

Mapping Telecommunication Gaps Through Socioeconomic and Infrastructure Indicators: A Case Study in Brazil

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Abstract—This study addresses the persistent digital divide in Brazil by integrating socioeconomic and infrastructure indicators to identify underserved municipalities with limited Internet access. Building upon the Economic Hardship Index (EHI) and the Access Density Index (ADI), we introduce two novel composite metrics: *connectivity potential* and *vulnerability score*. Unlike existing approaches that rely solely on technical or socioeconomic factors, our method captures the intersection of social fragility and infrastructure gaps. Using a vector-based formulation, these metrics reveal both high-potential municipalities, where latent demand for connectivity remains unmet, and critically vulnerable regions where compounded hardship and poor access coexist. Spatial analysis across Brazilian macro-regions, particularly in the North and South, uncovers local disparities that are hidden when only national-level averages are considered. The results highlight the relevance of region-specific strategies and provide a data-driven framework to support policy design, regulatory prioritization, and investment decisions aligned with digital inclusion goals, including those outlined in the IMT-2030 vision for 6G development.

Index Terms—connectivity metrics, digital divide, Internet access, social factors, Brazil.

I. INTRODUCTION

INTERNET access is a fundamental enabler of socioeconomic development, facilitating connectivity, information exchange, and access to economic opportunities. It is well established that Internet access is strongly correlated with education and income levels within a country [1], [2]. Individuals with higher income are more likely to benefit from better connectivity and the associated advantages. Expanding and equalizing Internet access has the potential to empower communities, particularly by improving access to online education, employment opportunities, and healthcare services, such as telemedicine, that can significantly improve quality of life in remote or underserved regions [3], [4].

As such, increasing Internet accessibility is key to promoting digital inclusion and addressing the digital divide, especially in developing regions. With the increasing availability of affordable mobile devices and the expansion of cellular

infrastructure, rural populations are increasingly able to benefit from online connectivity [5]. Furthermore, the Internet plays a critical role in mitigating knowledge disparities associated with socioeconomic status. In the contemporary digital environment, access to online information has become more closely linked to income and education than access to traditional media platforms such as newspapers and television [6]. This underscores the need for equitable access to the Internet as a means to reduce disparities in educational and information resources.

In addition, the expansion of broadband technologies, when coupled with digital literacy initiatives, enhances the potential for inclusive socioeconomic development. Integrating broadband deployment with sustainable development goals and community participation can help reshape the understanding of the digital divide [7]. This approach supports the development of national policies and community-driven programs that promote digital literacy and strengthen information and communication technology competencies, ultimately enabling individuals to participate more effectively in the digital economy. By prioritizing Internet access and digital skills development in disadvantaged regions, policymakers can create conditions for innovation, entrepreneurship, and broader economic inclusion.

A. Telecommunications in Brazil

The telecommunications sector in Brazil has evolved significantly since its origins in the late 19th century, when telegraphy and telephony were first introduced, primarily in urban centers and largely supported by foreign investment and technology. Recognizing its strategic importance, the Brazilian government began regulating the sector in the early 20th century, leading to state-driven expansion efforts in subsequent decades.

By the mid-20th century, telecommunications infrastructure saw substantial growth, driven by public sector policies aimed at expanding telephone and broadcasting services. During the military regime (1964–1985), infrastructure development became a national priority, leading to major investments in telecommunications. This period included the establishment of a state-owned company responsible for coordinating domestic and international communications, which also played a role in fostering local technological capabilities [8], [9].

In the 1990s, a wave of deregulation and privatization redefined the sector. The opening of the market to private and foreign investments improved service quality, increased competition, and accelerated infrastructure deployment, especially in mobile telephony and Internet services. These reforms positioned Brazil as a regional leader in telecommunications

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and contributed to broader economic modernization. Despite this progress, Brazil still faces major challenges in ensuring equitable Internet access. Urban areas report approximately 65% Internet penetration, while rural regions lag behind at only 34% [10]. This disparity is reinforced by regional economic differences, with the North and Northeast showing lower connectivity rates than the South, Southeast, and Center-West.

A tool to reduce this digital gap lies in 5G. While deployment of the technology can widen the digital gap, since more developed and high-income areas tend to receive better infrastructure first [11], adequate policy design and investment can be effective in mitigating this trend [12]. As shown in [10], cooperation between macro-operators and rural micro-operators can not only improve connectivity in rural areas but also turn economically unattractive regions into profitable ones. With investment typically focused on urban areas, encouraging deployment strategies such as these can reduce the digital gap without imposing obligations or penalties on the providers.

B. Urban-Rural Divide

The disparity in connectivity extends beyond Brazil and represents a global challenge. According to recent findings by [13], the urban-rural divide in Internet access remains significant, with rural areas consistently lagging behind in access to digital technologies. Despite progress in Internet infrastructure, rural communities, particularly in low- and middle-income regions, often experience limited connectivity.

Initiatives aimed at effectively connecting these areas also enable the deployment of advanced technologies in agriculture. In recent years, robotization and data collection have become integral to farming [14], requiring fast and reliable connections between various sensors, automated devices, and cloud-based services [15]. These applications not only boost agricultural productivity but also generate valuable data for understanding farming processes. This knowledge is essential for achieving hardware and software sufficiency within a circular economy framework [16].

To enable the deployment of these and other technologies, strategies to achieve rural connectivity have long been developed. Previous works have proposed approaches to cover unconnected rural areas, such as ad hoc networks for basic services (voice communication and low-data-rate services) [17]. Today, better options are available due the advent of 5G, with fixed wireless providing rural Internet access in par to urban experience [18].

C. Problem Formulation

Although Brazil's telecommunications sector has experienced substantial growth in recent decades, fueled by infrastructure expansion, mobile network deployment, and broadband diffusion, deep regional and socioeconomic disparities persist. Many municipalities, particularly those in rural, remote or economically marginalized areas, remain underserved in terms of access to reliable and high-speed Internet. This uneven distribution of telecommunication services reinforces

the digital divide, limiting access to essential services such as education, healthcare, and digital economic participation, and ultimately perpetuating structural inequalities across regions.

Addressing this issue requires more than nationwide infrastructure programs; it demands data-driven tools capable of identifying where interventions will yield the greatest social and economic returns. Mechanisms that combine infrastructure availability with indicators of social vulnerability can support regulators in designing more effective incentive schemes, concession obligations, and spectrum licensing strategies. Identifying such regions would help mitigate the challenges of 5G, which currently prevent the technology from fully connecting everyone, everywhere [19]. Notably, this approach aligns with the official objectives for 6G (IMT-2030), as defined by the International Telecommunication Union (ITU) [20], which emphasize equitable, high-quality connectivity as a global development goal.

D. Novelty and Contribution

The primary novelty of this work lies in the development of a connectivity assessment framework that jointly considers both technical infrastructure indicators and socioeconomic vulnerability. While previous work has demonstrated the effectiveness of utilizing socioeconomic indicators in telecommunication analysis, for example as a tool for spectrum sensing [21], we propose a novel application to policy design and investment prioritization. In this context, prior approaches typically focus on either network deployment metrics or demographic data in isolation, our methodology integrates both dimensions into two original composite indicators: *connectivity potential* and *vulnerability score*. This dual-perspective enables a more nuanced identification of municipalities where policy interventions may be most urgent or impacting.

Specifically, our main contributions are:

- We introduce a normalized, vector-based formulation that combines the Economic Hardship Index (EHI) and the Access Density Index (ADI) into interpretable metrics that support region prioritization. This addresses a key limitation in current telecommunications policy planning: the absence of objective, scalable criteria for selecting regions to receive support or regulatory obligations.
- By analyzing spatial patterns in connectivity potential and vulnerability across Brazilian municipalities, we uncover critical regions that are either overlooked by traditional infrastructure-focused metrics or misclassified due to disparities that are hidden when only national-level averages are considered. These insights support more equitable and effective allocation of public and private investment in telecommunications infrastructure.
- The proposed methodology is computationally simple, adaptable to different datasets, and replicable across countries, making it a practical tool for regulators, network planners, and policy designers seeking to reduce the digital divide under the IMT-2030 framework.

Tab. I defines the acronyms used in this paper.

TABLE I
LIST OF ACRONYMS.

Acr.	Definition
ANATEL	Brazilian National Telecommunications Agency
ADI	Access Density Index
CCI	Cellular Coverage Inequality Index
EHI	Economic Hardship Index
IBGE	Brazilian Institute of Geography and Statistic
ITU	International Telecommunication Union
SMP	Personal Mobile Service

II. RELATED WORK

The pivotal role of infrastructure in shaping the digital divide and its impact on social inequalities is highlighted by [22]. This recent review paper categorizes infrastructure as a key factor influencing the digital divide. Crucially, it emphasizes how profit-based discrimination by broadband carriers, who opt not to enter specific areas due to profitability concerns, negatively impacts broadband access. These infrastructure-related disparities primarily affect the first-level digital divide, which is the basic access gap. Consequently, this uneven distribution of Internet infrastructure intensifies existing social inequalities by restricting access to vital digital opportunities, thereby limiting citizens' social and economic capital and their participation in society. The paper underscores that while progress has been made, the digital divide, largely driven by these infrastructural limitations, remains ever-present and creates unequal opportunities for individuals.

Although the digital divide is often seen as a concern just for low-income and underdeveloped countries, it may be surprising to analyze the inequality in terms of connectivity in any society, even in highly developed countries. In [23], the authors discuss the increasing digital gap between urban and rural areas in Sweden. The evaluation includes the development of the Cellular Coverage Inequality Index (CCI) to measure the digital divide in cellular coverage. This index combines a measure of rurality (based on a weighted sum of distances to nearby centers of service) with data on 30 Mbit/s cellular coverage provided by the Swedish regulator. The CCI, similar to the Lorenz curve and Gini index in economics, quantifies the digital gap. A CCI close to 0 indicates equal distribution of cellular coverage, while a value close to 1 suggests coverage is concentrated in urban areas. The report illustrates the CCI's application in Sweden, helping to identify underserved regions. However, the CCI is solely based on technical aspects; there is no socioeconomic data involved in calculating it.

In the United States, significant disparities in Internet access exist across various demographic groups. Research indicates that children residing in households with limited computing resources and without adults who regularly use the Internet exhibit a decreased propensity for Internet engagement [24]. This underscores the critical need for household-level interventions to foster equitable Internet access among school-age children [24]. Furthermore, recently in [25], it was reported that a substantial proportion of school-age children (28.0%) did not utilize the Internet at either school or home, with

an additional 22.8% using it exclusively at home, thus highlighting persistent access issues linked to resource availability. Regrettably, these findings also suggest a correlation where a lack of in-home Internet use is associated with a reduced likelihood of Internet access at school. This could imply that such schools may lack the necessary educational technology resources due to fiscal constraints and/or limited broadband provider availability [25]. Consequently, these observations point to an uneven distribution of Internet service availability.

The study by [26], conducted in Chicago, highlights how the digital divide in urban areas is significantly influenced by neighborhood-level factors and the availability of broadband infrastructure, despite general network presence. The authors point out that federal broadband initiatives primarily targeted rural infrastructure, largely overlooking urban areas for affordable Internet access in high-poverty communities. The research revealed that cost and lack of skill are primary barriers to home Internet access in Chicago, particularly for African-Americans and Latinos, even when accounting for individual income. Furthermore, neighborhoods with high concentrations of African-American or Latino populations are disproportionately affected by perceived cost burdens, which could be due to factors such as limited competition among service providers or higher local prices for other necessities. These findings emphasize that while broadband service may be technically available, its affordability and the localized market dynamics of Internet service provision are critical in perpetuating urban digital inequalities.

The structure and performance of the Internet backbone also create accessibility issues. Network analysis reveals disparities in city accessibility to internet services, with service provider network designs significantly impacting connectivity. It is well known that the disparities are particularly notable between the size of the population and the accessibility of cities, underscoring the need for better infrastructure distribution strategies [27]. Moreover, the work by [28] details how the Internet's infrastructure reinforces and creates spatial disparities. It shows that backbone networks prioritize world cities, leading to uneven access. This selective investment by telecommunications carriers in economically attractive urban areas, and the concentration of critical interconnection points in a few cities, exacerbates digital inequality. The authors discuss the concepts of premium networked spaces versus unconnected network ghettos to illustrate how service provider infrastructure decisions create and perpetuate digital divide, leaving many areas underserved due to a focus on agglomeration rather than universal access.

A recent work [29] reveals that, in the modern U.S., the quality of Internet infrastructure significantly impacts local economic outcomes and exacerbates inequality. Using historical data, the study demonstrates that faster Internet, particularly for businesses, drives employment growth and shifts economic activity towards high-skilled services. This infrastructural advantage, however, increases local wage inequality, as high-skilled workers' earnings rise disproportionately. These findings underscore how quality Internet access, while a driver of growth, simultaneously widens economic disparities by favoring already advantaged areas and skilled labors.

Australia's rural digital divide is investigated by [30]. Despite national policies, rural areas face limited availability, inconsistent quality, unreliable speeds, and high-priced data plans, creating significant disparities with urban connectivity. This broadband quality divide stems from market failure and government deployment of inferior technologies in low-density areas. Consequently, rural users incur increased direct and indirect costs, exacerbating existing social and economic inequalities with urban populations. The authors argue that these rural-urban inequities will persist unless the interrupted nature of connectivity is addressed.

A contemporary spatial and multivariate analysis of global digital divide, focusing on technology access, infrastructure, and artificial intelligence uses, is provided in [31]. The study explicitly includes infrastructure as a dependent variable group, examining factors like international Internet bandwidth and population covered by mobile networks. Its findings reveal clear geospatial clusters, with advanced nations leading and significant disparities persisting in regions like Sub-Saharan Africa and parts of Central America. Crucially, the analysis indicates that more affluent nations tend to invest in and develop robust infrastructure, thus reinforcing global inequalities in connectivity. The paper also highlights a significant association between civil liberties and Internet access, proposing that political freedom encourages infrastructure expansion and broader Internet use. These results underscore that the availability and quality of Internet infrastructure, shaped by economic viability and policy environments, remain fundamental drivers of the global digital divide and its associated social inequalities.

From the preceding discussion, it is evident that Internet access plays a crucial role in social and economic development, with the potential to either narrow or widen the digital divide among communities and countries. Consequently, guiding investments not solely to the most profitable markets for access providers, but rather prioritizing communities that stand to benefit most from the social and economic impacts of Internet access, becomes paramount. For this purpose, the utilization of adequate metrics for economic and social inequalities serves as an invaluable tool.

A. Economic Hardship Index (EHI)

The EHI is a comprehensive metric quantifying community financial challenges by integrating socioeconomic indicators like unemployment, income, and housing affordability [32], [33]. It serves as a vital tool for policymakers and researchers to pinpoint areas of significant socioeconomic disparities and implement targeted interventions. Beyond economic assessment, the EHI highlights social ramifications, showing a correlation between higher EHI values and adverse health outcomes, such as elevated obesity rates due to limited access to nutritious food in disadvantaged neighborhoods [34]. This demonstrates the EHI's utility as a comprehensive indicator linking economic conditions to public health issues. The EHI is instrumental in understanding and addressing social inequalities, providing insights into how economic hardship perpetuates poverty and constrains upward mobility, especially in marginalized communities [34]. Analyzing EHI data enables

authorities to identify regions for urgent socioeconomic investment, fostering economic resilience and overall well-being.

Distinguishing itself from broader measures like the human development index [35], the EHI offers a more granular assessment of financial adversity at a sub-national level [34]. Its advantage lies in precisely identifying areas for urgent socioeconomic investment and targeted interventions. Moreover, the EHI's demonstrated high correlation with Internet accessibility in communities suggests its potential as a metric for prioritizing digital infrastructure investments in areas facing economic hardship, making it an indispensable tool for bridging the digital divide [36].

III. PROPOSED METHODOLOGY

Prior research examining the correlation between EHI and connectivity [36] has shown that regions with more favorable socioeconomic conditions (i.e., lower EHI) tend to exhibit higher levels of Internet access. Consequently, municipalities with strong socioeconomic indicators are generally expected to have better connectivity infrastructure. When such municipalities are found to have low access density, this may indicate unmet demand for Internet access, highlighting opportunities for targeted intervention by service providers or regulators.

Our methodology aims to use this correlation to identify regions of interest for investment and policy design. To do so, a vectorial approach is proposed in this section.

A. Socio-Economic Datasets

Our analysis draws on multiple data sources from the Brazilian Institute of Geography and Statistics, including the Continuous National Household Sample Survey,¹ Brazilian Census,¹ and Central Business Register.² These datasets provide comprehensive annual and multi-year estimates of social, economic, and housing characteristics across various geographic scales and demographic groups.

State-level poverty data from the Institute of Applied Economic Research,³ based on IBGE's Synthesis of Social Indicators and national poverty thresholds, were used for broader geographical analysis.

Reliable data at the municipal level are scarce, so we restricted the analysis to a single census year (2022). As result, time discrepancies have not occurred, and data for all Brazilian cities was available.

B. Adapting the EHI

In order to compute the above proposed metrics, it is necessary to calculate the EHI, in which case the following variables are typically used. *Unemployment*: Percentage of the population that is unemployed; *Dependency*: The ratio of individuals under 18 or over 65 to the total population; *Education*: Rate of individuals over 25 who have completed secondary education; *Income*: Average income per capita; *Poverty*: Percentage of the population living below the national

¹<https://servicodados.ibge.gov.br/api/docs/agregados?versao=3>

²<https://servicodados.ibge.gov.br/api/docs/pesquisas>

³<https://www.ipeadata.gov.br/>

poverty line; *Crowded housing*: Percentage of households with more than one resident per room.

In the Brazilian context, data availability varies according to both spatial granularity and temporal resolution. Given these limitations, certain adaptations were necessary in the composition of the EHI. Specifically: *Crowded housing* was replaced by the average number of residents per household; *Education* was represented by the literacy rate; *Income* was substituted with the average salary; and *Poverty* was excluded due to the unavailability of reliable data. Nevertheless, even with the exclusion of Poverty, the average income in EHI ensures that wealth-related information remains captured in the analysis.

The EHI calculation involves normalizing the values of each variable within the selected population. As an inequality indicator, normalization must be adjusted to reverse the growth direction of variables that are inversely proportional to socioeconomic inequality, such as income. To normalize the variables based on their relationship with inequality, different equations were applied. For variables directly proportional to inequality (where higher values indicate worse conditions, i. e. unemployment, dependency, poverty and crowded housing), variable $x \in X$ was normalized to x_{norm}^d as

$$x_{norm}^d = \frac{X_{max} - x}{X_{max} - X_{min}}. \quad (1)$$

For variables inversely proportional to inequality (where higher values indicate better conditions, i. e. education and average income), the normalization employed was

$$x_{norm}^i = \frac{x - X_{min}}{X_{max} - X_{min}}, \quad (2)$$

where

- X is the set of regional values for the given socioeconomic axis (e. g., the set containing each municipal income value);
- X_{max} is the maximum value in the set X ;
- X_{min} is the minimum value in the set X .

As in its original conception [32], [33], a simple average of all normalized variables is then calculated, attributing equal weights for all socioeconomic axes analyzed. This process yields an EHI value ranging from 0 to 1, where higher values indicate more severe socioeconomic conditions.⁴

C. Access Density Index (ADI)

Additionally, we incorporated mobile Internet access data from the Brazilian National Telecommunications Agency (ANATEL) via Open Data Portal.⁵ We used the Personal Mobile Service (SMP) access density as our connectivity indicator, given its strong correlation with Internet access availability and intensity, since this metric also reflects telecommunication infrastructure presence, as it directly relates to SMP deployment. The access density metric combines all 4G and 5G connections within a region, normalized by the resident

population. To address potential outliers, the calculation caps individual access density at 1.5 per person.

In this analysis, the access density values were unity-normalized, to enhance the visualization of relative differences across municipalities. Additionally, normalization ensures that both the EHI and access density contribute equally to the metric calculation. This normalized access measure is referred to as the Access Density Index (ADI).

D. Connectivity Potential and Vulnerability Score Calculation

To identify municipalities with high **connectivity potential**, each city is represented as a point on a two-dimensional plane, with ADI on one axis and EHI on the other. As illustrated in Fig. 1 (top), each point defines a vector whose magnitude reflects the municipality's relative position with respect to these two indicators. Since the objective is to highlight municipalities with low values on both axes (i.e., better socioeconomic indicators and lower access to Internet), those with greater connectivity potential correspond to vectors with smaller magnitudes. To obtain a normalized and crescent value, the metric is calculated as

$$\text{Connectivity Potential} = 1 - \sqrt{\frac{\text{EHI}^2 + \text{ADI}^2}{2}}. \quad (3)$$

This logic can be adapted to define a **vulnerability score**, designed to identify municipalities characterized by both poor socioeconomic conditions and limited Internet access. This is accomplished by applying the same vector-based approach, now using $1 - \text{EHI}$ as in Fig. 1 (bottom). The resulting metric facilitates the detection of underserved areas that may benefit significantly from investments in telecommunication infrastructure; information that can be particularly valuable to service providers and policy makers. The vulnerability score is calculated by

$$\text{Vulnerability Score} = 1 - \sqrt{\frac{(1 - \text{EHI})^2 + \text{ADI}^2}{2}}. \quad (4)$$

IV. CONNECTIVITY AND SOCIOECONOMIC ANALYSIS

To validate the proposed methodology for jointly analyzing connectivity and socioeconomic factors, it is essential to assess the correlation between these variables within the observed region. Moreover, the methodology must accurately reflect real-world conditions in its modeling approach and produce insights that support meaningful conclusions.

In this section, we begin by examining the relationship between socioeconomic factors and Internet access in Brazil, with particular focus on the distribution of the EHI and access density nationwide. We then use the identified correlations to explore real-world disparities, such as those between rural and urban areas and across different geographic regions. Finally, we demonstrate how our proposed metrics reinforce these findings by providing a concrete example.

⁴The original index consists of a value between 0 and 100. However, to apply a vector based approach and compare the utilized values at the same scale, a normalized 0 to 1 range was employed.

⁵<https://dados.gov.br/dados/conjuntos-dados/acessos-autorizadas-smp>

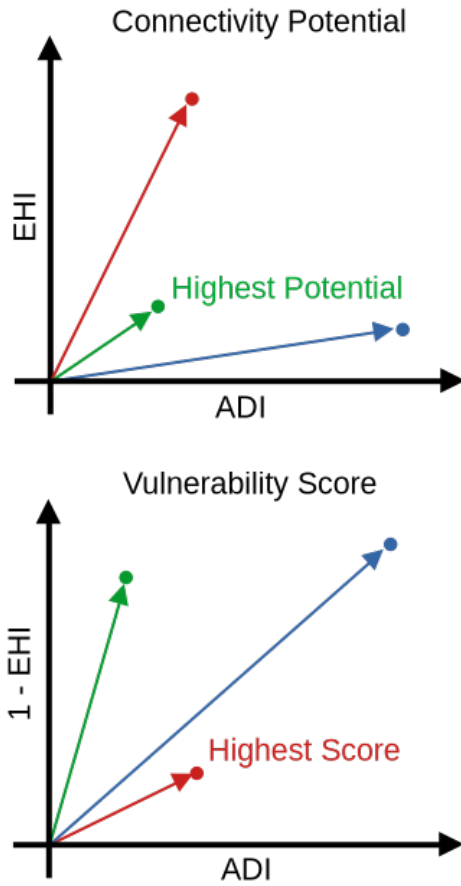


Fig. 1. Representative vectors of three illustrative municipalities with their respective EHI and ADI. The shorter vectors results in bigger metric values for both the connectivity potential and the vulnerability score.

A. Socioeconomic Factors Influencing Internet Access

The EHI and ADI distributions for the municipalities in Brazil are illustrated in Fig. 2. It reveals the presence of several regions with low EHI and high ADI, particularly in the Southeast. Conversely, areas with both high EHI and low ADI are especially concentrated in the North and Northeast.

Analyzing the correlation between the EHI and ADI, we found a Pearson correlation coefficient with a magnitude of 0.59. By comparison, the analysis conducted by the Chicago team [36] obtained a coefficient magnitude of 0.82 when reproduced with the same data used by the team, adding the Python lines below to their publicly available code.⁶

```
y=100 - chicago_df["hh_no_internet(%)"]
x=chicago_df["hardship_score"]
numpy.corrcoef(x=x, y=y)
```

Although our result indicates a weaker linear relationship, this difference can be attributed to the disparity in sample sizes and, consequently, the number of outliers. While the Chicago study examined only 77 community areas, our analysis includes 5,571 Brazilian municipalities.

⁶<https://github.com/uchicago-dsi/broadbandequity/tree/main/archived-chicago-code>

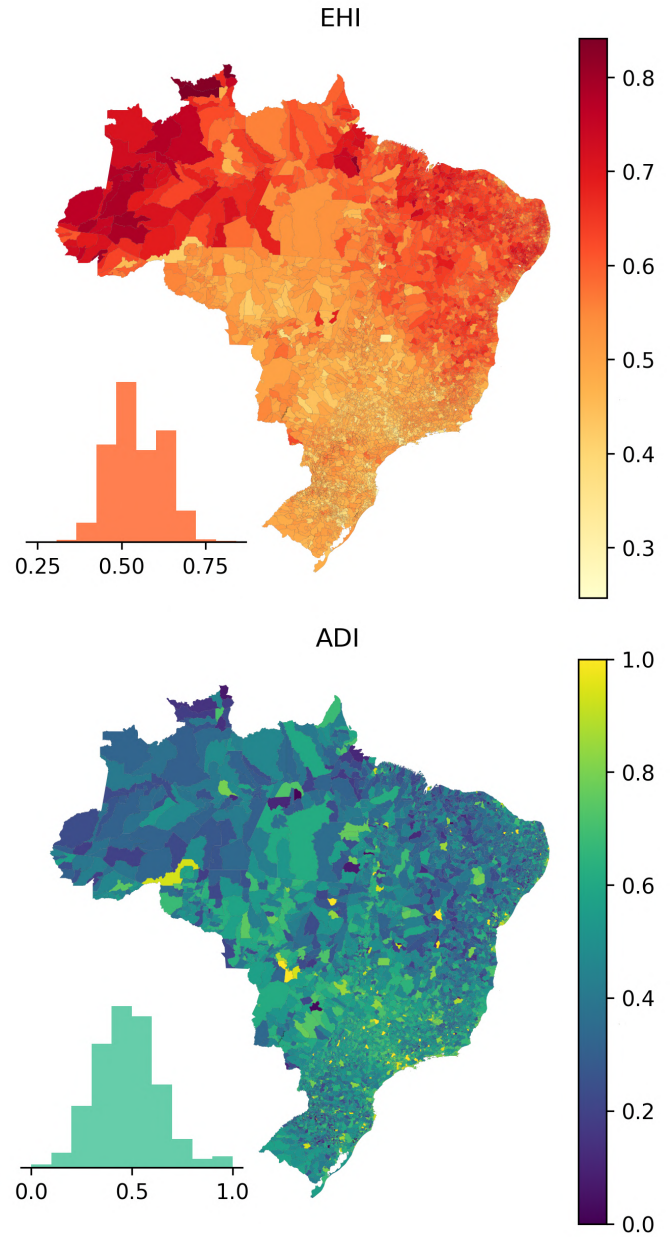


Fig. 2. EHI and ADI in the Brazilian cities. Data from 2022.

To further explore this effect, we conducted a similar correlation analysis at the state level, considering data for the 27 Brazilian Federative Units and including poverty indicators that are available only at this level of aggregation. Calculating the EHI and ADI for each state, the number of outliers is significantly reduced, resulting in a Pearson correlation coefficient of 0.84 in 2022. This finding supports the hypothesis that the relatively weaker correlation observed at the municipal level is largely influenced by sample size. Nevertheless, as we demonstrate in the following sections, the correlation between EHI and Internet access density, despite being lower at the municipal level, remains sufficiently strong to support a range of relevant and meaningful analyses.

Furthermore, when examining the individual components of the EHI separately, their correlations with ADI are consistently

weaker than that of the composite index, as shown in Tab. II. Among these components, some variables stand out, most notably the unemployment rate, which exhibits a comparatively stronger association.

TABLE II
PEARSON'S COEFFICIENT ABSOLUTE VALUES FOR CORRELATION WITH ACCESS DENSITY. DATA FROM 2022.

Index	Pearson's ρ
EHI	0.59
Unemployment	0.56
Literacy rate	0.52
Dependency	0.38
Residents per household	0.31
Average salary	0.29

B. Urban vs. Rural Divide in Internet Access

In Brazil, the disparity between urban and rural areas is evident when analyzing access density alongside the distribution of metropolitan regions. As municipalities become more distant from metropolitan centers, access density tends to decline. The rate of this decline varies across regions, with more pronounced drops observed in areas such as the North.

As shown in Fig. 3, a similar pattern emerges in the distribution of the EHI and ADI. The black contours in the image indicate metropolitan regions, showing that both indicators tend to get worse as the distance from more urbanized areas grows - specially comparing the lower right metropolitan regions with the extreme left of the region.

C. Regional Differences

Brazil is a country of continental dimensions, with regions that often exhibit markedly different socioeconomic characteristics. When analyzing the Southeast and North regions of the country, the difference in the distribution of EHI and ADI becomes clear, as can be seen in Fig. 4.

The ranking shown in Tab. III, which lists municipalities by their EHI values, highlights regional disparities. While six of the ten municipalities with the lowest EHI scores are located in the Southeast, all ten with the highest scores are in the North. This contrast underscores the uneven development across regions, observed on both EHI and ADI distributions.

Despite the stark differences between these regions, the correlation between EHI and ADI remains relatively consistent. The Pearson correlation coefficient was 0.58 in the North and 0.64 in the Southeast, indicating a similar relationship between socioeconomic vulnerability and Internet access in both areas.

D. Vulnerability Score and Connectivity Potential Analysis

When applying the proposed vulnerability score from Section III to identify the ten most vulnerable municipalities in Brazil, several overlaps with those exhibiting the lowest EHI values become evident. As shown in Tab. IV, all listed municipalities present both high EHI and low ADI, highlighting the effectiveness of the proposed method. Six of these municipalities are located in the North region, aligning with

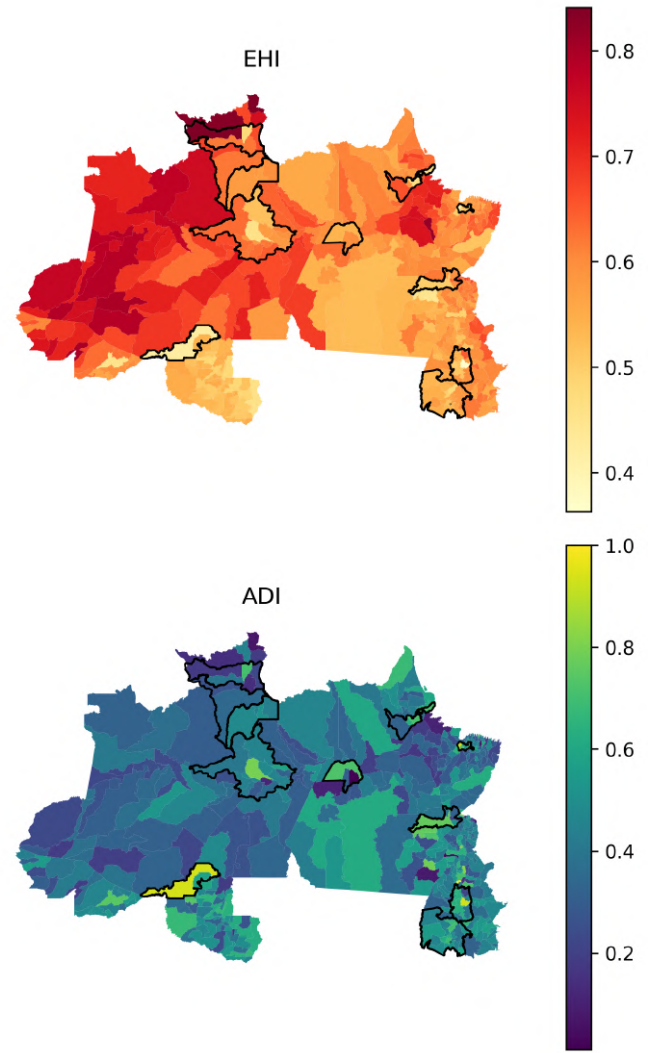


Fig. 3. Distribution of ADI and EHI around metropolitan regions in the North of Brazil. Metropolitan areas are outlined in black.

the previously identified socioeconomic fragility in that area. The remaining municipalities are in the Northeast, indicating this region as a secondary hotspot of vulnerability according to the proposed metric.

Then, by selecting the ten cities with the highest connectivity potential, Tab. V was obtained. Most of the municipalities in the list are located in the South region, indicating a significant disparity between socioeconomic conditions and connectivity in that area. Another region with high potential is the Central-West, which accounts for three of the remaining entries. These cities exhibit EHI values in the medium-to-low range, indicating great socioeconomic metrics, but their ADI is even lower than that of the vulnerable municipalities listed in Tab. IV.

V. PRACTICAL APPLICATION

As shown in Tab. IV and Tab. V, the vulnerability score and connectivity potential can be utilized at the national level to identify macro-regions of interest. Additionally, a more localized analysis enables the identification of specific

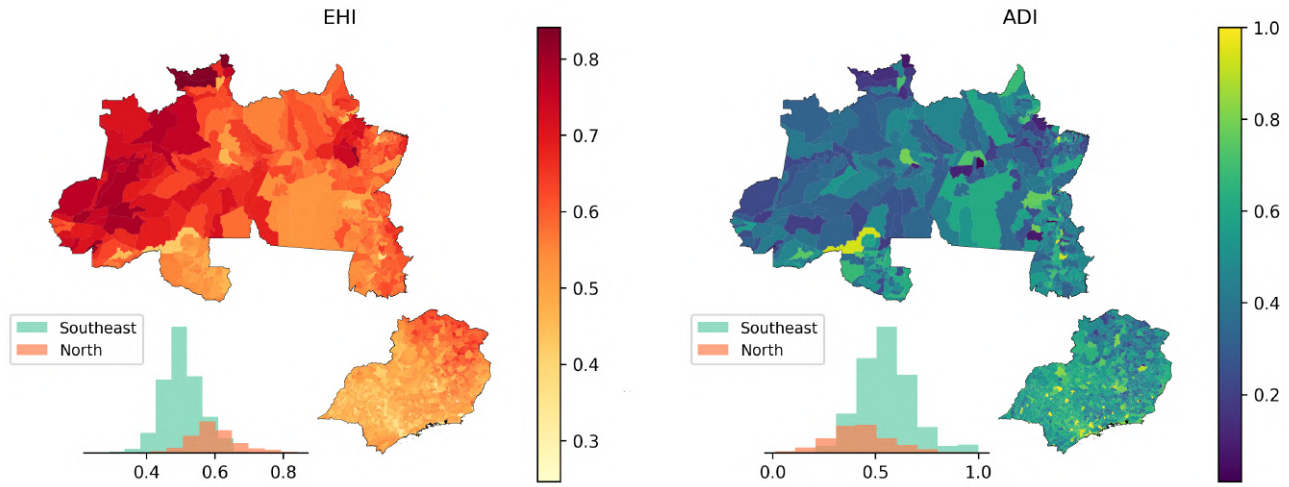


Fig. 4. Comparative of EHI and ADI distributions in North and Southeast regions.

TABLE III
ON THE LEFT ARE THE TOP 10 BRAZILIAN'S MUNICIPALITIES BY EHI IN 2022, AND ON THE RIGHT ARE THE BOTTOM 10.

Top 10 Cities				Bottom 10 Cities			
Municipality	EHI	ADI	Region	Municipality	EHI	ADI	Region
Barueri (SP)	0.25	1.00	Southeast	Tonantins (AM)	0.78	0.26	North
Florianópolis (SC)	0.28	0.92	South	Jutai (AM)	0.79	0.34	North
Macaé (RJ)	0.29	0.71	Southeast	Pauini (AM)	0.79	0.22	North
Fernando De Noronha (PE)	0.29	1.00	Northeast	Ipixuna (AM)	0.79	0.20	North
Jeceaba (MG)	0.30	0.78	Southeast	Itamarati (AM)	0.80	0.35	North
Gavião Peixoto (SP)	0.30	0.70	Southeast	Santa Rosa Do Purus (AC)	0.80	0.23	North
Vitória (ES)	0.32	0.83	Southeast	Bagre (PA)	0.81	0.21	North
Brasília (DF)	0.33	0.76	Central-west	Amajari (RR)	0.83	0.18	North
Porto Alegre (RS)	0.33	0.79	South	Alto Alegre (RR)	0.84	0.20	North
São Paulo (SP)	0.33	0.91	Southeast	Uiramutã (RR)	0.84	0.09	North

TABLE IV
TEN MOST VULNERABLE BRAZILIAN MUNICIPALITIES ACCORDING TO THE PROPOSED VULNERABILITY SCORE. THE CITIES THAT OVERLAP WITH THE BOTTOM 10 OF TAB. III ARE HIGHLIGHTED IN BOLD.

Municipality	EHI	ADI	Vulnerability Score	Region
Uiramutã (RR)	0.84	0.09	0.87	North
Amajari (RR)	0.83	0.18	0.83	North
Alto Alegre (RR)	0.84	0.20	0.82	North
Bagre (PA)	0.81	0.21	0.80	North
Cachoeira Grande (MA)	0.72	0.06	0.80	Northeast
Jenipapo Dos Vieiras (MA)	0.75	0.15	0.80	Northeast
Ipixuna (AM)	0.79	0.20	0.80	North
Milagres Do Maranhão (MA)	0.75	0.15	0.79	Northeast
Fernando Falcão (MA)	0.74	0.15	0.79	Northeast
Santa Rosa Do Purus (AC)	0.80	0.23	0.78	North

municipalities within these macro-regions that most urgently require, or would significantly benefit from, investment.

Similarly to the EHI and ADI, the connectivity potential and vulnerability scores exhibit spatial clustering. Municipalities with high connectivity potential, for example, are frequently surrounded by others with comparable potential. This spatial correlation allows for the identification of both individual municipalities of interest and regional clusters suitable for large-scale investment initiatives.

A concrete application of this approach is the analysis of

the North and South regions of Brazil. To emphasize regional characteristics and disparities, the following analyses focus exclusively on municipalities within each respective region.

A. Vulnerability Score in the North Region

The North region contends with both connectivity and socio-economic challenges. Its municipalities exhibit the highest vulnerability scores in the country, and as such, have a clear infrastructure lag.

TABLE V
TEN BRAZILIAN MUNICIPALITIES WITH HIGHEST CONNECTIVITY POTENTIAL.

Municipality	EHI	ADI	Connectivity Potential	Region
Balbinos (SP)	0.38	0.21	0.70	Southeast
Vale Real (RS)	0.44	0.01	0.69	South
São José Do Inhacora (RS)	0.44	0.04	0.69	South
Pilar De Goiás (GO)	0.43	0.16	0.68	Central-West
Westfalia (RS)	0.41	0.22	0.67	South
Mucum (RS)	0.46	0.06	0.67	South
Paraíso Das Águas (MS)	0.46	0.04	0.67	Central-West
Santa Rita Do Trivelato (MT)	0.47	0.09	0.66	Central-West
São João Do Polesine (RS)	0.47	0.11	0.66	South
Botuverá (SC)	0.41	0.26	0.66	South

The implementation of telecommunications infrastructure in this region is inherently complex. Factors such as dense forest cover and the widespread distribution of rivers must be carefully considered when determining optimal investment locations. Nevertheless, an initial assessment based on vulnerability scores proves valuable in identifying preliminary groupings of municipalities, thus limiting the complexity of in deep analysis to the most critical zones.

As illustrated in Fig. 5, the municipalities with the highest vulnerability scores, outlined in black, are situated among others with similarly high scores, forming extensive clusters delineated with dotted lines.

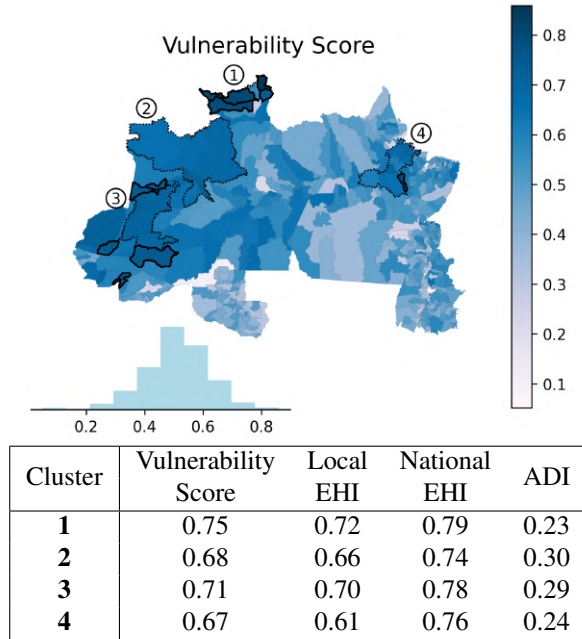


Fig. 5. Vulnerability score distribution in the North region. The 10 municipalities with the highest scores are outlined in solid lines; clusters of cities with high vulnerability scores are outlined in dotted lines. The table shows mean values for each identified cluster.

Across all clusters, ADI values remain low. While the national EHI underscores pronounced socioeconomic disadvantages, the local EHI (calculated considering only municipalities within the North region) indicates substantial fragility even in relation to regional norms.

Therefore, based on the spatial distribution and the quan-

titative indicators, coordinated inter-municipal initiatives are likely to yield significant impact in the region. Moreover, the observed concentration of clusters on the left side of the figure points to a particularly critical area that merits heightened attention.

B. Connectivity Potential in the South Region

The South of Brazil displays generally favorable socioeconomic indicators; however, connectivity is unevenly distributed throughout the region. The presence of small, dispersed municipalities and a predominantly mountainous geography poses significant challenges to the uniform development of telecommunications infrastructure.

In Fig. 6, several clusters of municipalities with high connectivity potential are observable, though they are notably smaller than those identified in the North. Additionally, a greater number of isolated cases are present: municipalities with high potential surrounded by others exhibiting lower connectivity potential.

The EHI values for these clusters were moderate at both local and national levels, indicating that the highlighted municipalities demonstrate some degree of socioeconomic development without critical levels of fragility. In contrast, the ADI values suggest connectivity limitations, with results comparable to those found in vulnerable municipalities in the North. With the exception of clusters #2 and #6, which showed relatively higher ADI and lower EHI, all groups had connectivity indices below 0.30.

A comparison between Tab. VI and the clusters identified in Fig. 5 reveals that EHI and ADI values tend to decrease when analyzing municipalities individually. While EHI values declined to low-to-moderate levels, suggesting improved socioeconomic conditions, the ADI values were significantly lower for some individual municipalities, indicating substantial connectivity gaps.

This distribution suggests that, in the South, targeted investments focused on specific municipalities, rather than broad regional initiatives, would likely yield greater effectiveness and efficiency.

VI. CONCLUSION

This work presented a quantitative approach to identify telecommunication gaps in Brazil by integrating infrastructure

TABLE VI

TEN MUNICIPALITIES IN THE SOUTH REGION WITH THE HIGHEST CONNECTIVITY POTENTIAL, CONSIDERING ONLY CITIES WITHIN THE REGION.

Municipality	Connectivity Potential	Local EHI	National EHI	ADI
Vale Real (RS)	0.70	0.42	0.43	0.01
São José do Inhamorá (RS)	0.69	0.43	0.44	0.04
Westfália (RS)	0.68	0.40	0.41	0.22
Botuverá (SC)	0.67	0.39	0.41	0.26
Muçum (RS)	0.66	0.47	0.46	0.06
Tangará (SC)	0.65	0.43	0.43	0.25
Coqueiros do Sul (RS)	0.65	0.49	0.48	0.07
São João do Polêsine (RS)	0.65	0.48	0.47	0.11
Boa Vista do Cadeado (RS)	0.65	0.47	0.46	0.15
Treviso (SC)	0.65	0.34	0.38	0.36

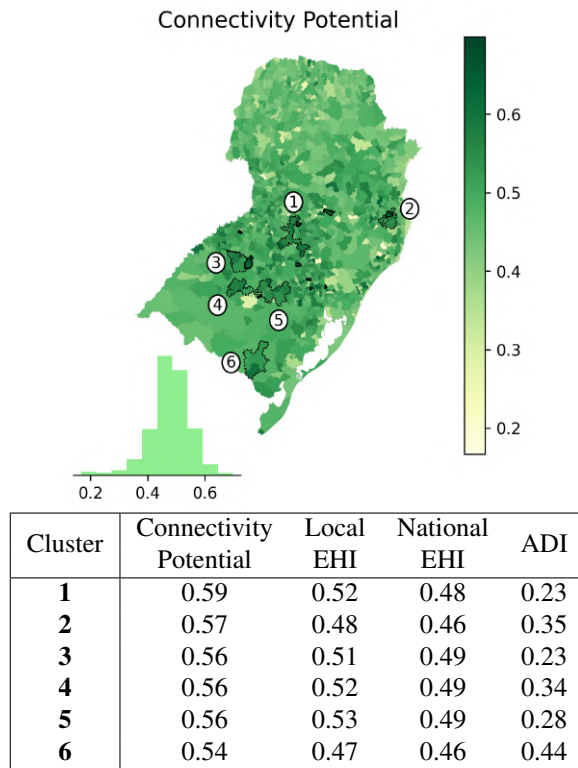


Fig. 6. Connectivity potential distribution in the South region. Outlined in black are the 10 regional municipalities with the highest potential; delineated with dotted lines are clusters of cities with high connectivity potential. The mean values obtained for each cluster are presented on the right.

and socioeconomic data. The proposed metrics, *connectivity potential* and *vulnerability score*, combine ADI and EHI to offer a dual-perspective view on where investments in connectivity can have the greatest impact. Our findings confirmed a strong correlation between social vulnerability and connectivity across municipalities, while also revealing important outliers: regions with favorable socioeconomic indicators but low infrastructure access, and vice versa.

Crucially, the proposed methodology addresses a common shortcoming in infrastructure planning, namely, the absence of objective, scalable criteria to guide public policy and resource allocation. By capturing both unmet demand and compounded need, the approach enables a more equitable distribution of

connectivity resources. Although this study is specific to Brazil, the proposed framework is generalizable and may support connectivity planning in other countries facing similar structural inequalities. Furthermore, the integration of social and technical indicators aligns with the broader goals of digital inclusion promoted by the ITU's IMT-2030 roadmap, offering a timely contribution to future 6G infrastructure development.

From a regulatory standpoint, the proposed metrics can directly support several policy instruments in the Brazilian context. For instance, spectrum auction obligations, such as those defined by ANATEL in recent 5G licensing processes, require operators to extend coverage to underserved municipalities. The connectivity potential and vulnerability scores provide objective, data-driven criteria for selecting which municipalities should be prioritized in such obligations, replacing ad hoc or purely demographic selection methods. Similarly, the metrics can guide the allocation of resources from the Universal Telecommunications Services Fund (FUST), enabling regulators to direct investments toward regions where the social return is expected to be highest. At the planning level, the spatial clustering analysis presented in Sections V.A and V.B offers actionable insights for network operators: clusters of vulnerable municipalities in the North suggest co-ordinated regional infrastructure projects, while the dispersed high-potential municipalities in the South point to targeted, municipality-level deployments. These examples illustrate how the proposed framework can bridge the gap between academic analysis and practical telecommunications planning.

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