Transportation Research Part D 149 (2025) 105072

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

E-bikes' impact on job accessibility and equity in São Paulo and Rio☆

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ARTICLE INFO

Keywords:
Cycling
Access
Transport inequality
Physical effort
Labor market

ABSTRACT

Despite their ability to address challenges associated with conventional cycling, the potential of e-bikes to improve accessibility to opportunities and equity remains largely unexplored. This study addresses this gap by evaluating e-bikes' impacts on job accessibility and spatial equity in São Paulo and Rio de Janeiro, Brazil's two largest cities. We calculated cumulative accessibility using different thresholds of travel time and physical effort, which were modeled using GPS data from a bike-sharing system. Results reveal that e-bikes significantly enhance job accessibility compared to conventional bicycles, particularly for longer cycling trips and trips in hilly areas. However, accessibility gaps persist in peripheral neighborhoods. Equity analyses using Moran's Index and the Concentration Index demonstrate that e-bikes reduce spatial disparities, benefiting lower-income groups, though absolute inequalities persist. Urban topography and structure critically shape outcomes, meaning that the impact of e-bikes varies both between and within cities.

1. Introduction

Accessibility studies in the literature have primarily focused on cars and public transport, paying less attention to micro-mobility, including bicycles (Heinen et al., 2010; Lee et al., 2017). In recent years, however, there is an increasing interest in proximity-based accessibility and measuring accessibility by active modes within the context of the 15-minute city (Bruno et al., 2024; Guzman et al., 2024). A particularly under-researched area is the potential of e-bikes to improve accessibility to opportunities and equity, despite their ability to address challenges associated with conventional cycling (Gehrke et al., 2020; Pritchard et al., 2019a,b). A notable exception is Knap et al. (2023), who examined e-bike penetration within the X-minute city framework. However, their approach relied on simplified adjustments of cycling speeds across urban contexts, overlooking the complexities of real-world e-bike usage and lacking a comprehensive equity analysis. Similarly, Ballo et al. (2023) provided qualitative insights into the potential impacts of e-bikes on accessibility and equity but did not present empirical measurements to substantiate their scenarios.

The impact of e-bikes on accessibility is primarily driven by two critical factors: the reduction in travel time and the decrease in physical effort required for cycling. Regarding travel time, e-bikes enable users to cover greater distances within the same timeframe, thereby expanding their access to opportunities such as jobs. The second factor, the reduction in physical effort, is equally important.

☆ This article is part of a special issue entitled: 'Accessibility Equity' published in Transportation Research Part D.

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https://doi.org/10.1016/j.trd.2025.105072
Received 30 April 2025; Received in revised form 21 October 2025; Accepted 21 October 2025
Available online 30 October 2025
1361-9209/

Traditional cycling, being a human-powered mode of transport, typically limits trip lengths to around 5 km, though this can vary based on individual fitness levels, infrastructure quality, and other factors. E-bikes mitigate this limitation by significantly decreasing the physical exertion required, potentially encouraging users to cycle longer distances. In the Netherlands, a global leader in e-bike use where about 40 % of cycling kilometers are currently made by e-bikes, the average conventional bicycle trip distance was 3.3 km in 2023, whereas e-bike trips were almost 70 % longer, at 5.6 km (de Haas and Kolkowski, 2023). A shift from conventional bikes to e-bikes could profoundly impact accessibility, particularly for individuals who may have previously been deterred by the physical demands of conventional cycling. It could also enhance equity by enabling low-income populations to access a greater number of job opportunities.

Although physical effort clearly plays a significant role in accessibility, to the authors' knowledge, no prior studies have incorporated it as an impedance factor in cycling accessibility research. Páez et al. (2020), for instance, compared distance, time, and metabolic energy cost functions in walking accessibility to water in central Kenya. They found that relying solely on distance or time might obscure critical barriers, particularly for vulnerable groups, and argued for the inclusion of metabolic energy to achieve a more equitable assessment in infrastructure-poor regions.

Beyond walking, a few studies have incorporated physical effort metrics in cycling-related analyses, though not directly within an accessibility framework. Liu and Suzuki (2019) introduced indices to assess e-bike applicability by comparing service areas to those of public transit and conventional bicycles, factoring in travel time and energy expenditure. Raffler et al. (2019) developed a method to assess cycling investment effectiveness by analyzing body energy, and Iseki and Tingstrom (2014) proposed a novel bikeshed analysis integrating topography, connectivity, and energy consumption. While these studies provide useful perspectives on effort and energy use in cycling, none apply these concepts to accessibility analysis.

These advantages are particularly relevant for accessing employment opportunities. Bertaud (2018) argues that cities primarily function as labor markets, where people come together to exchange skills, goods, and services. Hence, the efficiency of a city depends on how easily residents can access employment opportunities, as this directly influences productivity, economic growth, and social equity. Consequently, poor accessibility leads to inefficient labor allocation, economic stagnation, and exacerbated social inequities. By enabling longer trips and reducing physical effort, e-bikes could help mitigate these disparities, making it possible to reach job centers that would otherwise be difficult to access.

The benefits of accessibility, also for cyclists, are not equally distributed among areas and population segments. Measuring equity can be challenging, as it can be measured in many different ways. In the transport literature, it is typically addressed through egalitarian and sufficientarian approaches (Karner et al., 2024; van Wee, 2022). The egalitarian viewpoint advocates for equalizing opportunities despite differences in circumstances (Karner et al., 2024). In contrast, the sufficientarian approach argues that the primary concern is whether some individuals have levels of accessibility that are 'too low' (Cooper and Vanoutrive, 2022). The egalitarian approach is the most commonly used in the literature and is typically assessed using statistical distribution measures such as the Gini coefficient (Ben-Elia and Benenson, 2019; Tomasiello et al., 2020; Pritchard et al., 2019b). Despite its widespread use, Karner et al. (2024) argue that the Gini coefficient fails to capture vertical equity, as it does not adequately differentiate between groups based on their specific needs and capabilities. They suggest alternative approaches such as the Theil Index, Palma Ratio, and Concentration Index. Another method to assess equity is the bivariate Local Moran's I (Bittencourt & Giannotti, 2021; Knap et al., 2023). This method can be used to analyze the spatial correlation between accessibility and a sociodemographic variable, such as income, identifying statistically significant clusters of high-high observations (i.e., both the metric value and the sociodemographic indicator are high), low-low observations, as well as high-low and low–high observations (Bittencourt et al., 2021; Knap et al., 2023).

This study addresses three key research gaps: (1) the limited empirical evidence on how e-bikes influence accessibility to jobs; (2) the lack of accessibility models that incorporate travel time and physical effort as an impedance factor; and (3) the insufficient understanding of how e-bikes affect spatial equity across income groups and urban contexts.

To address these gaps, we examine how electric bicycles influence job accessibility and spatial equity in São Paulo and Rio de Janeiro, Brazil. Travel speeds and physical effort were estimated as impedance factors using large-scale GPS-based data. Accessibility is assessed across four travel time thresholds and four physical effort thresholds. Spatial equity is evaluated using Moran's Index and the Concentration Index (CI). The cities of São Paulo and Rio de Janeiro were selected due to their large populations, high levels of socioeconomic inequality, and distinct urban structures and topographies that present varying mobility challenges.

Accordingly, this paper seeks to answer the following research questions: (1) To what extent do e-bikes enhance job accessibility compared to conventional bicycles in São Paulo and Rio de Janeiro? (2) How do these accessibility gains vary spatially across different socioeconomic groups and urban structures? (3) Can e-bikes help reduce spatial equity gaps in job access?

Table 1
Key urban indicators for São Paulo and Rio de Janeiro.

	São Paulo	Rio de Janeiro
Population	11.451.999	6.211.223
Population density (inhabitants/km^2)	7.528,26	5.174,60
Average monthly wage of formal workers (in minimum wages)	4,4	3,9
Urban area (km^2)	914,56	640,34

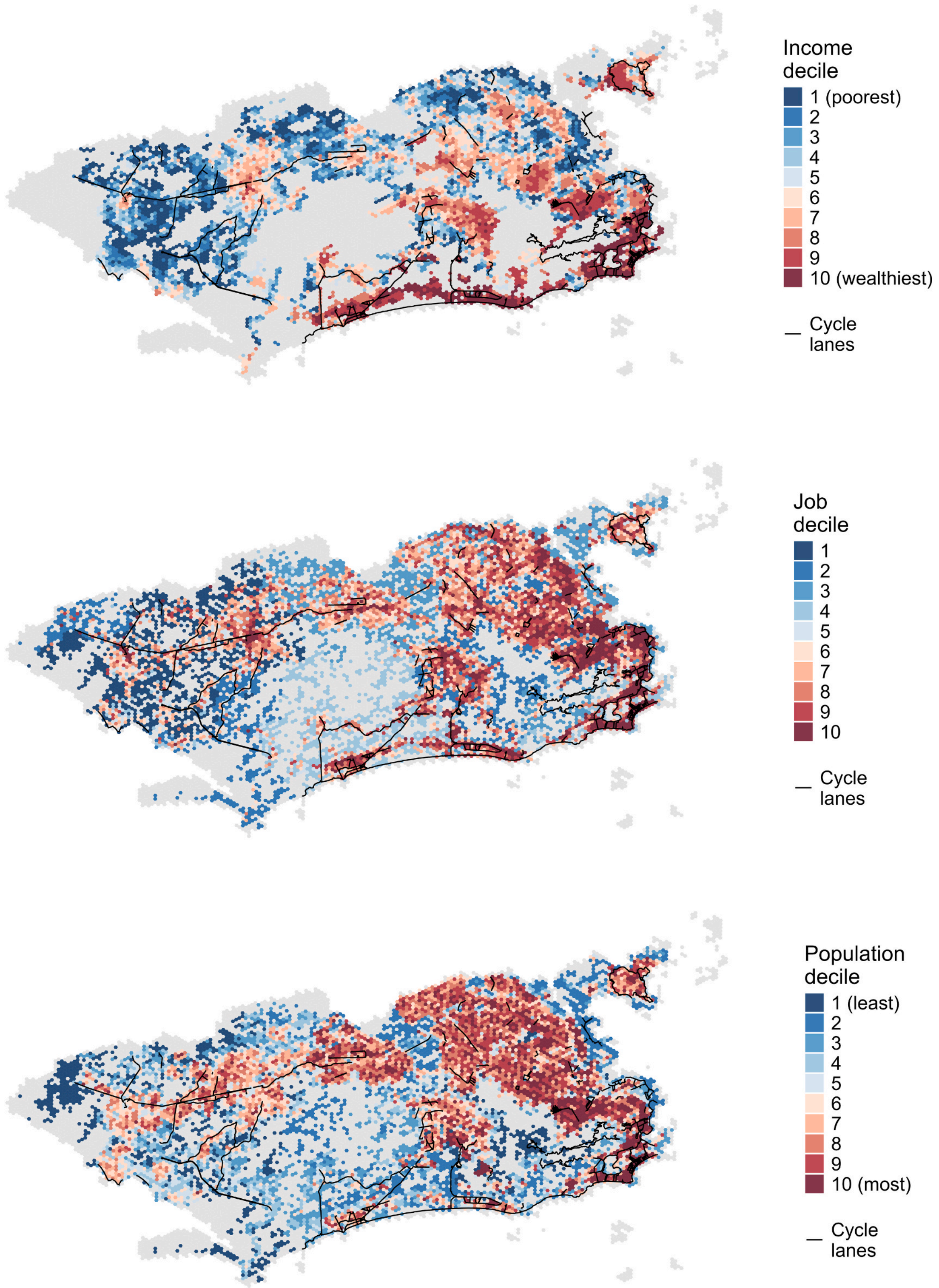

Fig. 1. Distribution of income, population, formal jobs and cycle lanes in Rio de Janeiro.

2. Methodology

2.1. Study area

This study focuses on the urban areas of São Paulo and Rio de Janeiro, two of the largest cities in Brazil. These cities exhibit diverse

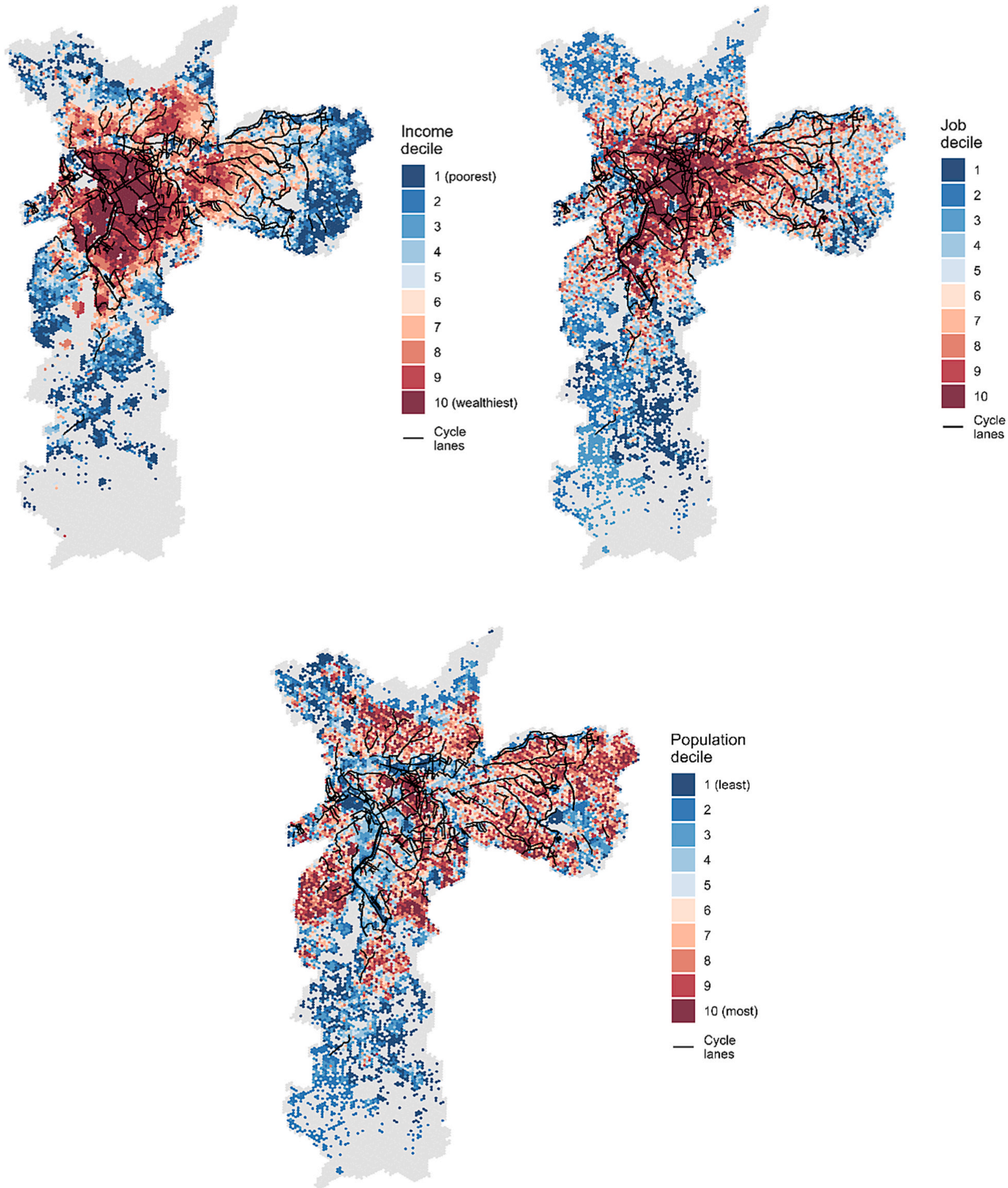

Fig. 2. Distribution of income, population, formal jobs and cycle lanes in São Paulo.

socioeconomic characteristics, varying levels of cycling infrastructure, and distinct urban mobility challenges. Table 1 summarizes key indicators for both cities (Instituto Brasileiro de Geografia e Estatística, 2022).

As shown in Table 1, São Paulo has a significantly larger population and urban area than Rio de Janeiro, with a higher population density and slightly higher average wages among formal workers. These differences reflect the greater economic scale and spatial complexity of São Paulo's urban environment. Figs. 1 and 2 illustrate the spatial distribution of income, formal jobs, population, and cycle lanes in Rio de Janeiro and São Paulo, respectively.

In Rio de Janeiro, higher-income populations are primarily concentrated along the southern coastal zones, while lower-income groups are more prevalent in the North and West Zones. Meanwhile, formal employment is highly centralized in the central business district (Centro) and its adjacent areas, reinforcing economic concentration in the city's core. Cycling infrastructure is mainly concentrated along the coast, particularly in the South Zone, but it does not form a cohesive network across the city.

In São Paulo, higher-income groups are primarily concentrated in the central-western and southwestern regions, while lower-income populations are more prevalent in the far southern and eastern peripheries. Population density is more dispersed, with higher counts appearing in central and eastern areas, though not necessarily aligning with the wealthiest neighborhoods. Meanwhile, formal employment is heavily concentrated in the central core, where the highest job counts significantly overlap with high-income areas, reinforcing the city's pattern of economic centralization. Although larger than Rio's, the cycling infrastructure is unevenly distributed and fragmented, with bike lanes more commonly found along select arterial roads. While some wealthier neighborhoods in the central-western region benefit from better access to cycling facilities, much of the peripheral urban area remains underserved. The overall network lacks connectivity, functioning more as isolated segments than an integrated system.

2.2. Data

The data used in this study come from multiple sources. Network data were extracted from OpenStreetMap using the OSMnx package (Boeing, 2017). Cycling infrastructure data for São Paulo were sourced from the Mapa de Infraestrutura Cicloviária, provided by the (Companhia de Engenharia de Tráfego de São Paulo, 2025), while those for Rio de Janeiro came from the municipal government (Prefeitura do Rio de Janeiro, 2022).

GPS data for modeling cycling speeds were obtained from Tembici, a leading bikesharing operator in Brazil, through an agreement with the University of São Paulo. These data include trips recorded between January and July 2023. Tembici operates a network of docking stations where users can rent and return bicycles, including newly introduced e-bikes with pedal-assist technology, enabling speeds of up to 25 km/h.

Elevation data were retrieved from the NASA Shuttle Radar Topography Mission via the OpenTopography DEM downloader plugin in QGIS (Win, 2024), with slope values computed using OSMnx in Python (Boeing, 2017).

Socioeconomic data and formal job opportunities for São Paulo and Rio de Janeiro were obtained from the aopdata package in R (Pereira et al., 2022). The datasets, corresponding to 2019—the most recent available year at the time of this study—are spatially aggregated using a hexagonal grid indexed by the H3 geospatial system, originally developed by Uber (Brodsky, 2018). Each hexagonal cell covers approximately 0.11 km^2, an area comparable to a city block, allowing for high-resolution spatial analysis.

2.3. Accessibility methodology

Accessibility has evolved in meaning over time. Hansen (1959) first defined it as the potential for interaction opportunities, while Geurs and van Wee (2004) described it as the extent to which land-use and transport systems enable individuals or groups to reach destinations via one or multiple transport modes. (Wu and Levinson, 2020) summarize it as the ease of reaching valued destinations. Building on this definition, accessibility is measured by travel impedance and reachable opportunities, varying based on transport mode, research focus, and data availability. Its outcomes are shaped by population distribution, economic activity, individual characteristics, and transport network performance (Geurs and van Wee, 2004; Pereira and Herszenhut, 2023; Wu and Levinson, 2020).

Although accessibility can be estimated in many ways (infrastructure-based, location-based, person-based, and utility-based measures), with some approaches also taking into account decay functions and competition, we opted to estimate accessibility using the cumulative opportunity measure, which employs a binary impedance function to count the number of opportunities within a certain travel time, distance, or cost from a reference point (Barboza et al., 2021; Geurs and van Wee, 2004). This is one of the most common indicators in accessibility analyses (Boisjoly and El-Geneidy, 2017; Papa et al., 2016; Pereira and Herszenhut, 2023), mostly because it requires little data and is easy to calculate and communicate. It can be defined as shown in Eq. (1):

$$A_i = \sum O_j \cdot f_t(c_{ij}), f_t(c_{ij}) = \begin{cases} 1 if c_{ij} \leq t \\ 0 if c_{ij} > t \end{cases} \tag{1}$$

In which A_i is the accessibility at point i; O_j represents the number of opportunities (like jobs, businesses, services, etc.) at location j; c_{ij} is the travel cost between i e j (time, distance, cost, or a combination of these elements); and the function $f_t(c_{ij})$ returns 1.0 if c_{ij} is less than or equal to a defined cost (t) and zero if it exceeds this threshold. The limiting cost t serves as a calibration parameter and largely depends on users' tolerance for travel costs and the transport mode (Boisjoly and El-Geneidy, 2017; Pereira, 2019). It is also important to note that the accessibility calculations focus solely on travel time and physical effort; the monetary costs associated with acquiring and maintaining an e-bike were considered outside the scope of this specific analysis. We estimated cumulative opportunities for various thresholds for both travel time and physical effort as part of a sensitivity analysis.

For the travel time thresholds, we selected 15, 30, 45, and 60 min. For conventional bicycles, there is general consensus that the typical range is around 5 km, with most commuting trips falling between 15 and 30 min in duration (Banerjee et al., 2022; Mohamed et al., 2024; Pritchard et al., 2019b). In São Paulo, the 2023 OD survey reports that the mean cycling trip duration is 21 min, with the third quartile at 30 min. E-bikes have the potential to extend this range by overcoming physical barriers and may even substitute for car trips over moderate distances (Banerjee et al., 2022; de Haas and Kolkowski, 2023; Rybels et al., 2024). Hence, by varying the travel time thresholds in 15-minute increments, our goal is to capture a comprehensive range of cycling behaviors for both conventional and electric bicycles, and assess how accessibility outcomes compare across these scenarios. As for physical effort, we represent it as the equivalent energy expenditure of cycling on flat terrain for 15, 30, 45, and 60 min.

We opted not to use gravity-based accessibility measures as results of Cumulative Measures are easier to interpret and typically strongly correlated to gravity-based measures (Kapatsila et al., 2023; Palacios and El-geneidy, 2022). Moreover, gravity-based measures may underestimate accessibility inequalities as trips taken by different groups can be mistakenly associated with willingness to travel (Giannotti et al., 2022). Moreover, we did not include measures including competition for opportunities. Mismatches between the spatial distribution of jobs and workers at short commuting distances are considered less relevant in Brazilian megacities, with relatively long commuting distances, compared to for example Dutch cities (Pritchard et al., 2019a; Knap et al., 2023). All the accessibility metrics were calculated using the *Accessibility* R package, provided by Pereira et al. (2024).

2.3.1. Travel time estimation

Cycling travel times were estimated using a linear mixed-effects speed model originally developed for São Paulo by Louro et al., (2025) (*unpublished results*) and subsequently extended to Rio de Janeiro using the same methodology. This model is based on GPS data from the Tembici bike-sharing system. For the accessibility calculations in this study, we utilized the model's fixed effects, which account for factors including road characteristics (e.g., slope, length), time of day, cycling infrastructure availability, among others.

The GPS data used to build the model were preprocessed by the bike-sharing provider, who classified each trip into three categories (*Utilitarian*, *Leisure*, and *Service*) through internal filtering criteria. These classifications, recorded in the variable *perfil_viagem* ("trip_profile"), were based on proprietary algorithms that, for example, excluded journeys with significant stops (e.g., stopping to deliver food) or round trips to nearby stations (e.g., short tours within parks or recreational areas). As the specific thresholds applied by the provider were not disclosed, we relied on this *perfil_viagem* variable to include only trips labeled as *Utilitarian*. Although the company did not provide detailed documentation of this procedure, Fortes et al. (2024) describe a similar classification process in their analysis of bike-sharing data across five Brazilian cities, offering a useful reference for researchers working with similar datasets. To apply the speed model consistently across the study areas, we used standardized parameters representing a baseline scenario—male gender, a weekday (Wednesday), and the morning peak period. Consequently, the resulting travel time and accessibility estimates in this study reflect the conditions defined by this baseline scenario.

It is also crucial to acknowledge that the speed model is derived from bike-sharing users. This user group may differ in demographics (e.g., age, income), cycling experience, and travel behavior compared to the general population of potential cyclists, which represents a limitation when generalizing the derived travel times and effort estimations. Specifically, Tembici users are more likely to be younger, more tech-savvy, and taking shorter trips within central areas. As a result, the model may underrepresent longer trips or those taken by low-income individuals who would rely on private e-bikes in peripheral areas. This could lead to an underestimation of travel time and effort for certain population groups, and should be taken into account when interpreting the results, especially in equity-focused analyses.

2.3.2. Physical effort estimation

The physical effort required for cycling was estimated using a model that calculates the power needed to traverse each road segment, based on road slope, cyclist speed, and bicycle type. The first step in computing physical effort for each edge was to determine the power applied by the cyclist, which can be calculated using Eq. (2), as proposed by (Wilson and Schmidt, 2020):

$$P = [C_a \bullet V^2 + m \bullet g \bullet (s + C_r)] \bullet V \tag{2}$$

In which P is the power needed for movement along the road segment; C_a is the aerodynamic coefficient; C_r is the roller resistance coefficient; m is the mass of a cyclist and a bicycle combined (kg); g is the acceleration of gravity (m/s^2); s is the slope of the road (m/m); and V is the bicycle speed (m/s).

We adopted an aerodynamic coefficient (Ca) of 0.3 for seated cycling and a rolling resistance coefficient (Cr) of 0.0032 for a typical bicycle tire on smooth asphalt, following the findings of Martin et al. (1998). For the combined cyclist and bicycle mass, we assume two cases: 90 kg (75 kg cyclist with a 15 kg bicycle) and 95 kg (75 kg cyclist with a 20 kg bicycle). The cyclist's speed (V) used was the same one from the travel time estimation. To assess the sensitivity of the results to body mass, we evaluated how power demand changes with different weights (the combination of the user's weight, plus the bicycle). At a speed of 15 km/h, each additional kilogram increases power demand by approximately 0.4 percent on flat terrain and by over 1 percent on an 8 percent slope. Heavier riders or bicycles therefore require more physical effort, particularly on inclined routes. These differences can lead to unequal physical burdens among users and reduce the number of destinations that can be reached for a given amount of energy, which may limit access and raise equity concerns in active transportation.

Next, to assess the power of the cyclist on the electric bicycle, the assistance ratio between the power of the electric motor and the power of the cyclist must be considered. Liu and Suzuki (2019) proposed the use of the assistance index a, as presented in Eq. (3):

$$a = \begin{cases} 1.4 : 0 \leq V \leq 10 \\ 1.4 - 0.1(V - 10) : V > 10 \end{cases} \quad (3)$$

This formulation reflects the typical behavior of pedal-assist systems, in which the motor provides a constant level of support at low speeds (up to 10 km/h) to aid acceleration and stability, and gradually reduces assistance as speed increases. It should be noted that the specific assistance profile may vary across e-bike models or control algorithms; however, the general principle of decreasing assistance with increasing speed remains consistent among most systems. After determining the assistance ratio, the power required to pedal the e-bike can be calculated by Eq. (4):

$$P_{be} = \frac{P_b}{(1 + a)} \quad (4)$$

where P_{be} is the power of e-bikes; P_b is the required power for the conventional bicycle, and a is the assistance ratio. Work is calculated as in Eq. (5):

$$W = Max(0, P.\frac{l}{V}) \quad (5)$$

where P is either the power for bikes or e-bikes. Since the user does not recover energy, we constrain work as non-negative, setting possible negative values to zero.

It is important to note two key limitations. First, the physical effort calculations use parameters representing an average cyclist, thereby simplifying the influence of individual variations such as age, weight, fitness level, and cycling style on actual exertion. Second, the e-bike model assumes a typical pedal-assist system (pedelec) with proportional assistance, aligning with common designs. Consequently, the presented results reflect these specific assumptions, and deviations in cyclist profiles or e-bike characteristics could grant different results.

2.4. Equity methodology

To assess spatial equity, we employed two complementary methods: the Concentration Index (CI) and bivariate Local Moran's I. First, we applied the traditional CI to measure the extent to which accessibility inequalities are systematically associated with income. The CI evaluates inequality by comparing the cumulative distribution of accessibility with the income-ordered population distribution (Karner et al., 2024). The value of the CI corresponds to twice the area between the concentration curve and the line of equality (the 45-degree line); it takes negative (positive) values when the curve lies above (below) this line. The index ranges from -1 to $+1$, where negative values indicate better accessibility for lower-income populations and positive values indicate a pro-rich distribution.

We computed CI values separately for accessibility by bike, e-bike, and e-bike gain (%) to quantify and compare disparities across transport modes. The CI was calculated using the accessibility R package provided by Pereira et al. (2024). Generally, the calculation method of the concentration index is as presented in Eq. (6) (Shen et al., 2020):

$$C = \frac{2}{\mu}.cov(h, r) \quad (6)$$

where h is the accessibility measure (e.g., number of jobs accessible), μ is its mean, and r is the fractional rank of income. We calculated CI values separately for accessibility by bike, e-bike, and e-bike gain (%) to compare inequalities across different transport modes.

In addition, we used an adjusted version of Local Moran's I, known as bivariate Local Moran's I (Anselin et al., 2002.; Knap et al., 2023; Lee, 2001; Weng et al., 2019), to analyze the spatial relationships between the calculated accessibility metrics and income. This method identifies statistically significant spatial clusters, including high-high (H-H), where both accessibility and income are high, low-low (L-L), high-low (H-L), and low–high (L-H) observations. The statistic is defined as shown in Eq. (7):

$$I_i^B = c.x_i.\sum\nolimits_j w_{ij} y_j \quad (7)$$

where x_i is the standardized income at location i, y_j is the standardized accessibility metric at neighboring locations j, w_{ij} is a spatial weight representing the relationship between location i and its neighbors j and c is A scaling constant that normalizes the statistic.

The analysis was conducted using the spdep R package (Bivand and Wong, 2018), which implements bivariate Local Moran's I and includes Monte Carlo permutation tests (999 simulations) to assess statistical significance. To define spatial relationships, we constructed a Queen contiguity spatial weights matrix, which considers two areas as neighbors if they share either a border or a vertex. This approach was chosen due to the irregular yet contiguous configuration of the urban spatial units in the study area, allowing for a more inclusive representation of spatial dependence. Minor topological issues were addressed by applying a snapping tolerance of 100 m, and areas with no adjacent neighbors were excluded from the analysis.

Both income and accessibility variables were z-score standardized prior to computing the statistic. To address the issue of multiple testing across spatial units, a Benjamini–Hochberg correction was applied to the resulting p-values, controlling for the false discovery rate (FDR). Only clusters with adjusted $p < 0.05$ were considered statistically significant and subsequently mapped.

3. Results and discussion

The results and discussion are organized into two main sections: accessibility and equity. Each section is divided into travel time and physical effort, with results for São Paulo and Rio presented to enhance comparability.

3.1. Accessibility

3.1.1. Travel time

As a first exploratory analysis, we present Table 2, which compares the population-weighted average percentage of jobs accessible by conventional bicycles and e-bikes in São Paulo and Rio de Janeiro across different travel time thresholds (15, 30, 45, and 60 min). The values represent the share of total jobs accessible within each time threshold, calculated using a population-weighted average as described in Eq. (8):

$$PopulationWeightedAccessibility(\%) = \left(\frac{\sum_i (AccessibleJobs_i xPopulation_i)}{\sum_i Population_i xTotalJobs}\right) x100 \tag{8}$$

where i denotes each spatial unit. Additionally, Table 2 includes the relative percentage gain in accessibility when switching from bicycles to e-bikes.

The results indicate that e-bikes significantly enhance job accessibility compared to conventional bicycles in both cities, with Rio de Janeiro exhibiting the greatest relative benefits. Improvements in Rio consistently exceed those observed in São Paulo across all thresholds, reflecting differences in the spatial structure of the two urban areas. In São Paulo, relative improvements are more uniform, while in Rio de Janeiro, the most substantial gain occurs at the 15-minute threshold, followed by a gradual decline as travel time increases.

Although the relative improvements in job accessibility are most pronounced at shorter travel times, absolute gains become substantially larger as travel time thresholds increase. This suggests that while the proportional impact of e-bikes diminishes over longer trips, their absolute contribution expands markedly due to the significant growth in the number of accessible jobs at extended travel times. These larger absolute gains at higher thresholds underscore the potential of e-bikes to expand the spatial reach of workers. In such contexts, a 45-minute e-bike commute can connect peripheral residents to central employment hubs that are otherwise inaccessible by conventional bicycle.

Next, we show in Fig. 3 the proportion of the population in São Paulo and Rio de Janeiro that can access varying shares of employment opportunities using conventional bicycles and e-bikes across different travel time thresholds.

The results indicate clear differences between the two cities. The first noticeable difference is that in São Paulo, the maximum share of jobs accessible is much higher than in Rio de Janeiro. This suggests that job distribution differs significantly between the two cities, affecting the feasibility of using bicycles for job access. Since São Paulo and Rio de Janeiro are the two largest Brazilian metropolises, it is expected that unimodal bicycle trips alone will not provide access to a large share of jobs. However, the results indicate that São Paulo offers significantly better job accessibility by bike compared to Rio.

Regarding the accessibility gains due to e-bikes, São Paulo shows higher absolute percentages of the population with access to jobs across most thresholds, while Rio de Janeiro experiences more relative improvements following e-bike adoption. At the 15-minute threshold, neither bicycle type provides access to a substantial share of jobs, with the maximum share accessible remaining below 20 %. For reference, in São Paulo, e-bikes enable 7.66 % of the population to access at least 10 % of jobs, compared to 5.38 % with regular bikes. In Rio, this share increases from 2.92 % to 6.81 % with e-bikes. At the 30-minute threshold, the advantages of e-bikes become more substantial. In São Paulo, e-bikes increase the population with access to 10 % of jobs from 26.10 % to 34.85 %, while in Rio, e-bikes expand access from 34.03 % to 48.70 % of the population, a greater relative gain.

The most dramatic differences emerge at longer travel times. At the 45-minute threshold, e-bikes enable 16.21 % of São Paulo's population to access 50 % of jobs, compared to 11.54 % with regular bikes. In Rio, e-bikes enable 8.51 % of the population to access 50 % of jobs, while regular bikes provide no such access. This trend continues at the 60-minute threshold. In São Paulo, e-bikes allow 42.17 % of the population to reach 50 % of jobs, compared to 28.80 % with regular bikes. In Rio de Janeiro, e-bikes increase the population with access to 50 % of jobs from 17.78 % to 31.48 %.

This shows that e-bikes can play a significant role in expanding the share of available jobs for a large portion of the population. Improving job accessibility through e-bikes can help reduce unemployment and underemployment by connecting workers to a wider range of employment opportunities. This is especially relevant for low-income populations who are more likely to be constrained by long, expensive commutes and limited access to private vehicles. By lowering the physical and economic costs of mobility, e-bikes can

Table 2
Comparison of population-weighted shares (%) of jobs accessible by bicycle and e-bike across travel time thresholds in São Paulo and Rio de Janeiro.

	São Paulo			Rio		
Threshold	Bike	E-Bike	Change	Bike	E-Bike	Change
15 min	2.2 %	2.8 %	27.3 %	2.8 %	3.9 %	39.3 %
30 min	9.0 %	11.5 %	27.8 %	9.5 %	12.6 %	32.6 %
45 min	20.2 %	25.6 %	26.7 %	18.4 %	24.0 %	30.4 %
60 min	34.2 %	42.1 %	23.1 %	28.4 %	36.3 %	27.8 %

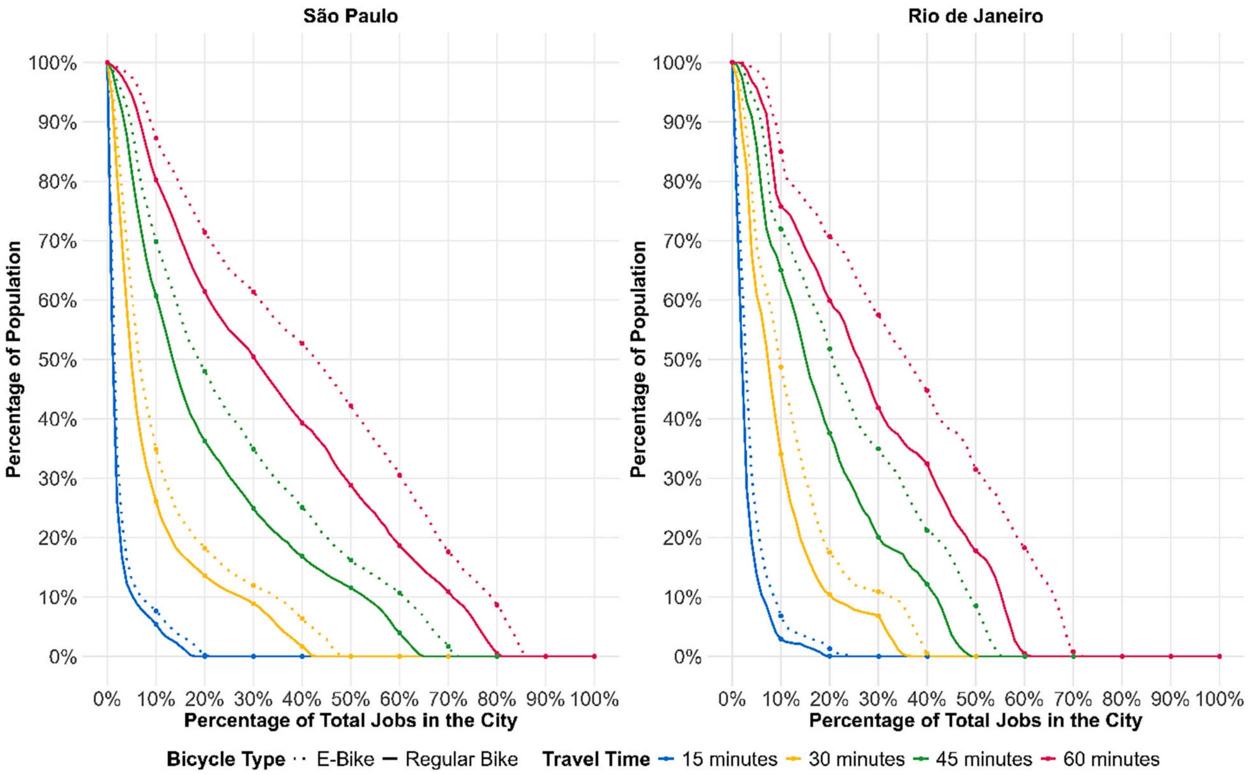

Fig. 3. Percentage of population with access to jobs by regular and electric bicycles in São Paulo and Rio de Janeiro across different travel time thresholds.

contribute to a more efficient labor market, improve job matching, and potentially increase productivity at the city level. Furthermore, by enabling access to a broader job base without requiring major infrastructure investments (when compared to motorized modes), e-bikes offer a cost-effective tool for addressing urban inequality and supporting more balanced economic development across metropolitan areas.

In order to better understand the spatial distribution of job accessibility and further illustrate the disparities observed in the aggregated results, Figs. 4 and 5 show the share of accessibility by both bike types and the gain provided by e-bikes compared to regular bicycles.

In São Paulo (Fig. 4), job accessibility is highly concentrated in central areas, where both regular bicycles and e-bikes provide the greatest access. However, a clear expansion of accessible areas is observed when using e-bikes. Since most jobs in São Paulo are centrally located, the benefits of e-bikes spread in all directions almost equally, except for the 60-minute threshold, where the benefit is more pronounced to the south.

Rio de Janeiro (Fig. 5) exhibits a distinct spatial dynamic. While e-bikes enhance accessibility citywide, the improvements are not as spatially extensive as those observed in São Paulo. This more limited spread is consistent with Rio's complex topography and urban structure. Unlike São Paulo, where accessibility gains radiate outward from the center, Rio's improvements are more concentrated near the CBD, located in the eastern part of the city. Notably, at higher travel time thresholds, areas in the northern region of Rio begin to show increased accessibility, as they gain the ability to reach the CBD. Despite these differences, in both cities, e-bikes substantially enhance job accessibility, particularly in peripheral areas where conventional cycling is less viable due to distance and elevation challenges.

However, despite the overall increase in accessibility, some peripheral areas in both cities continue to show low accessibility levels, even with larger travel time thresholds. In São Paulo, the eastern and southern regions still experience limited job access. Similar results were found for public transport by Boisjoly and El-Geneidy (2017), who observed that peripheral areas located near rapid transit have significantly lower accessibility than central areas with the same infrastructure, likely due to the concentration of employment opportunities in central areas. Pritchard et al. (2019b) also found that bike-and-ride options have the potential to substantially increase job accessibility in São Paulo, but most improvements are concentrated in middle to high income areas with already good accessibility. Peripheral areas, which tend to be the poorest and have the lowest transit accessibility, benefit the least. They also argue that incorporating bicycles as a means of accessing public transport is insufficient to counteract the broader structural factors causing low job accessibility in these regions. This is especially true in São Paulo, where, as in other large metropolitan areas worldwide, long travel distances are a major barrier to accessibility. To effectively improve access in these distant peripheral regions, only high-speed public transport systems are likely to make a significant difference. However, in smaller cities, where travel distances

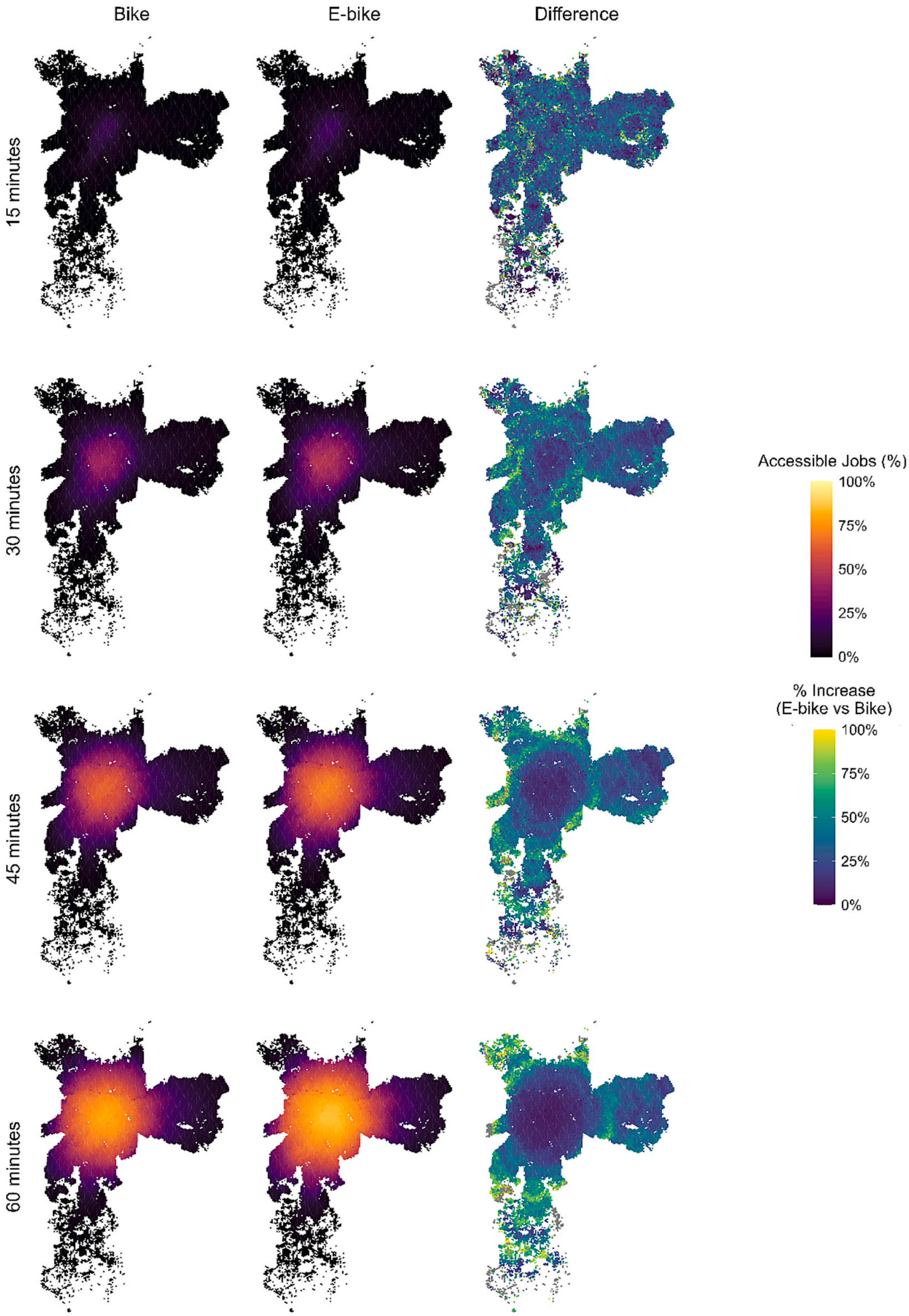

Fig. 4. Accessibility by bikes, e-bikes, and e-bike gain in São Paulo.

are shorter and urban sprawl is less pronounced, e-bikes could have a much greater impact by facilitating access to a larger share of employment opportunities.

Similarly, in Rio de Janeiro, the western areas remain poorly connected, reinforcing existing spatial inequalities. Carneiro et al.

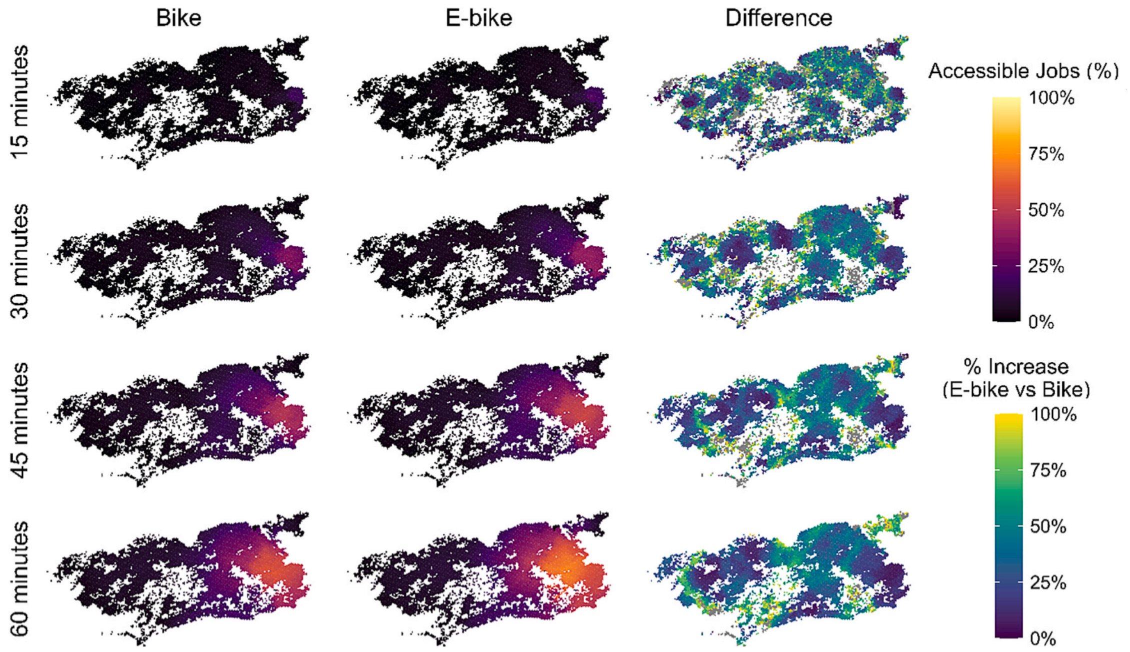

Fig. 5. Accessibility by bikes, e-bikes, and e-bike gain in Rio de Janeiro.

(2019) found similar results, highlighting an unequal distribution of accessibility: the areas farthest from the urban center have lower accessibility due to the high concentration of jobs in the city center and the greater distances between central and peripheral areas. The authors also emphasize the need for investments in public transportation to improve accessibility.

These findings suggest that while e-bikes significantly improve accessibility, they are not a standalone solution and should be complemented by broader transport and infrastructure improvements to address persistent gaps in job access. In large cities where formal job opportunities are primarily concentrated in central areas, as is common in many Latin American cities (Boisjoly and El-Geneidy, 2017), only high-capacity and fast public transport systems such as metro networks can enable people living in more distant neighborhoods to reach a substantial share of jobs within a reasonable travel time. For this reason, expanding high-capacity and fast public transport systems, developing safe and extensive cycling infrastructure, and implementing policies that promote mixed land use and affordable housing near employment centers are essential steps toward achieving more equitable access to opportunities.

3.1.2. Physical effort

Following the analysis in the previous section, we present Table 3, which, similar to Table 2, compares the population-weighted shares of total jobs accessible by conventional bicycles and e-bikes in São Paulo and Rio de Janeiro. However, instead of time-based thresholds, Table 3 uses energy-equivalent (physical effort) thresholds, reflecting different levels of physical effort. The table also reports the relative percentage gain in accessibility when switching from bicycles to e-bikes.

The results underscore the transformative impact of e-bikes in reducing physical effort barriers to job accessibility. Compared to conventional bicycles, e-bikes offer dramatic gains in accessibility when physical effort is considered instead of travel time, often increasing access to jobs by several hundred percent. As effort thresholds increase, relative gains decline, though absolute accessibility continues to rise sharply, particularly in São Paulo.

These findings underscore the role of e-bikes in overcoming physical limitations, by significantly lowering the effort required to

Table 3
Comparison of population-weighted shares (%) of jobs accessible by bicycle and e-bike across physical effort thresholds in São Paulo and Rio de Janeiro.

Threshold	São Paulo Bike	E-Bike	Change	Rio Bike	E-Bike	Change
15 min Equivalent	0.6 %	3.2 %	433.3 %	1.0 %	5.3 %	430.0 %
30 min Equivalent	2.5 %	15.8 %	532.0 %	4.4 %	22.1 %	402.3 %
45 min Equivalent	6.4 %	36.7 %	473.4 %	10.4 %	46.3 %	345.2 %
60 min Equivalent	12.5 %	59.7 %	377.6 %	19.0 %	69.3 %	264.7 %

cover comparable distances. This expanded accessibility can be especially impactful in hilly or spatially segregated urban areas, such as Rio de Janeiro, where topography can otherwise severely restrict active travel.

When comparing the physical effort and travel time, a key distinction emerges: while travel time improvements with e-bikes are meaningful but moderate (20–38 %), the reduction in physical effort leads to far more substantial accessibility gains. This contrast reveals that barriers to cycling commuting in many urban settings are not only proximity to jobs, but also the physical effort of cycling. E-bikes help to reduce this barrier, unlocking access to a far greater number of jobs without requiring proportionally longer trips. This suggests that policy efforts aimed at expanding (affordable) e-bike usage could return greater equity and inclusion by making active travel more feasible for a broader population.

To further examine these results, we show in Fig. 6 the proportion of the population in São Paulo and Rio de Janeiro that can access varying shares of employment opportunities using conventional bicycles and e-bikes across different travel time thresholds.

The results show that e-bikes provide significant advantages in both cities. At the effort equivalent of 15 min, accessibility remains limited. This confirms that at very low energy expenditures and travel times, bicycles do not offer significant job access in either city. As effort levels increase, the advantages of e-bikes become more apparent. In São Paulo, at the 30-minute equivalent threshold, e-bikes allow 30 % of the population to access approximately 20 % of jobs, while in Rio this value is 30 %. The most striking differences emerge at the 45-minute equivalent effort level, where 30 % of the population can access 50 % of jobs in São Paulo and 60 % in Rio.

These findings indicate that, although e-bikes significantly reduce travel time, their most substantial impact lies in the reduction of physical effort. This reduction can translate into a greater willingness to travel longer distances. For instance, if only travel time is considered, the impact of e-bikes on accessibility is measured by the additional distance covered in the same duration, say, 20 % more distance in 20 min, resulting in access to a greater number of jobs. However, what appears to happen in practice is that, rather than simply traveling faster, people are willing to travel for longer, perhaps 30 min instead of 20, because the physical effort is reduced. This means the real increase in job accessibility is much greater than what would be estimated from time-based models alone.

This behavior is already reflected in empirical data from the Netherlands. For example, De Haas and Kolkowski (2024) reported that in 2023, the average distance of a journey by conventional bicycle was 3.3 km, while e-bike trips were almost 70 % longer, averaging 5.6 km.

In order to better understand the spatial distribution of job accessibility and further illustrate the disparities observed in the aggregated results, Figs. 7 and 8 show the share of accessibility by both bike types and the gain provided by e-bikes compared to regular bicycles.

In São Paulo (Fig. 7), job accessibility remains highly concentrated in central areas, where both regular bicycles and e-bikes provide the greatest access. However, when considering energy expenditure instead of time, the accessibility benefits of e-bikes are even more pronounced. E-bikes substantially expand the range of accessible areas, particularly at higher energy-equivalent thresholds. Unlike the

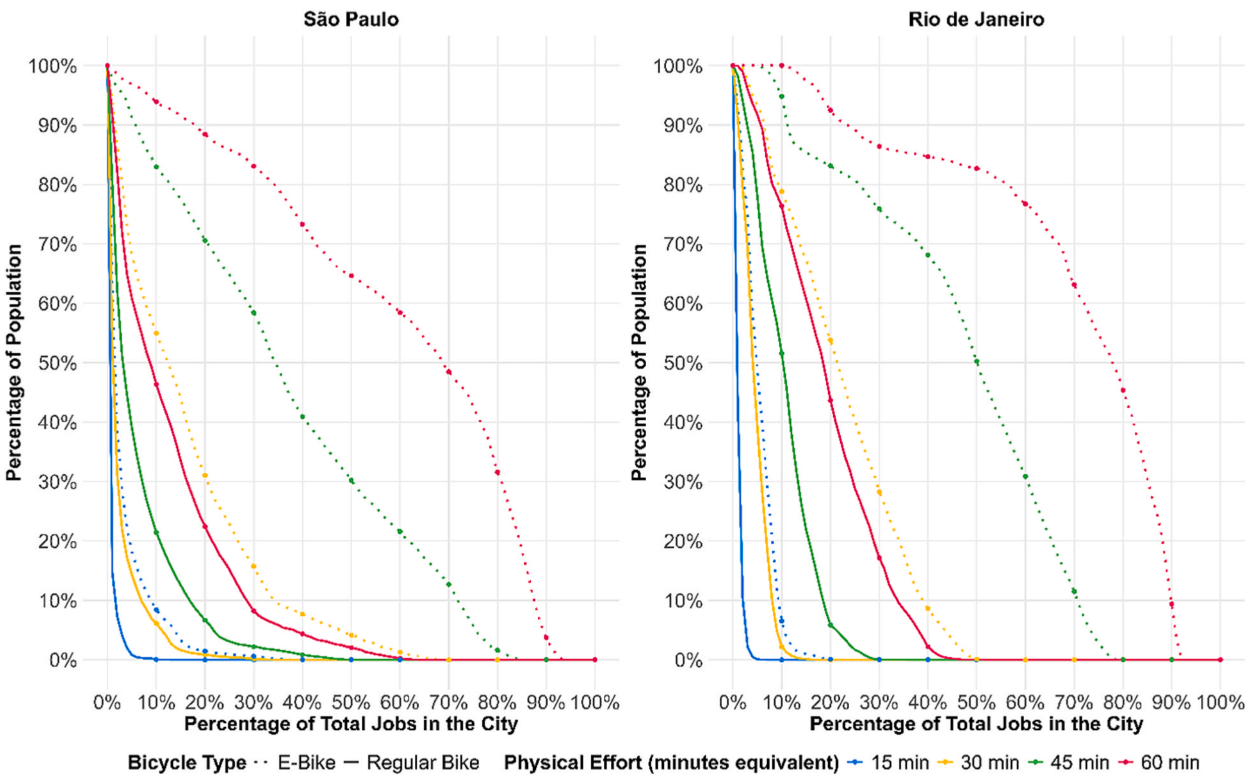

Fig. 6. Percentage of population with access to jobs by regular and electric bicycles in São Paulo and Rio de Janeiro.

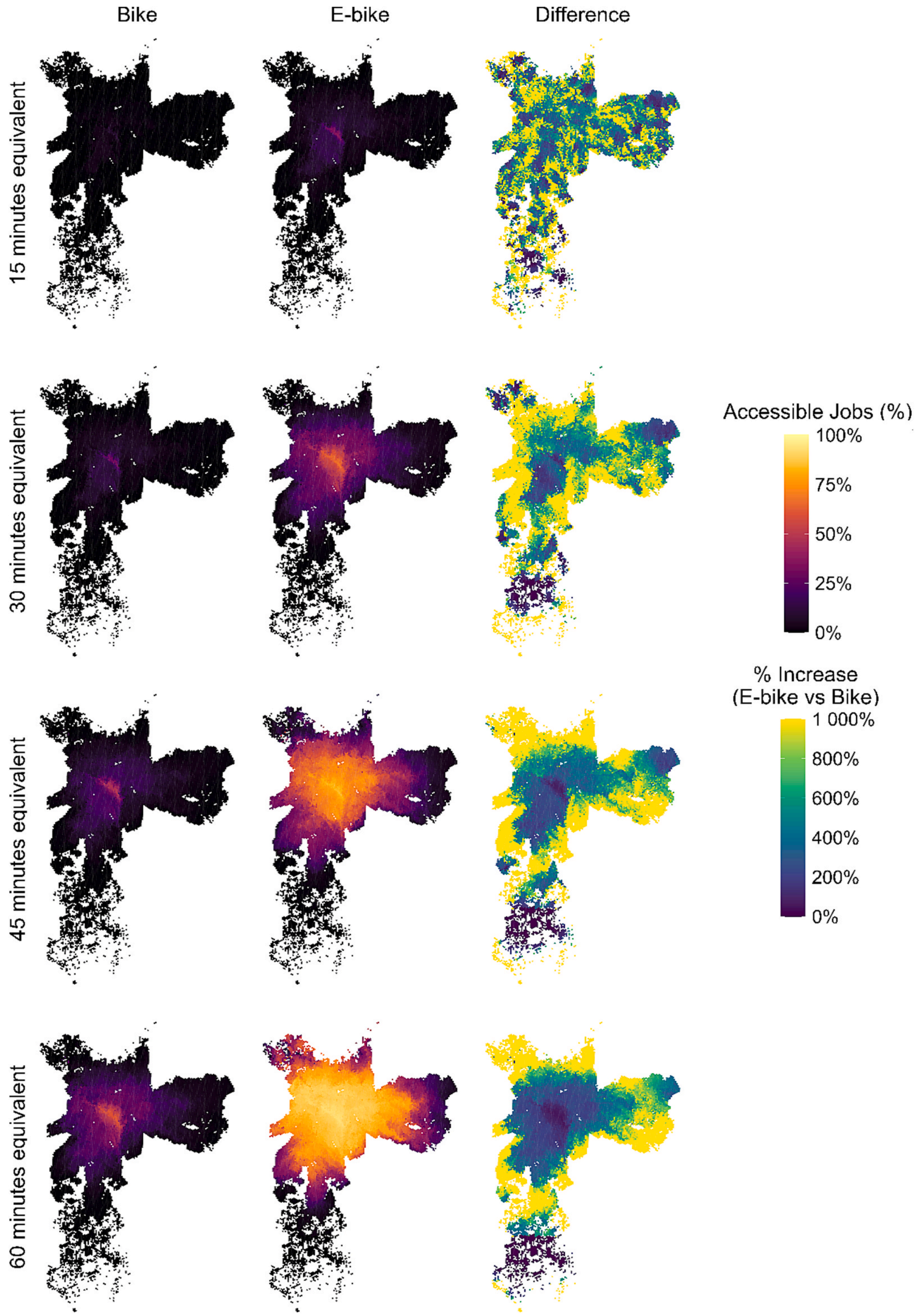

Fig. 7. Accessibility by bikes, e-bikes, and e-bike gain in São Paulo.

travel time analysis, where accessibility gains extended more uniformly, the energy-equivalent results show stronger benefits spreading southward and into peripheral areas, indicating that reduced physical effort enables access to jobs in regions that were previously less reachable.

Rio de Janeiro (Fig. 8) presents a different spatial pattern, consistent with its complex urban structure, as previously discussed.

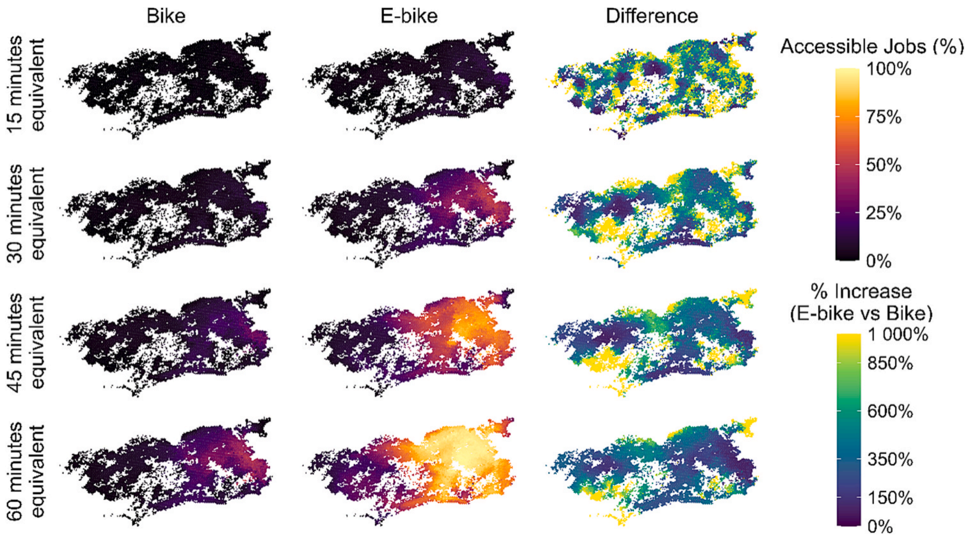

Fig. 8. Accessibility by bikes, e-bikes, and e-bike gain in Rio de Janeiro.

While accessibility improvements with e-bikes are evident, they are more unevenly distributed compared to São Paulo, where accessibility gains expand outward in all directions. Additionally, some peripheral areas in Rio experience high relative accessibility gains, indicating that e-bikes significantly mitigate some of the city's mobility challenges. Despite these differences, in both cities, e-bikes significantly enhance job accessibility, particularly in peripheral areas where conventional cycling remains limited due to the physical effort required.

Nevertheless, even with higher levels of physical effort, some regions continue to exhibit low accessibility. In São Paulo, the eastern and far southern areas remain relatively disconnected from major job centers, while in Rio de Janeiro, western areas still face accessibility challenges. These findings reaffirm that while e-bikes offer substantial benefits, they are not sufficient to provide access to a significant share of jobs for the entire population. Therefore, they should be integrated with broader transport policies and infrastructure improvements to ensure equitable access to employment opportunities across both cities.

3.2. Equity

3.2.1. Travel time

To assess the impact of e-bikes on equity, we first examined the CI across all travel time thresholds for both São Paulo and Rio de Janeiro. The results are presented in Table 4.

The results show that e-bikes contribute to a more equitable distribution of job accessibility, especially for longer commutes and in Rio de Janeiro. Across all travel time thresholds, the Concentration Index (CI) decreases when e-bikes are used instead of conventional bicycles, indicating improved equity. The impact of e-bikes becomes more pronounced with longer travel times, and Rio consistently experiences the largest percentage reductions in CI. Notably, Rio also starts with a lower CI than São Paulo, reflecting a more equitable baseline distribution of job accessibility. This can be partly explained by the spatial distribution of income and employment: in Rio, many lower-income residents live in neighborhoods relatively close to the city center, where most jobs are located, allowing them to benefit significantly from the extended range of e-bikes. In contrast, São Paulo's job opportunities are more concentrated in wealthier central areas, meaning that improvements in accessibility from e-bikes primarily benefit higher-income groups, resulting in smaller relative reductions in CI.

To further analyze equity, we examined the relationship between income deciles and job accessibility by both modes, along with the percentage increase in accessibility due to e-bike use across all travel time thresholds. Fig. 9 presents the results for São Paulo.

Job accessibility by both conventional and e-bikes follows a clear socioeconomic gradient, favoring higher-income groups. As for the accessibility gains, while they are similar across all income groups at shorter travel times, they become greater for low- and middle-

Table 4
Concentration Index (CI) for Bicycle and E-Bike Travel Time in São Paulo and Rio de Janeiro.

Threshold	São Paulo Bike CI	E-Bike CI	Change (%)	Rio Bike CI	E-Bike CI	Change (%)
15 min	0.474	0.473	−0.2 %	0.267	0.247	−7.5 %
30 min	0.444	0.428	−3.6 %	0.192	0.182	−5.2 %
45 min	0.377	0.346	−8.2 %	0.161	0.144	−10.6 %
60 min	0.302	0.262	−13.2 %	0.132	0.11	−16.7 %

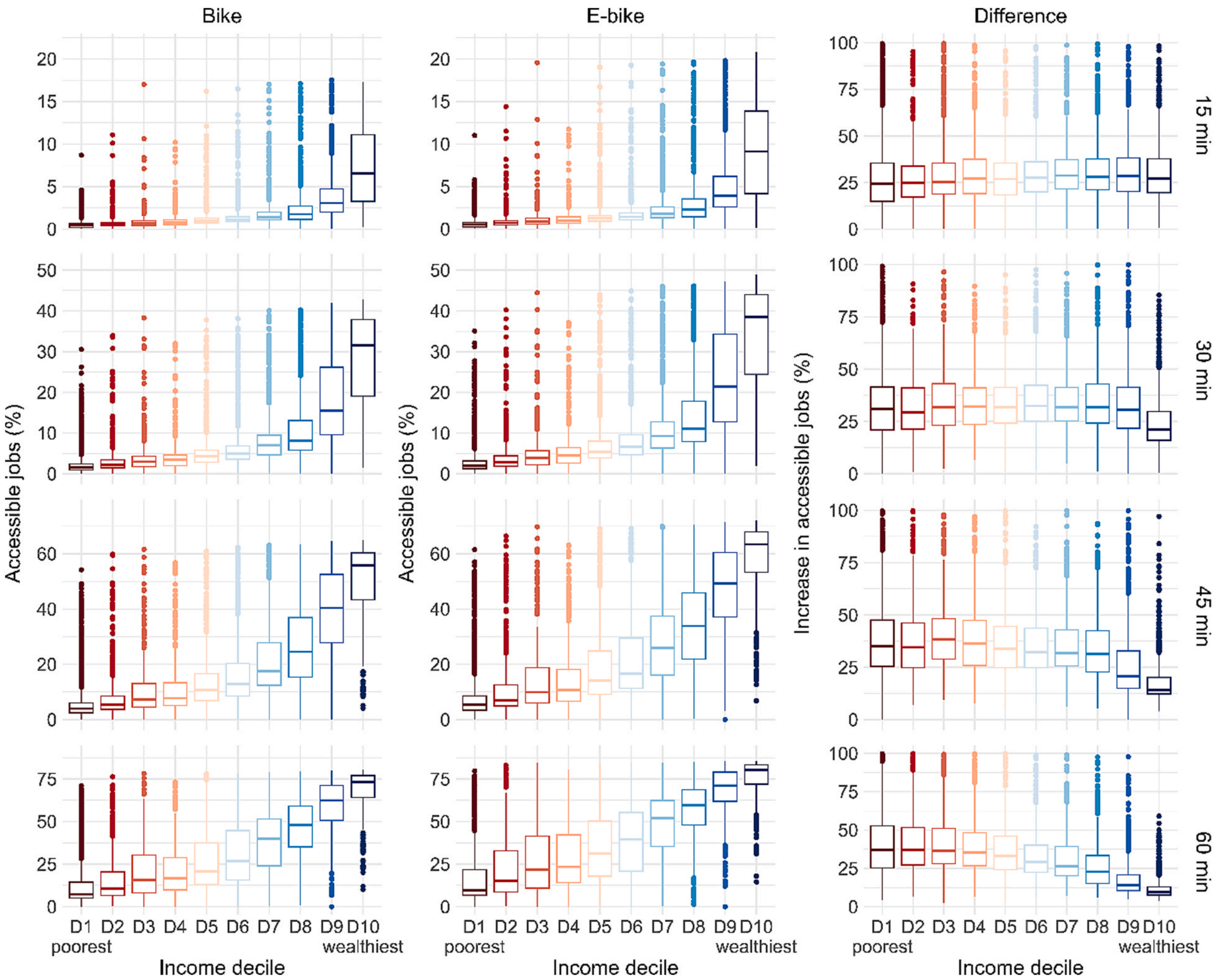

Fig. 9. Job accessibility by income decile across travel time thresholds in São Paulo.

income groups as travel time increases. This indicates that although e-bikes help reduce inequities, especially over longer distances, they do not fully eliminate the accessibility gap between income groups.

In Rio de Janeiro (Fig. 10), accessibility patterns for both conventional and electric bicycles differ significantly from those in São Paulo. While the wealthiest deciles still have higher accessibility, lower-income deciles exhibit the same or even better accessibility levels than middle-income groups. This trend is influenced by Rio's spatial structure, where some low-income areas are located close to job centers, as shown in Fig. 1.

Regarding relative gains, they are larger for low-income groups at 15 min, and at 30 and 45 min, they are almost evenly distributed. In general, higher-income areas tend to experience smaller gains compared to middle- and low-income areas, particularly as the travel time threshold increases.

While e-bikes are able to reduce accessibility inequalities in both São Paulo and Rio de Janeiro, particularly for longer commutes, they do not eliminate absolute advantages held by higher-income groups. The specific impact, however, varies significantly between the cities. Rio experiences larger overall reductions in CI and exhibits a complex accessibility pattern where some lower-income groups fare relatively well, unlike São Paulo's consistent gradient favoring wealthier groups. Furthermore, the distribution of relative accessibility gains from e-bikes differs across income groups and travel times in each city. Despite these distinct local dynamics, the overarching finding is that e-bikes enhance equity by expanding access, especially over distances challenging for conventional bikes, but they fall short of fully overcoming equity concerns.

To enhance the understanding of accessibility disparities, we also visualize the spatial distribution of accessibility and income in São Paulo and Rio using Local Moran's I bivariate analysis. Fig. 11 presents the resulting spatial clusters for São Paulo.

Both bikes and e-bikes follow a very similar pattern. There is a H-H cluster in the center, where most jobs and high income areas are located, which extends slightly south at the 15-minute mark and gradually takes on a more circular shape as the travel time threshold increases. It is also notable that a L-H cluster already exists at 15 min in the northern area of the center and then expands gradually as the travel time threshold increases. This suggests that as travel time increases, more low-income populations gain access to a significant

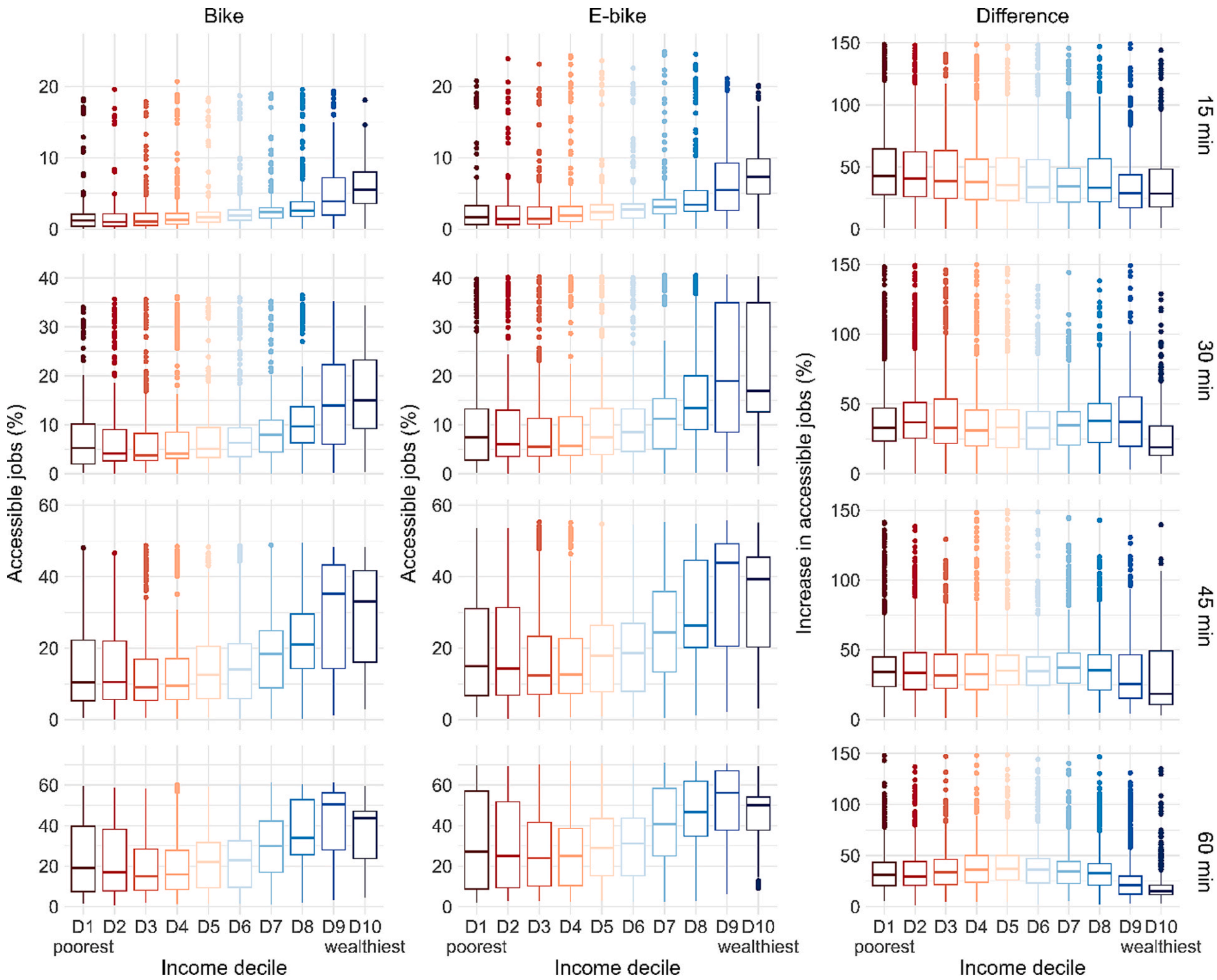

Fig. 10. Job accessibility by income decile across travel time thresholds in Rio de Janeiro.

number of jobs.

Conversely, L-L clusters are predominantly located in the peripheral areas of São Paulo. These regions experience the greatest transport disadvantages, with limited job access by bicycle and only marginal improvements from e-bikes. The persistence of these clusters highlights the compounded effects of urban marginalization, where long travel distances limit the benefits of active mobility options for lower-income residents.

Regarding the relation between accessibility gains and income, they are mostly negligible across income groups at the 15- and 30-minute thresholds but become more significant at 45 and 60 min. At 45 min, most clusters are H-L and L-L, indicating that accessibility gains remain small in central or higher-income areas that already had good accessibility. In contrast, larger gains tend to occur in peripheral or lower-accessibility areas, where the introduction of e-bikes substantially increases reachable job opportunities. This pattern becomes more pronounced at the 60-minute threshold, where some L-H clusters also emerge—highlighting low-income regions that experience notable improvements.

In Rio de Janeiro (Fig. 12), H-H and L-H clusters begin to form at the 15-minute mark, near areas where most jobs are located. Similar to São Paulo, both clusters expand as the travel time threshold increases. However, a key difference from São Paulo is that the LH cluster becomes larger than the HH cluster as travel time increases, highlighting that in Rio a part of the low income population lives closer to jobs compared to São Paulo.

Conversely, LL clusters are predominantly located in the west peripheral areas of Rio. These regions experience the greatest transport disadvantages, with limited job access by bicycle and only marginal improvements from e-bikes. The persistence of these clusters highlights the challenges posed by the job distribution and urban sprawl in Rio, where long travel distances limit the benefits of active mobility options for lower-income residents in these areas.

Regarding accessibility gains and income, they are mostly negligible in relation to income for the 15 min thresholds but become more significant from 30 min on. Most clusters, like São Paulo, are H-L and L-L, indicating that accessibility gains remain small in areas that already had high accessibility. At 60 min, this pattern still holds, but like São Paulo, some L-H clusters emerge in the far West of

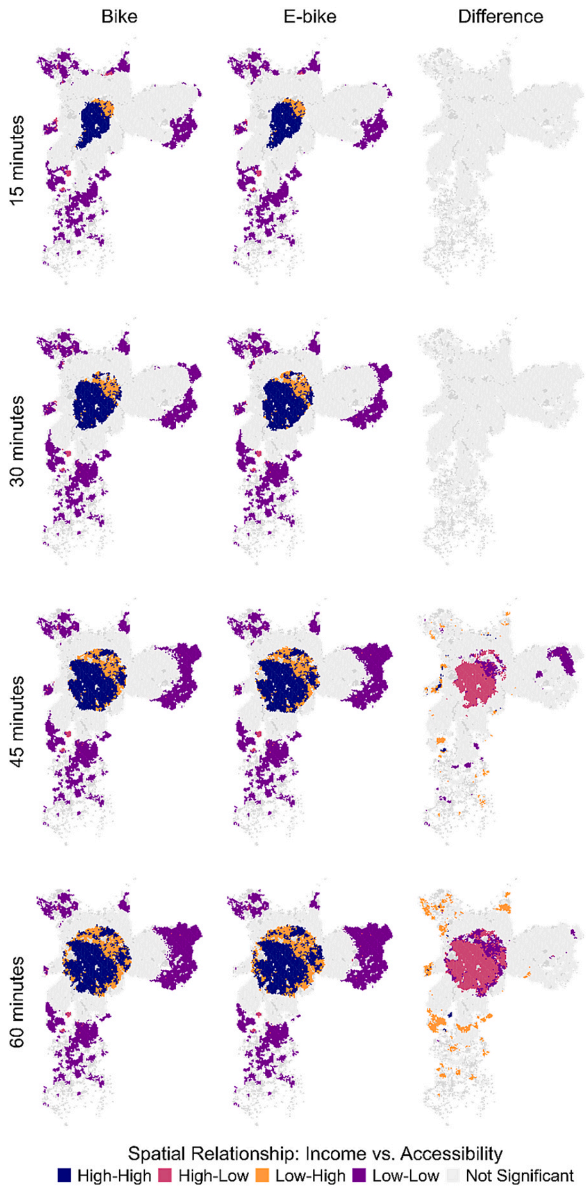

Fig. 11. Spatial clusters of bicycle and e-bike accessibility and income in São Paulo across travel time thresholds.

city, representing poor regions that experience significant accessibility improvements due to e-bikes.

Overall, the spatial clustering results for Rio reveal a pattern distinct from São Paulo. In Rio, some low-income populations live relatively close to areas with a high concentration of employment opportunities and benefit from meaningful accessibility gains with e-bikes. As noted earlier in Section 3.1.1, in São Paulo, the poor are generally located much farther from major employment centers, which limits the potential of e-bikes to reduce the accessibility gap. Nonetheless, the western part of Rio remains particularly disadvantaged, with long distances that severely constrain accessibility, even with e-bikes.

3.2.2. *Physical effort*

Building on our analysis of travel time, we next evaluate the impact of e-bikes on equity across all physical effort thresholds for both São Paulo and Rio de Janeiro. Table 5 presents the Concentration Index values across all energy thresholds.

The results show that e-bikes improve equity in job accessibility across both cities, but their impact differs significantly between São Paulo and Rio de Janeiro. In São Paulo, e-bikes substantially reduce CI values across all energy thresholds, with the effects becoming stronger as the effort thresholds increase. This suggests that e-bikes can play a transformative role in mitigating physical effort disparities in São Paulo. In contrast, Rio de Janeiro follows a more non-linear pattern. The largest reductions occur at the shortest (−31.0 %) and longest (−29.2 %) thresholds, indicating that e-bikes make short trips physically easier for lower-income groups while also

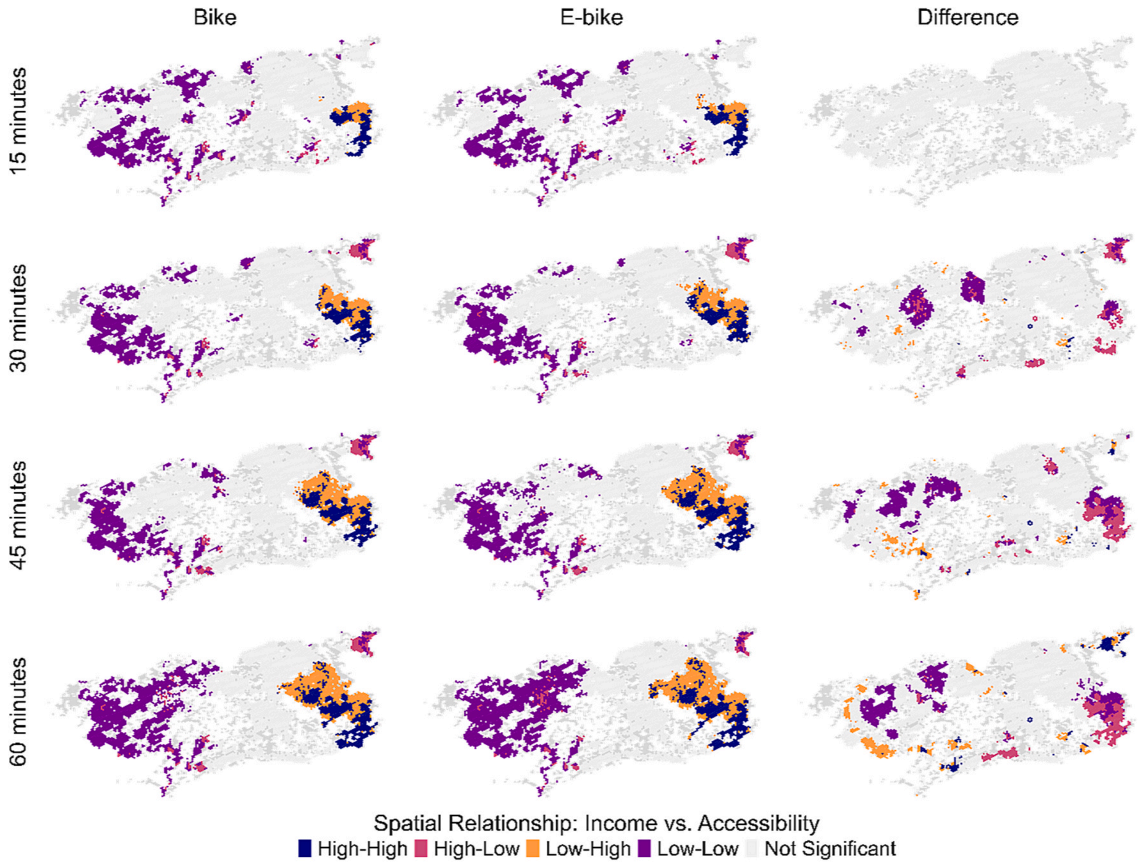

Fig. 12. Spatial clusters of bicycle and e-bike accessibility and income in Rio de Janeiro across travel time thresholds.

Table 5
Concentration Index (CI) for Bicycle and E-Bike Energy Expenditure in São Paulo and Rio de Janeiro.

Threshold	São Paulo Bike CI	E-Bike CI	Change (%)	Rio Bike CI	E-Bike CI	Change (%)
15 min Equivalent	0.535	0.502	−6.2 %	0.105	0.0724	−31.0 %
30 min Equivalent	0.513	0.389	−24.2 %	0.0678	0.0559	−17.5 %
45 min Equivalent	0.46	0.28	−39.1 %	0.0573	0.0489	−14.7 %
60 min Equivalent	0.408	0.186	−54.4 %	0.0493	0.0349	−29.2 %

benefiting those with longer commutes.

The reductions in CI were significantly smaller when accounting for travel time, suggesting that e-bikes' primary impact lies in reducing physical effort rather than drastically cutting travel duration. This highlights their greatest benefit: increasing accessibility and promoting equity by enabling longer trips that would be too demanding on a conventional bike. This effect is particularly significant in São Paulo and Rio, where job opportunities are highly concentrated in specific areas. Expanding e-bike use in these cities could greatly improve job access, especially for people living more than 30 min away by bicycle. Ultimately, this would enhance equity by making these jobs, which were previously accessible mainly to higher-income individuals, more available to a broader population.

Another notable finding is that in Rio, the CI based on physical effort is significantly lower than when considering travel time. As shown in Figs. 5 and 8, this reflects the fact that many low-income residents live relatively close to central areas with a high concentration of jobs. When energy is considered, e-bikes allow these populations to reach a much larger number of opportunities using the same amount of physical effort on a regular bike. This leads to improved equity outcomes. In contrast, this effect is less evident in São Paulo, where low-income populations are generally located farther from job centers, and even with e-bikes, disparities remain. These findings highlight the potential of e-bikes to reduce accessibility inequalities, especially when effort rather than time is used as the basis for comparison.

To further analyze equity, we also examined the relationship between income deciles and job accessibility by both modes, along with the percentage increase in accessibility due to e-bike use across all physical effort thresholds. Fig. 13 presents the results for São Paulo.

Job accessibility, when analyzed through the lens of physical effort, also favors higher-income groups, although the difference between groups is smaller than when considering travel time. The adoption of e-bikes increases the overall share of accessible jobs much more than when considered travel time, although the disparities remain, with lower-income groups continuing to experience lower overall accessibility.

The biggest difference when comparing to travel time is in terms of relative equity gains. Accessibility improvements start evenly distributed at lower physical effort thresholds but become more pronounced for lower- and middle-income groups as effort thresholds increase. This suggests that e-bikes are particularly effective in mitigating accessibility disparities when physical effort is considered as a key constraint, making cycling a more viable option for lower-income populations.

In Rio de Janeiro (Fig. 14), accessibility patterns for both conventional and electric bicycles differ significantly from those in São Paulo, as was also the case when considering travel time. With a conventional bicycle, accessibility is fairly even across income deciles. When using e-bikes, the differences between deciles remain relatively small overall, but low-income groups show much greater internal variation. This suggests that while some low-income populations benefit substantially from e-bikes, others, particularly those living in the distant western parts of the city, see little improvement due to their physical isolation and limited infrastructure. At the same time, the highest-income groups do not necessarily have the greatest access to jobs when physical effort is considered. This is likely because many wealthier residents live in areas farther from the city center or in hilly regions where even e-bikes offer limited gains in accessibility.

Regarding relative gains, they are distributed almost evenly across all travel time thresholds. Low-income areas tend to experience greater gains than middle and high-income areas at the smallest threshold, but this difference decreases across higher thresholds.

To further understand accessibility disparities, we visualize the spatial distribution of accessibility and income in São Paulo and Rio

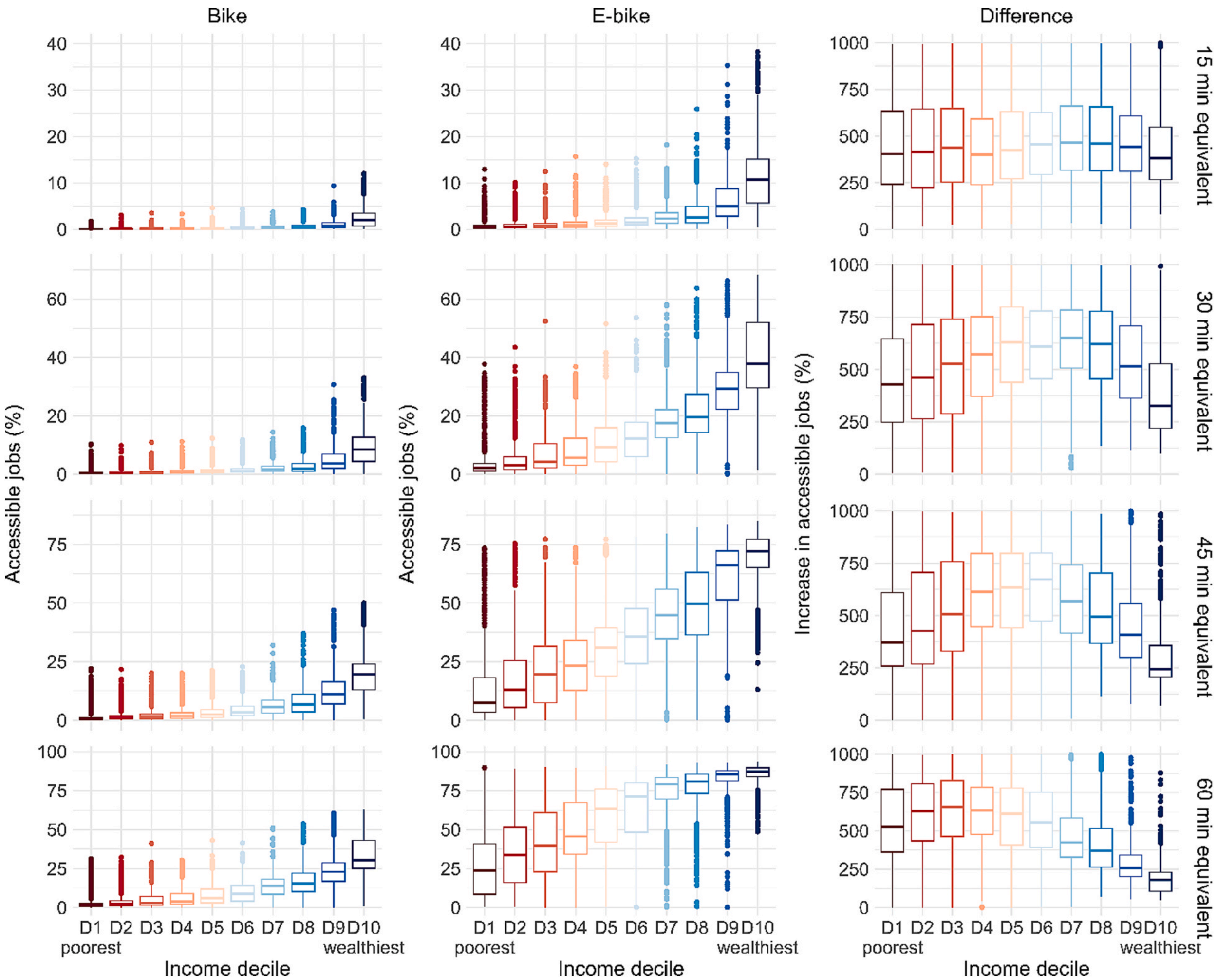

Fig. 13. Job accessibility by income decile across energy expenditure thresholds in São Paulo.

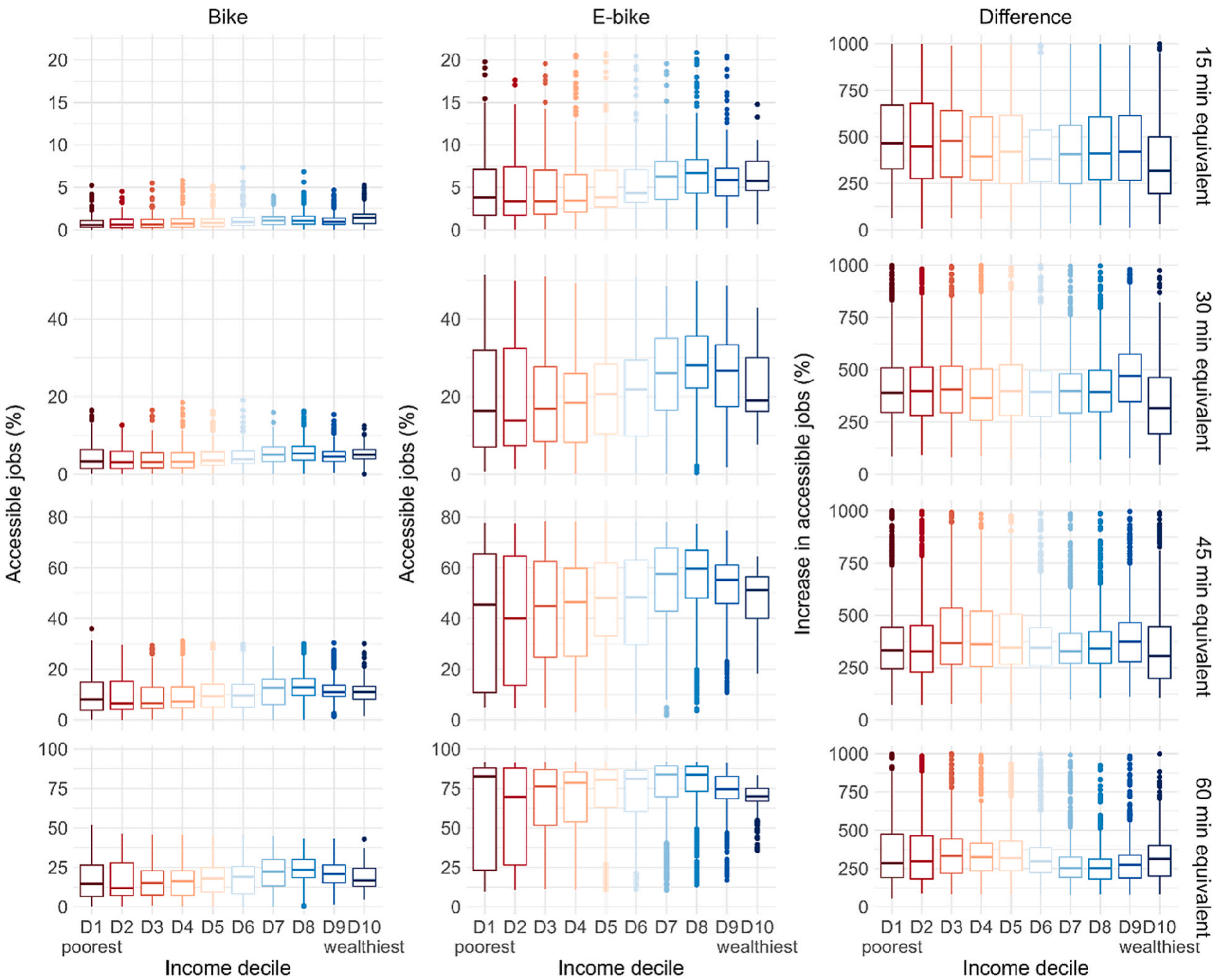

Fig. 14. Job accessibility by income decile across travel time thresholds in Rio de Janeiro.

using Local Moran's I bivariate analysis. Fig. 15 presents the resulting spatial clusters for São Paulo.

The clusters follow a different spatial pattern when physical effort is considered compared to travel time. For conventional bikes, a H-H cluster appears in the central area but is more concentrated toward the western part, where most jobs are located, and extends southward. As the travel time threshold increases, this cluster does not form a circular shape, like with travel time, but instead becomes more irregular. Additionally, a L-H cluster emerges in the northern part of the center.

The pattern for e-bikes, however, differs significantly. While still concentrated near the city center, both the H-H and L-H clusters are much larger and more circular than those for conventional bikes. Notably, the L-H cluster is significantly bigger, suggesting two key insights. First, the difference between accessibility patterns for conventional bikes when considering travel time versus physical effort highlights the major impact of terrain. This suggests that conventional bike accessibility, when evaluated purely based on travel time, likely overestimates actual accessibility since terrain constraints are not considered. Second, the more circular shape of e-bike accessibility clusters indicates that e-bikes help restore the accessibility pattern seen with travel time alone. This suggests that e-bikes could play a crucial role in mitigating terrain-related accessibility barriers, making cycling a more viable commuting option.

This is particularly important because, with conventional bikes, proximity to job centers does not necessarily translate into bike accessibility due to physical effort constraints, likely pushing more people toward motorized transport or public transit. The large size of the L-H cluster for e-bikes suggests significant potential for expanding job accessibility for populations living at a reasonable distance from employment hubs.

However, one aspect remains unchanged: the presence of low-low (L-L) clusters in São Paulo's peripheral areas, particularly in the east and south. In these areas, long travel distances continue to limit the benefits of active mobility, reinforcing reliance on motorized transportation and deepening accessibility inequalities.

Regarding accessibility gains, they become more significant at 30 min, mostly the same trend as when travel time was considered, indicating that accessibility gains remain small in areas that already had high accessibility when compared to further areas, where the gains are much higher. Some L-H clusters emerge starting from 45 min equivalent, in the northwest regions, representing poor regions

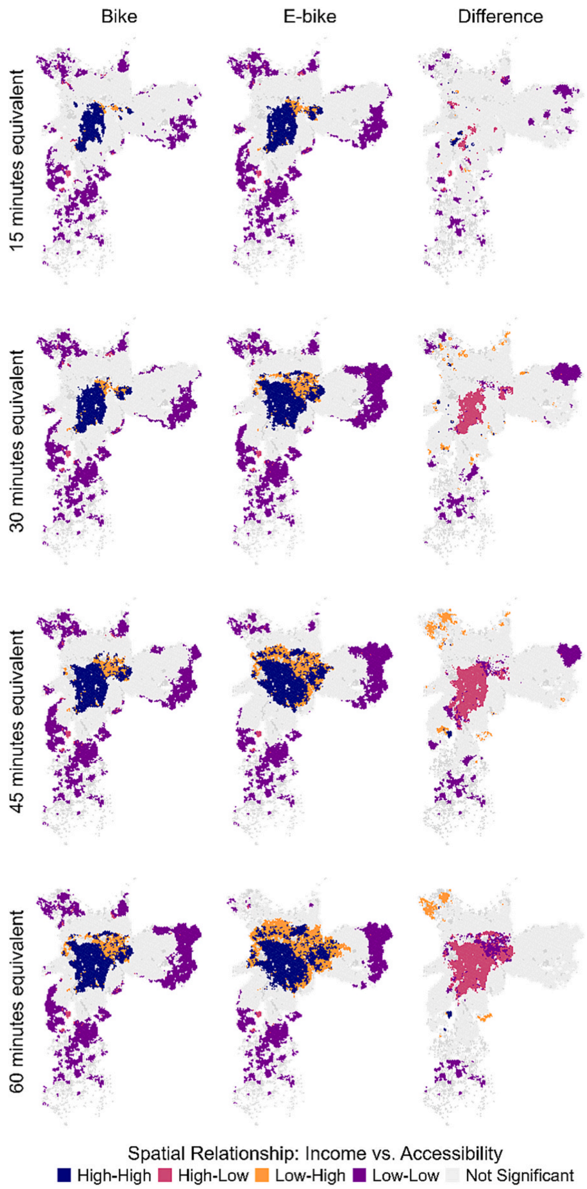

Fig. 15. Spatial clusters of bicycle and e-bike accessibility and income in São Paulo across physical effort thresholds.

that experience significant accessibility improvements due to e-bikes.

Overall, the spatial clustering results for São Paulo show that while e-bikes do not fully eliminate ingrained spatial disparities, they can significantly improve accessibility in low-income areas closer to the city center. This highlights the regions that would likely benefit the most from unimodal trips while also emphasizing the need for complementary policies, such developing safe and extensive cycling infrastructure, to maximize their equity benefits.

In Rio de Janeiro (Fig. 16), the most prominent feature is the presence of an L-H cluster for both bikes, with a significant increase in its size as the travel time equivalent threshold increases. The clusters form a somewhat similar pattern for both bike types, but the size of the cluster for e-bikes is much larger. There is also an H-H cluster, located further east, which is smaller for bikes than for e-bikes.

A key difference from São Paulo is that the L-H cluster in Rio is much larger than the H-H cluster, indicating that e-bikes can have a greater impact on low-income regions in Rio than in São Paulo. Conversely, L-L clusters follow the same pattern as travel time, remaining predominantly in Rio's western peripheral areas and unchanged from the travel time situation. These regions experience significant transport disadvantages, with limited job access by bicycle and only marginal improvements from e-bikes. The persistence of these clusters highlights the challenges posed by job distribution and urban sprawl in Rio, where long travel distances limit the benefits of active mobility options for lower-income residents.

Regarding accessibility gains, most clusters are H-L and L-L, suggesting that accessibility improvements remain small in areas that

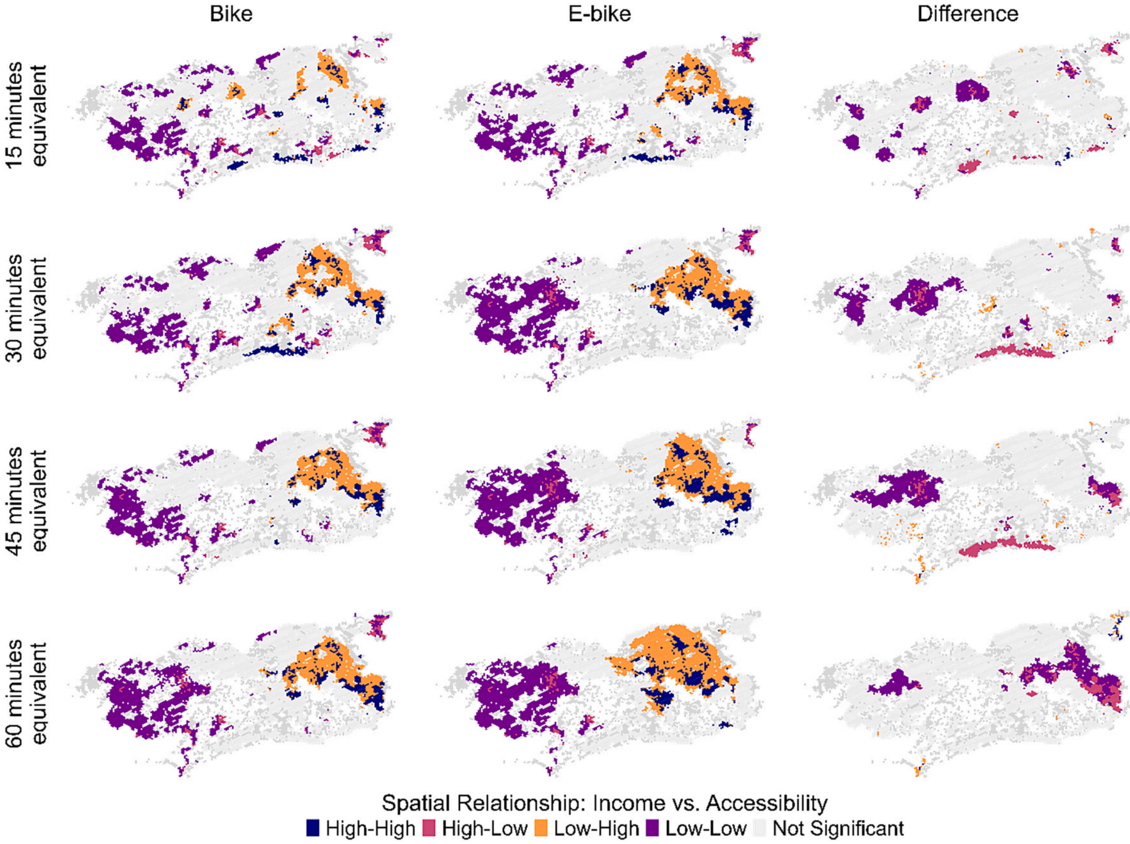

Fig. 16. Spatial clusters of bicycle and e-bike accessibility and income in Rio de Janeiro across physical effort thresholds.

already had high accessibility compared to others. In general, the spatial clustering results for Rio underscore that while e-bikes can play a significant role in improving accessibility in low-income areas, they do not fully disrupt entrenched spatial disparities, similar to the pattern observed in São Paulo. However, their impact is much greater in Rio than in São Paulo.

In conclusion, accessibility and equity outcomes related to e-bikes can vary significantly from city to city, as demonstrated by the results observed in São Paulo and Rio de Janeiro. The spatial distribution of jobs and population, along with the broader urban structure, plays a critical role in determining how effectively e-bikes enhance access to opportunities. These findings underscore the need for more comparative research across diverse urban contexts, in both developing and developed countries, to better understand the potential of e-bikes to improve access to employment and essential services.

A key advantage in many developed countries is the higher purchasing power, which makes e-bikes, still relatively costly, more accessible to a larger share of the population. In addition, several cities in developed countries benefit from well-connected and extensive cycling infrastructure, which allows users to take full advantage of the mobility improvements that e-bikes offer. In contrast, many cities in developing countries face substantial barriers, including limited infrastructure and affordability challenges, which constrain the equitable use of e-bikes.

Affordability remains a significant barrier to accessing e-bike sharing, particularly for low-income populations. In Brazil, pricing structures vary across cities, but monthly plans typically cost around R$40.00 (1 USD = R$5.56 as of mid-2025), with an additional charge of approximately R$8.00 for each ride with electric bikes. These cumulative costs can be prohibitive for users with limited incomes, given that the minimum wage as of 2025 is R$1,518 (273 USD) per month. However, Fortaleza, a city in northeastern Brazil, has introduced inclusive programs that integrate bike-sharing with public transportation, including access to electric models for public transit users, for free, as well as charging R$20.00 per month, or R$80.00 per year, for other users, including e-bikes. Such initiatives align with global efforts to reduce inequalities in shared mobility systems, as seen in the US where equity requirements in shared micromobility programs have been implemented to address disparities (Brown and Howell, 2024). These examples highlight the potential for policy interventions to mitigate cost barriers and promote more equitable access to active and sustainable mobility. Such initiatives highlight the potential for policy interventions to mitigate cost barriers and promote more equitable access to active and sustainable mobility.

Further research focused on specific population groups and their unique mobility needs is needed to examine the equity implications of e-bike use across different contexts. Ballo et al. (2023) discuss various qualitative scenarios regarding the possible impact of e-bikes on accessibility and equity. Their work highlights that the effects depend heavily on local conditions and travel behaviors, with some groups gaining accessibility while others may experience losses depending on how transportation systems evolve and integrate. Equity-oriented planning, supported by targeted investments in infrastructure and affordability measures, will be critical for realizing the full potential of e-bikes as a tool for inclusive urban mobility in a range of global settings.

4. Conclusions

This study evaluated the impacts of e-bikes on job accessibility and spatial equity in São Paulo and Rio de Janeiro, introducing physical effort alongside travel time as a key impedance factor. Our findings demonstrate that e-bikes substantially enhance job accessibility compared to conventional bicycles, particularly over longer distances and when higher physical effort thresholds are considered. This highlights the potential of e-bikes to overcome traditional barriers to cycling, such as distance and topography.

The analysis revealed significant variations in accessibility gains both between and within the two cities, underscoring the critical role of urban topography and structure in shaping e-bike impacts. While São Paulo generally offers higher absolute job accessibility by bicycle, Rio de Janeiro showed greater relative improvements with e-bikes, likely due to its urban structure making pedal assistance more impactful.

From an equity perspective, e-bikes were found to partially reduce spatial disparities in accessibility, providing greater relative gains for lower-income groups, especially when physical effort limits accessibility. However, despite these relative improvements, significant absolute accessibility inequalities persist, with central, higher-income areas retaining advantages. Furthermore, peripheral areas in both cities continue to face accessibility challenges, even with e-bikes, indicating that e-bikes alone are insufficient to bridge the urban accessibility divide.

This research contributes by quantifying e-bike impacts in major Global South cities and by incorporating physical effort as a novel and important impedance metric in cycling accessibility studies. The results suggest that promoting e-bike use can be a valuable strategy for improving access to opportunities and fostering greater transport equity. However, realizing the accessibility and equity potential of e-bikes requires complementary policies beyond simply promoting their use, such as developing continuous and safe cycling networks, and affordable pricing schemes for shared e-bike systems. Furthermore, strategies to improve integration with public transport hubs and policies could help maximize uptake and benefits, especially for lower-income workers using public transport.

CRediT authorship contribution statement

Thiago Vinicius Louro: Writing – review & editing, Writing – original draft, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Anna Beatriz Grigolon:** Writing – review & editing, Supervision, Data curation, Conceptualization. **André Luiz Cunha:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization. **Karst T. Geurs:** Writing – review & editing, Validation, Supervision, Methodology, Data curation, Conceptualization.

Declaration of competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Thiago Vinicius Louro reports financial support was provided by Coordination of Higher Education Personnel Improvement. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

References

Anselin, L., Syabri, I., Smirnov, O., 2002. Visualizing multivariate spatial correlation with dynamically linked windows. Proceedings, CSISS Workshop on New Tools for Spatial Data Analysis Vol. 2.

Ballo, L., De Freitas, L.M., Meister, A., Axhausen, K.W., 2023. The E-Bike City as a radical shift toward zero- emission transport: Sustainable? Equitable? Desirable? J. Transp. Geogr. 111, 103663.

Banerjee, A., Łukawska, M., Jensen, A.F., Haustein, S., 2022. Facilitating bicycle commuting beyond short distances: insights from existing literature. Transp. Rev. 42 (4), 526–550.

Barboza, M.H.C., Carneiro, M.S., Falavigna, C., Luz, G., Orrico, R., 2021. Balancing time: using a new accessibility measure in Rio de Janeiro. J. Transp. Geogr. 90, 102924. https://doi.org/10.1016/j.jtrangeo.2020.102924.

Ben-Elia, E., Benenson, I., 2019. A spatially-explicit method for analyzing the equity of transit commuters' accessibility. Transp. Res. A Policy Pract. 120, 31–42.

Bertaud, A., 2018. Order without design: how markets shape cities. MIT Press.

Bittencourt, T.A., Giannotti, M., Marques, E., 2021. Cumulative (and self-reinforcing) spatial inequalities: Interactions between accessibility and segregation in four Brazilian metropolises. Environ.Plann. B: Urban Anal. City Sci. 48 (7), 1989–2005.

Bivand, R.S., Wong, D.W., 2018. Comparing implementations of global and local indicators of spatial association. TEST 27 (3), 716–748.

Boeing, G., 2017. OSMnx: New methods for acquiring, constructing, analyzing, and visualizing complex street networks. Comput. Environ. Urban Syst. 65, 126–139. https://doi.org/10.1016/j.compenvurbsys.2017.05.004.

Boisjoly, G., El-Geneidy, A.M., 2017. How to get there? a critical assessment of accessibility objectives and indicators in metropolitan transportation plans. Transp. Policy 55, 38–50. https://doi.org/10.1016/j.tranpol.2016.12.011.

Brodsky, I., 2018. H3: Uber's hexagonal hierarchical spatial index. Uber Engineering Blog. https://eng.uber.com/h3/.

Brown, A., Howell, A., 2024. Mobility for the people: Equity requirements in US shared micromobility programs. J. Cycling Micromobility Res. 2, 100020. https://doi.org/10.1016/j.jcmr.2024.100020.

Bruno, M., Monteiro Melo, H.P., Campanelli, B., Loreto, V., 2024. A universal framework for inclusive 15-minute cities. Nat. Cities 1 (10), 633–641. https://doi.org/10.1038/s44284-024-00119-4.

Carneiro, M., Toledo, J., Aurélio, M., & Orrico, R. (2019). Espraiamento urbano e exclusão social. Uma análise da acessibilidade dos moradores da cidade do Rio de Janeiro ao mercado de trabalho. EURE (Santiago), 45(136), 51-70.

Companhia de Engenharia de Tráfego de São Paulo Mapa de infraestrutura cicloviária CET-SP 2025 Retrieved April 1, 2025, from https://www.cetsp.com.br/consultas/bicicleta/mapa-de-infraestrutura-cicloviaria.aspx.

Cooper, E., Vanoutrive, T., 2022. Is accessibility inequality morally relevant?: an exploration using local residents' assessments in ModestoCalifornia. J. Transp. Geogr. 99, 103281.

M. de Haas, L. Kolkowski (2023, November 28) Cycling Facts 2023 [brochure]. Netherlands Institute for Transport Policy Analysis (KiM).

Gehrke, S.R., Akhavan, A., Furth, P.G., Wang, Q., Reardon, T.G., 2020. A cycling-focused accessibility tool to support regional bike network connectivity. Transp. Res. Part D: Trans. Environ. 85, 102388. https://doi.org/10.1016/j.trd.2020.102388.

Geurs, K.T., van Wee, B., 2004. Accessibility evaluation of land-use and transport strategies: Review and research directions. J. Transp. Geogr. 12 (2), 127–140. https://doi.org/10.1016/j.jtrangeo.2003.10.005.

Giannotti, M., Tomasiello, D.B., Bittencourt, T.A., 2022. The bias in estimating accessibility inequalities using gravity-based metrics. J. Transp. Geogr. 101, 103337. https://doi.org/10.1016/j.jtrangeo.2022.103337.

Guzman, L.A., Oviedo, D., Cantillo-Garcia, V.A., 2024. Is proximity enough? A critical analysis of a 15-minute city considering individual perceptions. Cities 148, 104882. https://doi.org/10.1016/j.cities.2024.104882.

Hansen, W.G., 1959. How accessibility shapes land use. J. Am. Instit. Plann. 25 (2), 73–76. https://doi.org/10.1080/01944365908978307.

Heinen, E., van Wee, B., Maat, K., 2010. Commuting by bicycle: an overview of the literature. Transp. Rev. 30 (1), 59–96. https://doi.org/10.1080/01441640903187001.

Instituto Brasileiro de Geografia e Estatística. (2022). Cidades@. IBGE. https://cidades.ibge.gov.br/.

Iseki, H., Tingstrom, M., 2014. A new approach for bikeshed analysis with consideration of topography, street connectivity, and energy consumption. Comput. Environ. Urban Syst. 48, 166–177. https://doi.org/10.1016/j.compenvurbsys.2014.07.008.

Kapatsila, B., Palacios, M.S., Grisé, E., El-Geneidy, A., 2023. Resolving the accessibility dilemma: Comparing cumulative and gravity-based measures of accessibility in eight Canadian cities. J. Transp.Geogr. 107, 103530. https://doi.org/10.1016/j.jtrangeo.2023.103530.

Karner, A., Pereira, R.H.M., Karner, A., 2024. Advances and pitfalls in measuring transportation equity. Transportation. https://doi.org/10.1007/s11116-023-10460-7.

Knap, E., Ulak, M.B., Geurs, K.T., Mulders, A., van der Drift, S., 2023. A composite X-minute city cycling accessibility metric and its role in assessing spatial and socioeconomic inequalities – a case study in Utrecht, the Netherlands. J. Urban Mobility 3, 100043. https://doi.org/10.1016/j.urbmob.2022.100043.

Lee, R.J., Sener, I.N., Jones, S.N., 2017. Understanding the role of equity in active transportation planning in the United States. Transp. Rev. 37 (2), 211–226. https://doi.org/10.1080/01441647.2016.1239660.

Lee, S.-I., 2001. Developing a bivariate spatial association measure: an integration of Pearson's r and Moran's I. J. Geogr. Syst. 3 (4), 369–385. https://doi.org/10.1007/s101090100064.

Liu, L., Suzuki, T., 2019. Quantifying e-bike applicability by comparing travel time and physical energy expenditure: a case study of Japanese cities. J. Transp. Health 13, 150–163. https://doi.org/10.1016/j.jth.2019.04.001.

Louro, T.V., Grigolon, A.B., Tirachini, A., Cunha, A.L., Geurs, K.T.. How do e-bikes measure up? Analyzing speed differences and network impacts of São Paulo's bikesharing system (Version 1) [Preprint]. EngrXiv. https://doi.org/10.31224/5719.

Martin, J.C., Milliken, D.L., Cobb, J.E., McFadden, K.L., Coggan, A.R., 1998. Validation of a mathematical model for road cycling power. J. Appl. Biomech. 14 (3), 276–291. https://doi.org/10.1123/jab.14.3.276.

Mohamed, F., Chandrabose, M., Mohammad Forkan, A.R., Owen, N., Sugiyama, T., 2024. Variations in cycling distances by trip purpose and socio-demographic attributes: Implications for spatial scales to assess environmental correlates of cycling. Int. J. Environ. Res. Public Health 21 (12), 1648.

Páez, A., Anjum, Z., Dickson-Anderson, S.E., Schuster-Wallace, C.J., Martín Ramos, B., Higgins, C.D., 2020. Comparing distance, time, and metabolic energy cost functions for walking accessibility in infrastructure-poor regions. J. Transp. Geogr. 82. https://doi.org/10.1016/j.jtrangeo.2019.102564.

Palacios, M.S., El-geneidy, A., 2022. Cumulative versus gravity-based accessibility measures: which one to use? Findings. https://doi.org/10.32866/001c.32444.

Papa, E., Silva, C., te Brömmelstroet, M., Hull, A., 2016. Accessibility instruments for planning practice: a review of European experiences. Article 3 J. Transp. Land Use 9 (3). https://doi.org/10.5198/jtlu.2015.585.

Pereira, R.H.M., 2019. Future accessibility impacts of transport policy scenarios: Equity and sensitivity to travel time thresholds for Bus Rapid Transit expansion in Rio de Janeiro. J. Transp. Geogr. 74, 321–332. https://doi.org/10.1016/j.jtrangeo.2018.12.005.

Pereira, R. H. M., & Herszenhut, D. (2023). *Introduction to urban accessibility: A practical guide with R*. https://doi.org/10.38116/9786556350547.

Pereira, R. H. M., Herszenhut, D., Braga, C. K. V., Bazzo, J. P., Oliveira, J. L. A., Parga, J. P., Saraiva, M., Silva, L. P., Tomasiello, D. B., & Warwar, L. (2022). Distribuição espacial de características sociodemográficas e localização de empregos e serviços públicos das vinte maiores cidades do Brasil. *http://www.ipea.gov.br*. https://repositorio.ipea.gov.br/handle/11058/11225.

R.H.M. Pereira, D. Herszenhut, J. Reid (2024). Research, I.-I. for A. E accessibility: Transport Accessibility measures (Version 1.4.0) [Computer software].

Prefeitura do Rio de Janeiro. (2022). Rede Cicloviária do Rio de Janeiro - Existente e Planejada (2022). Data.Rio. Retrieved April 1, 2025, from https://www.data.rio/content/7b5f9b11095a4c00b2956d2ba0aa646d.

Pritchard, J.P., Stępniak, M., Geurs, K.T., 2019a. Equity analysis of dynamic bike-and-ride accessibility in the Netherlands. In: Measuring Transport Equity. Elsevier, pp. 73–83.

Pritchard, J.P., Tomasiello, D.B., Giannotti, M., Geurs, K., 2019b. Potential impacts of bike-and-ride on job accessibility and spatial equity in São Paulo, Brazil. Transp. Res. A Policy Pract. 121, 386–400. https://doi.org/10.1016/j.tra.2019.01.022.

Raffler, C., Brezina, T., Emberger, G., 2019. Cycling investment expedience: Energy expenditure based Cost-Path Analysis of national census bicycle commuting data. Transp. Res. A Policy Pract. 121, 360–373. https://doi.org/10.1016/j.tra.2019.01.019.

Rybels, S., Vanoutrive, T., Corradi, D., Coppens, T., 2024. Bicycle commuting beyond short distances: built environment, socio-demographic factors and type of bicycle influencing the choice to cycle to three university campuses. Article 4 Eur. J. Transp. Infrastruct. Res. 24 (4). https://doi.org/10.59490/ejtir.2024.24.4.7013.

Shen, C., Zhou, Z., Lai, S., Lu, L., Dong, W., Su, M., Zhang, J., Wang, X., Deng, Q., Chen, Y., Chen, X., 2020. Measuring spatial accessibility and within-province disparities in accessibility to county hospitals in Shaanxi Province of Western China based on web mapping navigation data. Int. J. Equity Health 19 (1), 99. https://doi.org/10.1186/s12939-020-01217-0.

Tomasiello, D.B., Giannotti, M., Feitosa, F.F., 2020. ACCESS: an agent-based model to explore job accessibility inequalities. Comput. Environ. Urban Syst. 81, 101462.

Van Wee, B., 2022. Accessibility and equity: a conceptual framework and research agenda. J. Transp. Geogr. 104, 103421.

Weng, M., Ding, N., Li, J., Jin, X., Xiao, H., He, Z., Su, S., 2019. The 15-minute walkable neighborhoods: Measurement, social inequalities and implications for building healthy communities in urban China. J. Transp. Health 13, 259–273. https://doi.org/10.1016/j.jth.2019.05.005.

Wilson, D.G., Schmidt, T., 2020. Bicycling Science, fourth edition. MIT Press.

Win, K. N. (2024). OpenTopography DEM Downloader (Version 3.0) [QGIS plugin].

Wu, H., Levinson, D., 2020. Unifying access. Transp. Res. Part D: Transp. Environ. 83, 102355. https://doi.org/10.1016/j.trd.2020.102355.