.593 (0.236)	0.945 (0.409)	1.243 (0.627)	0.586 (0.214)	1.762 (0.848)
Qualified manual workers	0.631 (0.272)	0.415* (0.182)	0.445 (0.228)	1.335 (0.731)	0.795 (0.335)	2.695+ (1.384)
Service or retail workers	1.436 (0.583)	0.452+ (0.197)	0.927 (0.434)	2.162 (1.175)	0.494+ (0.203)	1.753 (0.940)
Students	0.133** (0.089)	0.375 (0.226)	0.047*** (0.039)	2.579 (1.886)	9.375** (6.682)	1.311 (1.109)
Unskilled manual workers	2.203 (1.462)	0.092** (0.067)	0.235 (0.212)	8.439** (6.088)	0.146+ (0.163)	2.039 (1.474)
Distance to the city centre	0.922*** (0.017)	0.961* (0.016)	0.914*** (0.021)	0.974 (0.021)	1.022 (0.018)	1.077*** (0.021)
N	388	388	388	388	388	388
AIC	460	456	364	352	450	349
Tjur R2	0.265	0.248	0.309	0.165	0.231	0.215
Log.Lik.	−208	−206	−160	−154	−203	−153

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table A4
Emission coefficients of travel modes and vehicle types used for estimating GHG emissions associated with travel activity.

Travel mode	Vehicle type	Emission coefficient	Fuel use	Electric energy use	Average load	Sources and assumptions
		[kg CO_2 / pkm]	[l / 100 km]	[kWh / 100 km]	[pax]	
Private car	Gasoline ICEV	0.164	7.16		1.64	Fuel and energy use from survey;
	Diesel ICEV	0.197	7.08			Fuel carbon intensity from Prussi et al. (2020);
	LPG ICEV	0.116	7.64			Share of electric drive in PHEV: 50 %;
	HEV	0.145	6.65			Electricity carbon intensity from KOBiZE (2022) adjusted using Scarlat et al. (2022) method
	PHEV	0.142	6.68	18.2		
	BEV	0.092		17.3		
	Weighted average	0.169				Weighted by travel distance
Tram or bus	Diesel bus	0.081	42		18	Fuel and energy use and average load based on data provided by operators;
	Electric bus	0.067		152		Share of electric buses in bus performance: 8 %;
	Tram	0.064		289	36	Share of buses in transport performance: 50 %;
	Weighted average	0.072				Electricity carbon intensity from KOBiZE (2022) adjusted using Scarlat et al. (2022) method;
Urban train	Electric	0.084		740	70	Average load based on data provided by operators; Electricity carbon intensity from KOBiZE (2022) adjusted using Scarlat et al. (2022) method;
E-bike or e-scooter	E-bike	0.005		0.6	1	Share of e-bikes: 50 %; Electricity carbon intensity from KOBiZE (2022) adjusted using Scarlat et al. (2022) method; Electric energy use from Weiss et al. (2020)
	E-scooter	0.011		1.4		
	Weighted average	0.008				

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compenvurbsys.2024.102196.

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