SILESIAN UNIVERSITY OF TECHNOLOGY PUBLISHING HOUSE

SCIENTIFIC PAPERS OF SILESIAN UNIVERSITY OF TECHNOLOGY 2025
ORGANIZATION AND MANAGEMENT SERIES NO. 232

EFFICIENCY INDICATORS OF PUBLIC TRANSPORT AS A TOOL SUPPORTING SMART CITY DEVELOPMENT

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Purpose: The purpose of this paper is to evaluate the efficiency of public transport systems as a supporting tool for smart city development. The study focuses on four cities within the Upper Silesian-Zagłębie Metropolis (Zabrze, Gliwice, Bytom, Ruda Śląska) and aims to identify strengths, weaknesses and spatial accessibility gaps in their transport networks using quantitative indicators and geospatial analysis.
Design/methodology/approach: The research combines an indicator-based assessment with spatial accessibility analysis. Five original indicators were proposed: Inter-city Connectivity Ratio (ICR), Daily Service Frequency (DSF), Transport Capacity Potential (TCP), Number of Lines per 1,000 Inhabitants (IL), and Bus Stop Density (BSD). Data were obtained from Statistics Poland (GUS), the Metropolitan Transport Authority (ZTM) and GIS-based mapping of stops and 500 m/1 km buffers using QGIS. Thresholds for interpreting the indicators were derived from literature, European metropolitan benchmarks, and international accessibility guidelines.
Findings: The study shows that all analysed cities achieve high levels of inter-city connectivity and service frequency, meeting smart mobility objectives. However, significant micro-scale accessibility gaps are revealed when analysing walking distances at 500 m, particularly in peripheral, low-density residential areas. While average values of BSD and other indicators suggest good accessibility, GIS analysis highlights the need for targeted, local interventions (e.g., new stops or route adjustments) to ensure inclusive mobility. The methodology provides a replicable framework for other metropolitan areas.
Originality/value: This paper contributes to the literature by integrating quantitative efficiency metrics with spatial GIS analysis in the context of smart city mobility. It provides actionable insights for policymakers and transport authorities on aligning public transport services with sustainable urban development goals. The framework and findings can inform planning strategies aimed at improving equity, accessibility, and integration of public transport in metropolitan regions.
Keywords: Public transport efficiency; Smart city; Spatial accessibility; Metropolitan mobility; GIS; Urban transport planning.
Category of the paper: Research paper.

1. Introduction

Urban mobility has become a central pillar of contemporary debates on sustainable urban development and smart city implementation (Rey-Moreno et al., 2023). In the 21st century, cities face unprecedented challenges related to rapid urbanisation, climate change, and increasing socioeconomic inequalities. These dynamics compel urban planners and policymakers to seek innovative and integrative approaches that ensure accessibility, environmental sustainability, economic efficiency, and social inclusiveness (Shao, Min, 2025). Among the various urban systems, public transport stands out as a key enabler of smart city functions (Polis Network, 2016). Efficient, accessible, and integrated public transport systems not only facilitate daily mobility but also support environmental goals, enhance urban cohesion, and improve the overall quality of life (Brzeziński, 2024).

The concept of the smart city encompasses the use of digital technologies and data-driven decision-making to optimise urban infrastructure and services (Chadalawada, 2022). In the realm of transport, smart city frameworks promote solutions such as integrated ticketing, real-time passenger information, intelligent traffic management, and multimodal transport hubs (Darsena et al., 2020; Elassy et al., 2024; Puzio et al., 2025). However, beyond technological innovation, the foundation of any effective transport system lies in its operational efficiency and user-oriented planning (Cazuza de Sousa Junior et al., 2023). Optimization of public transport is therefore not only a matter of digitalization but also of network design, service reliability, and alignment with user expectations (Ejdys, 2014).

Measuring and analysing the effectiveness of public transport becomes essential for any city aspiring to align itself with the smart city paradigm (Mohammadi et al., 2022). Transport efficiency indicators provide valuable tools for understanding the functioning and performance of public transit systems (Transportation Research Board, 2021; Henning, 2011). Indicators such as inter-city connectivity, bus frequency, vehicle availability, stop density, and lines per capita provide quantifiable insights into the quality, reach, and reliability of transportation networks (Chowdhury et al., 2014; Lee, 2025). These measures enable city authorities to assess whether current systems meet mobility demands, highlight areas for improvement, and support evidence-based policymaking. They also facilitate international benchmarking and comparability, as promoted by frameworks such as the OECD/ITF Sustainable Urban Mobility Indicators (2020).

At the same time, comprehensive evaluation requires recognizing both direct and indirect impacts of public transport. Litman (2021) emphasizes that efficiency assessments must consider benefits such as reduced congestion, lower emissions, improved accessibility for non-drivers, and enhanced public health through active mobility. This perspective complements technical indicators by embedding them in a wider framework of sustainability and equity. Similarly, the HiTrans best practice guidelines argue that network quality must be assessed in terms of competitiveness with private cars, especially in medium-sized European cities where dispersed settlement structures limit transport efficiency (Nielsen et al., 2005).

The Upper Silesian-Zagłębie Metropolis (Górnośląsko-Zagłębiowska Metropolia, GZM) presents a particularly relevant case for exploring these dynamics. As a metropolitan area comprising 41 municipalities, including major cities such as Katowice, Gliwice, Zabrze, Bytom, and Ruda Śląska, GZM constitutes a polycentric urban structure with complex transportation needs. The population density, historical development patterns, and administrative fragmentation have resulted in a diverse and sometimes fragmented transport infrastructure. The establishment of a centralised Metropolitan Transport Authority (ZTM) has been a significant step toward greater integration and coordination of public transport in the region. Nevertheless, disparities in service levels, infrastructure investment, and intercity connectivity remain evident.

This paper focuses on evaluating public transport efficiency in four selected cities within the GZM: Zabrze, Gliwice, Bytom, and Ruda Śląska. These cities were chosen due to their demographic and spatial differences, as well as their strategic location within the metropolis. Each of these cities contributes differently to the regional transport network, with varying levels of service provision and infrastructural development. By applying a set of transport efficiency indicators to these cities, this study aims to identify strengths and weaknesses in their public transport systems and assess their alignment with smart city objectives.

The study employs data from the Central Statistical Office (GUS), the Metropolitan Transport Authority (ZTM), and spatial analysis conducted in QGIS. Five original indicators were proposed: Inter-city Connectivity Ratio (ICR), Daily Course Frequency (DCF), Transport Capacity Potential (TCP), Number of Lines per 1,000 Inhabitants (IL), and Bus Stop Density Indicator (BSD). These indicators not only reflect the operational characteristics of the transport system but also provide a foundation for strategic planning and monitoring.

The originality of this research lies in the combined use of these novel efficiency indicators with spatial accessibility analysis based on GIS. While previous studies have typically focused either on operational performance or on accessibility outcomes in isolation, this paper integrates both perspectives within a single methodological framework. This multidimensional approach provides a new lens for evaluating urban transport systems in medium-sized European metropolitan regions and generates insights that are directly applicable to smart city and sustainable mobility policies.

Furthermore, this research highlights the importance of spatial accessibility, particularly the availability of public transport stops within walking distance of residential areas. Using geospatial tools, the study maps public transport coverage in terms of 500-meter and 1-kilometer buffers around transit stops. This analysis reveals how equitably services are distributed and identifies potential accessibility gaps that may hinder mobility for certain population groups.

In sum, the overarching objective of this article is to demonstrate how efficiency indicators can be effectively applied to assess public transport in a smart city context. By integrating operational, spatial, and social dimensions, the research contributes to the discourse on sustainable mobility and provides practical insights for policymakers in the GZM and beyond.

2. Methods

The methodological framework adopted in this study was designed to enable a comprehensive and multidimensional evaluation of the efficiency of public transport systems as a component of smart city development. The applied approach combines indicator-based assessment with spatial analysis supported by Geographic Information Systems (GIS). This dual perspective allows for both quantitative measurement of transport performance and qualitative evaluation of accessibility patterns.

2.1. Research Design and Data Sources

The research is grounded in secondary data collected from official statistical repositories and administrative bodies responsible for public transport management. In particular, data were obtained from the Local Data Bank of Statistics Poland (GUS) and the Metropolitan Transport Authority (ZTM) of the Upper Silesian-Zagłębie Metropolis. Supplementary information on the spatial distribution of stops was collected and processed using the QGIS software, which enabled integration of transport infrastructure with the spatial structure of the analysed cities.

The methodological design was structured around two complementary components: (1) construction of efficiency indicators and (2) assessment of the spatial coverage of urban areas by public transport stops.

2.2. Efficiency Indicators

To assess the operational and structural dimensions of public transport, five key efficiency indicators were proposed and calculated:

1) **Inter-city Connectivity Ratio (ICR)**

$$ICR = \frac{Number\ of\ lines\ serving\ more\ than\ one\ city}{Total\ number\ of\ urban\ lines} \times 100\%$$

What it measures: the proportion of transport lines that connect more than one city within the metropolis. It reflects how strongly the city's transport network is embedded in the wider metropolitan system rather than being limited to local, intra-urban connections.

Why it matters: high inter-city connectivity reduces fragmentation, improves access to regional labour and education markets, and supports smart city development through integrated mobility.

Interpretation:

- < 20% → weak inter-city integration, risk of isolation (This level of integration indicates that the vast majority of lines are located within municipal boundaries. Therefore, intercity travel relies primarily on private cars).
- 20-40% → partial integration but not sufficient for regional cohesion (Moderate integration reflects partial interconnection, yet still insufficient for a metropolitan area).
- 40% → strong integration, enabling functional metropolitan mobility (High integration denotes that a substantial proportion of transport lines serve inter-city connections).

2) Daily Service Frequency (DSF)

$$DSF = \frac{Daily\ number\ of\ line\ departures}{Number\ of\ urban\ lines}$$

What it measures: the average number of trips operated per line during one day. It indicates how often vehicles arrive at stops, directly affecting passenger waiting time and perceived service quality.

Why it matters: frequency is one of the most critical factors for public transport attractiveness compared to private cars. High frequency reduces waiting time and increases reliability, both of which are central to smart mobility.

Interpretation:

- < 15 trips/line/day → low frequency, users perceive service as unreliable.
- 15-30 → moderate attractiveness but may not compete with cars.
- 30 → high-quality service, supporting sustainable modal shift.

3) Transport Capacity Potential (TCP)

$$TCP = \frac{Total\ daily\ number\ of\ departures}{Population} \times 1000$$

What it measures: the number of daily trips in relation to population size (per 1000 inhabitants). It shows whether the transport supply is adequate to meet the mobility needs of residents.

Why it matters: this indicator links transport capacity with demand (population). It allows to identify undersupply (risk of exclusion) or oversupply (inefficient resource allocation). For smart cities, balancing capacity and demand is key to sustainability.

Interpretation:

- < 5 trips/1000 residents → severe undersupply, risk of transport exclusion.
- 5-15 → acceptable but insufficient to trigger behavioural change.
- 15 → good availability, encouraging public transport use.

4) Number of Lines per 1000 Inhabitants (IL)

$$LI = \frac{Number\ of\ bus\ and\ tram\ lines}{Population} \times 1000$$

What it measures: the density of the transport offer in demographic terms, i.e., how many lines are available for every 1000 inhabitants.

Why it matters: it indicates whether residents have multiple route options. A higher value reflects network flexibility, giving users alternatives and reducing overcrowding. In smart city mobility, network diversification is crucial for inclusiveness.

Interpretation:

- < 0.1 → poor coverage, limited choices for passengers.
- 0.1–0.3 → moderate accessibility, adequate for medium-density cities.
- 0.3 → high accessibility, multiple routes support resilient mobility.

5) Bus Stop Density Indicator (BSD)

$$BSD = \frac{Total\ number\ of\ bus\ stops\ in\ the\ city}{Area\ of\ the\ city\ (in\ km^2)}$$

What it measures: The indicator reflects the spatial accessibility of public transport by quantifying the density of bus stops per square kilometer. It indicates how evenly the network is distributed across the urban area and how far residents must typically walk to reach the nearest stop.

Why it matters: High density of bus stops ensures short walking distances and equitable access to public transport, especially important in smart city strategies for elderly, disabled, or mobility-impaired users. Conversely, low density may lead to transport exclusion in peripheral or low-density neighbourhoods.

Interpretation:

- < 1 bus stop/km² → poor coverage, long walking distances.
- 1-3 bus stops/km² → moderate coverage, adequate in medium-density cities.
- 3 bus stops/km² → high accessibility, typical of well-developed metropolitan systems.

The Bus Stop Density (BSD) indicator is calculated as the number of public transport stops located within the boundaries of the analysed area divided by the area's surface in square kilometres. To determine its value, it is therefore necessary to accurately count the number of stop points within the studied city or district and precisely determine the area's size. Stop location data can be obtained from official sources (e.g., the Metropolitan Transport Authority) or from databases such as OpenStreetMap using the QuickOSM plugin in QGIS. After loading the stop layer, the dataset can be manually updated to reflect the most current state of the transport infrastructure. The calculation can be supported by GIS tools. For example, in QGIS, the "Count Points in Polygon" algorithm can be applied to automatically count the number of stops within a defined area (e.g., city or district boundaries).

To further evaluate accessibility, buffers with a radius of 500 m and 1000 m can be generated around each stop, as illustrated in Figure 1.

Figure 1. 1 km buffer around the bus stop.

Source: prepared using QGIS.

Analysing the overlap of these buffers with the built-up areas makes it possible to identify zones that meet the statutory recommendations on maximum walking distances to public transport stops included in the Polish housing special act (500 m in cities with more than 100,000 residents, 1000 m in smaller towns). This approach allows not only the calculation of the BSD value but also a spatial diagnosis of areas with potentially limited access to public transport.

The interpretation of the efficiency indicators developed in this study required the adoption of threshold values distinguishing low, moderate, and high performance. Since there are no universally established benchmarks for such indicators, the thresholds were determined through:

- comparative reasoning with European metropolitan areas noted for high transport performance and integration, e.g., Vienna (European Economic and Social Committee, 2004), Copenhagen (OECD, 2009). Ruhr region and Randstad (Centre for Cities, 2016);
- literature evidence highlighting functional requirements of metropolitan public transport (Vuchic, 2005; Priemus and Zonneveld, 2003);
- planning standards and guidelines from international bodies (OECD/ITF, 2020; UITP, 2018) emphasizing accessibility and frequency.

There are no universally established threshold values for the Inter-city Connectivity Ratio (ICR), which measures the share of inter-municipal transit lines. Functional urban area frameworks emphasise the importance of inter-municipal commuting (European Economic and Social Committee, 2004; OECD, 2009), and comparative studies of highly integrated metropolitan regions, such as the Randstad and Rhine-Ruhr, confirm that extensive inter-city connections are a key component of successful metropolitan transport systems (Centre for Cities, 2016). While studies underline the need for integrated networks (Vuchic, 2005; Priemus, Zonneveld, 2003), they do not propose numeric benchmarks. In this study, ICR values below 20% are interpreted as indicating weak system integration, values between 20 % and 40 % as moderate integration, and those above 40% as strong. The upper threshold reflects empirical modal-split patterns in Vienna, where approximately 39% of trips are undertaken by public transport, which is indicative of a highly integrated system (European Commission (DG MOVE), 2025; European Commission, 2020).

Another critical measure is the Daily Service Frequency (DSF), since service frequency is a key determinant of user satisfaction and modal shift (Vuchic, 2005). Urban planning and accessibility guidelines suggest that a minimum of 2-4 departures per hour, corresponding to roughly 15-30 trips per line per day, is required for an attractive public transport offer (OECD/ITF, 2020). Consequently, fewer than 15 trips per line per day are considered insufficient, 15-30 denote a moderate level of service, and more than 30 indicate a high-quality offer. UITP (2018) also stresses that frequent and reliable service is fundamental to inclusive and accessible mobility systems.

Similarly, there are no formal benchmarks for the Transport Capacity Potential (TCP) expressed as the number of trips per 1000 inhabitants per day. Sustainable transport planning highlights the need to match capacity with demand (Litman, 2021; OECD/ITF, 2020). Against this backdrop, values below 5 trips per 1000 residents indicate undersupply, values between 5 and 15 are interpreted as intermediate, while those above 15 represent adequate supply. These thresholds align with conditions observed in well-integrated metropolitan regions such as the Ruhr area or the Randstad, where public transport serves a substantial share of commuting flows (Centre for Cities, 2016; OECD, 2009).

The Number of Lines per 1000 Inhabitants (IL) also lacks internationally standardised values. Comparative analyses of metropolitan areas demonstrate that higher line densities correlate with greater public transport use (European Commission, 2020). Therefore, values below 0.1 lines per 1000 inhabitants are considered a poor offer, 0.1-0.3 indicate a moderate level, and values above 0.3 are indicative of a good supply.

Finally, the Bus Stop Density Indicator (BSD) should be assessed in relation to accessibility norms. Urban accessibility guidelines recommend walking distances to public transport stops not exceeding 500-1000 metres, which in dense urban areas corresponds to approximately 1-3 stops per km² (European Commission (DG MOVE), 2025; OECD/ITF, 2020; Federal Transit Administration, 2015). Consequently, less than 1 stop per km² denotes poor spatial accessibility, 1-3 stops per km² is considered satisfactory, while more than 3 stops per km² is regarded as very good. This interpretation is consistent with accessibility research and UITP's inclusive mobility guidelines (UITP, 2018).

These thresholds are functional benchmarks informed by literature, planning standards, and regional patterns—not rigid norms. They provide a structured framework for interpreting transport efficiency within smart city contexts and for comparison across cities.

3. Results

The analysis of metropolitan public transport efficiency for Zabrze, Gliwice, Bytom and Ruda Śląska was carried out using a set of indicators assessing inter-city connectivity, service frequency, transport capacity, network density and spatial accessibility.

The ICR values indicate a strong level of inter-municipal connectivity in most of the analysed cities. Bytom achieved the highest share of inter-city lines at 83% (Fig. 2), followed by Ruda Śląska (82%) (Fig.3) and Zabrze (79%) (Fig. 4). Gliwice recorded a lower value of 63% (Fig. 5), which, while below the others, still falls within the high integration category. According to the adopted interpretation thresholds, values above 40% are classified as strong integration, enabling cohesive regional travel and supporting smart city development objectives. From this perspective, all four cities demonstrate high inter-city integration, confirming the importance of a dense, cross-boundary network in metropolitan areas.

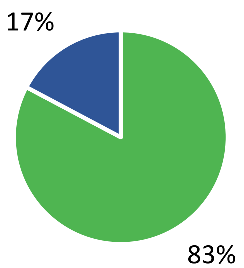

Figure 2. Chart of the percentage of connections with other cities (ICR) for the city of Bytom (green - lines operating in more than one city, blue - lines operating in one city).

Source: own study.

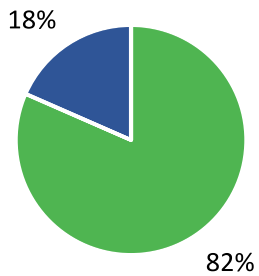

Figure 3. Chart of the percentage of connections with other cities (ICR) for the city of Ruda Śląska (green - lines operating in more than one city, blue - lines operating in one city) .

Source: own study.

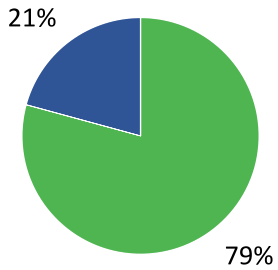

Figure 4. Chart of the percentage of connections with other cities (ICR) for the city of Zabrze (green - lines operating in more than one city, blue - lines operating in one city).

Source: own study.

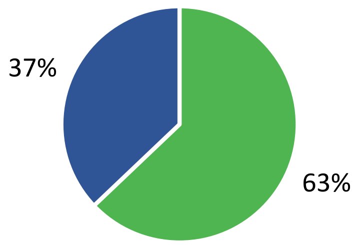

Figure 5. Chart of the percentage of connections with other cities (ICR) for the city of Bytom (green - lines operating in more than one city, blue - lines operating in one city).

Source: own study.

The DSF analysis highlights that service frequency plays a decisive role in transport attractiveness. According to Fig. 6, all analysed cities significantly exceed the high-quality threshold of 30 trips per line per day. Bytom achieves the highest daily service frequency at around 53.7 trips per line, followed by Ruda Śląska (50.3), Gliwice (46.6) and Zabrze (44.4). These results show that all four cities fall into the high-quality group (>30), which helps people choose public transport instead of cars and makes it a real alternative to driving. The results confirm that residents in all analysed cities have access to frequent and reliable services, a key factor for smart and sustainable mobility.

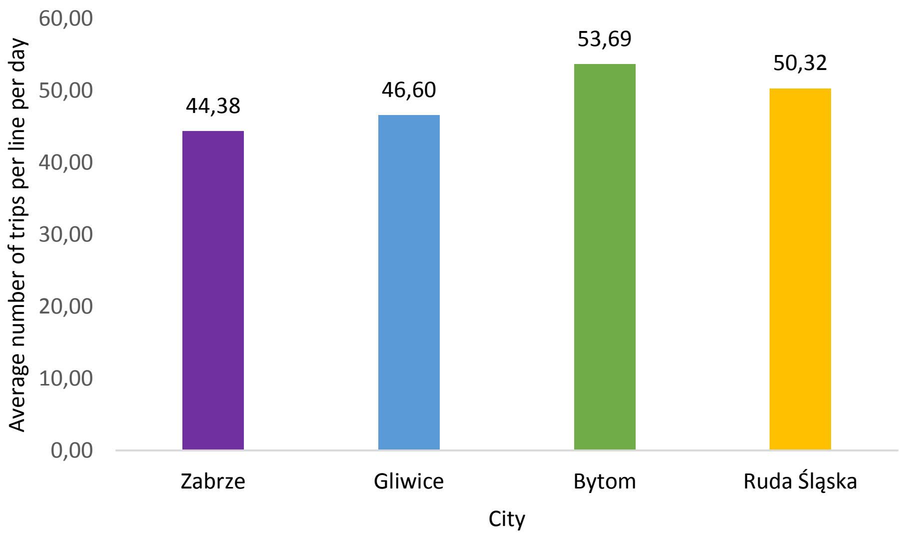

Figure 6. The Daily Service Frequency (DSF).

Source: own study.

The Transport Capacity Potential (TCP) indicator (Fig. 7), measuring the total number of daily trips per 1000 residents, further highlights differences in service provision.

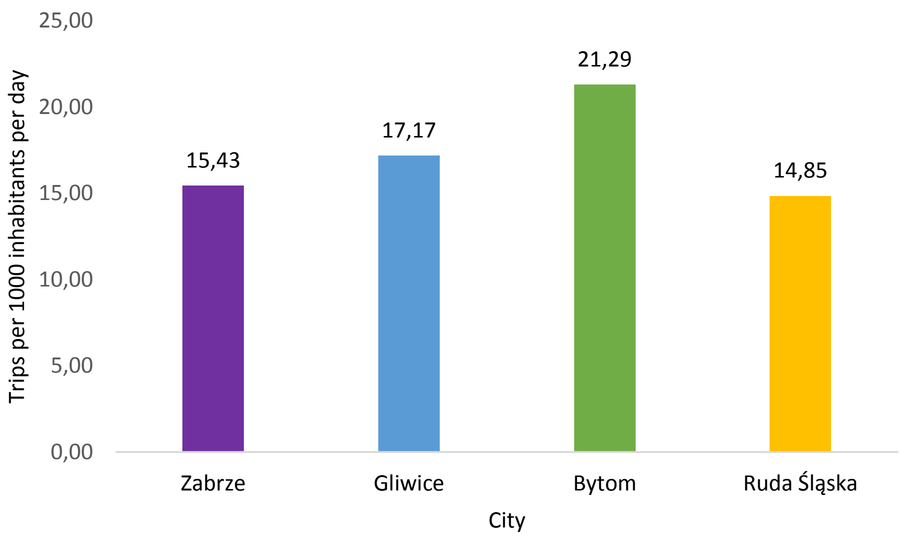

Figure 7. The Transport Capacity Potential (TPC).

Source: own study.

Bytom records the highest value with 21.29 trips/1,000 inhabitants, followed by Gliwice (17.17), Zabrze (15.43) and Ruda Śląska (14.85). According to the adopted interpretation, <5 trips/1000 residents/day indicates a severe undersupply and a risk of transport exclusion, 5-15 represents an acceptable but insufficient level to trigger behavioural change, while values above 15 denote good availability that encourages public transport use. Bytom clearly exceeds this threshold, confirming its well-developed service provision, while Gliwice and Zabrze also fall within the good availability category. Ruda Śląska, with a value just below 15, remains slightly behind and may require targeted improvements to strengthen accessibility. The Number of Lines per 1000 Inhabitants (IL) reflects the density of the transport offer in demographic terms — how many bus and tram lines are available for every 1000 residents. This indicator matters because a higher value provides passengers with multiple route options, increases network flexibility, and reduces the risk of overcrowding. It is also crucial for inclusiveness in smart city mobility, because a varied network gives all users fair access. In the analysed cities, IL ranges from 0.30 in Ruda Śląska to 0.40 in Bytom (Fig. 8).

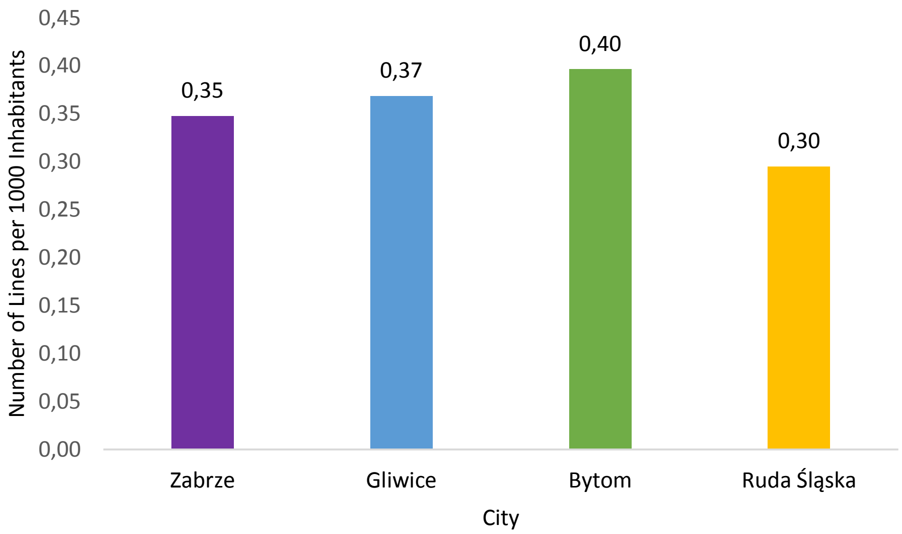

Figure 8. The Number of Lines per 1000 Inhabitants (IL).

Source: own study.

According to the adopted interpretation thresholds, <0.1 indicates poor coverage and limited choices for passengers, 0.1-0.3 denotes moderate accessibility adequate for medium-density cities, while >0.3 reflects high accessibility, where multiple routes support resilient and inclusive urban mobility. Thus, Bytom and Gliwice, both above 0.35, provide high accessibility; Zabrze also falls within this high category, while Ruda Śląska, at 0.30, remains at the upper end of moderate accessibility.

The last indicator analysed is the bus stop density index (BSD), which reflects the spatial accessibility of public transport, measured by the number of stops per square kilometer. As shown in Figure 9, Zabrze has the highest BSD at 4.69 stops/km², followed by Bytom (4.3 stops/km²), Ruda Śląska (3.67 stops/km²) and Gliwice (3.14 stops/km²). According to the adopted interpretation (<1 stop/km² – poor coverage; 1-3 stops/km² – moderate; >3 stops/km² – high accessibility), all analysed cities exceed the 3 stops/km² threshold, confirming a high level of accessibility typical of well-developed metropolitan systems. This density ensures short walking distances and equitable access, which is particularly important in smart city strategies targeting the elderly and mobility-impaired users.

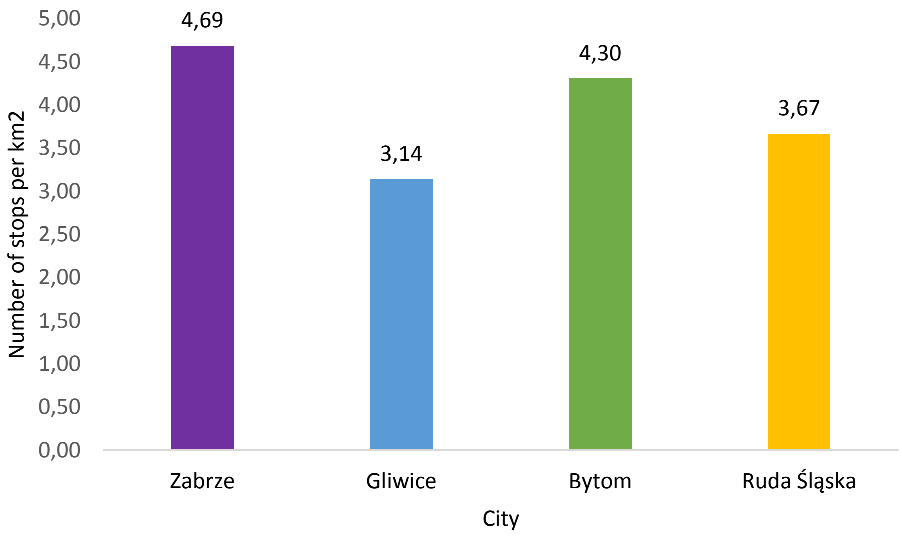

Figure 9. The Bus Stop Density (BDS).

Source: own study.

A detailed GIS analysis of the spatial coverage provides further insights into the distribution of stops and accessibility gaps. Figures 10-13 illustrate the location of stops and the 1 km buffers in Zabrze, Gliwice, Bytom and Ruda Śląska. At this buffer level, nearly all built-up areas are covered, demonstrating that the majority of residents can reach a stop within a 10-15 minute walk. The highest spatial coverage is observed in Zabrze and Bytom, where even peripheral districts are within the 1 km service area. The maps were prepared in QGIS using spatial data from OpenStreetMap, which ensured both accuracy and comparability of the analysis across cities. The integration of OSM data allowed for the identification of peripheral gaps that are not always visible in official statistics, highlighting the added value of open-source geoinformation. This methodological approach offers a clear and reproducible way of assessing public transport accessibility, which can also be applied to other cities and metropolitan areas.

As shown in Figure 9, Zabrze records the highest bus stop density among the four analysed cities. This finding is also reflected in the 1 km buffer analysis presented in Figure 10, which demonstrates that more than 80% of built-up residential areas are located within the service area. Only small peripheral fragments remain outside the buffer, confirming the generally high level of accessibility in the city.

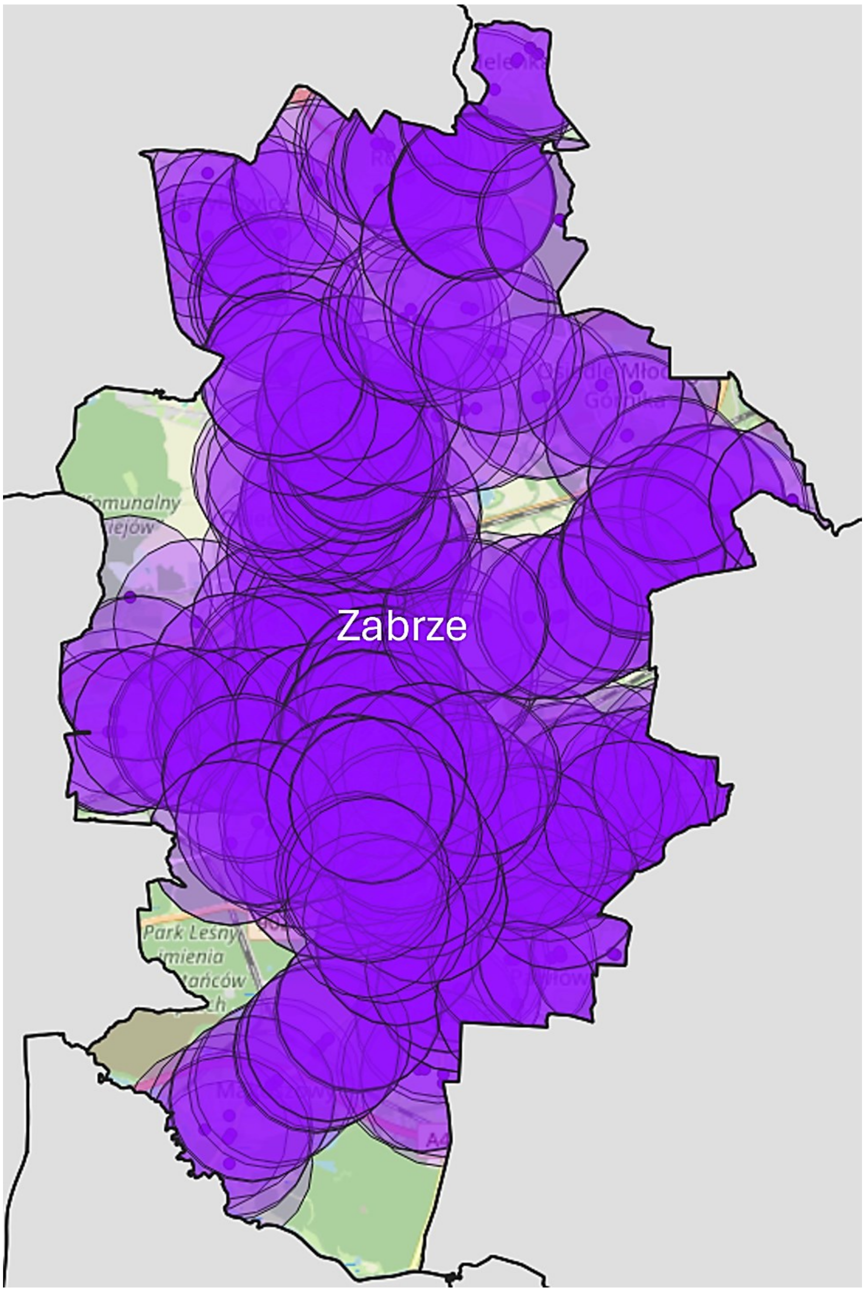

Figure 10. A map of the area covered with a 1-kilometer buffer of pedestrian distances around each stop for Zabrze.

Source: own study, prepared using QGIS and OpenStreetMap data.

As can be seen in Figure 11 for Gliwice, the overall coverage is high, yet some accessibility gaps remain on the periphery. Nearly all central and inner-district built-up areas fall within the 1 km buffer, but small fragments of development are uncovered. These include the northernmost built-up area of Czechowice on the left of the map and a housing estate above the Ostropa district near the Sośnicowice boundary above the A4 corridor. These gaps correspond to zones of dispersed housing, whereas the dense urban core exhibits full coverage, indicating broadly satisfactory accessibility at the 1 km scale.

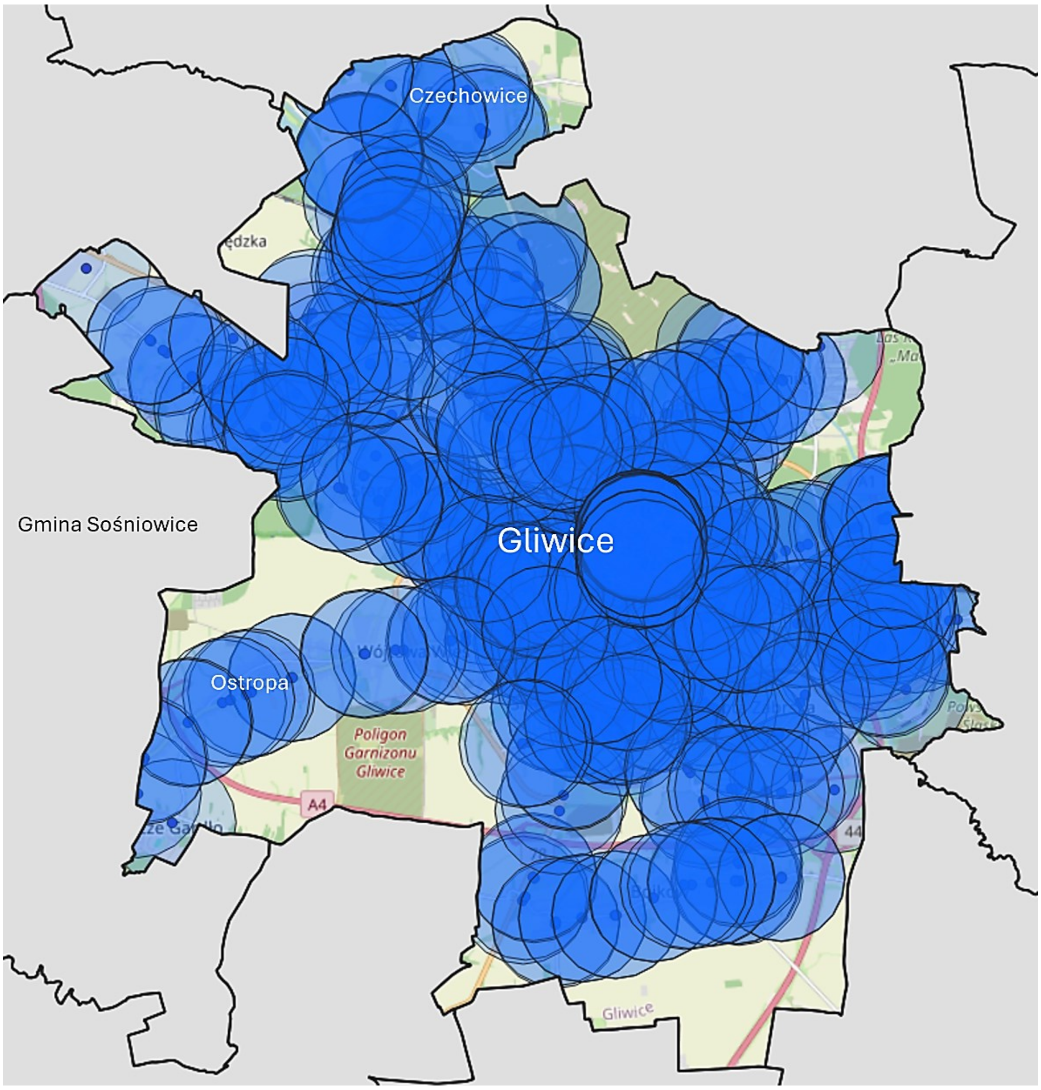

Figure 11. A map of the area covered with a 1-kilometer buffer of pedestrian distances around each stop for Gliwice.

Source: own study, prepared using QGIS and OpenStreetMap data.

The map for Bytom in Figure 12 shows that almost all of the city's residential development is located within a 1-kilometer buffer. The very few uncovered fragments are situated on the periphery and are typically industrial or undeveloped areas rather than residential zones. The compact settlement structure of Bytom contributes to its nearly complete service coverage, with excellent accessibility in the city centre and surrounding districts.

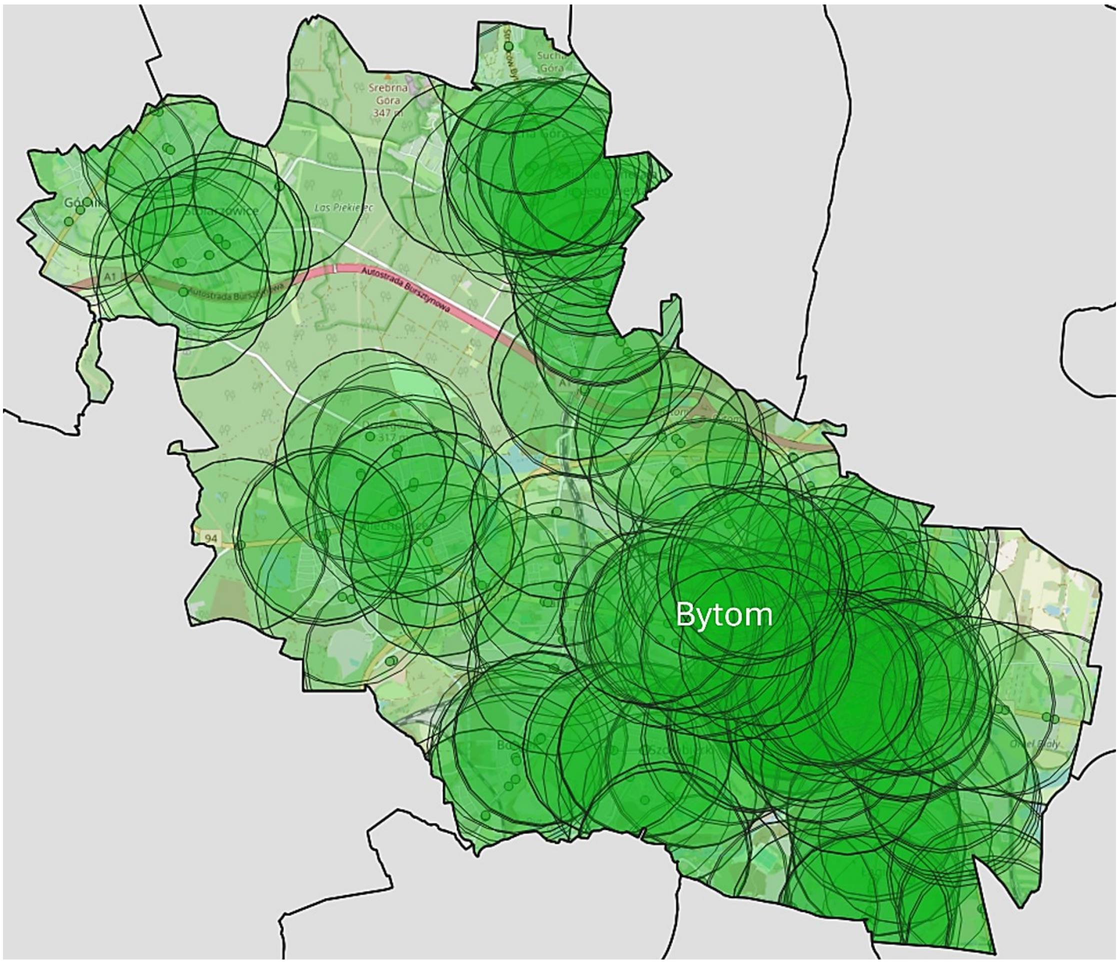

Figure 12. A map of the area covered with a 1-kilometer buffer of pedestrian distances around each stop for Bytom.

Source: own study, prepared using QGIS and OpenStreetMap data.

Most Ruda Śląska residents also have convenient access to public transport within a 1 km walk (Figure 13). The central and inner-city districts are fully covered, with only some areas on the southern and western outskirts lying outside the buffer. These gaps correspond to more dispersed or mixed-use development patterns and larger areas of greenery or former industrial land. Nevertheless, the majority of the built-up area maintains good spatial accessibility to stops.

In summary, the 1 km buffer analysis highlights that while all four cities perform well in terms of stop coverage and meet smart mobility objectives, there are localised peripheral gaps in low-density districts. These findings provide a foundation for fine-grained 500 m buffer analyses to target micro-scale improvements.

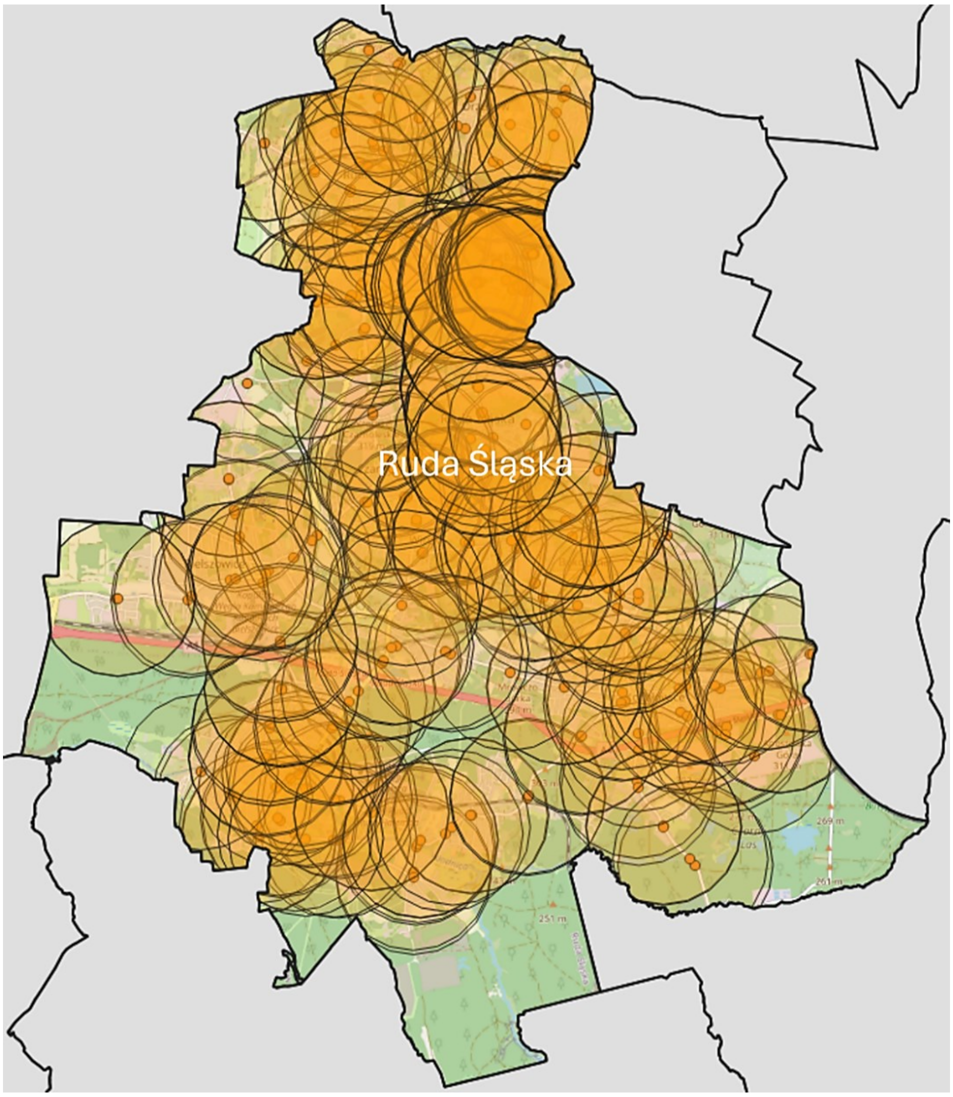

Figure 13. A map of the area covered with a 1-kilometer buffer of pedestrian distances around each stop for Ruda Śląska.

Source: own study, prepared using QGIS and OpenStreetMap data.

As shown in Figure 14, in north Zabrze, there is a large light-grey built-up fragment on the left (labelled "1" in the thesis) and several housing/streets (labelled "2") lying beyond 500 m from the nearest stop; on the right side the coverage improves, yet a part of Rokitnica remains outside the buffer (labelled "3"). In south Zabrze (Fig. 15), coverage is generally good, but a built-up section of Maciejów at the top-right edge near the Gliwice border has no stop within 500 m (labelled "4"); other southern areas are acceptably covered.

Taken together, these findings show why BSD >3 stops/km² is a helpful first-order signal (high accessibility), but micro-scale gaps at 500 m matter for everyday usability and equity. For Zabrze this points to targeted, low-cost fixes, e.g., adding or relocating stops in Rokitnica and Maciejów.

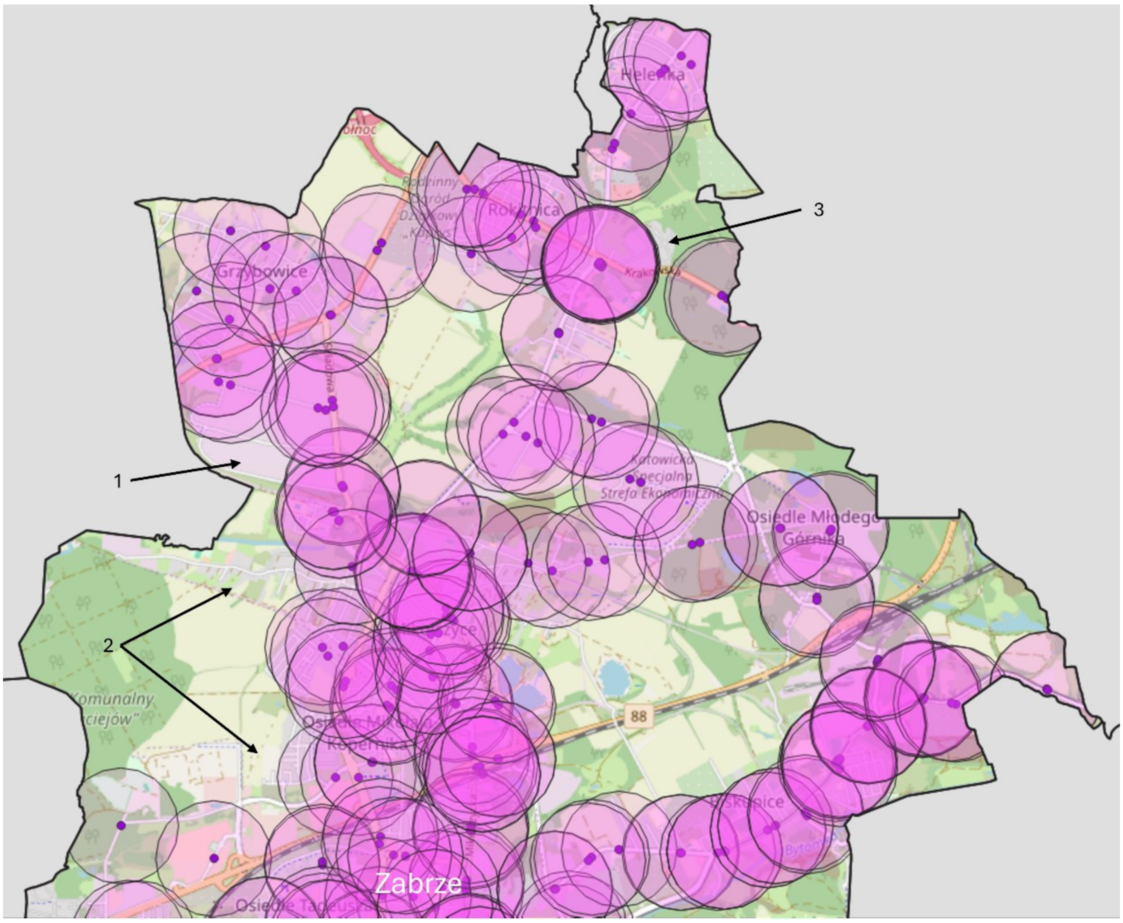

Figure 14. A map of the area covered with a 500-meter buffer of pedestrian distances around each stop for the northern part of Zabrze.

Source: own study, prepared using QGIS and OpenStreetMap data.

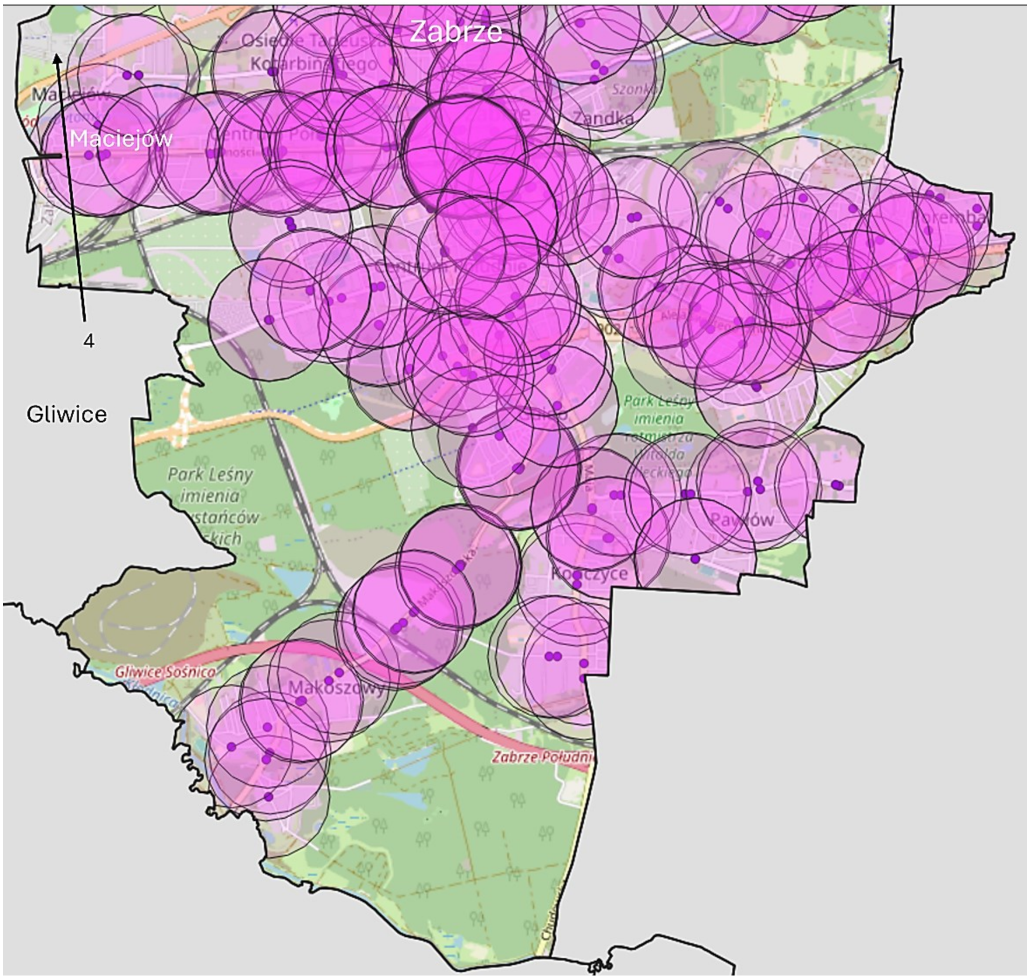

Figure 15. A map of the area covered with a 500-meter buffer of pedestrian distances around each stop for the southern part of Zabrze.

Source: own study, prepared using QGIS and OpenStreetMap data.

While the citywide BSD in Gliwice exceeds the high-accessibility threshold, a closer look at walking-distance coverage reveals important local differences. At the stricter 500 m walking threshold, north Gliwice (Fig. 16) shows clear coverage gaps: a larger uncovered area in Żerniki, located east of the A1, and additional uncovered built-up fragments in Czechowice (the northernmost part of the city). These are continuous residential patches beyond 500 m from the nearest stop, signalling a need for targeted adjustments.

In south Gliwice (Fig. 17), there are many small gaps between the 500 m buffers, mostly in single-family housing areas where buildings are spread out. Because of this layout, some homes are still over 500 m from a stop, even though there are many stops overall. This shows how the average BSD can hide these small local access problems".

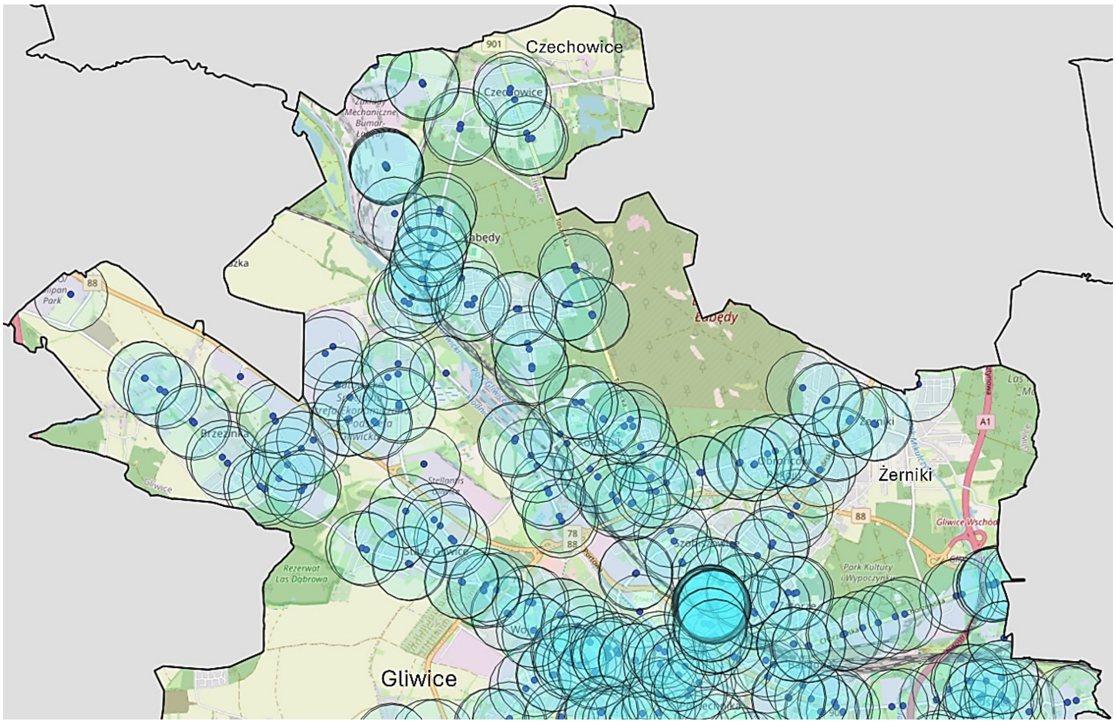

Figure 16. A map of the area covered with a 500-meter buffer of pedestrian distances around each stop for the northern part of Zabrze.

Source: own study, prepared using QGIS and OpenStreetMap data.

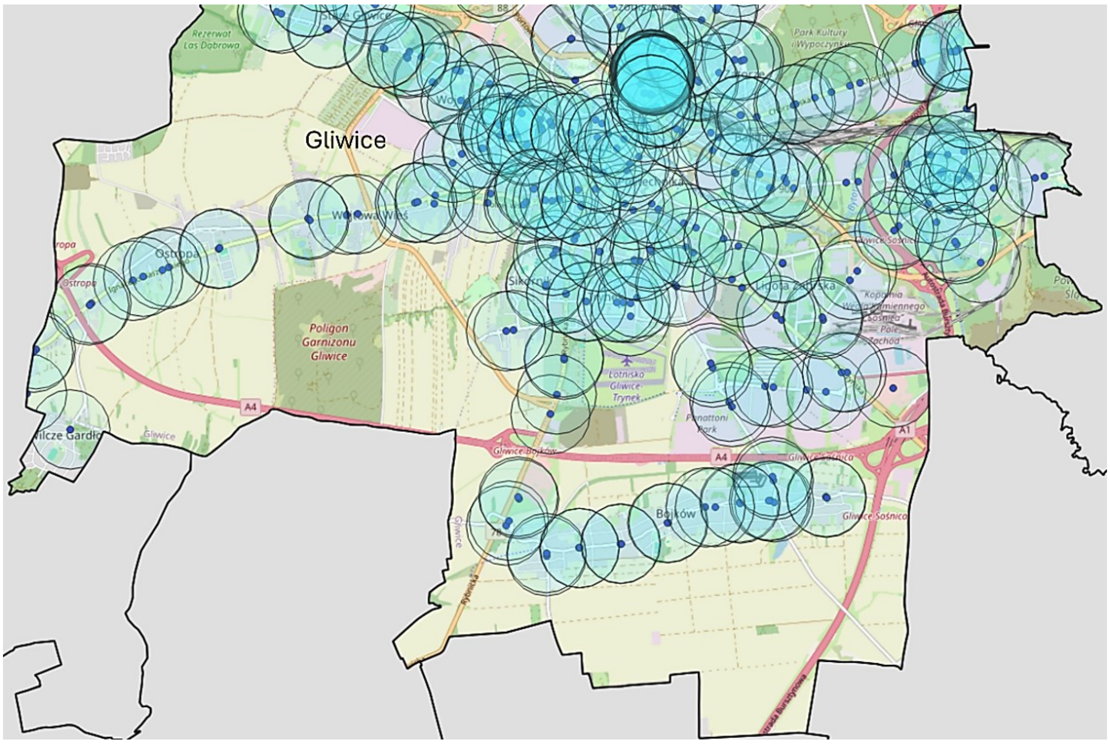

Figure 17. A map of the area covered with a 500-meter buffer of pedestrian distances around each stop for the southern part of Zabrze.

Source: own study, prepared using QGIS and OpenStreetMap data.

Bytom has one of the highest stop densities among the analysed cities (BSD ≈ 4.3 stops/km²; Fig. 9), which on average terms suggests short walking distances and good overall network coverage. However, as can be seen in Figure 18, at the stricter 500 m buffer, some housing estates and single-family streets appear outside the service area. While central Bytom is well covered, the deficits are mainly located on the city's edges in low-density residential zones. This implies a need for small-scale interventions—such as adding or relocating stops or making short route adjustments—to translate the high citywide BSD into uniform 500 m walking access.

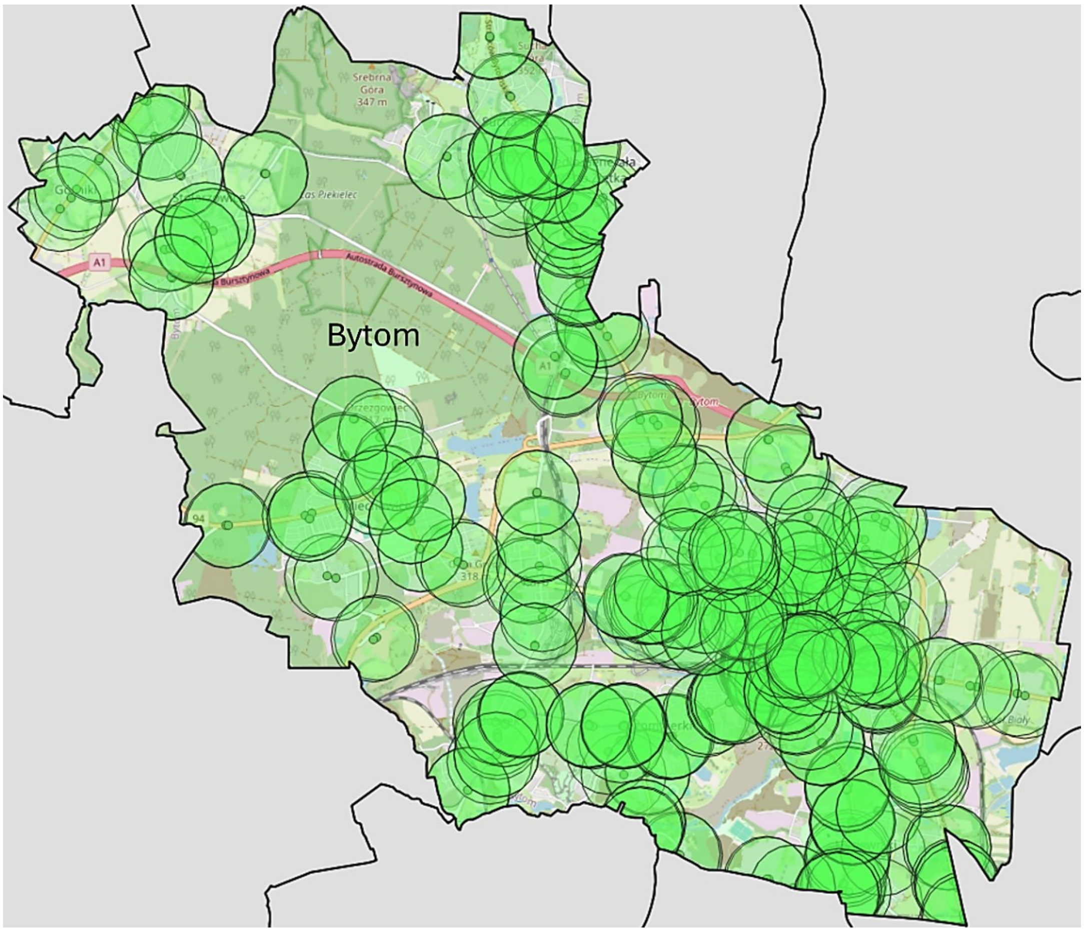

Figure 18. A map of the area covered with a 500-meter buffer of pedestrian distances around each stop in Bytom.

Source: own study, prepared using QGIS and OpenStreetMap data.

Ruda Śląska achieves BSD ≈ 3.7 stops/km² (Fig. 9), also placing it above the high-accessibility threshold in average terms. As shown in Figure 19, at the 500 m buffer, accessibility drops more noticeably in these peripheral low-density areas. Central neighbourhoods maintain good coverage. Addressing these gaps would require denser stop spacing or minor route adjustments in critical residential pockets.

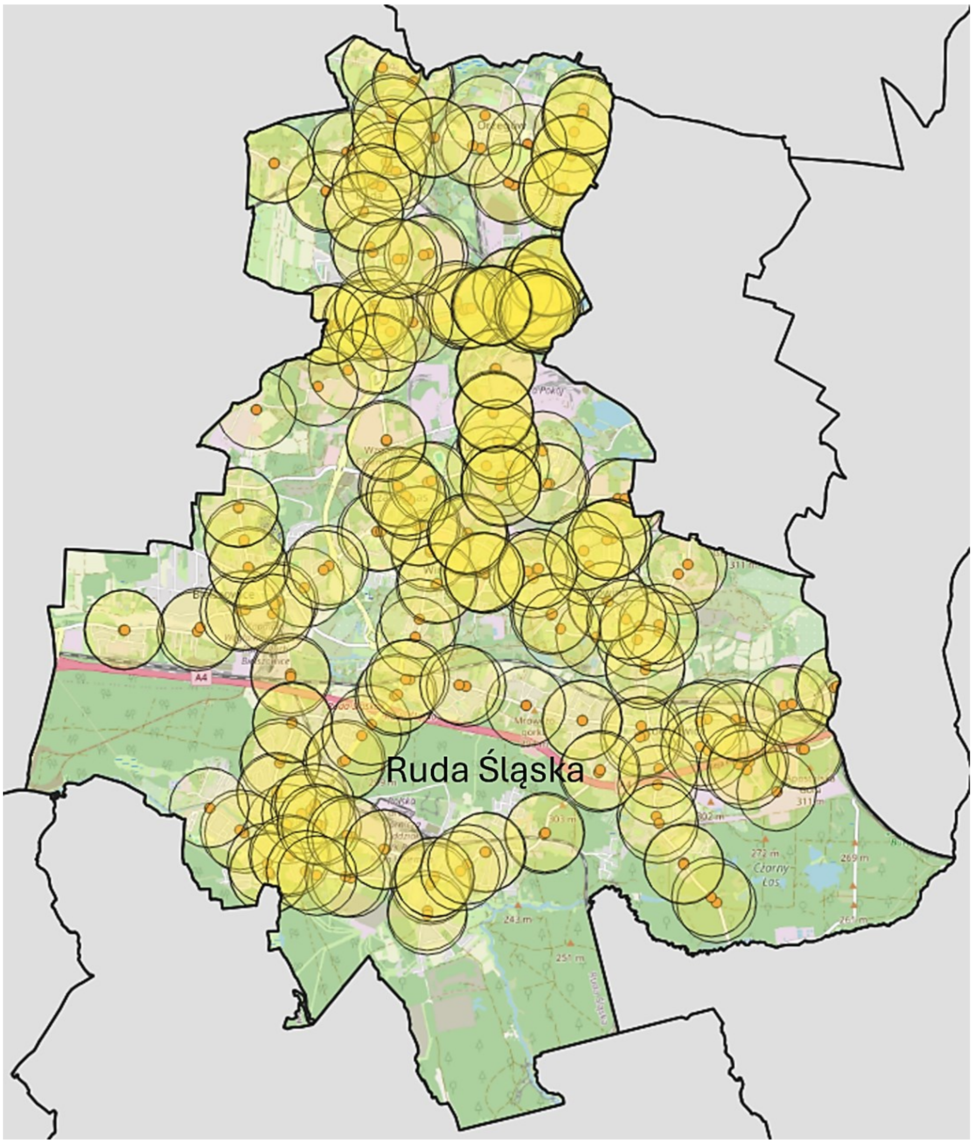

Figure 18. A map of the area covered with a 500-meter buffer of pedestrian distances around each stop in Ruda Śląska.

Source: own study, prepared using QGIS and OpenStreetMap data.

Summarising the analyses of the 500 m buffer in all four cities, it can be seen that despite high accessibility throughout the city, there are local gaps in services in the peripheral districts with low population density. These results suggest that micro-scale planning interventions, such as the addition of stops, minor route adjustments or complementary first/last-mile solutions, could enhance inclusiveness and ensure that even residents on the urban fringe have equitable access to public transport.

4. Discussion

The findings of this study confirm that public transport systems in Zabrze, Gliwice, Bytom and Ruda Śląska exhibit high levels of efficiency when measured through the proposed indicators. Strong inter-city integration (ICR > 60%) and high daily service frequency (DSF > 44) align with international evidence emphasizing the importance of connectivity and frequency for modal shift towards public transport. Vuchic (2005) as well as the Centre for Cities (2016) highlight that dense, cross-boundary networks and frequent services are prerequisites for making public transport competitive with private cars in metropolitan regions. Our results resonate with these conclusions, demonstrating that the analysed GZM cities already meet such benchmarks.

At the same time, the Transport Capacity Potential (TCP) values (14.85-21.29 trips per 1,000 inhabitants) and the Number of Lines per 1000 Inhabitants (IL, 0.30-0.40) indicate that service supply in demographic terms is adequate but heterogeneous. Similar patterns were identified in OECD/ITF (2020) reviews, which stress that cities with strong aggregate capacity may still face localized undersupply, particularly in low-density suburban districts. Our results for Ruda Śląska (TCP below 15) confirm this risk, suggesting that capacity allocation must be fine-tuned to match local demand.

The spatial accessibility analysis using bus stop density (BSD) and GIS-based buffers provides further insights. While all four cities surpass the high-accessibility threshold (>3 stops/km²), the 500 m buffer analysis reveals gaps in peripheral areas. Comparable discrepancies between average indicators and local accessibility outcomes have been documented in Nordic smart city strategies (Müller-Eie, Kosmidis, 2023) and OECD/ITF (2020) guidelines, which warn against relying solely on macro-scale efficiency measures. Our results for districts such as Rokitnica in Zabrze and Żerniki in Gliwice illustrate these challenges, showing how inclusiveness and equity may be compromised despite overall high performance. Based on these insights, it is recommended to implement targeted, low-cost interventions such as:

- adding or relocating stops in underserved areas,
- minor route adjustments,
- first/last-mile solutions (e.g., micro-mobility, demand-responsive transit) (Manning and Babb, 2023; Ferguson and Sanguinetti, 2021).

In doing so, the GZM can strengthen both the efficiency and equity of its public transport system, thereby advancing its smart city objectives.

The originality of this study lies in the integration of quantitative performance indicators with GIS spatial analysis. Previous research often assessed either operational efficiency (Henning, 2011; Chowdhury et al., 2014) or accessibility outcomes (European Commission, 2020) in isolation. By combining both approaches, our study provides a multidimensional framework that better reflects smart city principles, where efficiency, inclusiveness, and sustainability must be pursued simultaneously (Brzeziński, 2024; Shao, Min, 2025; Tamakloe et al., 2024). This methodological integration fills an existing gap and offers a replicable tool for other metropolitan regions.

Finally, the implications of our findings support international trends such as the “15-minute city” and transit-oriented development (OECD/ITF, 2020). At the same time, international evidence demonstrates that efficiency indicators must be embedded in broader frameworks of sustainability and resilience (Kaiser and Schaffer, 2025). Litman (2021) stresses that evaluation of public transport must account for external benefits such as reduced congestion, environmental gains, and health impacts, while Müller-Eie and Kosmidis (2023) point out that Nordic smart city mobility strategies often fail in addressing equity. Insights from Saudi Arabian cities suggest that smart mobility solutions can significantly enhance operational efficiency when supported by robust infrastructure and effective governance (Alotaibi et al., 2025). Similar conclusions are drawn in reviews of smart public transport systems worldwide (AlFalasi, 2025). Furthermore, energy efficiency considerations (Augustyn, 2025) and sustainability indicators (da Silva Tomadon et al., 2024) provide an additional dimension for strengthening policy decisions.

Building on these insights, future research should aim to operationalise these broader perspectives in the context of the GZM. First, the scope of analysis ought to be extended to all municipalities within the metropolis and compared with other Polish and European regions to capture inter-metropolitan diversity. Incorporating dynamic data sources (real-time GPS, ticketing and mobile phone data) would allow for monitoring temporal variations in efficiency and service quality.

5. Summary

This study set out to evaluate the efficiency of public transport systems in four cities of the Upper Silesian-Zagłębie Metropolis (Zabrze, Gliwice, Bytom, Ruda Śląska) using a combination of five original indicators and GIS-based accessibility analysis. The proposed indicators – Inter-city Connectivity Ratio (ICR), Daily Service Frequency (DSF), Transport Capacity Potential (TCP), Number of Lines per 1,000 Inhabitants (IL), and Bus Stop Density (BSD) – provided a multidimensional framework for assessing operational, demographic, and spatial aspects of public transport performance. By linking these measures to international benchmarks (OECD/ITF, DG MOVE, UITP, SUMI), the study demonstrated both strong regional integration and local weaknesses that may limit inclusiveness.

While many previous works have focused either on operational measures (Henning, 2011; Chowdhury et al., 2014) or accessibility norms (European Commission, 2020; UITP, 2018), this paper combines both approaches. The findings show that high aggregate values of connectivity, frequency, and stop density can mask micro-scale inequalities visible only through fine-grained GIS analysis, a point also emphasised in international studies of metropolitan mobility (OECD/ITF, 2020; Müller-Eie, Kosmidis, 2023).

The results confirm that the four analysed cities meet or exceed many thresholds for high-quality service, aligning with literature that underscores the role of frequency, connectivity, and diversity of routes in fostering modal shift and competitiveness with private cars (Vuchic, 2005; Centre for Cities, 2016). At the same time, spatial gaps at the 500 m scale demonstrate that equity and inclusiveness remain challenges even in generally well-performing systems. This echoes broader critiques in the literature that smart mobility strategies often neglect vulnerable groups and localised accessibility (Litman, 2021; Müller-Eie, Kosmidis, 2023).

By explicitly combining indicator-based efficiency assessment with spatial equity analysis, the study offers a replicable framework for policymakers and practitioners. The approach highlights not only where systems perform strongly but also where targeted, low-cost interventions such as additional stops, minor route adjustments, or first/last-mile solutions can enhance inclusiveness. In doing so, the paper contributes to the international discourse on smart and sustainable mobility by showing how locally adapted measures can be grounded in globally recognised standards.

Acknowledgements

This paper was published as part of the statutory research ROZ 1: BK-264/ROZ1/2024 (13/010/BK_24/0081) at the Silesian University of Technology, Faculty of Organization and Management.

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