Access to public transportation at the regional scale: An analysis of bus services in Minas Gerais State, Brazil

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Abstract
Regional public transportation is a critical service that connects rural and urban dwellers to a wide variety of economic, educational, medical, and recreational opportunities outside of their communities. In contrast to the many studies on public transportation access at the local scale, regional-scale studies remain rare, especially in the Global South. To address this knowledge gap, this study examines access to the regional bus system of Minas Gerais state, Brazil via a new index adapted to the minimal data typically available at the regional scale. Within Minas Gerais, major urban areas and some of their neighboring municipalities had the highest levels of bus access. Conversely, 49 of 853 municipalities (5.7%) lacked access to the regional bus system entirely. These inaccessible municipalities had smaller populations and were located on or near state borders, while municipalities with high levels of transportation access tended to have higher population densities, gross domestic product (GDP) per capita, and concentrations of paved highways. These results confirm that regional bus access is associated with the demographic, economic, infrastructure, and spatial characteristics of municipalities. Ultimately, this study reveals significant disparities in regional bus access throughout Minas Gerais, providing a foundation for further research on transportation accessibility and mobility in Brazil while demonstrating methods suitable for analyzing regional transportation access in low-data contexts around the world.

Keywords: Transportation access; public transportation; regional transportation; bus networks

1. Introduction

Transportation systems connect people to resources and services that would otherwise remain out of reach, thus mitigating spatial in equalities (Chen et al., 2018; Jaramillo et al., 2012; Pyrialakou et al., 2016). This is especially evident at the regional scale, where transportation systems link human settlements across the urban–rural spectrum, from remote towns to megacities. For rural residents, regional transportation enables access to resources that are often concentrated in cities, such as employment, schools, medical facilities, and basic necessities like food (Del Rio et. al, 2017; Hanson et al., 2021; Marr, 2015). In both urban and rural communities, women, elders, children, low-income individuals, and people with disabilities are more likely to rely on collective transportation, especially public transportation (De Almeida et al., 2021; Fioravante, 2008; Hanson et al., 2021; Murray and Davis, 2001). For many of these individuals, access to public transportation permits far greater spatial accessibility (Saghapour et al., 2016; Weiss et al., 2015; Vitale Brovarone and Cotella, 2020). Recognizing the widespread need for public transportation, the United Nations Sustainable Development Goals call for universal access to public transportation infrastructure throughout both urban and rural areas (2021).

Brazilian law affirms the importance of public transportation at all levels of government. The Federal Constitution grants the federal government the power to provide interstate passenger transportation, while municipal governments are responsible for their own internal transportation services (art. 21, 30). Regional transportation is implicitly delegated to the state governments (Constituição Federal, art. 25), and this power is explicitly included in state constitutions. For instance, the constitution of Minas Gerais grants the state the power to provide intermunicipal and metropolitan highway transportation directly or via concession (art. 9). In 2015, the Congress of Brazil further emphasized the government's role as a transportation provider by passing the 90th Amendment to the Constitution. The amendment added transportation to the constitutional list of *direitos sociais* (social rights) alongside education, health, food, work, and shelter (Constituição Federal, amend. 90). By defining transportation as a social right, the national government declared its intentions to improve transportation for all,

especially for the most marginalized, as increased access to opportunities and services via transportation facilitates the realization of other social rights (Ferreira Ribas, 2017). However, social rights have not yet been realized to the same degree as fundamental rights due to the potentially enormous costs of ensuring universal access to transportation, housing, and similar necessities (Dos Santos Nakamura, 2018 Ferreira Ribas, 2017).

The aspirational nature of transportation as a social right is reflected by the regional transportation policy of Minas Gerais state. All collective highway transportation between municipalities, including by regional bus, is defined as a "public service" in the state transportation regulations (Decreto n° 44603, de 22 de agosto de, 2007), and the State Secretary of Transportation and Public Works (SETOP) oversees hundreds of regional bus lines operated by private companies under line by-line concessions. Demand for regional bus services is significant: in 2017, public bus passengers comprised 29 % of regional travelers in Minas Gerais (SEINFRA, 2020). While transportation is defined as a social right and public service, the regional bus system is subject to practical limitations intended to maintain its economic sustainability. Proposed bus lines must undergo SETOP viability studies to verify passenger demand, and active bus lines must remain meet SETOP economic viability standards and remain profitable enough to maintain the interest of private bus concessionaires (Decreto 44.603, art. 70). By caveating the public right to transportation with economic limitations, the laws of Minas Gerais may allow regional bus access gaps to emerge.

Prior studies have identified significant gaps in regional bus access, often linking low access to rurality, remoteness, and limited infrastructure (Hanson, et al., 2021; Johansson et al., 2017; Marr et al., 2015; Neretin et al., 2020; Velaga et al., 2012). However, this body of research is geographically and methodologically limited as it focuses largely on the Global North and often relies on qualitative observations of access rather than comprehensive and statistically validated analyses. Research on this subject in Brazil is even more limited, and no prior study has analyzed regional bus access across all municipalities of a Brazilian state. This dearth of research has left basic questions unanswered: How does access to the regional bus system vary across municipalities? What, if any, commonalities exist among municipalities with little or no access to regional bus services?

This case study responds to these questions by presenting a detailed analysis of regional public bus access in Minas Gerais state via a new index tailored to the regional scale. The study begins with a review of previous regional and local bus access studies in Section 2. Section 3 de scribes Minas Gerais, the regional bus datasets, the design and application of the Regional Transportation Access Index (RTAI), and its use in a descriptive statistical analysis of municipalities. In Section 4, municipal RTAI results are described in the context of Minas Gerais and spatial, economic, and demographic patterns of bus access are examined. Finally, Section 5 links these regional bus access patterns to previous local and regional findings and suggests areas of future study.

2. Literature Review

2.1 The Local Scale

Much of the literature on public transportation access focuses on local transportation systems, especially within major urban areas (Hansson et al., 2019). Within urban areas, access to public transportation tends to be highest in the city center and lowest in peripheral areas (Chen et al., 2018; Jaramillo et al., 2012; Lee et al., 2021). Moreover, outlying areas are often served by fewer modes of public transportation than core areas (Girão et al., 2017; Saghapour et al., 2016) and often have less extensive or suitable road infrastructure, especially in the case of rapidly urbanizing slum areas (Delmelle and Casas, 2012; Hernández and Titheridge, 2016). Urban transportation access has often been linked to socioeconomic factors. Areas with limited access to public transportation often have high concentrations of low-income residents (Jaramillo et al., 2012; Lee et al., 2021). In contrast, bus stop proximity has been positively associated with real estate values (Rodríguez and Targa, 2004; Yang et al., 2019).

Major Brazilian cities largely conform to these spatial and socioeconomic patterns. Cities such as São Paulo, Rio de Janeiro, and Belo Horizonte exhibit high access to transportation in high-income core

areas and low access in low-income peripheries (Boisjoly et al., 2017; Girão et al., 2017; Lessa et al., 2019). Moreover, low-income peripheral neighborhoods face access gaps, as they exhibit both high demand and low access to public transportation (Boisjoly et al., 2017; Lessa et al., 2019). In some low-income areas, it is infeasible to create or extend bus lines due to steep slopes and lack of basic road infrastructure (Sakamoto and Lima, 2016). Local public bus services within less populous, predominantly rural municipalities have also been hindered by varied topography and poor road conditions. Consequently, a fleet of rural public school buses designed for rough terrain was introduced in 2007 (De Morais et al., 2012; Rodrigues and Pereira, 2022; Sakamoto and Lima, 2016). Collectively, these studies suggest that spatial marginality, low socioeconomic status, and inadequate road infrastructure are negatively associated with access to public transportation in Brazil at the local scale.

2.2 The Regional Scale

Spatial, economic, and infrastructure disparities have also been identified in regional transportation access studies, though these studies are far rarer than their local-scale counterparts (Hansson et al., 2019) and often focus on rural areas. Rural and remote areas typically exhibit lower access to regional transportation, and lower spatial accessibility, than urban areas (Benvenuto and Caulfield, 2020; Kaiser and Barstow, 2022; Vitale Brovarone and Cotella, 2020). In large, high-income countries—such as Canada, the United States, and Australia— regional public transportation systems are less extensive, due in part to the perception that private vehicles meet individual transportation needs (Hanson et al., 2021; Marr et al., 2015; Nutley, 2003; Pyrialakou et al., 2016). However, there is often an unmet need for public transportation in rural areas as low rates of car access are common, especially among low-income residents and seniors (Del Rio et al., 2017; Nutley, 2003; Marr, 2015; Murray and Davis, 2001). Smaller high-income countries such as Sweden and Lithuania have achieved greater overall regional bus coverage, but rural areas typically exhibit lower ridership than their urban counterparts (Johansson et al., 2017; Ranceva et al., 2022).

Low ridership and high operating costs often lead to the elimination of bus routes that serve rural communities (Hanson, et al., 2021; Johansson et al., 2017; Neretin et al., 2020; Velaga et al., 2012). Some rural areas maintain limited public transportation services such as air ambulances, dial-a-ride shuttles for the elderly or disabled, and school buses, but these services do not meet the daily transportation needs of most rural residents (Hanson et al., 2021; Shay et al., 2016). Rural residents may also face pronounced seasonal bus service disruptions as unpaved roads wash out or winter roads thaw (Aka, 2010; Hernandez and Titheridge, 2016; Neretin et al., 2020; Yeo et al., 2016). Some remote settlements are not connected to the road system at all, forcing residents to walk or hitchhike to reach collective transportation service points (Yeo et al., 2016). As a result of these transportation limitations, rural residents often exhibit lower mobility than urban residents, especially in the case of low-income residents (Gálvez-Arango and Antunes Lessa, 2022; Jovic and Rankovic Plazinic, 2013; Vitale Brovarone and Cotella, 2020; Zhao and Yu, 2021).

Regional transportation in Brazil lies at the intersection of two understudied contexts in transportation geography: the regional scale and the Global South (Hernandez and Titheridge, 2016; Hansson et al., 2019; Vitale Brovarone and Cotella, 2020). Brazil is also a particularly relevant location for this research as it shares characteristics with both high-income countries (extensive highway network and public transportation services) and middle and lower-income countries (significant concentration of unpaved roads, lower rates of car ownership). While previous studies of regional transportation in Brazil are few, they have suggested that regional bus access may be associated with several municipal characteristics. A study of 240 Brazilian cities found that the most populous cities receive more frequent regional transportation ser vices and are linked to more destinations than smaller cities across all collective transportation modes, including the public bus system (IBGE, 2017). Conversely, qualitative case studies have suggested that poor road infrastructure may prevent the introduction of regional bus ser vices to rural Brazilian communities (De Almeida et al., 2021; De Morais et al., 2012). This very limited body of research hints at some of the transportation access patterns already identified within regional and

local bus systems throughout the world. However, additional research is required to determine if these patterns are truly present across Brazilian regional bus systems, such as that of Minas Gerais.

3. Methodology

3.1 Study Area

Minas Gerais is Brazil's second-largest state; its population of over 20.5 million is comparable to that of Zambia. While Minas Gerais is classified as part of the populous and economically powerful Southeast, the state's semiarid north has strong ecological, cultural, and socioeconomic similarities with the Northeastern states of Brazil, and the west has economic ties to neighboring Goiás state and Brasília. In contrast, the south is characterized by a wetter climate and denser pattern of population distribution, much like neighboring portions of São Paulo and Rio de Janeiro states. The Belo Horizonte metropolitan area, home to the state capital and over 6 million residents, is located in the geographic center of the state. Other major cities include Uberlândia in the west, Juiz de Fora in the south, and Montes Claros in the north. Minas Gerais is divided into 853 municipalities. Brazilian municipalities typically contain an urban seat, smaller outlying settlements, and uninhabited areas. Many municipalities have internal divisions called districts which were established around significant settlements outside of the municipal seat.

The settlements of Minas Gerais are primarily linked by highways, as is much of Brazil outside of the Amazon basin. The state has 39,739 km of roads, of which 19.5 % remains unpaved (DER-MG, 2020). Though the state contains the most extensive rail network in Brazil with over 5,000 km of rail lines, passenger rail services are limited to a single line between Belo Horizonte and the capital of neighboring Espírito Santo state and a few short tourist routes in the south (SEINFRA, 2020). Air transportation is used primarily for international and interstate travel, as intrastate flights are too expensive and too limited in choice of destination to compete with road travel (SEINFRA, 2020; Turolla et al., 2008). Therefore, the vast majority of regional passenger transportation in Minas Gerais, and in much of Brazil, occurs on the roads. While private vehicle ownership has increased over the past two decades, public bus passengers make up 29 % of intermunicipal travelers in Minas Gerais (SEINFRA, 2020). It is this regional public bus system, typically referred to as "intermunicipal" within official documents to distinguish it from metropolitan services, that serves as the subject of this study.

3.2 Data

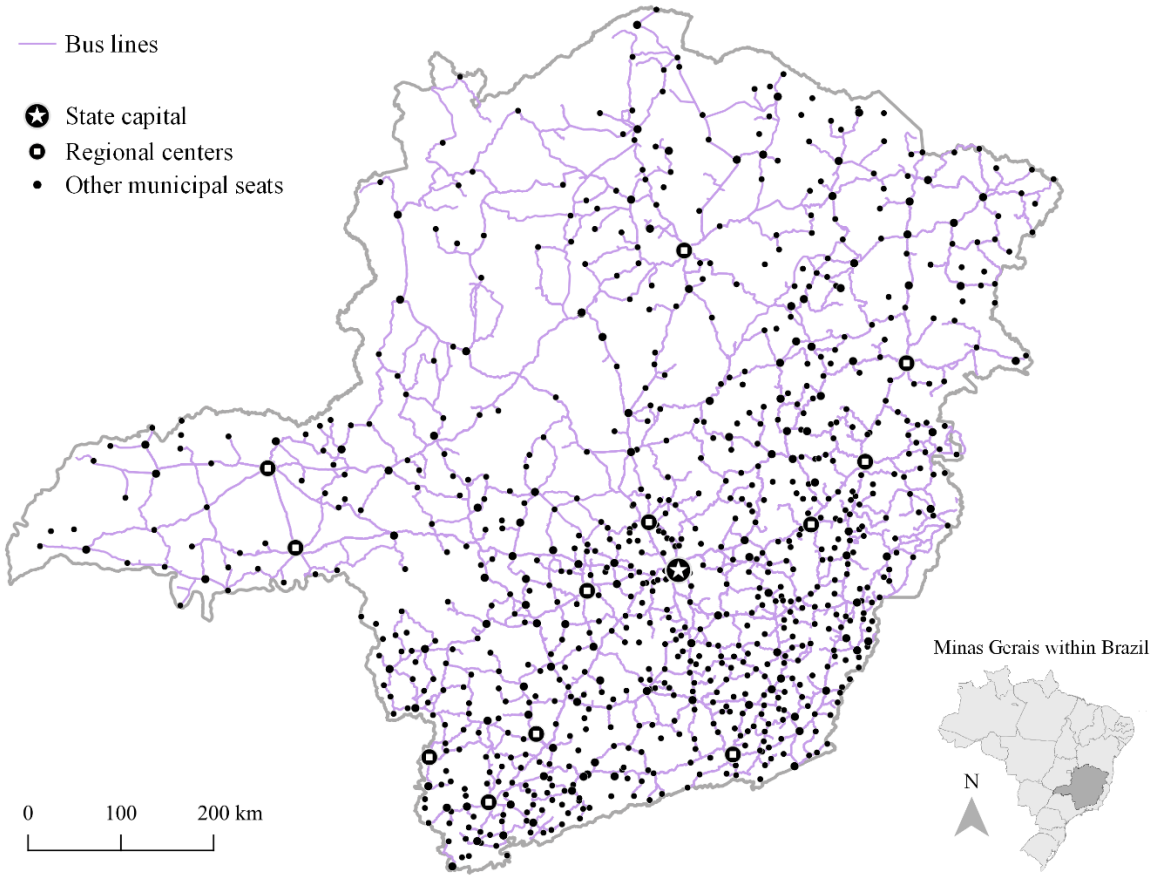
Regional bus system data was obtained from the departure schedule and itinerary datasets of the Minas Gerais Department of Construction and Roadways (DER-MG), both downloaded in March of 2022. Both datasets included 1,145 distinct bus lines. The schedule dataset included days and times of operation for each line with separate entries for outbound and inbound trips. The itinerary dataset included a total of 8,801 stops, many of which were served by multiple lines. While these stops are used to describe the overall route and determine fares, buses may stop at any point a passenger requests along their defined route, yielding many additional potential stops for each line.

The itinerary dataset included a location name and municipality name for each stop rather than geographic coordinates or street ad dresses. Therefore, stop location names were matched to a list of place names provided by the Brazilian Institute of Geography and Statistics (IBGE) to determine their precise locations and spatial distribution (IBGE, 2010). Several factors complicated this process, including spelling variations, typographical errors, duplicate place names, and the inclusion of location names that represented features other than settlements (e.g., bridges, schools, mines). Initially, 5,285 stops were matched to official place names and coordinates listed by the IBGE and mapped in QGIS 3.20. An additional 1,030 stops were later identified and mapped by cross-referencing IBGE municipal maps and OpeStreetMap (IBGE, 2020a). Ultimately, 71.8 % of stop locations were mapped, including at least two stops (origin and destination) for every bus line.

Bus lines were initially visualized as polyline features connecting bus stops via straight lines. These polylines were converted to street routes using OpenRouteService, an open-source routing program, via its QGIS plugin (mode = driving-hgv, preference = fastest). The resulting spatial dataset

included precise routes for all 1,145 active lines in the regional bus system (Fig. 1). Lines that only operated on select holidays and lines designated inactive were removed before analysis, leaving 976 active, regularly operating lines in the final dataset.

Figure 1 The regional bus system of Minas Gerais and municipal seats



3.3 Index and Statistical Analysis

Access to public transportation has been discussed extensively within scientific literature, but it is typically analyzed across major urban areas rather than regions (Geurs and Wee, 2004; Hansson et al., 2019). As data availability and granularity increases, due in part to the rise of the smart city, urban transportation metrics have become increasingly complex (Páez et al., 2012). These metrics rely on point of interest inventories, origin–destination surveys, and real-time passenger data to link transportation supply to land-use and passenger demand, permitting incredibly detailed transportation accessibility analyses (Lee et al., 2021; Pyrialakou et al., 2016; Saghapour et al., 2016). At the regional scale, however, this extensive and granular data is rarely available (Benvenuto and Caulfield, 2020), limiting the applicability of local-scale analytical techniques.

There are, however, several local transportation access indices that use simpler metrics and readily available data such as bus routes, timetables, and population figures, making them more suitable models for a regional index (Chen et al., 2018; Lessa et al., 2019). These indices evaluate service coverage, frequency, and destination variety but assume that each bus line has a fixed number of predetermined stops, which is not the case in Brazilian regional bus operations. A regional bus may make spontaneous stops along its route according to passenger requests, so there is no limit to the number or location of regional bus stops. Therefore, local-level measurements must be modified for use in regional

analysis to account for the variability of regional bus stops.[1] Many local-scale transportation metrics also depend on normative assumptions of passenger behavior, such as reasonable wait and travel times, which remain uncertain over much larger, more topographically varied spatial units (Hansson et al., 2019). Even simpler indices, such as that of Lessa et al., which focuses on the concentration of bus lines, stops, and departures, were developed for the relatively consistent population and infrastructure density of an urban area, not the urban-rural continuum of a region (2019). At the regional scale, "urban and rural areas cannot be studied in isolation, especially considering the intertwined dynamics of transportation, which… move[s] people and resources in both directions" (Kaiser and Barstow, 2022). Therefore, measurements developed for local-scale analysis of transportation access must be adapted for use at the regional scale.

The Regional Transportation Access Index (RTAI) described in this paper incorporates and adapts common elements of local transportation access indices for use at the regional scale. The RTAI hews most closely to the Accessibility Index (AI) of Lessa et al. (2019) and the Public Transport Supply Index of Chen et al. (2018), which evaluate three facets of transportation access: service coverage, frequency, and variety of routes or destinations available. These indices are suitable models for a regional transportation access index as they rely on simple, easily transferrable measurements and commonly available data such as bus route locations, departure times, and population counts. However, even these relatively simple indices assume a fixed distribution of bus stops, such as bus stops per capita in a given neighborhood (Chen et al., 2019; Lessa et al., 2019t), which is not the case in Brazil because buses may make additional stops according to passenger requests. Therefore, these local-level measurements must be modified for use in regional analysis to account for the variability of regional bus stops.

The RTAI[2] evaluates similar dimensions of transportation access used in the indices of Lessa et al. and Chen et al., but uses indicators and units of observation that account for the variability of regional bus stops. For each municipality within the region of interest, the following three indicators are calculated: service coverage (percent of municipal population living in a district served by a bus line), destination variety (number of additional municipalities reachable by bus), and service frequency (ratio of average weekly departures per bus line). Similar factors (proximity to transportation, frequency of service, and potential destinations) have also been used in the small body of quantitative research on regional transportation access (IBGE, 2017; Murray and Davis, 2001; Ranceva et al., 2022). The RTAI is derived from three indicators:

1. Service Coverage

The service coverage indicator (Eq. 1) is the percentage of the municipal population living in a district served by at least one regional bus line:

$$C_m = \frac{x_p}{x_m} \qquad (1)$$

In which x_p is the population living in all districts of municipality m that are served by a regional bus line, x_m is the total population of municipality m, and C_m is the service coverage indicator. Recent district-level population data was available due to the 2022 census (IBGE, 2022), but this indicator could alternatively be calculated using granular population estimates from WorldPop if sub-municipal data is not available for the region of interest (WorldPop, 2016). In Brazil, districts are formed around distinct settlements to facilitate localized administration; they are essentially a municipality in miniature (Carvalho, 1956).[3] This

[1] The author has also observed unscheduled, on-demand stops during regional bus journeys in Ceará state, Brazil, as well as parts of Argentina, Chile, Mexico, Paraguay, and Peru, suggesting that this characteristic may be prevalent among regional bus services in Latin America.

[2] A preliminary version of the RTAI, including slightly different indicators, was described in a conference progress note (Gálvez-Arango and Antunes Lessa, 2022).

[3] IBGE provides several other sub-municipal spatial units but they are un suitable for this analysis as they do not have clearly defined boundaries (*localidades*), are applied only to major cities (*bairros*), or reflect practical work areas for census workers rather than distinct communities (*setores censitários*).

indicator uses district-level bus coverage to capture the availability of regional bus services relative to population centers within each municipality.

2. Destination Variety

The destination variety indicator (*Dm*) is the quantity of unique municipal destinations reachable via the regional bus system, in other words: the number of municipalities crossed by at least one bus line that also passes through the municipality of origin. Passengers can request to disembark at any point along a bus route, whether or not the requested stop is part of the officially defined route, so it is more appropriate to measure the number of municipalities passengers can reach rather than attempt to calculate a precise number of destination points.

3. Service Frequency

The service frequency indicator (Eq. (2) indicates the ratio of average weekly trips per line among all the lines that pass through the municipality of interest:

$$F_m = \frac{\sum_l^n t_l}{L_m} \qquad (2)$$

In which l is a line that passes through municipality m, t_l is the number of weekly trips for line l, L_m is the number of bus lines that pass through municipality m, and F_m is the frequency indicator. This indicator captures the temporal dimension of transportation access.

After calculating each indicator for a given municipality, the value of each indicator is standardized (min–max), and the RTAI is generated by taking the mean of the standardized indicator values. The 853 municipalities were divided into four groups based on RTAI score: a null access group (RTAI = 0), and low, mid, and high access groups derived by the Jenks natural breaks method (Table 1). These municipal groups were statistically compared in terms of several demographic, economic, infrastructural, and spatial variables. These variables were chosen because they were associated with bus access in previous studies at the local and/or regional scale (Table 2). Kruskal-Wallis tests were applied to RTAI and indicator-based municipal groupings to determine if levels of regional transportation access were associated with the aforementioned municipal variables (Table 2). The non-parametric Kruskal-Wallis test was chosen because several of the RTAI indicators were not normally distributed and did not have equal variances, violating the requirements of the ANOVA test (Ostertagova et al., 2014). Mann-Whitney U tests were applied post-hoc to identify significant differences between municipal groupings, and Benjamini-Hochberg corrections were applied to minimize the chance of Type I errors across multiple tests while maximizing statistical power (Frane, 2015). Tests were conducted in R 4.1.1 (R Core Team, 2021).

Table 1 Municipal transportation access classifications

Access Level	RTAI score range	Count of municipalities	Percent of municipalities
High	0.400 – 1.000	130	15.2%
Mid	0.311 - 0.399	631	74.0%
Low	0.001 - 0.310	43	5.0%
Null	0.000 - 0.000	49	5.7%

Table 2 Municipal variables

Category	Variable	Measurement	Prior Studies Discussing Similar Variables
Urban hierarchy / rurality	Population	Total number of residents	IBGE, 2017 (Brazil)
	Population density	Residents per km^2 of area	Ponrahono et al., 2015 (Malaysia) Pyrialakou et al., 2016 (USA) Neretin et al., 2020 (Russia)
Economic status	Percent of residents in poverty [4]	Percent of residents enrolled in Bolsa Família (social assistance) program	Boisjoly et al., 2017 (Brazil) Del Rio et al., 2017 (USA) Hernandez and Titheridge, 2016 (Colombia)
	Cars per capita	Number of cars per capita	Marr, 2015 (Canada) Nutley, 2003 (Australia)
	GDP per capita	GDP per capita, in reais (R$)	Benvenuto and Caulfield, 2020 (Brazil)* Weiss et al., 2018 (Global)*
Road infrastructure	Presence of paved highways	Length of paved highways (km) per 100 km2 of area	Hernandez and Titheridge, 2016 (Colombia) Neretin et al., 2020 (Russia) Sakamoto and Lima, 2016 (Brazil)
Peripherality	Proximity to state border	Distance from municipal centroid to state border, in km	Chen et al., 2018 (Canada) Girão et al., 2017 (Brazil) Jaramillo et al., 2012 (Colombia) Lee et al., 2021 (South Korea) Lessa et al., 2019 (Brazil)

* = Denotes broader studies on accessibility rather than just access to transport

4. Results and Discussion

4.1 Regional Bus Access Across Minas Gerais: The RTAI and its Indicators

Of the 853 municipalities in Minas Gerais, most (74 %) had mid-level access to the regional bus system, while 15.2 % had high access and 5 % had low access. The remaining 49 municipalities (5.7 %) were not served by the regional bus system, yielding indicator and RTAI scores of 0. These inaccessible municipalities were distributed throughout the state, with the exception of a northwest area which is crossed by major highways linking Belo Horizonte to Brasília. Additionally, 19 of 49 inaccessible municipalities bordered another state, placing them on the periphery of Minas Gerais. Low and mid access municipalities were distributed across the entire state. At the other extreme, high access municipalities were largely concentrated in the south and central portions of the state (Fig. 2). The state capital of Belo Horizonte received the highest RTAI score (0.692), largely due to its variety of destinations (D_m = 499) and moderately frequent departures (F_m = 19.85 trips per week per line). This high level of regional bus access was unsurprising given Belo Horizonte's position as the capital, primate city, and geographic center of Minas Gerais.

[4] To receive the Bolsa Família in 2017 (year of most recent data available), residents had to live under the federal poverty line defined by a monthly per capita household income of R$ 178 or less. Bolsa Família statistics likely underestimate the actual concentration of low-income residents as some extremely poor residents (such as those who are homeless or undocumented) may not have enrolled in the Bolsa Família program.

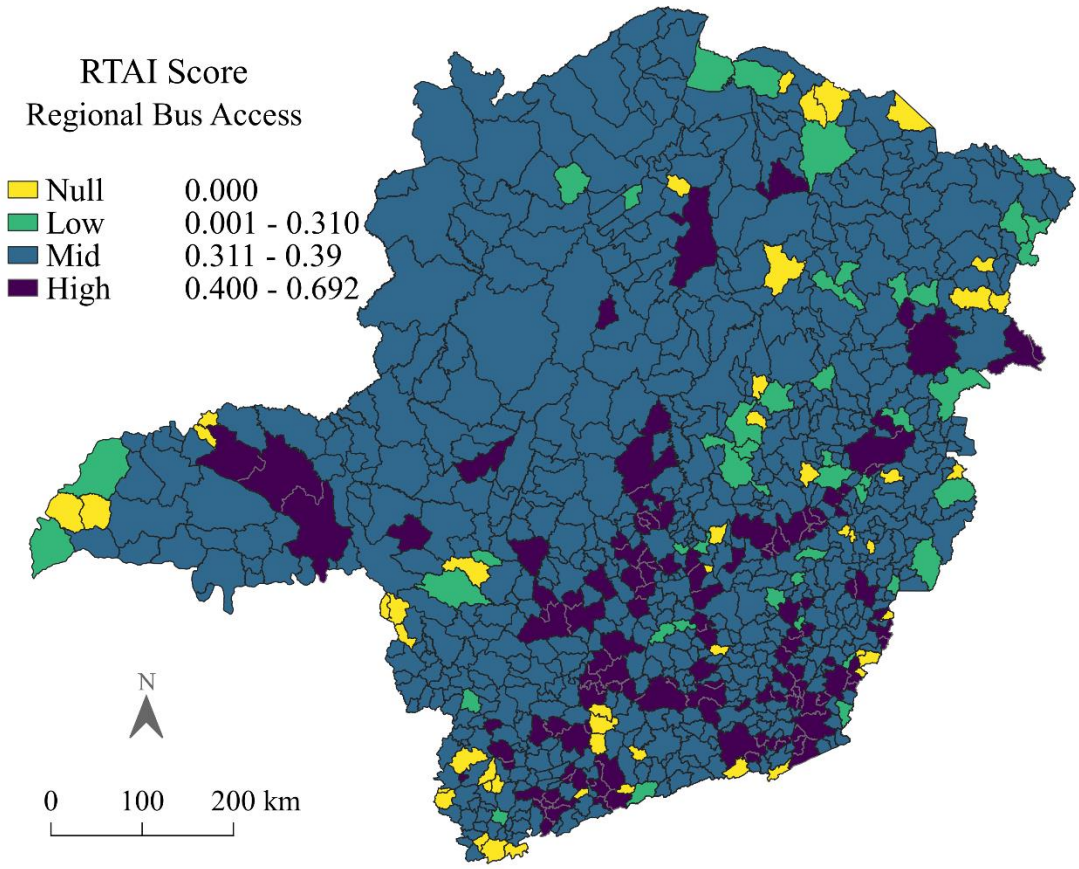


Figure 2 Regional Transport Access Index Scores

Some of the highest RTAI scores, however, were observed in municipalities with small populations, such as Maria da Fé (14,247 residents, RTAI = 0.639), Matias Barbosa (14,121 residents, RTAI = 0.622), and Guidoval (7,131 residents, RTAI = 0.622), ranked second through fourth in RTAI score, respectively. These municipalities each had fewer than 10 destinations, but their RTAI scores were increased by average frequencies (F_m) of over 200 weekly trips per line. These extremely high trip frequencies primarily occurred in the south, where some regional bus lines operated like metropolitan lines, providing half-hourly service between small municipalities and nearby regional centers like Juiz de Fora and Ubá. In contrast, northern municipalities tended to have fewer weekly trips per line (Fig. 3). The median number of weekly bus trips per line across Minas Gerais was 14.58 or just over two trips each day.

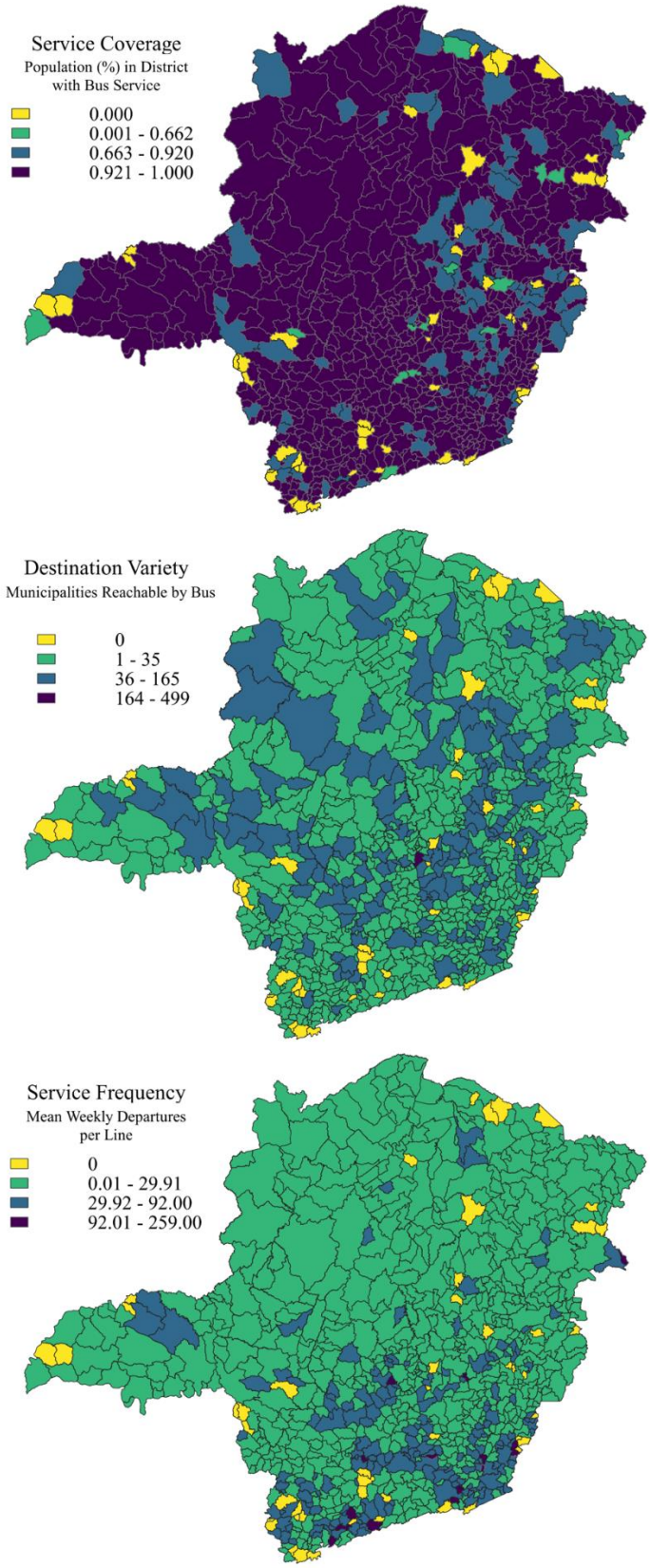


Figure 3 RTAI Indicator Scores

The destinations indicator (D_m) also displayed considerable variation across municipalities. Regional centers such as Juiz de Fora (165 potential municipal destinations), Governador Valadares (130), and Ipatinga (125) had the highest destination indicator scores after Belo Horizonte. This result aligns with the IBGE finding that major cities and state capitals have the highest quantity of destinations reachable by regional bus throughout Brazil (IBGE, 2017). The median number of potential destinations across Minas Gerais, was 16, and 18 % of municipalities had 5 or fewer potential municipal destinations.

The service coverage indicator yielded far more uniform results, as 75 % of municipalities had regional bus service across all of their constituent districts, including the entire municipal population (C_m = 1.00). This uniformity was due in part to the administrative divisions and history of Minas Gerais. Over time, many municipal districts grew large enough in population to split off into new, smaller municipalities without internal divisions (Carvalho, 1956). By 2022, 55 % of municipalities had only one district, leading to perfect origin indicator scores (C_m = 1.00) if they had any regional bus service. The service coverage indicator is therefore limited in its ability to evaluate differences in bus coverage across single-district municipalities. Among multi-district municipalities, 16 % to 100 % of the municipal population lived within a district served by the regional bus system (C_m = 0.16–1).

4.2 Significance Testing

As this is a preliminary examination of regional bus access, statistical testing was used to characterize municipalities of different transportation access levels rather than identify causal factors behind these differences. Access to transportation was significantly associated with all municipal variables tested (Table 3). Pairwise post-hoc tests revealed starker differences at either end of the access spectrum as the high and null access municipalities were often significantly distinct from all other municipal access groups.

Table 3 Results of Kruskal-Wallis tests and post-hoc Mann-Whitney U tests

	P-value	Access groups showing significant differences in post-hoc comparisons
Population	0.0000*	Null-Low, Null-Mid, Null-High, Low-High, Mid-High
Population density	0.0000*	Null-High, Low-Mid, Low-High, Mid-High
Percent of residents in poverty	0.0000*	Null-Low, Null-High, Low-Mid, Low-High, Mid-High
Cars per capita	0.0000*	Null-Low, Null-High, Low-Mid, Low- High, Mid-High
GDP per capita	0.0000*	Null-High, Low-Mid, Low- High, Mid-High
Paved highway density	0.0000*	Null-Mid, Null-High, Low-Mid, Low-High, Mid-High
Distance from state border	0.0000*	Null-Low, Null-Mid, Null-High

* = significant at p = 0.05 for Kruskal-Wallis tests; significance for post-hoc Mann-Whitney U tests based on Benjamini-Hochberg corrected p-values

In terms of population, the high access municipalities had larger, more densely distributed populations than all other municipalities. This finding agrees with previous regional-scale studies which found the highest levels of transportation access typically occurred in denser, more populous settlements, especially major cities (IBGE, 2017; Nutley, 2003; Neretin et al., 2020; Ponrahono et al., 2015). Conversely, municipalities without regional bus service had significantly smaller populations in comparison to all other groups (median = 5,265 residents). The largest null access municipality had a population of just 26,097, while the low, mid, and high access groups had municipalities with over 100,000 residents. Small municipal populations provide smaller markets for bus ticket sales, perhaps disincentivizing the creation and retention of bus lines that serve those municipalities (Hanson, et al., 2021; Johansson et al., 2017; Neretin et al., 2020; Velaga et al., 2012).

High access municipalities also had a significantly higher concentration of paved highways (median = 10.53 km/100 km2), followed by mid access, then low access and inaccessible municipalities—which were not significantly different from one another (Table 4). Previous studies of transportation access in both urban and rural contexts have linked low levels of transportation access and the absence of appropriate transportation infrastructure (Delmelle and Casas, 2012; Sakamoto and Lima, 2016). This study supports and expands upon that relationship, identifying an association between high transportation access and the abundance of sufficient transportation infrastructure. Ultimately, this relationship may indicate an operational limiting factor because most Brazilian commercial buses are built to operate on paved roads, making travel on dirt roads more challenging and potentially damaging to vehicles (De Morais et al., 2012). In Minas Gerais, government-defined regional bus fares increase based on milage traveled on dirt roads, perhaps attempting to compensate for increased vehicle maintenance costs (Portaria n◦ 2203, de 26/12/2006).

Table 4 Summary statistics of municipal variables by regional bus access level

	Statistic	Population	Population density	Residents in poverty	Cars per capita	GDP per capita	Paved highway density	Distance from state border
		Residents	Res./km^2	%	Cars/cap.	R$	km/ 100 km^2	km
High	Median	16,763	60.18	19.32	0.28	21,983	10.53	88.94
	Min	2,049	6.66	6.49	0.10	7,606	2.16	4.131
	Max	2,315,560	6,988.18	61.13	0.63	157,353	32.48	311.20
	S.D.	223,279	659.70	9.78	0.07	19,526	0.06	78.68
Mid	Median	7,451	20.37	28.65	0.23	14,744	5.76	85.76
	Min	833	1.21	3.09	0.02	6,429	0.00	3.04
	Max	621,863	3,193.20	74.98	0.75	313,035	29.77	321.09
	S.D.	31,936	180.65	13.40	0.10	22,571	0.05	79.38
Low	Median	7,817	15.74	34.75	0.18	11,128	2.78	93.96
	Min	1,690	2.77	10.46	0.04	5,984	0.00	2.84
	Max	329,749	2,126.26	63.14	0.39	249,336	19.22	240.19
	S.D.	58,018	347.77	12.74	0.09	47,782	0.04	76.80
Null	Median	5,265	18.35	26.91	0.21	14,663	4.43	28.49
	Min	1,538	3.34	5.50	0.05	7,667	0.00	3.41
	Max	26,097	225.38	68.36	0.45	200,430	13.59	220.18
	S.D.	5,143	34.77	14.79	0.10	29,274	0.03	65.84

The relationship between regional bus access and economic factors remains unclear. High access municipalities had significantly higher GDP per capita (median = R$21,983) than all other municipalities and lower concentrations of residents below the poverty line (median = 19.32 %). However, the null and mid access groups did not differ statistically across these economic indicators, and the low access group actually showed significantly lower economic prosperity, in terms of these indicators, than the null access group. Thus, municipalities without regional bus access are not clearly distinguished from others by economic factors. In contrast, prior studies of Brazil's major cities found a positive association between local bus access and socioeconomic status, at least at the extremes of the socioeconomic spectrum. Communities with the lowest levels of access tended to be very low-income, while those with high access levels tended to be higher income (Girão et al., 2017; Lessa et al., 2019). This study, however, shows that the clear, positive association between community socioeconomic status and bus access found in major urban areas does not hold true at the regional level in Minas Gerais.

The null access municipalities were located significantly closer to the state border than higher access municipal groups. 65 % of these municipalities were located within 50 km of the state border (Fig. 4), placing them on the periphery of Minas Gerais. Despite their proximity to the border, only 3 of the 49

null access municipalities were served by an interstate bus line (ANTT, 2022), leaving most of these municipalities truly isolated from long-distance public bus networks. This tendency for inaccessible municipalities to be located on the periphery of the state mirrors the core-periphery pattern of bus access noted in studies of major Brazilian cities (Boisjoly et al., 2017; Girão et al., 2017; Lessa et al., 2019). Although peripherality is strongly associated with poverty in Brazilian cities, inaccessible (largely peripheral) municipalities did not exhibit marked economic differences from municipalities with midlevel access to the regional bus system.

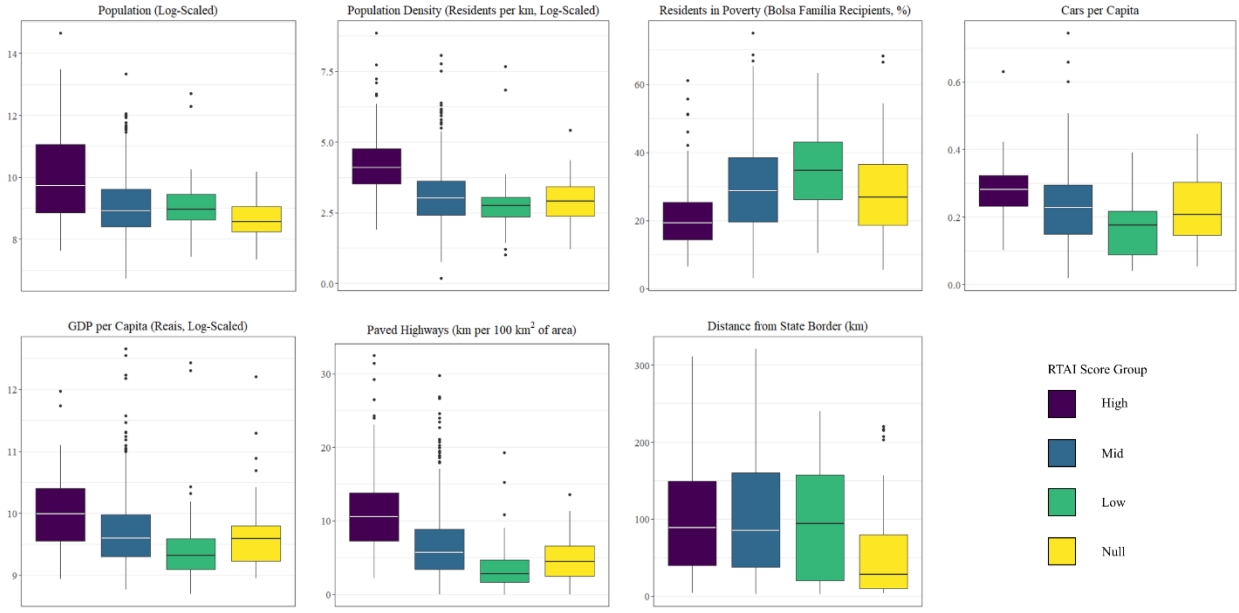


Figure 4 Municipal characteristics by RTAI score groups

While the high access municipal group had significantly higher median values across several of the demographic, economic, and infrastructure factors tested, it often exhibited similar minimum values to lower access groups (Table 4). There were several municipalities that enjoyed a high level of regional bus access despite being comparatively rural, poor, and/or lacking in road infrastructure. The presence of these exceptional high access municipalities demonstrates that no single economic, spatial, demographic, or infrastructural factor is a definitive barrier to regional bus access.

5. Conclusion

This study expands the limited body of research on regional transportation access, which is especially understudied in the Global South (Hernandez and Titheridge, 2016), via a case study of regional bus services in Minas Gerais, Brazil. Prior descriptions of regional transportation access in Brazil were limited in geographic scope and lacked statistical validation (IBGE, 2017; De Almeida et al., 2021). In contrast, this study assesses regional bus access across all municipalities of Minas Gerais state via a new index, the RTAI, adapted to the particular challenges of regional-scale analysis. This case study demonstrates how public transportation access can be analyzed at the regional level even with limited data. It also identifies municipal characteristics associated with disparate levels of regional bus access. Because the RTAI requires only simple inputs (bus stop locations and schedules), it could therefore easily be applied to other states of Brazil as well as other countries with extensive regional bus networks, such as Mexico, Peru, and Paraguay. This study also provides a foundation for further studies on regional transportation, as access to transport is an essential component of transportation accessibility, quality of service, and mobility analyses (Hansson et al., 2019; Páez et al., 2012; Pyrialakou et al., 2016; Ranceva et al., 2022).

While the RTAI's simplicity makes it suitable for low-data contexts, it focuses on spatial and temporal dimensions of access to transport and does not assess other potentially relevant factors such as affordability, passenger capacity, and reasonable proximity to bus lines. Several of these dimensions are particularly difficult to evaluate at the regional scale, such as reasonable proximity, which ranges from 800 m to over 3 km across prior studies (Hansson et al., 2019). Therefore, further research is needed to develop measurements for additional transportation access factors at the regional scale.

This study identified extreme variations in access to regional public bus transportation across Minas Gerais. Municipalities with the highest levels of transportation access consisted of major cities and several small municipalities linked to major cities by high-frequency, pseudo-metropolitan bus routes. In total, 49 out of 853 municipalities lacked access to the bus system entirely, and most of these municipalities were located on or very close to state borders. Furthermore, this study identified significant geographic, demographic, economic, and infrastructural differences between municipalities of different transportation access levels, especially high access and null access municipalities. High access municipalities had significantly larger, denser populations, greater economic prosperity, and higher concentrations of paved highways than municipalities with lower access levels, while null municipalities had significantly smaller populations and greater proximity to the state border.

This study also identified and validated several patterns of access characteristic of regional bus systems, such as associations between total population, population density, and transportation access. These associations were previously noted in regional-level studies in Canada, Malaysia, and the Russian Far East, where smaller towns and rural areas received very limited regional bus service, if any (Marr, 2015; Neretin et al., 2020; Ponrahono et al., 2015). Extending public transportation services to rural and remote communities poses a significant challenge to regional policymakers in Minas Gerais and beyond, hindering the achievement of universal transportation provision.

Ultimately, it is clear that the "social right" to transportation envisioned in the Brazilian Constitution has yet to be fully realized in terms of regional bus access. In Minas Gerais alone, nearly 1.3 million residents live in municipalities with no access to the regional bus system or with low levels of access characterized by infrequent service and limited route options. Minas Gerais is not unique in Brazil. The other states face common challenges in planning and maintaining their regional bus systems including inconsistently paved roads, difficult terrain, and dispersed rural settlements often burdened by low spatial accessibility (Benvenuto and Caulfield, 2020; Rodrigues and Pereira, 2022). Case studies in rural Minas Gerais and Brazil 's Northeast region have described how residents of communities with inadequate access to public transportation must rely on unsafe, costly, and unreliable transportation methods, thereby limiting their access to healthcare and other key services (De Almeida et al., 2021; Kaiser and Barstow, 2022; Soares et al., 2017).

While access to regional transportation should be improved, it may be financially unsustainable to simply extend bus lines into municipalities with little or no existing service. These municipalities tend to have spatial and infrastructural characteristics that would make it more challenging and less profitable to operate regular regional bus services, such as sparser population distributions, remote locations, and fewer paved roads. Policymakers should instead investigate flexible public transportation solutions—transport on demand, ride or car sharing, etc.—bearing in mind that different regions and municipalities may require localized solutions depending on their topography, population distribution, and socioeconomic characteristics (Poltimäe et al., 2022; Velaga et al., 2012; Vitale Brovarone and Cotella, 2020). Indeed, Brazil has already implemented a localizable public transportation scheme in the form of Caminho da Escola, a bus, boat, and bicycle-based rural school transportation system that has increased school attendance rates across the country (De Morais et al., 2012; Rodrigues and Pereira, 2022).

Flexible transportation services can address some travel needs, but they should be accompanied by expanded local services to minimize the need for additional travel (Vitale Brovarone and Cotella, 2020). In Minas Gerais, and throughout Brazil, flexible regional transportation services could be designed to complement programs that already serve rural and remote communities such as Educação á Distança (online distance education) and Mais Médicos (medical services for remote and underserved areas). In addition to flexible regional transportation options, researchers and policymakers should investigate the

determinants of regional transportation access disparities. Together, these two strands of research can aid the development of more accessible and sustainable regional public transportation systems and advance the pursuit of universal access to public transportation across both urban and rural communities.

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Appendix A. Municipal Data Sources

Municipal Variable	Measurement	Sources
Population	Total number of residents	IBGE, 2022
Population density	Residents per km^2 of area	IBGE, 2021 & IBGE, 2020b; Calculated in R
Percent of residents under the poverty line	Percent of residents who receive Bolsa Família benefits	PNUD Brasil, 2020 & Ministério da Cidadania, 2017
Cars per capita	Number of cars per capita	SENATRAN, 2021
GDP per capita	GDP per capita, in reais (R$)	IBGE, 2019
Presence of paved highways	Length of paved highways (km) per 100 km2 of area	DER-MG, 2021; Digitized and calculated in QGIS
Proximity to state border	Distance from municipal centroid to state border, in km	IBGE, 2020b; Calculated in QGIS

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