 DOI: 10.1590/2175-3369.016.e20230236

Assessing mobility resilience and vulnerability in the context of challenging transportation fare policies: a case study of Rio de Janeiro

Avaliação da resiliência e da vulnerabilidade da mobilidade no contexto de políticas desafiadoras de tarifas de transporte: um estudo de caso do Rio de Janeiro

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How to cite: Santos, T., Cardoso, M., Silva, M. A. V., & Fernandes, V. A. (2024). Assessing mobility resilience and vulnerability in the context of challenging transportation fare policies: a case study of Rio de Janeiro. *urbe. Revista Brasileira de Gestão Urbana*, v.16, e20230236. https://doi.org/10.1590/2175-3369.016.e20230236

Abstract

Resilience of urban mobility is an emerging topic, with most studies focusing on natural disasters or technical disturbances. However, there is a gap in understanding the resilience and vulnerability of urban mobility in the face of economic threats and inadequate transport policies, particularly in developing countries such as Brazil, characterized by social inequality and urban segregation. This study sheds light on the issue of urban inequalities and segregation, aiming to identify the most vulnerable and resilient areas of Rio de Janeiro in the event of an economic crisis. We assessed the resilience and vulnerability of the public transport system with commonly used accessibility indicators, applying fuzzy logic to data from 160 districts. We considered a scenario without the fare subsidy program. The results indicate that districts with better access to high-capacity transport systems and job opportunities exhibit higher levels of resilience and lower vulnerability. However, the study also uncovers socio-spatial inequalities, with resilience values tending to be higher in coastal areas and central business districts, exacerbating disparities. Addressing urban inequalities and segregation requires not only improving travel times and transportation systems but also considering the economic impact on vulnerable populations and promoting decentralized employment opportunities.

Keywords: Resilience. Vulnerability. Public transport. Spatial segregation.

Resumo

A resiliência da mobilidade urbana é um tema emergente, com a maioria dos estudos focando em desastres naturais ou distúrbios técnicos. No entanto, há uma lacuna na compreensão da resiliência e da vulnerabilidade da mobilidade urbana diante de ameaças econômicas e políticas de transporte inadequadas, principalmente em países em desenvolvimento, como o Brasil, caracterizados por desigualdade social e segregação urbana. Este estudo lança luz sobre a questão das desigualdades e da

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segregação urbana, com o objetivo de identificar as áreas mais vulneráveis e resilientes do Rio de Janeiro, no caso de uma crise econômica. Avaliamos a resiliência e a vulnerabilidade do sistema de transporte público usando indicadores de acessibilidade comumente usados, aplicando lógica difusa a dados de 160 distritos. Consideramos um cenário sem o programa de subsídio tarifário. Os resultados indicam que os distritos com melhor acesso a sistemas de transporte de alta capacidade e oportunidades de emprego apresentam níveis mais elevados de resiliência e menor vulnerabilidade. No entanto, o estudo também revela desigualdades socioespaciais, com valores de resiliência tendendo a ser maiores nas áreas costeiras e nos distritos centrais de negócios, exacerbando as disparidades. É evidente que enfrentar as desigualdades urbanas e a segregação requer não apenas melhorar os tempos de viagem e os sistemas de transporte, mas também considerar o impacto econômico nas populações vulneráveis e promover oportunidades de emprego descentralizadas.

Palavras-chave: *Resiliência. Vulnerabilidade. Transporte público. Segregação espacial.*

Introduction

Segregation in Latin American cities is an urban phenomenon that warrants attention due to its impact on various issues affecting disadvantaged communities. Within these large cities, poverty levels and economic inequalities create obstacles for the poorest residents, not only in terms of where they live but also in their day-to-day mobility (Rubiano-Bríñez, 2021).

One of the objectives of equitable transportation policies is to improve people's access to key destinations, such as work, healthcare, and school. In addition, equitable transportation policies are essential for people with special needs, such as the elderly, the disabled, and low-income people, who are generally more dependent on public transportation (Pereira et al., 2019).

However, municipal administrators worldwide are challenged by other problems that are part of the high complexity of acute and chronic issues, including those related to economic development, social polarization, segregation, climate changes, and ecological degradation (Spaans & Waterhout, 2017). The increasing number of shocks and disruptions, such as the global financial crisis in 2008, Brexit in 2020, and the outbreak of the coronavirus pandemic in 2020, along with their highly uneven spatial impacts, contributed to the concept's popularity of resilience. This is happening in the context of understanding the varying ability of regions to react and recover from exogenous shocks (Giannakis & Papadas, 2021).

In Brazil, recent environmental catastrophes, sanitary issues, and social and economic challenges highlight the urgent need for public policies to enhance city resilience. Disruptive events include: the ruptures of two large mining waste dams in Minas Gerais (2015, 2019); the dengue epidemic with 1,253,919 probable cases in 2024; the economic recession (2014-2016), intensified by the 2020 COVID-19 crisis; and the floods in Rio Grande do Sul, affecting over 2 million people since April 2022[1].

These shocks have the potential to trigger challenges that could impact the vibrancy of cities and, by extension, urban mobility. These challenges may encompass elevated sea levels, flooding, earthquakes, and a depletion of essential natural resources like fossil fuels (Abdrabo & Hassaan, 2015; Coaffee, 2008; Fernandes et al., 2017; Martins et al., 2019; Spaans & Waterhout, 2017).

The literature on the resilience and vulnerability of transportation systems primarily addresses threats from disasters, climate change, and systemic technical problems (Boschetti et al., 2017; Jaroszweski et al., 2014; Leichenko, 2011; Meerow, 2017; Nahiduzzaman et al., 2015; Tromeur et al., 2012). While important, there is a need for deeper exploration of economic issues and accessibility in emerging economies.

The challenges in mobility have a direct impact on individuals' daily expenses. It is crucial to specify that these challenges encompass issues such as limited access to transportation options, long travel times, and high costs. The current transportation system exacerbates socio-spatial segregation by disproportionately burdening certain communities with additional travel time and expenses (Rubiano-Bríñez, 2021).

[1]See about it in: Peduzzi (2024).

One strategy in Brazil to mitigate urban inequalities is fare integration. Fare integration allows users to pay one fare for multiple modes of transportation or a reduced price compared to the sum of individual fares. For example, a user taking a bus and a Bus Rapid Transit (BRT) pays only for the first mode. This is crucial for those living far from areas with more opportunities, enabling them to reach their destinations without incurring high transportation costs. In countries like Brazil, where economic productivity is concentrated in urban areas, equitable opportunities depend on policies addressing accessibility and mobility inequalities.

This research analyzes the connection between mobility resilience and inadequate transportation fare policies, a crucial yet often overlooked aspect in developing nations marked by extreme urban social inequality. It addresses a gap in current research by providing a methodological and exploratory analysis of a South American case study, advancing the understanding of mobility resilience in the face of inadequate transport policies.

Santos et al. (2020) introduced the methodological approach utilized in this study. Their analysis was conducted at an aggregate level, focusing solely on the 33 administrative regions of Rio de Janeiro. When examining vulnerability and resilience at the neighborhood level, the findings indicated a correlation: the most vulnerable areas exhibited lower resilience, and conversely, demonstrated an association between these two levels.

Building on the study of Santos et al. (2020), we improve the original procedure by introducing a different aggregation level. Instead of using 33 administrative regions for Rio de Janeiro, we use 160 districts and submit a further interaction to calculate the level of resilience and vulnerability. Considering these situations, our key research questions are: (i) How can Rio de Janeiro assess its resilience and vulnerability in the absence of its fare subsidy program, utilizing accessibility indicators? and (ii) if different geographic aggregation levels are used, do the results of resilience and vulnerability levels change?

Theoretical background

Resilience is associated with the ability of a system to persist, adapt, and transform itself, recover, and absorb impacts (Gaitanidou et al., 2017; Marchese et al., 2018), in the face of internal or external threats. It presents itself as a suitable concept for evaluating complex systems where dynamic interactions exist between different scales and factors, as is the case in urban spaces (Fernandes et al., 2017). Additionally, resilience involves being prepared to adapt to unprecedented and unexpected changes (Ahern, 2011). The concept used to measure resilience in this study considers the aspects presented by Holling (1973)[2] and subsequently discussed by Folke et al. (2010), dividing the concept into persistence, adaptation, and transformation.

Based on the literature on the subject and from the perspective of urban mobility, the concept of persistence is defined as the capacity of an individual or group to sustain their established mobility patterns without detriment to their quality of life. Adaptability, on the other hand, involves the ability to embrace alternative mobility patterns, also without compromising the quality of life, enabling the completion of daily activities during crisis through opportunism, creativity, or extra effort. Finally, transformability is centered around the potential to forge new mobility patterns that impact both quality of life and socioeconomic aspects (Cardoso et al., 2021; Fernandes et al., 2017; Meerow & Newell, 2019; Santos et al., 2020).

These aspects were used by Fernandes et al. (2019) and Martins et al. (2019), applying them to urban mobility and considering the scarcity of fossil fuels as a threat to mobility – both in Brazil.

Fernandes et al. (2019) argue that the resilience approach provides a novel perspective on transportation solutions, moving beyond considerations of energy consumption or CO_2 emissions. Instead, it explores the vulnerability of urban mobility to threats against fossil fuels. Their study focused on Rio de Janeiro, simulated a scenario with increased gasoline and oil-based public transportation costs,

[2]Holling (1973) harked back to the previously discussed attributes of resilience and applied them to socio-ecological systems, stressing the stability of these systems. Independently of the scope, the concepts presented involving resilience focus on the ability of a system to withstand threats or adapt to changes.

revealing that over 50% of the city's districts exhibit low-medium or low urban mobility resilience. These districts are characterized by limited accessibility to metro stations and a higher proportion of residents with lower incomes.

Martins et al. (2019) introduced a resilience assessment approach using accessible origin–destination datasets to measure a comprehensive resilience indicator. The methodology considers the potential shift from motorized to active modes in mobility disruptions. The spatial distribution of trips emphasizes the relative importance of resilient trips in the urban area, with varying income levels showing different sensitivities to resilience changes.

Although the concept of resilience converges to the ability of a system to continue functioning even when a threat materializes, some definitions presented in the literature have mentioned vulnerability when studying resilience (Gaitanidou et al., 2017; Mattsson & Jenelius, 2015), suggesting a correlation between the two concepts. Scientists have used the idea of vulnerability in two senses. The first involves the magnitude of the disturbance a community or system can absorb. In contrast, the second is related to the speed of recovery achieved in the face of a materialized threat. Furthermore, the vulnerability degree is related to the threat's nature and the system's resilience (Langridge et al., 2006).

Concerning urban planning, vulnerability is the exposure of a city to shocks in terms of magnitude and frequency (Boschetti et al., 2017), or also the susceptibility to incidents that can in some way affect a system (Berdica, 2002). When assessing urban vulnerability, the method must consider the dynamic capacity of this system since this concept is context-dependent (Salas & Yepes, 2018). Analysis of the vulnerability of a public transportation system considers interruptions that can substantially reduce the ability of the system to serve its purpose (Cats & Jenelius, 2014).

Unlike resilience's concept, vulnerability does not have a shared definition: some authors associate it with interruptions, while others define it as susceptibility to a damaging event. It is important to note that vulnerability is not necessarily the opposite of resilience: In some situations, a system can be resilient to a threat while simultaneously being vulnerable.

When the concepts of resilience and vulnerability are considered in the context of complex systems, such as cities, one must ask "what for is the city resilient?" as suggested by Meerow & Newell (2019), or alternatively, "vulnerable to what?" as suggested by Marandola & Hogan (2006). Vulnerability and resilience will always be defined in relation to a threat or a set of threats[3] and they depend on the context in which this urban space is situated. Brazil presents its singularities for the study of the resilience and vulnerability theme.

Rapid urbanization in Brazil led to unprepared cities facing numerous issues accommodating the surging population. Additionally, the mechanisms underlying the conformation of segregation patterns and segregation dynamics are multifaceted, involving historical, economic, and political factors that contribute to the uneven distribution of resources and opportunities across urban areas. Furthermore, the emergence of new urban centers introduced a socio-spatial segregation dynamic (Silva et al., 2016).

Prevailing segregation patterns in Brazilian metropolises contribute to perpetuating social inequalities and the vulnerability of large population segments based on their urban location (Carvalho, 2020). Historically, the center-periphery model characterizes this, with the center as the concentration site for the upper class and the periphery for the lower classes (Ribeiro & Ribeiro, 2021).

Spatially reproducing inequality, especially in the periphery, with longer commutes and higher costs for basic needs, renders emerging economies more susceptible to challenges affecting mobility patterns. Segregation, a prominent spatial-urban inequality manifestation in Brazilian metropolises, exhibits a significant contrast between the urban spaces of the wealthiest and the poorest. Studying any aspect of the Brazilian urban space requires considering the social and economic segregation specificities in its metropolises, large, and medium-sized cities (Villaça, 2011). Peripheral areas and *favelas* lack access to proper transportation, needing multiple transfers to access urban opportunities like employment. Fare integration becomes crucial, allowing users to transfer with a single fare, mitigating social inequalities shaped by Brazil's urban space construction.

[3]Resilience and vulnerability in the context of urban space are broad themes. See Meerow et al. (2016) and Pan et al. (2021) for a review of literature on the subject.

Materials and methods

This methodology is based on Santos et al. (2020). We improved the original procedure by introducing a different aggregation level. In this article, we used 160 districts of Rio de Janeiro instead of 33 administrative regions to calculate and analyze the levels of resilience and vulnerability, employing fuzzy logic.

Fuzzy logic is a useful tool for dealing with decisions in which the phenomenon is imprecise and vague Sałabun et al., 2019), and it is associated with urban resilience (Bozza et al., 2015; Olazabal & Pascual, 2016), sustainable transport (Rajak et al., 2016; Sałabun et al., 2019) and transportation network (Freckleton et al., 2012). We used fuzzy rules to measure the levels of vulnerability resilience based on linguistic values with the employment of accessibility indicators. The procedure applied in this article involves a hierarchical structure based on indicators of accessibility using inference blocks. In formulating this procedure, we used nine quantitative input variables that indicate a known degree of certainty for each variable, so the fuzzy logic inference system uses IF-THEN rules.

Case study: Rio de Janeiro

The city of Rio de Janeiro is the region studied, divided into 160 districts. The city is the capital of the state of Rio de Janeiro. It has a population of just over 6.2 million inhabitants (IBGE, 2022), with high indices of social inequality and demanding access to education, health, and leisure services/activities.

Rio de Janeiro has the following main modes of public transport: subway, train, ferry system, BRT (Bus Rapid Transit), LRT (Light Rail Transit), and buses. The subway system has 41 stations, three lines in operation and 14 integration points (MetrôRio, 2023). LRT allows the connection of the Port Region to the city center and Santos Dumont Airport in a faster, safer, and more sustainable way. It serves users of the various existing public transport systems and distributes these passengers in the various regions within the central area of the city (VLT, 2023). There is also a ferry system, which consists of mass transport by waterway. The system has 15 vessels and operates six lines in five stations and three mooring points (CCR Barcas, 2023). The BRT has 31 lines in 3 corridors (‘Transoeste’, ‘Transcarioca’, and ‘Transolímpica’) and 133 stations (CMTC, 2023). As for buses, there are 302 lines and 3.143 collectives serving the city of Rio de Janeiro (2023).

Figure 1 shows the current configuration of the public transportation network in the city. The metro network is entirely within the municipality of Rio de Janeiro, although its operation falls under state jurisdiction. Currently, studies are being conducted to expand its network to other municipalities, especially in the Baixada Fluminense, similar to what is already happening with the railway network.

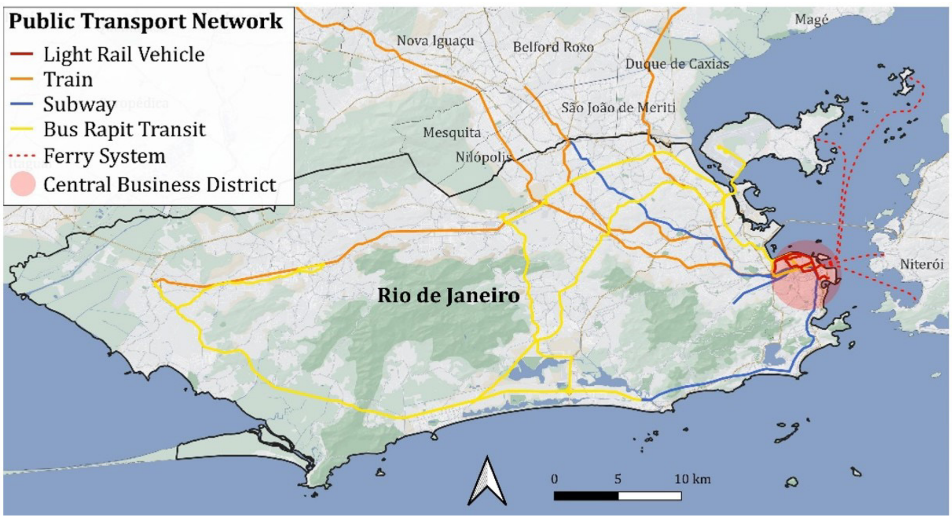

Figure 1 - City of Rio de Janeiro and current Public Transportation Network.

Besides, currently, it has free public transport for specific types of users: (i) a person with a disability; (ii) a person over 65 years old; (iii) a student from public school on the home-to-school route; (iv) a low-income university student.

Input variables – accessibility indicators

Threats related to economic changes that can affect the accessibility of public transportation generally involve data on employment, household income, social development indicators, and population, besides the average trip time and fare cost of public transport for each origin-destination pair under consideration. The input variables used are based on accessibility indicators.

The two accessibility indicators used regarding access to jobs are travel time and travel cost, which are appropriate to measure resilience against the threat chosen: cancellation of subsidized fares (as part of a fare integration program). Equations 1, 2, 3, and 4 represent the indicators (Deboosere & El-Geneidy, 2018; El-Geneidy et al., 2016):

$$A_i = \sum_{j=1}^{n} O_i f(C_{ij}) \tag{1}$$

$$f(C_{ij}) = \begin{cases} 1 \ if \ C_{ij} \leq t_{thereshold} \\ 0 \ if \ C_{ij} > t_{thereshold} \end{cases} \tag{2}$$

where A_i is the accessibility in census tract j, O_i is the number of jobs in census tract *i*, C_{ij} is the travel time between census tracts *i* and *j*, and $t_{thereshold}$ is the average duration of a commute by public transport in the region (Deboosere & El-Geneidy, 2018, p. 56).

Based on time:

$$C_{ij} = t_{ij} \quad (3)$$

Based on fare cost:

$$C_{ij} = F_{ij} \quad (4)$$

where Fij is the cost of transit fare to travel from zone i to zone j (El-Geneidy et al., 2016, p. 305-306).

These equations were used to calculate the intervening opportunities, travel time, number of jobs that can be accessed from an origin within 60 minutes, and number of jobs that can be accessed with the cost of a single fare.

Besides indicators based on travel time and cost, we also considered average monthly income since the threat involves an economic change (higher travel cost). We defined nine input variables, as identified in Table 1. It contains variables, their description, and the literature source of each one.

The number of jobs accounted for refers to formal jobs occupied in the city of Rio de Janeiro, according to the demographic census. Up to the present moment, there are no official sources that account for the number of informal jobs in the city. The SDI (Social Economic Index) is an index based on life expectancy at birth, educational level, and comfort and sanitation. In other words, it is conceptually similar to the Human Development Index, but it replaces the “Income” index with the “Comfort and Sanitation” index. Distance matrices are calculated by the Google API, considering the distance traveled between the origin and destination using public transportation.

As indicated in Table 1, input variables were obtained from three sources: the Brazilian national census, conducted every 10 years by the Brazilian Institute of Geography and Statistics (IBGE); Google API; and RioCard (the company that manages and distributes multiple fare cards). The 2010 census is the most recent because the 2020 census was delayed due to covid-19[4].

[4] On the page Censo 2022 (IBGE, 2022), it can find more information about the delay and the results that have been disclosed up to the present moment.

Table 1 - Input Variables

Variables	Description	Source
Employment	number of formal jobs in the destination district	Brazilian National Census (IBGE, 2010)
Population	population of the district of origin	Brazilian National Census (IBGE, 2010)
Intervening opportunities	number of jobs that can be reached sooner than or in equal time required to reach a given destination district from the district of origin	Brazilian National Census (IBGE, 2010) and Google Distance Matrix API (time)
Travel time	time necessary to arrive at the destination from the origin	Google Distance Matrix API
Jobs (60 minutes)	number of jobs that can be reached within 60 minutes by public transportation	Google Distance Matrix API
Jobs (1 fare)	number of jobs that can be reached by paying a single fare, irrespective of the number of travel modalities	Google Distance Matrix API
Fare difference	difference between the fare paid without and with the subsidy	Google Distance Matrix API and Rio Card
Income	nominal per capita household income	Brazilian National Census (IBGE, 2010)
SDI	social development index	Brazilian National Census (IBGE, 2010)

Empirical model

In formulating the analysis model, each node corresponds to a fuzzy rule base, called an inference block (IB), for computation of linguistic variables, by aggregation and composition to produce an inferred result, also in the form of a linguistic variable (Cury, 2007). Fuzzy logic is a tool used to solve complex problems because it can figure conclusions and produce responses based on vague, ambiguous, and/or qualitatively incomplete or imprecise data (Adjetey-Bahun et al., 2016; Cosenza et al., 2016). The main concepts necessary for modeling fuzzy systems are described next, based on articles by Faizi et al. (2018), Sałabun (2014), Sałabun et al. (2019), and Yager (2000):

- **Definition 1**: Fuzzy set and pertinence function. The characteristic function μ_A of a crisp set $A \subseteq$ X attributes a value of 0 or 1 to each member in X, so a crisp set permits only one complete association ($\mu_A(x) = 1$) or no association ($\mu_A(x) = 0$). This function can be generalized to the function μ_A, provided the value attributed is in a specified interval, that is, $\mu_{\tilde{A}}$: X → [0, 1]. The attributed value indicates the classification of the member of the element in set A. The function $\mu_{\tilde{A}}$ is called the pertinence function and the set $\tilde{A} = (x, \mu_{\tilde{A}}(x))$, where $x \in$ X, defined by $\mu_{\tilde{A}}(x)$ for each $x \in$ X, is called a fuzzy set.
- **Definition 2.** The rule base consists of the logical rules of a determined causal relationship that exists in a system among input and output fuzzy sets.
- **Definition 3**. The fuzzy rule. A simple fuzzy rule can be based on a conditional statement. The reasoning process uses logical connections based on IF-THEN, OR, and AND.
- **Definition 4**. A typical fuzzy model uses rules based on 'IF-THEN' logic. More formally, the process used to determine the output of a given input is called fuzzy inference. Based on this inference, the output is called the degree of pertinence, in which the value varies from 0 to 1, and is determined by Equation 5:

$$E_i(y) = T(\tau_i B_i(y)) \quad (5)$$

where: E_i is a fuzzy subset, τ_i is the degree of this function; and B_i is the fuzzy subset of the linguistic concepts defined in space y.

- **Definition 5**. For the procedure described in this article, we considered rules using "AND" as a set of variables (for example, IF the number of jobs at the destination is high AND the population of the origin is high, THEN the potential for use is high). This is denoted by Equations 6 and 7:

$$T(\tau_i B_i(y)) = \tau_i \wedge B_i(y) \; (\wedge = \min) \tag{6}$$

$$T(\tau_i B_i(y)) = \tau_i B_i(y) \; (\text{output}) \tag{7}$$

Besides these, the operator $S(E_1(y), E_2(y), \ldots E_n(y))$ for the method that considers the union of rules with "OR" involves Equations 8 and 9:

$$S(E_1(y), E_2(y), \ldots, E_n(y)) = \text{Max}_i(E_i(y)) \tag{8}$$

$$S(E_1(y), E_2(y), \ldots, E_n(y)) = 1 - \prod(1 - E_i(y)) \tag{9}$$

- **Definition 6**. To obtain a crisp output, it is necessary to "defuzzified" the result, denoted by y*. According to the centroid method, the defuzzification function is given by Equation 10:

$$y^* = \frac{\sum_y E(y)y}{\sum_y E(y)} \tag{10}$$

Thus, we formulated nine inference blocks, represented in Figure 2.

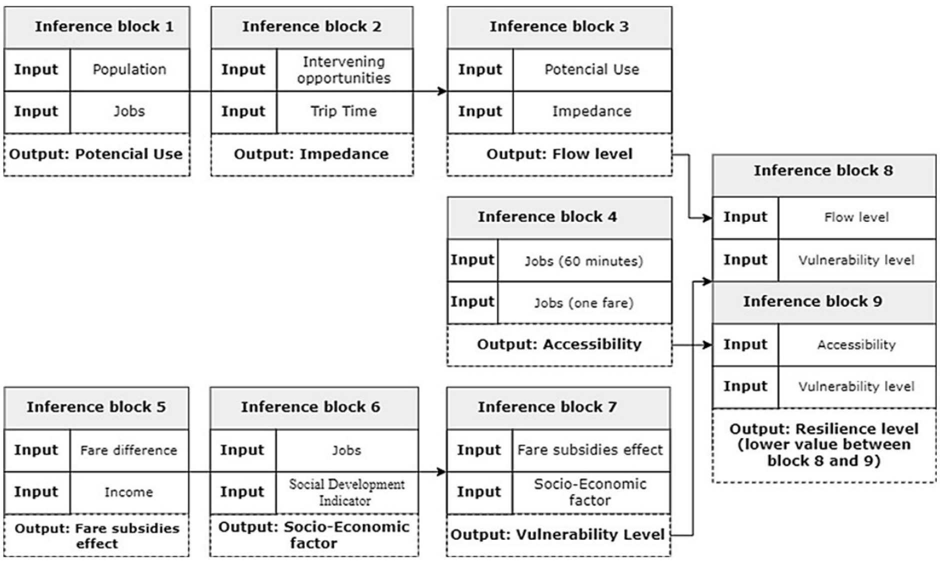

Figure 2 - Inference Blocks.

Each inference block represented in Figure 2 has a set of rules considering the linguistic values. The nine inference blocks created have a total of 266 rules with linguistic values represented by trapezoidal, triangular, and Gaussian functions, also considering that each rule has a weighting factor called the Certainty Factor (CF), ranging from 0 to 1, which indicates the degree of importance of each rule in the rule base of the fuzzy logic.

In inference block 1, the 'potential use' output associates the population of the origin with employment at the destination. For example, if the population at the origin is high and employment at the destination is high, there is a significant of public transportation users in this origin who are likely to travel to that destination, given its high attractiveness. In other words, the potential use of the public transportation network between both regions is high.

In inference block 2, the output “impedance,” which can be characterized as a resistance or impediment factor to movement, associates travel times with access to opportunities, which may include workplaces, educational facilities, leisure spots, healthcare facilities, among others, and other intervening opportunities along the traveled route. Stouffer (1940) introduced the concept of intervening opportunities, which asserts that the number of people traveling a certain distance is directly related to the number of opportunities available at that distance and inversely related to the number of intervening opportunities, that is, opportunities those individuals would have while taking alternative routes. According to Ortúzar & Willumsen (2011), the fundamental concept of the intervening-opportunities is that the act of making a trip is not directly tied to distance, but rather to the relative accessibility of opportunities that fulfill the purpose of the trip.

In inference block 2, among other rules, it considers that if intervening opportunities are high until reaching the destination and the time is high, then the impedance is high. In this context, impedance refers to movement resistance, encompassing obstacles like travel time, distance to key locations, and other barriers encountered along the route.

In inference block 3, we have two inputs: potential use and impedance. The potential use associates the population at the origin with the employment at the destination. This means that if a destination has a high number of jobs and the population at the origin is also high, the origin-destination link tends to have a high usage potential.

The flow level consists of the relationship between the potential of use and impedance, for example: if the potential of use is high and impedance is low, then the flow level is high. In inference block 4, the output is accessibility. In this case, it is established that if the quantity of jobs available within 60 minutes by public transportation is high and the quantity of jobs available with 1 fare is high, then the accessibility is high.

In inference block 5, the output is the effect of fare integration. This block examines the interaction between input variables: fare difference and income (origin). The fare difference represents the disparity between the full cost of using public transportation to a destination and the cost paid with the provided fare integration. In this case, the interaction is with input variables: fare difference and income (origin). The fare difference is the subtraction between the full value of using public transportation to a destination and the value paid with the provided fare integration. Within inference block 5, one of the rules stipulates that the effect of integration increases with both the fare difference to a destination and the income of the origin neighborhood. Put simply, when the fare difference is higher and the income of the origin neighborhood is lower, the effect of integration on transportation usage increases. Inference block 6 deals with socioeconomic factors, where there is an interaction between employment variables at the origin and the social development indicator (SDI). The higher the number of jobs at the origin and the higher the SDI, the higher the socioeconomic factor. Inference block 7 outputs the level of vulnerability, with interaction between the effect of fare integration and socioeconomic factors. The higher the effect of fare integration and the lower the socioeconomic factor, the higher the level of vulnerability.

The resilience level was considered the lower value between inference blocks 8 and 9. In inference block 8, it is the interaction between the flow level (output of inference block 3) and the vulnerability level (output of inference block 7). Inference block 9 is the interaction between accessibility (output of inference block 4) and vulnerability level (output of inference block 7).

Table 2 presents the description of the output variables used in the logical architecture of the problem employing fuzzy logic.

Through the application of fuzzy logic, we prepared two matrices – one representing the level of resilience, the other representing the level of vulnerability. These were 160 x 160 matrices supported by all the steps carried out so far. The matrices and the code used in the Matlab software are available at: github.com/talitaflor/resiliencia

To present our results, we designed maps of the city’s districts. First, the vulnerability map was constructed according to the arithmetic mean of the values obtained in each district. Then, the same procedure was used to build the resilience map.

Table 2 - Description of the output variables of each inference block

Variables	Description	Inference block
Potential use	measures the Origin-Destination connection used based on population and employment variables	1
Impedance	measures opposition to the movement	2
Flow level	measures the flow of the connection Origin-Destination based on the impedance and potential for use	3
Accessibility	measures the easiness of reaching a destination	4
Effect of fare integration	calculates the importance of fare integration	5
Socioeconomic factor	measures the socioeconomic factor of each connection	6
Level of vulnerability	measures the level of vulnerability based on fare integration and socioeconomic factor	7
Level of resilience	measures the level of resilience based on the smallest value between the flow level and vulnerability level (inference block 8) and accessibility and vulnerability level (inference block 9)	Smallest value between inference blocks 8 and 9

Source: Authors (2023).

Results and discussions

First, we present the results on the level of resilience and vulnerability, highlighting the levels of income and employment in each district. We also present maps indicating the average vulnerability and resilience of 160 districts of Rio de Janeiro. In the second part, we discuss the results and compare previous studies on vulnerability and resilience analysis in the city of Rio de Janeiro.

Level of vulnerability and resilience

Figure 3 plots the average vulnerability and average income results obtained. According to quadrants I and II, the first income bracket (US$ 1,000)[5] includes all vulnerability levels. Hence, there is no relationship between the level of vulnerability and income.

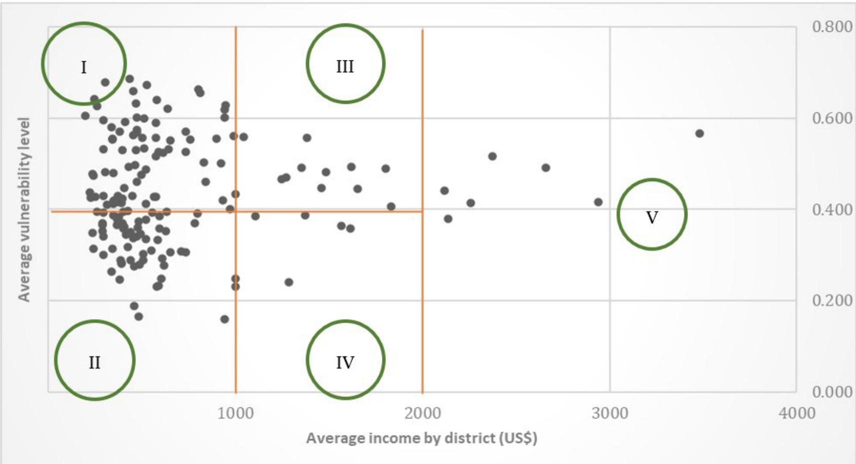

Figure 3 - Average Vulnerability and Income.

Analysis of the ten districts with the highest average vulnerability levels indicated that none offer mass transit options (commuter train or subway) – Barra de Guaratiba, Guaratiba, Vargem Grande, Alto da boa vista, Vargem Pequena, Camorim, Rocinha, Paquetá, Jacarepaguá e Anil. Furthermore, of these districts, two have a lower average household income level than the citywide average (Rocinha and Guaratiba).

[5] US$ 1 = R$ 4,86. Minimum wage (2010): R$ 510

Figure 4 plots the average vulnerability and the number of jobs. There is no linear relationship between these two variables. Still, it is remarkable that four of the ten most vulnerable districts are among those with the lowest number of formal jobs in the city. In this graph, the downtown district (which has 627 thousand jobs) was removed for better visualization.

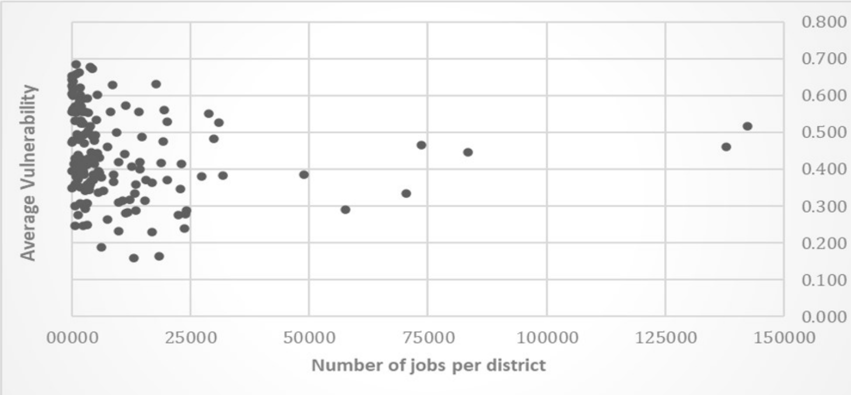

Figure 4 - Average Vulnerability and number of jobs per district.

This shows that the worst indices of average vulnerability, if the fare subsidy comes to an end, are not associated only with isolated factors. For example, districts may have critical levels of income or formal jobs, but the absence of mass transit occurs in all of them. A spatial analysis of the districts with the lowest vulnerability levels showed that they are located near the downtown district (which has the most significant number of jobs). Furthermore, seven of the ten least vulnerable districts have mass transit options (subway and/or commuter train). Finally, three of them are among the 30 with the highest income levels.

Regarding the number of jobs offered by the districts, the downtown district stands out, with approximately 627 thousand legal jobs, equal to 28% of all formal jobs in the city. For the districts with the lowest average vulnerability levels, the predominant factors in the analysis are not income or the number of jobs available but rather the presence of mass transit and proximity to the downtown district.

Regarding the level of resilience, none of the ten districts with the lowest average resilience levels is served by mass transit, corroborating the findings regarding the lowest vulnerability levels. Conversely, the ten districts with the highest average resilience levels are also the ten with the lowest vulnerability levels (Praça da Bandeira, Cidade Nova, Estácio, Centro, Méier, Engenho Novo, Maracanã, Santa Teresa, Engenheiro Leal e Todos os Santos). Seven of these districts have mass transit (commuter train, subway, or both). Figure 5 plots the relationship between average resilience and average income. For an average monthly income of US$ 1,000, resilience levels vary widely, from 0.32 to 0.85.

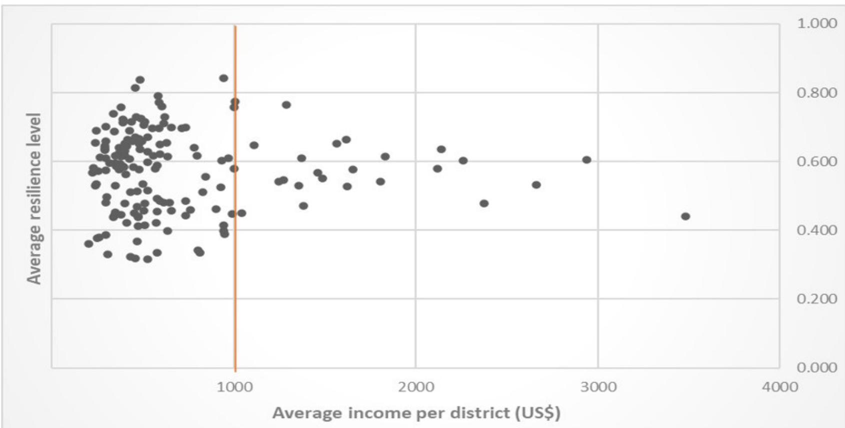

Figure 5 - Average Resilience and Income.

Figure 6 depicts the relationship between average resilience and employment opportunities. A remarkable finding is the concentration of districts with up to 25 thousand formal jobs, in which average resilience levels are included.

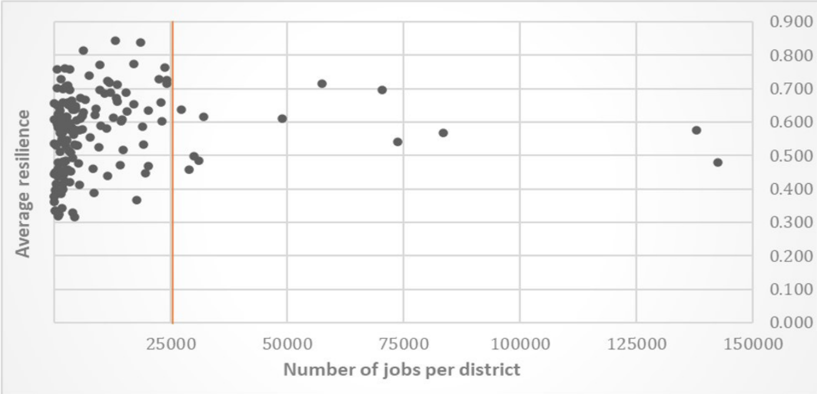

Figure 6 - Average Resilience and number of Jobs per district.

Discussions

We presented two key research questions. The first concerns how to measure the level of resilience and vulnerability if its current program of fare subsidies ceases to exist, and the second is whether the change in the level of aggregation affects which are the most resilient and vulnerable regions.

Santos et al. (2020) proposed the methodological procedure adopted in this article for the first key research question. However, those authors presented an aggregate analysis that considered only the 33 administrative regions of Rio de Janeiro. By analyzing the level of vulnerability and resilience by neighborhood, the result was that the most vulnerable areas were the least resilient and vice versa, showing a correlation between these two levels. Figure 7 illustrates the maps with the average levels of vulnerability and resilience for the 160 districts of the city of Rio de Janeiro.

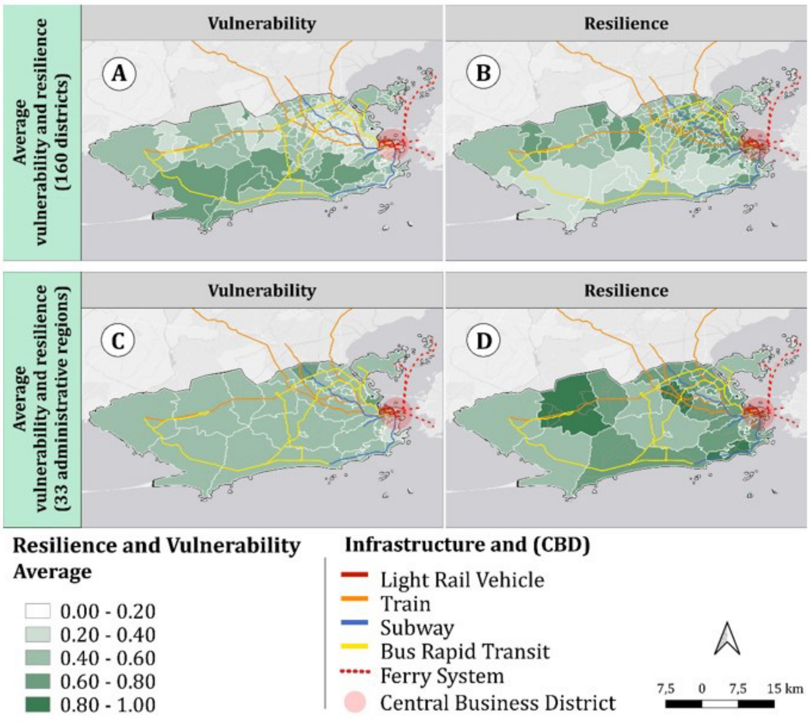

Figure 7 - Maps indicating average vulnerability and resilience of Rio de Janeiro.

Figure 7 displays 4 maps. Map A shows the average vulnerability for 160 neighborhoods, while map B depicts the average resilience at the same level of aggregation. Maps C and D illustrate the average vulnerability and resilience, as assessed by Santos et al. (2020), for 33 administrative regions in Rio de Janeiro.

In maps with lower levels of aggregation (A and B), there is a noticeable differentiation in resilience and vulnerability levels due to the absence of tariff integration. Areas with lower vulnerability are near the Central Business District (CBD), as well as in the northern and southern parts of the city. Similarly, areas with higher resilience levels are near the CBD.

In map C, with a lower level of aggregation for vulnerability levels, it is noted that almost the entire city of Rio de Janeiro has similar levels of vulnerability to the absence of tariff integration. On the other hand, map D shows various levels of resilience in the city. Regions with trains or subways have higher resilience levels, as well as areas near the CBD and the coastal area with subway availability.

This demonstrates that even when using the same method, the level of data aggregation influences results and analyses. A higher level of aggregation allows for a more refined analysis of the data and a better understanding of the impact of the threat of tariff integration absence.

Beyond the specific analyses of resilience and vulnerability related to fare integration, it is crucial to consider the dimension of socio-spatial segregation in the urban context of Rio de Janeiro. The differentiated distribution of these indicators on the maps may be intrinsically linked to broader issues of social inequality and segregation.

The concentration of areas with higher resilience near the Central Business District (CBD) may reflect historical patterns of urban development and investments, resulting in socio-spatial disparities. Identifying these patterns can contribute to a more comprehensive understanding of urban dynamics, enabling the formulation of more equitable and inclusive policies to address social challenges associated with mobility and access to urban services. Thus, the analysis of the maps not only informs about the implications of fare integration but also provides valuable insights for addressing broader issues of segregation and social justice in the city.

Regarding the second key research question, change in the aggregation level also affected results for the most resilient regions. In the study by Santos et al. (2020), the coast concentrated most resilient areas, possibly due to the high average income and ease of reaching downtown jobs, due to the presence of mass transit. By reducing the level of aggregation to districts and using the same procedure, we found that the most resilient regions are concentrated in districts with numerous job opportunities and located near downtown (more to the north of the city), but not necessarily the districts with the highest income levels.

Similarities for the most resilient areas, in the analysis by 33 administrative regions and 160 districts, are the presence of mass transit, the supply of jobs, and the ease of reaching the downtown area, which is responsible for 28% of the formal jobs in the city. This means that it is not one factor that makes a region resilient or less vulnerable to stress but all the conjunctures.

For purposes of comparison with previous studies, we compared three articles on resilience and vulnerability analysis in Rio de Janeiro. The articles consider different threats: (i) violence in public transport (Cardoso et al., 2021), (ii) lack of fare integration (Santos et al., 2020), and (iii) scarcity of fossil fuels (Fernandes et al., 2019).

The first article Cardoso et al. (2021) related to violence in public transport uses variables such as population, number of jobs, travel time, and number of criminal incidents associated with public transport, with an analysis of 21 administrative regions (ARs). The results showed that the south (Lagoa, Copacabana, Botafogo) and the north zone concentrate the most resilient administrative regions (Vila Isabel and Tijuca). Both have a high concentration of jobs and mass public transport. High-income levels are also a characteristic of the south zone.

The second study Santos et al. (2020) is related to the absence of fare integration. The most resilient administrative regions were: Tijuca, Lagoa, Copacabana, Botafogo, and Barra da Tijuca. Tijuca is in the north zone where public transport is available, close to the Center Business District (CBD). Barra da Tijuca has similar characteristics to the administrative regions of Botafogo and Copacabana. The most vulnerable are: Paquetá, Ilha do Governador, Cidade de Deus, and Rocinha. The results of these articles show that the most resilient regions are similar. The ARs of Tijuca, Lagoa, Copacabana, and Botafogo are the most resilient toviolence (Cardoso et al., 2021) and integration fares (Santos et al., 2020). For the analysis of the level of vulnerability, the most vulnerable regions are different, although both articles use the same level of aggregation.

The third article, focusing on Rio de Janeiro, examines resilience amid fossil fuel scarcity (Fernandes et al., 2019). Simulating a gasoline and oil-based transportation cost increase, the study reveals over 50% of Rio's districts exhibit low-medium or low urban mobility resilience. These areas, marked by limited metro station accessibility and higher proportions of residents with reduced incomes, were analyzed across the city's 160 neighborhoods. The most resilient neighborhoods to fuel price hikes were Centro, Copacabana, Ipanema, Botafogo, Gávea, and Barra da Tijuca. These areas excel in public transport access, job opportunities, and income levels. Table 3 presents the comparison of the results of the three articles discussed and the present article.

Table 3 - Comparison of results on resilience and vulnerability in Rio de Janeiro

	Threat			
	Violence (Cardoso et al, 2021)	**Fare System (Santos et al, 2020)**	**Fossil Fuels (Fernandes et al, 2019)**	**Present article**
Resilience analysis	The most resilient regions are in the south zone (coastal area) and the north zone. Both are characterized by a high concentration of jobs and the availability of mass public transport. The south zone is also characterized by a high average income	The most resilient regions are in the south, north, and west zones. The West Zone (specifically, Barra da Tijuca) has income characteristics, PT availability, and jobs similar to the South Zone.	Districts with lower levels of resilience are in areas with lower accessibility to metro stations and more citizens with reduced income levels	The most resilient areas are not related to income level, but the availability of jobs and mass public transport
Vulnerability analysis	The most vulnerable regions are associated with low income. The authors argue that economic vulnerability brings a higher incidence of crimes.	The most vulnerable administrative regions are distant from the CBD, with low concentration of jobs and without access to high-capacity public transport.	No vulnerability analysis	The most vulnerable districts are far from the CBD, with low concentration of jobs and without access to high-capacity public transport.
Variable inputs	Population, Jobs, intervening opportunities, travel time, criminal occurrences associated with PT and police coverage	Population, Jobs, Average Nominal Income, Social Development Indicator, Fare difference (fare paid with and without subsidy), Travel time	Income, Jobs, Metro Access/District (%), Train Access/District (%), Bicycle Access to Metro Stations (%), Bicycle Access to Train Stations (%)	Population, Jobs, Average Nominal Income, Social Development Indicator, Fare difference (fare paid with and without subsidy), Travel time
Aggregation Level	21 Administrative Regions	33 Administrative Regions	160 districts	160 districts

Conclusions

This study sheds light on the issue of urban inequalities and segregation. The findings reveal a correlation between resilience and vulnerability levels in Rio de Janeiro, particularly in relation to economic threats and inadequate transport policies.

Our first key research question is how to measure the level of resilience and vulnerability. We considered the presence or absence of subsidized fares (through an integrated system) with the use of more than one public transportation mode in Rio de Janeiro. The second key research question is about changing the level of resilience and vulnerability if there is a change in the level of geographic aggregation.

Based on these two questions, we present that the procedure was initially described by Santos et al. (2020), and as recommended by those authors, we used more detailed geographic aggregation. This required changing the form of analysis to simplify comprehension. For this reason, we worked with averages to indicate the levels of resilience and vulnerability. In our more disaggregated analysis, we found that the levels of resilience and vulnerability had a negative correlation, unlike what Santos et al. (2020) found in their more aggregated analysis. Besides proposing a way to measure resilience, this method can be applied to other Brazilian cities.

We examined Rio de Janeiro's 160 districts, assessing vulnerability and resilience levels, focusing on the hypothesis of no fare subsidy, reducing commuting costs. Our approach circumvented the need for Origin-Destination analysis, using Brazilian National Census and Google Distance Matrix API data. Fuzzy logic facilitated complex problem analysis, yielding matrices for each origin-destination pair, totaling 25,600 links.

Results inform sustainability and resilience policies for Rio. Mass transit systems, including suburban trains, subways, and buses in reserved lanes, enhance resilience and reduce vulnerability. Recommendations include policies encouraging formal job creation in peripheral areas for an equal geographic distribution of employment opportunities.

Our study is a valuable tool for policy discussions, identifying critical neighborhoods with greater vulnerability and lower resilience to fare integration absence. Addressing urban inequalities requires improving travel times, and transportation systems, and considering economic impacts on vulnerable populations, promoting decentralized employment.

This procedure supports sustainable mobility indicators, aiding policy development for cityscape maintenance, quality of life preservation, and resilience to economic stress. In emerging countries, such as Brazil, our study reveals deficient conditions in balancing economic growth and sustainable development, leading to increased resilience values in coastal and central business districts, exacerbating socio-spatial inequality.

Our research underscores challenges in Rio, extending beyond reducing suburban travel times through technological advances. Transportation costs significantly affect socioeconomically vulnerable populations, hindering accessibility to urban opportunities. Future research should apply our method to other Brazilian cities, consider additional variables, and explore the impact of various fare policies on resilience and vulnerability.

For future research, we suggest applying this method to other Brazilian cities for comparative analysis. Encouraging studies with additional variables for measuring vulnerability and resilience to economic threats is essential. Analyzing the impact of diverse fare policies, considering population income, and examining scenarios to determine regional resilience and vulnerability are recommended. Exploring the creation of formal jobs in peripheral areas can be valuable in assessing alterations to resilience and vulnerability to economic threats. Future studies should investigate the statistical correlation between vulnerability and resilience.

A limitation of our research is focusing solely on the absence of fare subsidies, neglecting the effects of subsidy reduction or increase on resilience or vulnerability. Replicability is limited by specific urban environment characteristics, making the study inapplicable to cities lacking public transportation with fare subsidies. Utilizing the arithmetic mean, while improving result evaluation, may impede a detailed analysis on a more refined scale.

Urban resilience, as measured in our model, is confined to an economic threat, and does not encompass all factors influencing a city's functioning. Future studies should explore how different political contexts may affect urban resilience, acknowledging its application within administrative and political frameworks.

Acknowledgements

We thank the reviewers and editors for their helpful comments and suggestions.

Data availability statement

The dataset that supports the results of this paper is available at SciELO Data and can be accessed via https://doi.org/10.48331/scielodata.0IIE7I.

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Special Section: Urban Inequalities and Segregation (Guest editors: Joana Barros, Agnes Silva de Araujo, Flavia F Feitosa)

Received: June 20, 2023
Approved: June 04, 2024