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ASSESSMENT OF SPATIAL EQUITY OF SCHOOL AND WORKPLACE LOCATIONS FROM THE PERSPECTIVE OF SOURCE AND DESTINATION: A CASE STUDY IN POLAND

Sławomir Goliszek 

Institute of Geography and Spatial Organization
Polish Academy of Sciences
Twarda 51/55, 00-818 Warsaw: Poland
e-mail: sgoliszek@twarda.pan.pl

Abstract

This study provides a comprehensive assessment of spatial disparities in transport accessibility to key urban services – kindergartens, primary and secondary schools, and workplaces – in Szczecin, Poland. Framed within the concept of spatial justice, the research examines how differences between public transport (PT) and private transport (PrT) influence both the level and equity of access to education and employment opportunities. The methodological approach combines cumulative accessibility measures with inequality metrics, including the Lorenz curve and the Gini coefficient. Accessibility was calculated for time thresholds ranging from 5 to 60 minutes, in 5-minute increments, using GTFS-based public transport data and Google Maps API data for car travel. The analysis incorporates age-differentiated population groups corresponding to specific trip purposes (3-6, 7-15, 16-18, and 19-65 years), enabling a socially grounded evaluation of spatial equity. The results reveal a clear and systematic advantage of private transport in both the extent and the equity of accessibility. The most pronounced disparities occur within the 20-30-minute travel time window, which is critical for daily school and work commutes. Public transport accessibility is strongly concentrated in central areas, while peripheral districts experience persistent deficits, particularly in access to workplaces and primary schools. Gini coefficients indicate higher inequality in PT than in PrT, with the greatest disparities observed in workplace accessibility. The findings highlight structural mismatches between residential areas, service locations, and the public transport network. They underscore the need for equity-oriented transport and urban planning policies to improve medium-range PT connections and reduce accessibility gaps in peripheral areas. Transport accessibility should be understood not only as a matter of efficiency, but also as a fundamental component of social equity and urban justice.

Keywords

spatial equity • private transport • public transport • cumulative accessibility • Gini

Introduction

Access to educational institutions, employment opportunities, and other public services is a key indicator of sustainable urban development. It directly affects residents' quality of life and contributes to creating more inclusive communities (Zhao et al., 2023). The spatial accessibility of such services – especially education and employment – remains the subject of intensive research across various countries and socio-spatial contexts (Martínez & Viegas, 2013). At the same time, increasing emphasis is being placed on the role of social justice as a foundational principle in urban spatial planning, particularly in ensuring equitable access to education, employment, and other public resources (Goliszek et al., 2020). These issues are inherently linked to the concept of spatial equity, which was already emphasised in the 1980s by scholars such as Cave and Chester (1981) and Pacione (1989).

Despite advances in planning theory and practice, accessibility to educational services and workplaces remains uneven due to spatial variations in both demand and supply. Limited access may lead to marginalisation and social exclusion (Bruno et al., 2024; Liu et al., 2024), especially among low-income households, for whom inadequate accessibility can increase daily living costs and restrict opportunities for upward social mobility (Liu & Kwan, 2020; Herszenhut et al., 2022). From the perspective of spatial justice, the fair and equitable allocation of opportunities and resources in urban space is a fundamental principle that underpins the right to the city and to basic services (Beach et al., 2018). Unequal access to education and employment challenges not only efficiency but also these basic rights, raising ethical concerns about social equity and collective well-being (Harvey, 2009). From a transport planning and urbanism perspective, these challenges require integrated approaches linking land use, mobility systems, and service provision (Farrington, 2007).

While considerable research has examined spatial disparities in accessibility to

workplaces or educational services independently, few studies have integrated both domains to assess their combined spatial and social equity within metropolitan contexts, particularly in medium-sized Central and Eastern European cities (Sharma & Patil, 2024). Moreover, there remains a methodological gap in linking the detailed demographic structure of potential users with variations in both public and private transport accessibility across a single urban area. Addressing this gap, this study specifically analyses two forms of accessibility via public transport (PT) and private transport to educational institutions (kindergartens, primary, and secondary schools) and workplaces in Szczecin (Goliszek, 2022b). The primary objective is to provide an integrated empirical assessment of spatial disparities in transport accessibility and how they relate to the distribution of population and daily activity destinations, with explicit attention to age-differentiated demand. The analysis incorporates demographic data for age groups 3-6, 7-15, 16-18, and 19-65, reflecting the spatial distribution of students and employment within the city. Quantitative methods are applied, including cumulative accessibility measures, the Lorenz curve, and the Gini coefficient, enabling a comprehensive assessment of spatial and social equity. A secondary objective is to formulate policy recommendations for education, transport, and urban planning in Szczecin, including guidance on potential locations for future public investments.

The article's structure was designed to enable a systematic assessment of spatial justice. First, the study area (Szczecin) was characterised, and four key components of the analysis were described in detail: land-use, transport, temporal, and individual components. Next, the research methodology was presented, based on cumulative accessibility measures and inequality analysis tools such as the Lorenz curve and the Gini coefficient.

The subsequent section presents the research findings, including an analysis of accessibility to kindergartens, schools, and workplaces; a comparison of the effectiveness of public

and private transport; and the identification of accessibility gaps. The article concludes with a discussion comparing the obtained results with the international literature, followed by a summary outlining the study's limitations, directions for future research, and recommendations for transport planning and the development of public services.

Literature review

Spatial justice, inequality, and social exclusion

The relationship between accessibility and spatial justice has long been a topic of discussion in urban studies. The normative dimension of spatial equity was already emphasised in the 1980s (Cave & Chester, 1981; Pacione, 1989). Contemporary research continues to underline the importance of equitable access to public services as a condition for inclusive development (Goliszek et al., 2020).

In recent years, growing scholarly attention has been devoted to the spatial allocation of public services, including education, healthcare, green spaces, and recreational infrastructure, and their distribution across social groups (Sabokbar et al., 2021; Sharma & Patil, 2024). While access to all these services is important, education exhibits unique temporal and spatial patterns because school trips typically occur at fixed times and are concentrated during peak morning and afternoon hours, distinguishing them from more flexible or dispersed usage of healthcare or green spaces (Del Conte et al., 2022). These differences underscore the need for service-specific analyses of accessibility and equity (Geurs et al., 2001). Nevertheless, spatial exclusion continues to disproportionately affect lower-income populations. Empirical studies highlight inequalities in access to transport (Delmelle & Casas, 2012; Vale et al., 2016), as well as to basic services such as education and healthcare (Mayaud et al., 2019; Feitosa et al., 2021; Marques et al., 2021; Tuhkanen et al., 2022), reinforcing broader socio-spatial disparities.

Improved accessibility facilitates participation in social, economic, and cultural life, whereas limited accessibility may intensify processes of marginalisation (Bruno et al., 2024; Liu et al., 2024). These dynamics highlight the importance of integrating equity considerations into transport and urban policy frameworks (Farrington, 2007).

Evolution of accessibility measures and inequality metrics

Because accessibility is not spatially homogeneous, its assessment requires precise analytical tools. Accessibility measures, including potential models for educational services, enable the identification of underserved areas and support more equitable spatial planning (Rosik et al., 2021; Tahmasbi et al., 2019).

Cumulative accessibility indicators remain widely applied due to their methodological transparency and practical relevance. In parallel, inequality metrics such as the Lorenz curve and the Gini coefficient (Gini, 1912) have been increasingly used to evaluate the distribution of opportunities and the degree of spatial concentration (Chestnut & Boschmann, 2022; Tsou et al., 2005). These tools allow researchers to move beyond average accessibility values and assess the equity of distribution across population groups and territories. In this context, the Gini coefficient ranges from 0 (perfect equality, where all groups or areas have the same level of accessibility) to 1 (maximum inequality, where all accessibility is concentrated in a single group or area). Values close to 0.3 or lower are often interpreted as reflecting relatively equitable access, while values above 0.5 can indicate significant inequity in the distribution of opportunities. These benchmarks provide a frame of reference for interpreting subsequent results (Geurs et al., 2001).

Workplace accessibility has been extensively analysed as a measure of transport equity (Geurs & van Wee, 2004; Deboosere & El-Geneidy, 2018; Cui et al., 2020; Dixit & Sivakumar, 2020). However, focusing exclusively on employment may provide an incomplete

understanding of urban systems and limit comparisons with other essential services (Kelobonye et al., 2019; Wang et al., 2023). Consequently, accessibility to a broad range of key services is increasingly recognised as central to sustainable urban development, integrating land-use patterns with transport system performance (Cervero, 1996; Shafiq et al., 2025; Wan and Titheridge, 2024). Accessibility is widely used as a core concept in research on urban spatial structure and transport network efficiency (Goliszek, 2024; Kawabata, 2009; Pereira et al., 2021).

Measures of spatial concentration are also crucial for assessing the distributional effects of transport investments (Jurkowski, 2025). Improved access to PT may increase property values and potentially stimulate gentrification processes consistent with Transit-Oriented Development (TOD) principles (Marks et al., 2016; Lutz et al., 2024).

Service governance and the local context of Szczecin

Responsibilities for educational facility planning differ across countries (Baixinho, 2008). In Poland, municipalities manage kindergartens and primary schools, which requires responsiveness to demographic change (Marques et al., 2021). At the same time, educational facilities perform an important “anchor” function in neighbourhoods, shaping community identity and spatial cohesion (Wolf et al., 2022). Secondary schools are administered by county authorities, and their service areas are broader than those of primary schools but narrower than those of universities (Guzik, 2003; Walaszek, 2016).

Szczecin provides a particularly relevant case study due to its spatial structure and historical transport barriers, including the need to cross the river. In response to these challenges, the Szczecin Rapid Tram (SST) project was launched in 2015, significantly improving mobility and increasing PT’s modal share. Such investments represent an important mechanism for mitigating transport exclusion and optimising the spatial distribution of population

and activities, particularly given the uneven distribution of workplaces and educational institutions (Dorrian et al., 2008; Sun et al., 2018; Babaei & Rajabi-Bahaabadi, 2019).

The SST initiative forms part of a broader modernisation trend in Polish cities. Similar tram system upgrades have been implemented in Poznań (Gadziński & Radzimski, 2016), Kraków, and Warsaw, where infrastructure improvements and priority systems have enhanced tram efficiency (Niedzielski et al., 2024).

By situating the analysis within both international debates on spatial equity and the specific institutional and infrastructural context of Szczecin, this study contributes to a more comprehensive understanding of transport accessibility and social justice in medium-sized Central and Eastern European cities (Kujala et al., 2018; Tiznado-Aitken et al., 2021).

Study area

Szczecin, located in northwestern Poland, is a city characterised by a distinctive riverine and port layout, covering an area of 300.55 km². As of June 30, 2019, its population totalled 402,100, resulting in a population density of 1347.1 inhabitants per square kilometre. Szczecin ranks as Poland’s fourth-largest and seventh-most populous urban centre. Based on data from the City Office, the author of the monograph divided Szczecin into 1869 census districts, which simultaneously serve as transportation zones. This large number of districts relative to the city’s size enables precise analysis and accurate interpretation of results, even when data are aggregated at the level of districts or neighbourhoods.

The study adopts the current administrative division of Szczecin, approved in 1990 with minor adjustments to district and neighbourhood boundaries and changes in district statutes. Szczecin is divided into four districts: Zachód (West), Prawobrzeże (Right Bank), Północ (North), and Śródmieście (City Centre), as well as 37 residential neighbourhoods.

The accessibility of PT to various services and facilities in Szczecin has been previously examined in several studies (Poelman & Dijkstra, 2015; Stępnik et al., 2019). The socio-economic structure and the spatial distribution of trip origins and destinations in Szczecin are highly heterogeneous. The city's left bank concentrates more residents and workplaces, significantly influencing the daily travel patterns of inhabitants living on the right bank.

Land-use component

The distribution of educational institutions reflects the provisions of Article 35, Section 2 of the Polish Education Law, which stipulates that the school structure corresponds to the compulsory education requirements. Student enrollment data for 2018 were obtained from the Registry of Schools and Educational Institutions¹. The analysis included kindergartens, primary schools, lower secondary schools (gymnasia), upper secondary schools, technical schools, vocational schools, specialised schools, and post-secondary institutions. The sources of trips to educational facilities are children and youth, divided into three age groups: 3-6, 7-15, and 16-18 years. Regarding modes of access to educational institutions, two groups were distinguished: younger children (3-15 years), who are most often transported by parents or walk on foot, and older youth (16-18 years), who typically use PT or travel independently (Fig. 1).

The Central Statistical Office of Poland maintains the register. Data on workplaces in Szczecin² for 2018 were sourced from the REGON³. This database contains information on firm locations, the commencement date of operations, and declared employment

size categories: 1-9, 10-49, 50-249, 250-999, and over 1000 employees. For companies employing over 1000 people, verification was conducted through email and telephone contact. For the remaining categories, the number of workplaces was estimated to be half of the upper bound of each employment range. Despite methodological limitations, this approach was considered the most appropriate under the available conditions. The population of working age (18-60 years for women and 18-65 years for men) was taken as the source of trips in the analysis of accessibility to workplaces (Fig. 2).

Transport component

Models of PT have increasingly relied on schedule-based (El-Geneidy et al., 2016; Fransen et al., 2015) or real-time GTFS data (Pereira et al., 2021). The first GTFS data in Poland was introduced in Szczecin in 2008. Before this, accessibility studies often focused on the limited impact range of bus and tram stops. However, the GTFS format enables more precise spatial accessibility analysis than previous methods (Gadziński & Beim, 2010). A model based on GTFS data was created to calculate the travel time matrix for PT. The basic road network, including pedestrian paths and connections between specific travel sources and destinations, was built using selected road segments from the BDOT 10k topographic database (Goliszek, 2021). The author assumed an average walking speed of 4.5 km·h⁻¹. The literature has no consensus on the average walking speed used in transport accessibility analysis. For instance, Reyes et al., 2014 suggest an average walking speed of 3.2 km·h⁻¹ for children, while Fransen et al., 2015 and Ritsema van Eck et al., 2005 propose 4 km·h⁻¹, with Fransen et al., 2015 considering this also the average walking speed for adults, and Ritsema van Eck et al., 2005 emphasising that this speed refers to linear motion. The PT network was based on GTFS data from October 2018, published by the City Transport Authority of Szczecin (Fig. 3).

¹ <https://www.gov.pl/web/edukacja/rejestr-szkol-i-placowek>

² <http://szczecin.stat.gov.pl/>

³ The REGON register is a continuously updated collection of information on entities of the national economy maintained in an IT system, consisting of a central database and field databases seated in 16 statistical offices.

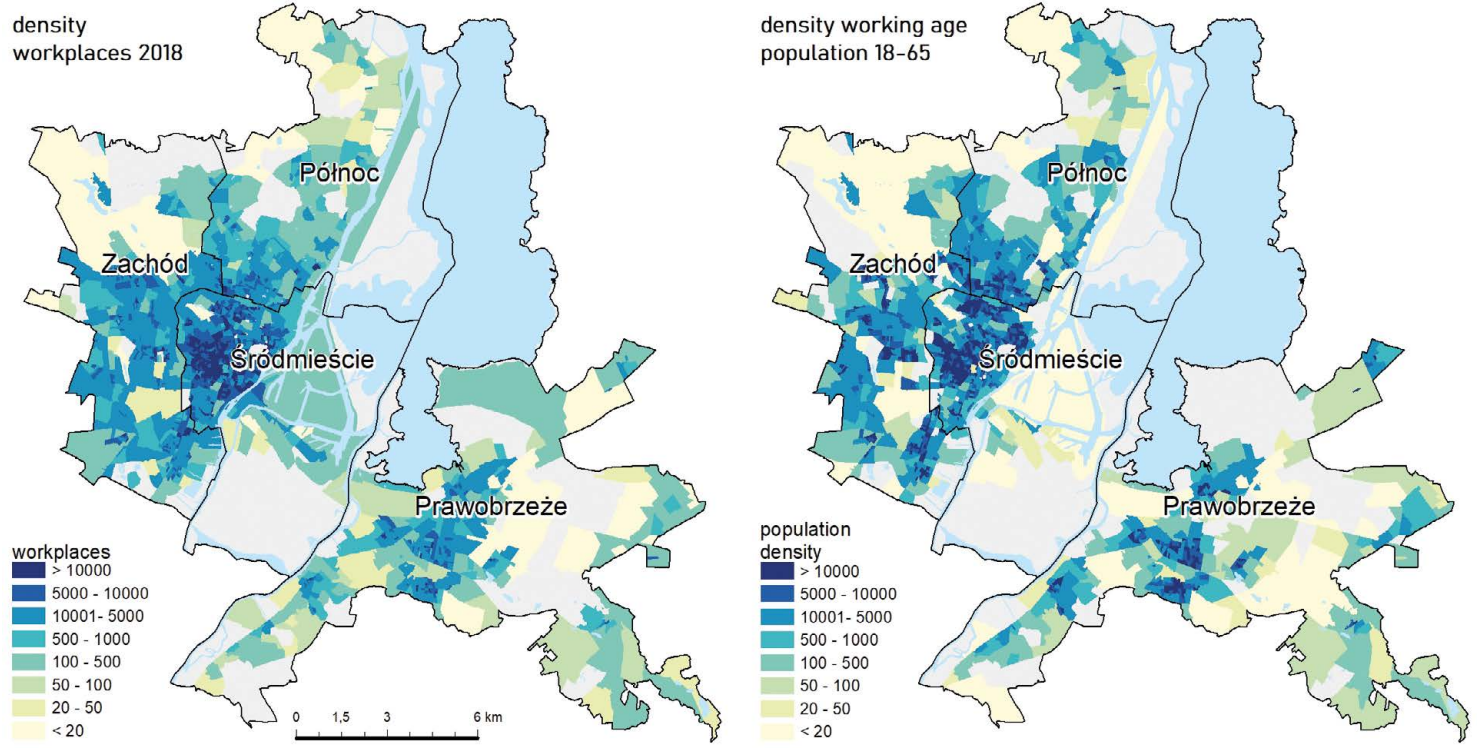


Figure 1. The density of workplaces (map on the left) and the density of the working-age population (map on the right) in the census districts

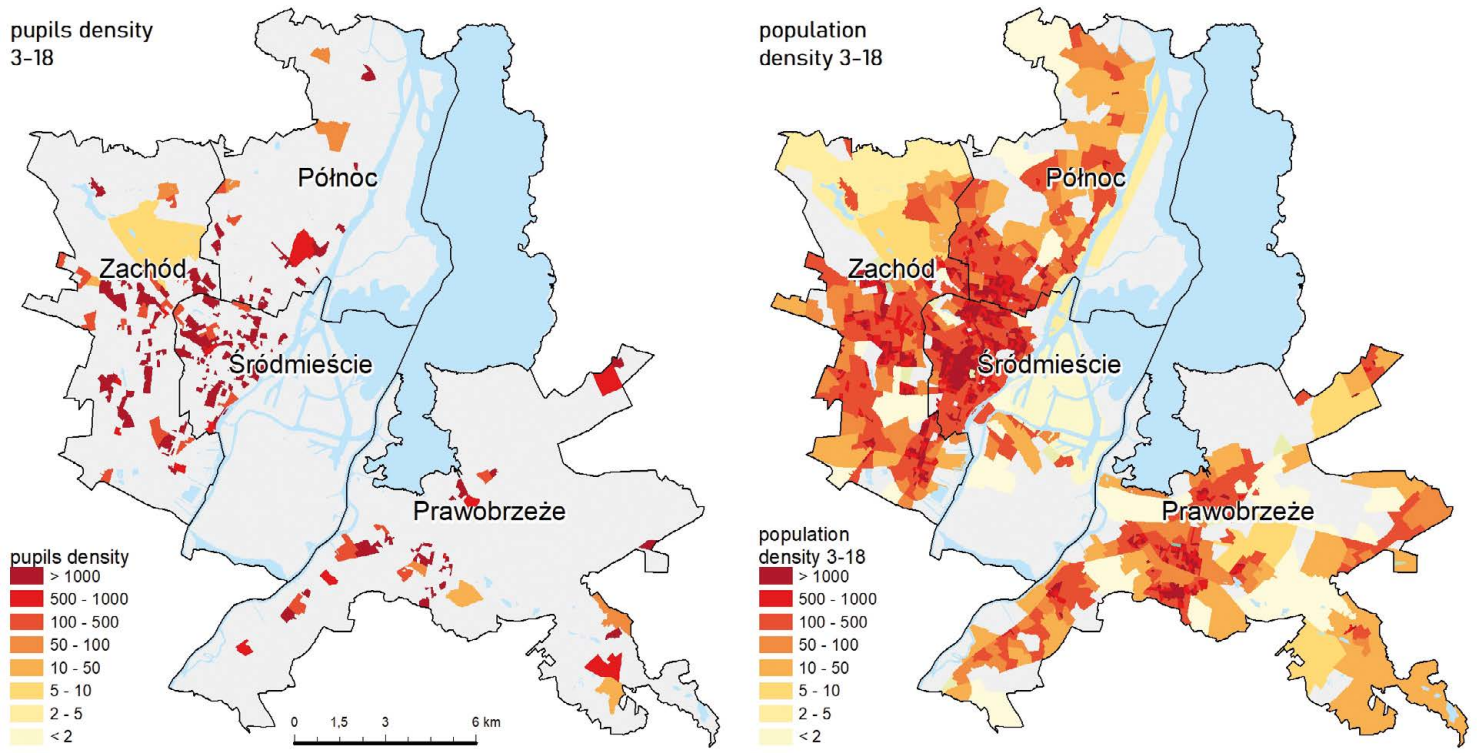
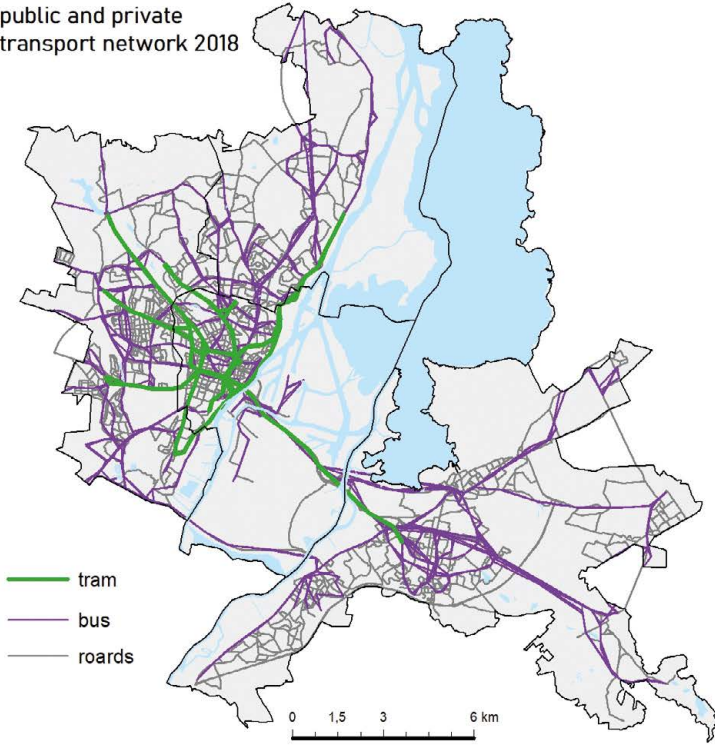


Figure 2. Population density of students aged 3-18 (map on the left) and population density of children aged 3-18 (map on the right) in census tracts

public and private
transport network 2018



census enumeration
and districts

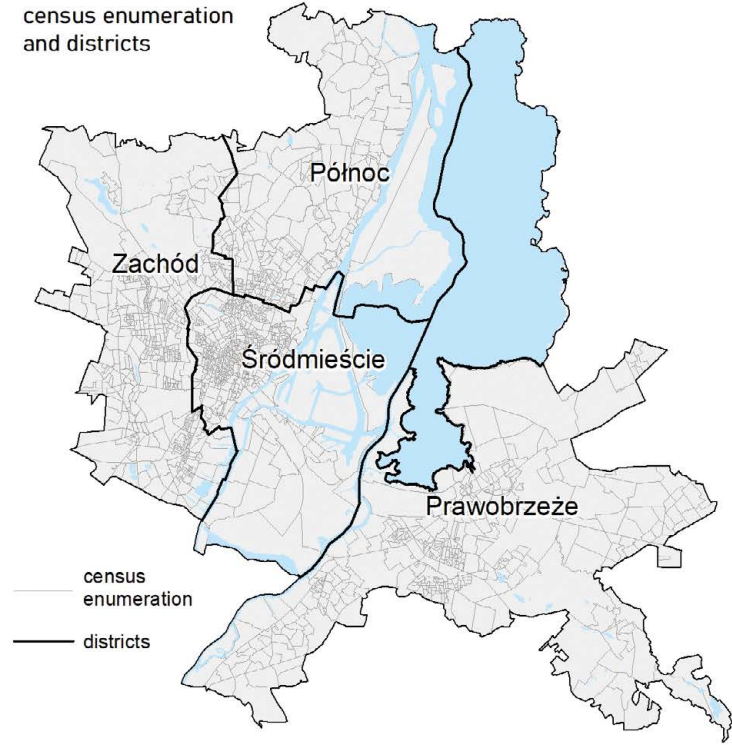


Figure 3. The network of public and PrT (left map) and the division into districts, neighbourhoods and neighbourhoods in Szczecin (right map)

Currently, PrT models often rely on data from various GPS systems (TomTom, Here) and websites that collect real-time travel data for PrT on selected road segments (Lagrell et al., 2018; Wang et al., 2013). The PrT model includes four components: reaching the car, driving time (calculated using Google Maps® API data), parking, and walking to the final destination (Salonen and Toivonen, 2013). The parking time added to the model represents the walking time between the centre of a census area and the nearest road/street. Measuring parking time is practically impossible due to its variability across different cities in Poland. However, there is a correlation between peak hours and parking availability in city centres (Assemi et al., 2020; Goliszek, 2021). Several companies provide such services (e.g., TomTom or Google Maps/Transit), but Google Maps API is the only application with direct access to this data. TomTom and Here collect, process, and sell data to users. A dedicated application written in Python 2.7 was used to download real-time data from the Google Maps API. The study employed a road model for PrT in Szczecin, based on data from Google Maps API (Wang and Xu, 2011), utilising a custom Python 2.7 application. The data sets from October and November 2018 allowed for comparing both models. The ability to compare PT and PrT systems has opened up numerous new research opportunities and yielded many interesting findings (Fig. 3). Such analyses, considering different times of day, help determine when the differences in the performance of private and PT are minimal (El-Geneidy & Levinson, 2007; Shirgaokar, 2014; Beria et al., 2017).

Temporal component

The temporal component in accessibility analysis allows us to capture the dynamics of changes in travel time and user behaviour, which is impossible in a static approach. It is crucial to distinguish between network dynamics (short-term changes in status, e.g., traffic intensity) and their evolution (long-term structural changes, van Wee et al., 2013).

The use of mobile phone data and the GTFS standard enables the precise determination of cumulative and potential accessibility at different times of the day (Goliszek, 2025).

Recent literature increasingly emphasises the need to incorporate the so-called temporal component into transport accessibility analyses (Berechman, 1981; Geurs et al., 2001; Geurs & van Wee, 2004). This component refers to the variability in travel times across time of day, day of the week, and season. It is particularly relevant in urban peak-hour travel, which typically follows a radial pattern – towards the city centre in the morning and away in the afternoon (Baradaran & Ramjerdi, 2011)

In the present study, the temporal component encompasses two key aspects: PT time-tables and congestion in the road network, particularly during peak hours. Travel time in PrT is difficult to estimate precisely due to the variability of traffic conditions and the impact of random events such as accidents or sudden weather changes. Conversely, PT schedules do not account for extraordinary events, even though disruptions such as tram breakdowns can significantly affect travel times.

The perceived value of time also differs across social groups, a phenomenon that has been the subject of separate investigations (Urbanek, 2021).

Individual component

The individual component encompasses the demographic and socio-economic characteristics of transport network users, including factors such as age, gender, income, and level of education. These differences shape how accessibility is perceived and influence the ability and motivation to travel. The literature identifies three primary determinants of mobility: needs, abilities, and opportunities for travel (Vlek & Steg, 2007).

Needs refer to obligatory activities (e.g., work, school); abilities concern physical and technical competencies (e.g., driving skills); and opportunities are defined by external conditions that enable travel, which are

themselves influenced by factors such as gender, age, and social status (Hanson & Pratt, 1995; McLafferty & Preston, 1992; Kwan & Hong, 1998).

This study utilises population data disaggregated by age groups. It incorporates accessibility variants that exclude possession of a driver's license, thereby enabling an assessment of the role of PTation in ensuring mobility.

Methods

Understanding spatial accessibility and distribution is central to transport equity research, particularly in urban contexts where access to education and employment significantly shapes social inclusion and life chances. In this study, two complementary methodological approaches were employed to evaluate accessibility and spatial inequality in Szczecin: cumulative accessibility measures and Lorenz curve (Lorenz, 1905) analysis, including the associated Gini coefficient (Gini, 1912).

Cumulative accessibility provides a binary assessment of whether destinations can be reached within a given time threshold, offering a straightforward and interpretable measure of potential access (Miller, 2005). This method is widely applied in transport geography to evaluate the reachability of essential services, such as schools and workplaces, and to compare the performance of different transport modes (e.g., PT vs. PrT).

To assess inequality in accessibility across the urban area, the study incorporates the Lorenz curve, a graphical tool developed initially in economics to represent income distribution and the Gini coefficient, a scalar summary of distributional inequality (Fridstrom et al., 2001). These tools have increasingly been adopted in transport studies to assess disparities in access, offering valuable insights into how the transport system serves equitably different population groups or spatial units (Lucas et al., 2016; Chen et al., 2019).

Cumulative accessibility was calculated using the following formula:

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

$$f(C_{ij}) = \begin{cases} 1 & \text{if } C_{ij} \leq t_j \\ 0 & \text{if } C_{ij} > t_j \end{cases} \quad (2)$$

where:

A_i – denotes the accessibility from location i to opportunities j ,

O_j – represents the number of opportunities (e.g., workplaces, school places) at location j , and

C_{ij} – is the travel cost (e.g., time) between i and j . The function

$f(C_{ij})$ – applies a threshold t_j , beyond which accessibility is assumed to be null (Niedzielski, 2021; Thompson et al., 2019). This method is commonly used to evaluate access to public goods and changes in accessibility resulting from transport infrastructure improvements (Talen, 1996; Talen & Anselin, 1998; Gutiérrez, 2001).

It is worth noting that accessibility can vary even within a single location, depending on internal and external factors. For instance, a site with good spatial positioning might still be less accessible for specific populations, such as specialised workers preferring peripheral residences. Moreover, spatial mismatches between supply and demand may lead to competitive effects (Shen, 1998; Geurs et al., 2001).

The Lorenz curve does not assume that perfect equality is possible or desirable, but instead visualises the degree of concentration in access. To provide a quantitative comparison of accessibility distributions, the Gini coefficient is calculated as:

$$Gini(S) = 1 - \frac{2}{n-1} \left(n - \frac{\sum_{i=1}^n iy_i}{\sum_{i=1}^n y_i} \right) \quad (3)$$

where:

y_i – is the cumulative value of accessibility for the i^{th} unit (e.g., population unit or spatial

cell) sorted in ascending order. The Gini coefficient ranges from 0 (perfect equality) to 1 (complete inequality). As a form of variability measure, it is independent of the mean, and thus allows consistent comparisons across transport modes and spatial contexts.

Both Lorenz curves and the Gini index were applied to the same attribute: accessibility to schools and workplaces by both private and PT. This allowed for a comparative assessment of inequality within and across transport modes, spatial units, and destination types (Ben-Elia & Benenson, 2019). These tools have been widely adopted in recent transport equity studies (Stępnik & Goliszek, 2017; Chen et al., 2019).

Accessibility calculations were based on average morning peak travel times, centred on 8:00 AM (median of 7:30-8:30 window). Both PT and PrT trips fall under mandatory travel, which typically exhibits high temporal regularity and significance for urban functioning.

Results

This section presents the cumulative accessibility analysis results for selected public services in Szczecin, focusing on educational institutions (kindergartens, primary schools, and secondary schools) and workplaces. Accessibility was evaluated based on travel times by PT and PrT, considering time thresholds of 10, 20, 30, and 60 minutes. The analysis incorporates multimodal trips, including walking segments between residences and transport stops and between stops and destinations.

The spatial distribution of accessible facilities within each time threshold reveals significant variation across the urban area, reflecting the PT network's structure and the location of service points. Results are presented separately for each service and time threshold category, focusing on identifying areas of low and high accessibility and patterns of spatial inequality.

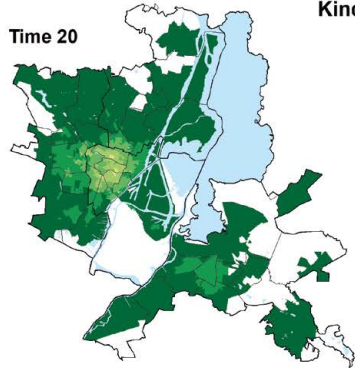
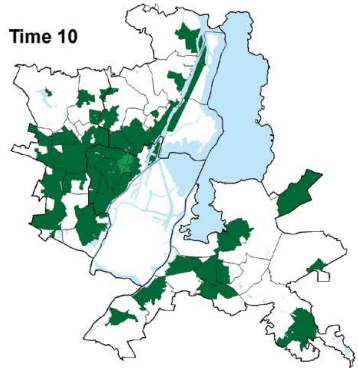
PT accessibility

Cumulative accessibility by public transport (PT) in Szczecin exhibits a clearly differentiated spatial pattern, strongly reflecting the city's monocentric structure and the concentration of services and workplaces in the central district of Śródmieście.

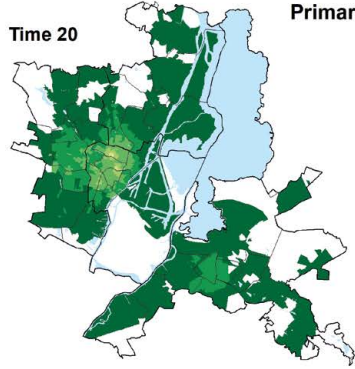
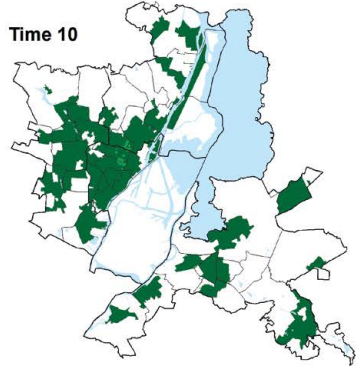
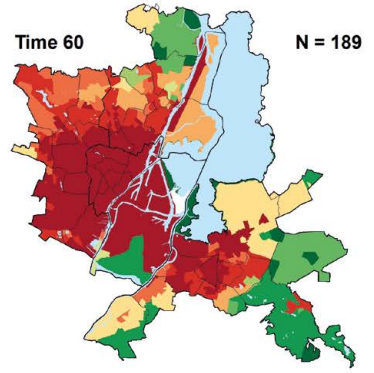
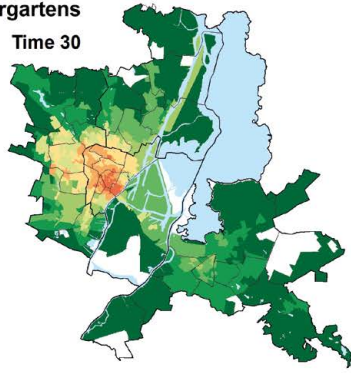
For kindergartens and kindergarten facilities, a 10-minute PT trip primarily covers the central part of Śródmieście, where the density of stops and the overlap of tram and bus lines ensure very high accessibility. Peripheral deficits are visible in the northwestern part of Zachód, the northern areas of Północ, and especially in the eastern part of Prawobrzeże. Within 15 minutes – an important threshold for everyday childcare trips that often combine walking and PT – access to at least one kindergarten is observed across almost the entire left-bank part of the city. The most pronounced deficits persist in the far eastern Prawobrzeże and in sparsely served northern zones.

At the 30-minute threshold, accessibility increases substantially: at least one kindergarten becomes reachable from nearly the whole city, and in central areas (Śródmieście and central Zachód), up to approximately 50% of all facilities in the city can be accessed. Only the northeastern part of Prawobrzeże remains effectively excluded within this time frame, indicating structural PT disadvantages in this sector. The extension to 60 minutes eliminates almost all remaining gaps, confirming that PT provides citywide coverage, although at the cost of substantially longer travel times for peripheral residents.

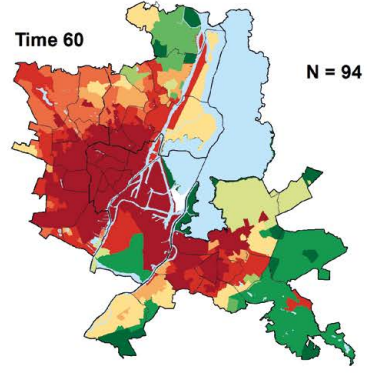
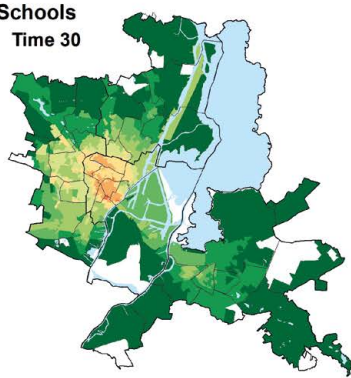
A similar spatial logic applies to primary schools. Within 10-15 minutes, the highest accessibility levels are recorded in Śródmieście, while northwestern Zachód, northern Północ, and extensive areas of Prawobrzeże remain outside effective reach. Notably, in northern Północ, the area without access within 15 minutes is more extensive than for kindergartens, extending toward the northeastern fragment of Zachód. At 30 minutes, cumulative accessibility rises markedly in the



Kindergartens



Primary Schools



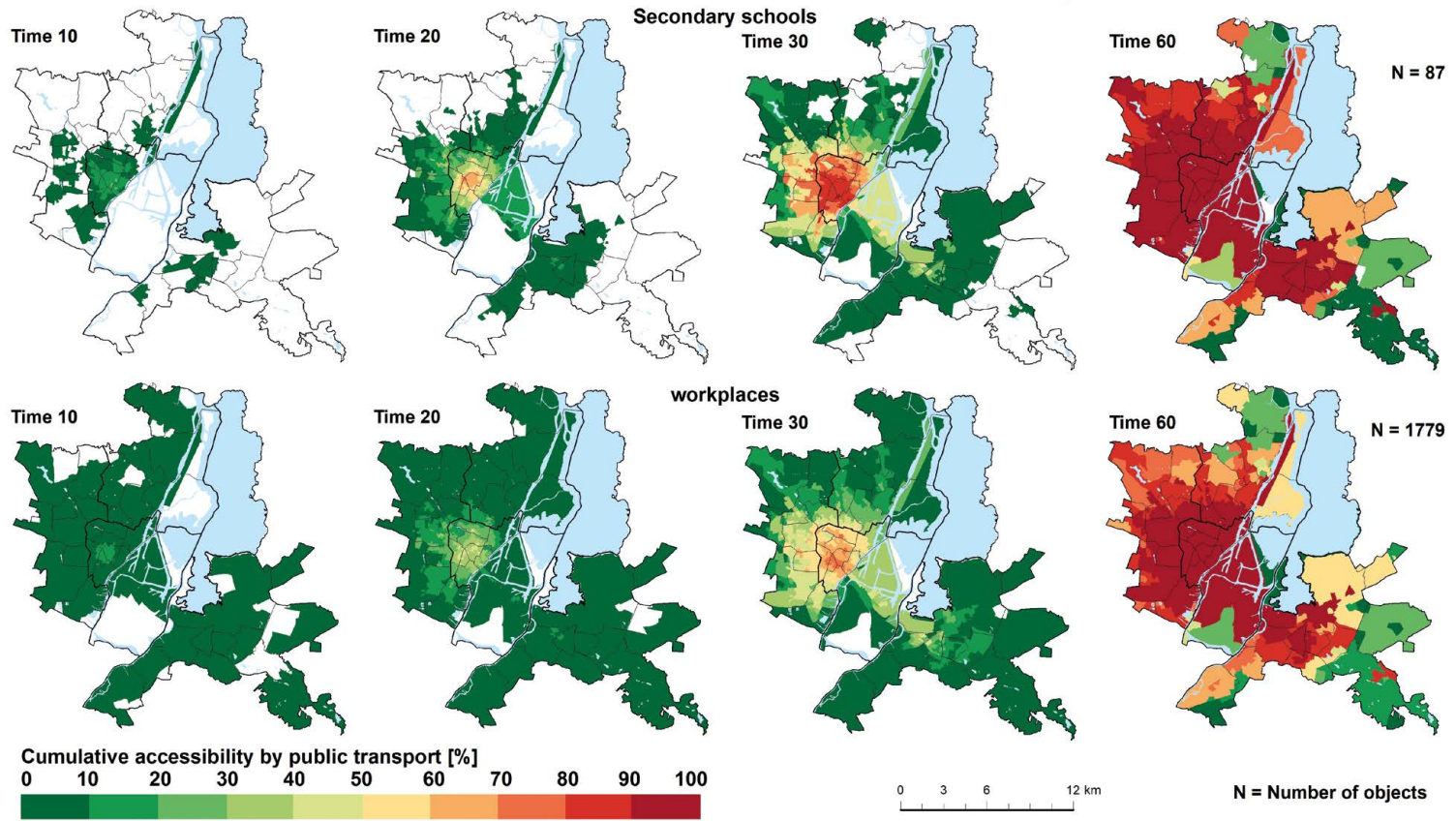
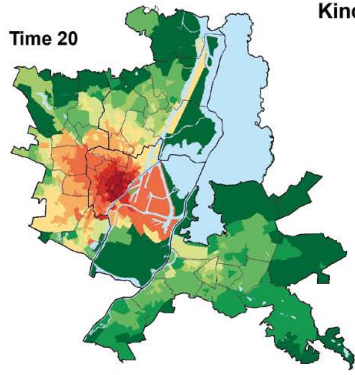
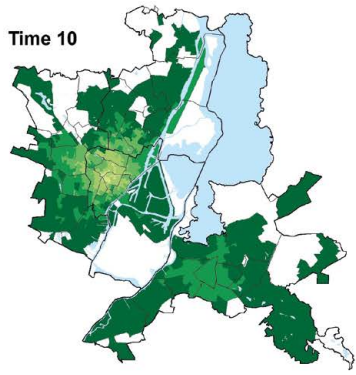
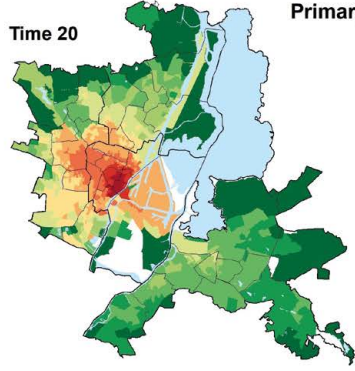
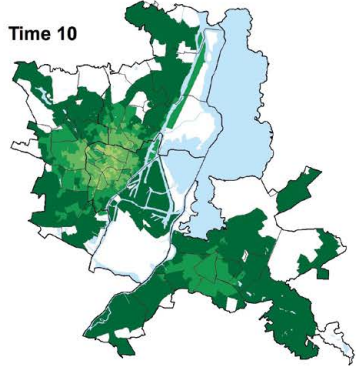
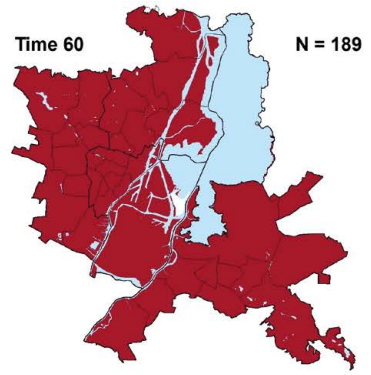
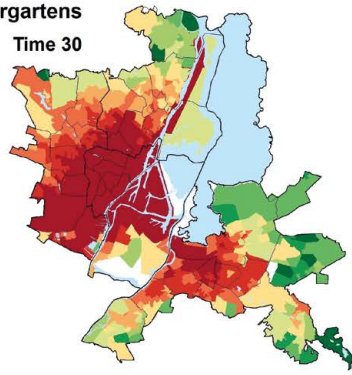


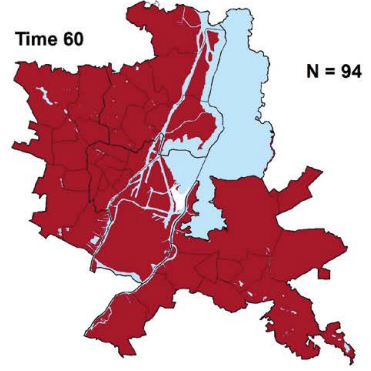
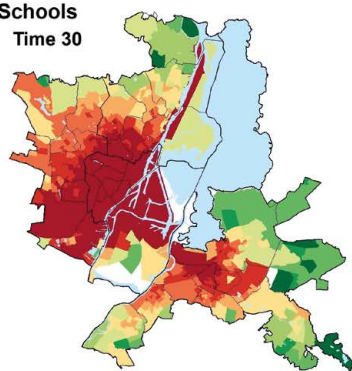
Figure 4. Cumulative accessibility of kindergartens, primary, secondary schools and workplaces by PT based on GTFS data



Kindergartens



Primary Schools



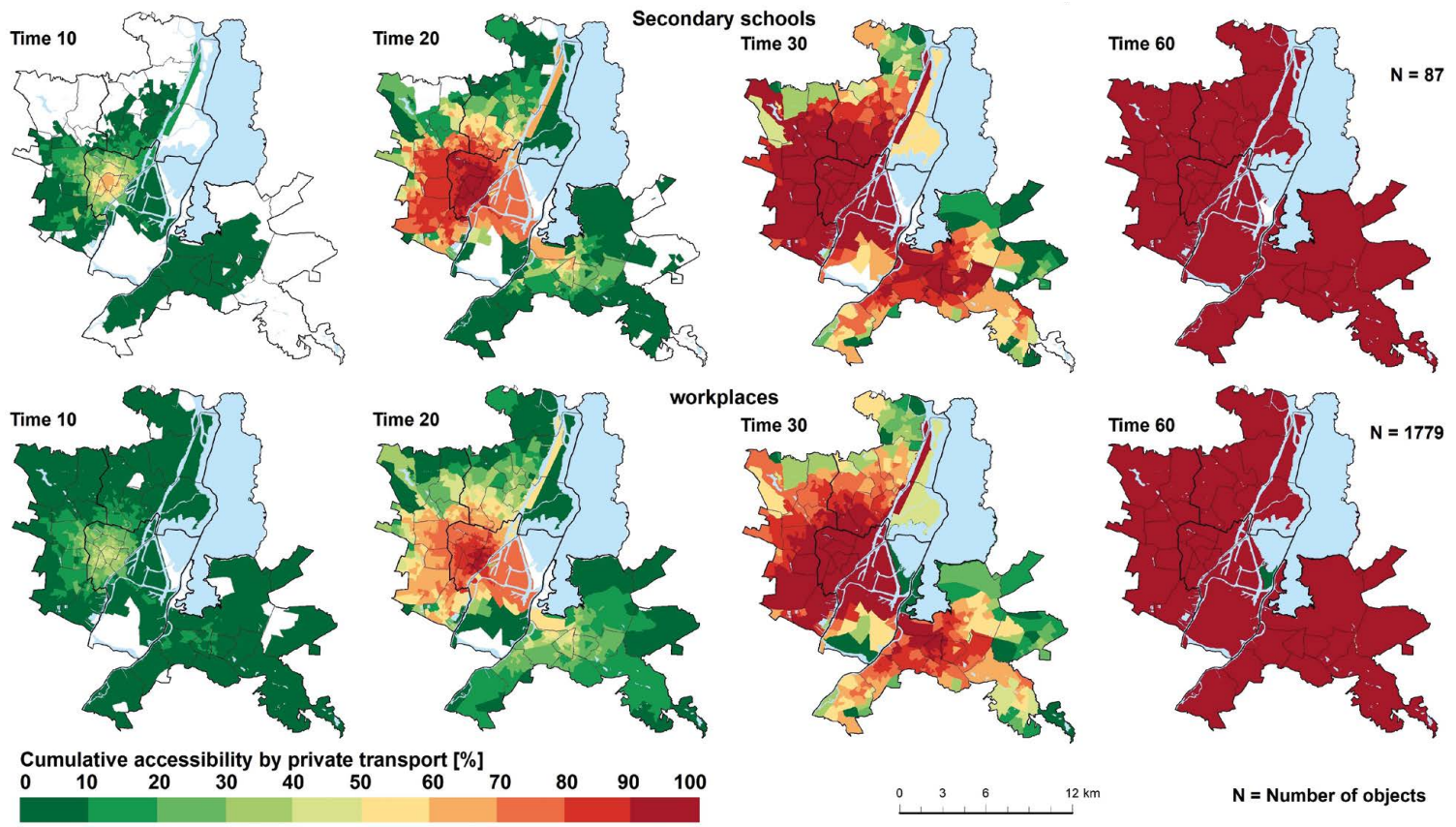


Figure 5. Cumulative accessibility of kindergartens, primary, secondary schools and workplaces by PrT based on Google Maps API data

city centre, central Zachód, and southern Północ, yet parts of northwestern Prawobrzeże still remain weakly connected.

In secondary schools, spatial polarisation is even stronger. Within 15 minutes, large parts of Północ, northern Zachód, and almost all of Prawobrzeże (except its central zone) lack access. However, the concentration of secondary schools in Śródmieście and their good connectivity via fast tram corridors significantly improve accessibility in areas along these lines. At 30 minutes, accessibility in Śródmieście reaches up to 80% of all secondary schools in the city, while central Zachód and southern Północ achieve around 50%. Even parts of Prawobrzeże located near fast tram stops approach comparable levels, illustrating the importance of high-capacity PT infrastructure in mitigating spatial inequalities.

PT workplace accessibility confirms the dominance of the city centre. Within 10 minutes, at least one workplace is reachable from virtually all parts of the city, though the share of total workplaces accessible remains modest outside central areas. Within 20 minutes, residents of Śródmieście can reach up to 40% of all workplaces. At the 30-minute threshold, strong differentiation becomes evident: Śródmieście offers access to approximately 50-60% of workplaces (and in some central zones even higher shares), while most other districts provide access to only 10-20%. Peripheral deficits are particularly evident in eastern Prawobrzeże and in the northern sections of Północ and Zachód. The 60-minute threshold ensures near-complete coverage, yet spatial inequalities in shorter, more policy-relevant time bands remain substantial (Fig. 4).

Car accessibility

Cumulative accessibility by private car generally produces higher values and reduces, though does not eliminate, spatial disparities.

For kindergartens, access within 10 minutes is possible from almost the entire city, with only minor peripheral gaps along

administrative boundaries. In contrast to PT, car accessibility within 15 minutes covers extensive areas, and in central Śródmieście, more than half of all kindergartens are within 15 minutes. Extending the threshold to 20 minutes makes nearly all facilities citywide accessible, and from the centre, up to 80% can be reached. At 30 minutes, accessibility exceeds 90% in large areas of southern Północ, southern Zachód, the port and residential parts of Śródmieście, and northwestern Prawobrzeże. The weakest 30-minute accessibility persists in eastern Prawobrzeże and northern Północ. By 60 minutes, cumulative accessibility reaches 90-100% citywide.

Primary schools show a nearly identical pattern. Within 10-15 minutes, gaps are observed in northwestern Zachód, northern and northwestern Północ, southern Śródmieście, and parts of Prawobrzeże. After 30 minutes, almost all primary schools are accessible from central Śródmieście, southern Zachód, and northwestern and central Prawobrzeże. The least accessible zones remain northeastern Prawobrzeże and northern Północ, indicating that even car travel does not fully compensate for the disadvantages of peripheral location.

For secondary schools, up to 50% of institutions are reachable within 10 minutes in Śródmieście, reflecting their strong central concentration. Outside the centre, accessibility remains below 10% in central Prawobrzeże and the southern parts of Zachód and Północ. After 20 minutes, more than 90% of secondary schools are accessible from Śródmieście, while large peripheral sectors still lag behind. Within 30 minutes, nearly all secondary schools become accessible from Śródmieście and most of Zachód, whereas eastern Prawobrzeże and the northernmost Północ continue to display the lowest values. At 60 minutes, accessibility reaches 90-100% across the city.

Workplace accessibility by car is markedly superior to PT at shorter thresholds. Within 10 minutes, nearly the entire city is covered, and from central Śródmieście, about 30% of all workplaces are reachable. Within

20 minutes, accessibility from the centre increases to approximately 70-80% of workplaces, while peripheral areas typically achieve only 0-20%. At 30 minutes, more than 90% of workplaces are accessible from Śródmieście, central Prawobrzeże, and the southern parts of Północ and Zachód. By 60 minutes, cumulative accessibility reaches 90-100% across Szczecin.

Overall, the comparison confirms that car travel significantly compresses perceived spatial distance and reduces extreme exclusion, yet the central-peripheral gradient remains visible in both modes. Public transport accessibility is strongly shaped by network structure and the presence of high-capacity corridors, whereas car accessibility is influenced by the spatial distribution of destinations and the road network hierarchy (Fig. 5).

Cumulative accessibility comparison: PT vs. PrT

The results demonstrate apparent differences in cumulative accessibility to key urban destinations – kindergartens, primary schools, secondary schools, and workplaces – depending on the mode of transport and travel time.

Kindergartens. Accessibility by PrT increases rapidly, reaching 74.2% within 25 minutes and nearly complete coverage (99.9%) at the 60-minute threshold. In contrast, PT achieves only 25.7% within 25 minutes, and despite a steady increase, it reaches 89.2% after 60 minutes. The gap between transport modes is most prominent in the 10-30 minute window, emphasising the car's efficiency in reaching early education facilities.

Primary schools. A similar pattern emerges. PrT access reaches 71.1% in 25 minutes and 99.9% in 60 minutes. PT lags significantly, with only 23.7% of schools accessible in 25 minutes and 87.5% in 60 minutes. Again, PrT use offers faster and broader access across the entire time spectrum.

Secondary schools. Overall, accessibility to secondary education is slightly higher. With PrT, over 65% of schools are reachable in 20 minutes, and nearly full access is achieved

within 40 minutes. PT reaches only 19.5% within 20 minutes and 92.5% by 60 minutes. The steepest difference gradient is observed in the 10-30 minute range.

Workplaces. Access to employment follows a similar trend. PrT users can reach 75.3% of workplace locations within 25 minutes and nearly 100% within an hour. For PT users, only 25.3% of workplaces are accessible within 25 minutes, rising to 88.4% at 60 minutes.

The data indicate a consistent and substantial advantage of PrT use in cumulative accessibility across all examined categories. The divergence is most notable in the 10-30 minute travel time window, where PT still offers limited coverage. These findings underscore spatial inequalities in access depending on transport mode, particularly for residents in peripheral districts Fig. 6.

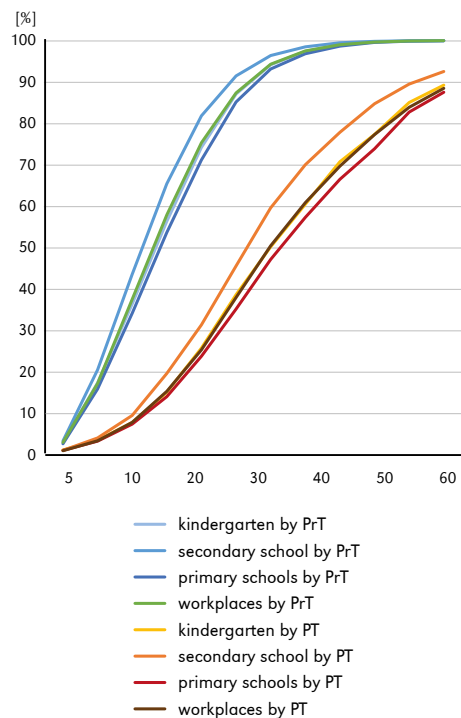


Figure 6. Percentage of cumulative accessibility of kindergartens, primary, secondary schools and workplaces by private and PT

Accessibility gap between private and PT

The analysis of accessibility gaps reveals a clear and systematic advantage of (PrT) over PT across all examined destinations – kindergartens, primary schools, secondary schools, and workplace locations. The magnitude of this gap varies over time and by destination type, but it is most pronounced in the 20-30 minute travel window.

Kindergartens. The gap in cumulative accessibility grows from 0.4 percentage points at 5 minutes to a maximum of 12.1 percentage points at 25-30 minutes. Beyond 30 minutes, the difference gradually decreases, reaching just 2.7 percentage points at the 60-minute threshold. This pattern indicates that while PrT offers faster initial access, the gap narrows as travel time increases and PT coverage expands.

Primary Schools. A similar trend is observed, with the gap peaking at 12.5 percentage points at 30 minutes and declining. The advantage of PrT is obvious between 15 and 35 minutes, suggesting a spatial disparity in PT coverage during medium-range trips.

Secondary Schools. The accessibility gap is highest overall in this category, reaching 12.6 percentage points at 25 minutes. The gap decreases sharply after 35 minutes, dropping to 1.9 percentage points at 60 minutes. This indicates significant limitations in PT connectivity to secondary schools, especially for shorter and medium-length trips.

Workplaces. The accessibility gap to employment locations is among the most consistent. It grows from 0.5 points at 5 minutes to 12.5 points at 25 minutes, followed by a steady decrease to 2.9 points at 60 minutes. This highlights that even workplace accessibility – a key factor in urban functionality – is significantly shaped by transport mode, particularly in the first half-hour of commuting.

In all categories, the disparities peak between 20 and 30 minutes, suggesting that urban residents who rely on PT face the most significant accessibility challenges in mid-range travel scenarios. Although extended travel times (over 40 minutes) allow PT users to gradually “catch up,” the time disadvantage remains measurable even at 60 minutes. These findings underscore the importance of improving medium-distance PT links

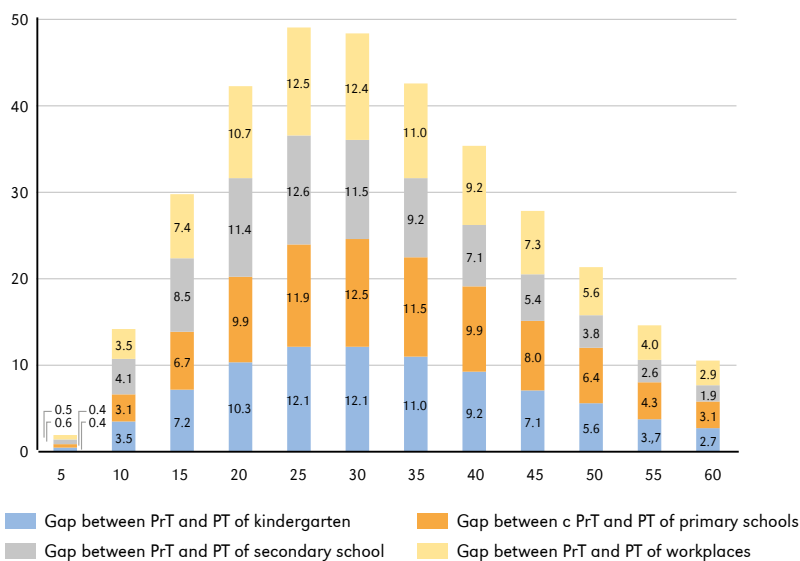


Figure 7. Gap between cumulative accessibility of kindergartens, primary, secondary schools and workplaces by private and PT

to reduce spatial inequalities in access to key services and employment.

In this study, Lorenz curves were constructed to represent the distribution of accessibility to specific destinations – kindergartens, primary schools, secondary schools, and workplaces – weighted by the population eligible to access them. Specifically, the curves are based on accessibility per capita for each relevant demographic group: children aged 3-6 for kindergartens, 7-15 for primary schools, 16-18 for secondary schools, and working-age individuals (18-65) for places of employment. This approach enables a more socially nuanced assessment of spatial accessibility.

The Lorenz curve illustrates the cumulative share of accessibility against the cumulative share of the population. The closer the curve lies to the diagonal (line of perfect equality), the more equally distributed accessibility is across the population. Conversely, the further the curve deviates from the diagonal, the greater the inequality, indicating that a smaller portion of the population enjoys a disproportionately higher level of accessibility. At the same time, the remainder faces transport barriers or limited access.

In the context of commute and service access analysis, a more pronounced bow in the Lorenz curve reflects greater variability in travel times or ease of access – that is, fewer

individuals benefit from convenient access. At the same time, a larger share of the population must contend with structural disadvantages in the transport network.

This population-weighted perspective enhances the Gini index's interpretability by linking abstract inequality measures directly to affected user groups, thereby aligning the analysis with equity-oriented planning principles (Fig. 8).

Across all destination types, transport by PrT is associated with lower Gini coefficients, indicating a more equitable spatial distribution of accessibility than PT. This finding reflects the higher flexibility and speed of PrT, particularly in less well-connected peripheral urban zones, where PT options may be limited or infrequent.

For kindergarteners, the Gini coefficient is 0.5858 for PT and 0.4707 for PrT. This indicates moderate inequality in access via public transit, likely due to the dispersed nature of early childhood facilities and limited coverage of local routes. In contrast, PrT offers significantly more uniform access.

Primary schools exhibit the highest inequality in PT access among all education levels, with a Gini coefficient of 0.6046, compared to 0.4993 for PrT. This suggests that even though primary schools are well-distributed, the coverage and efficiency of PT do not

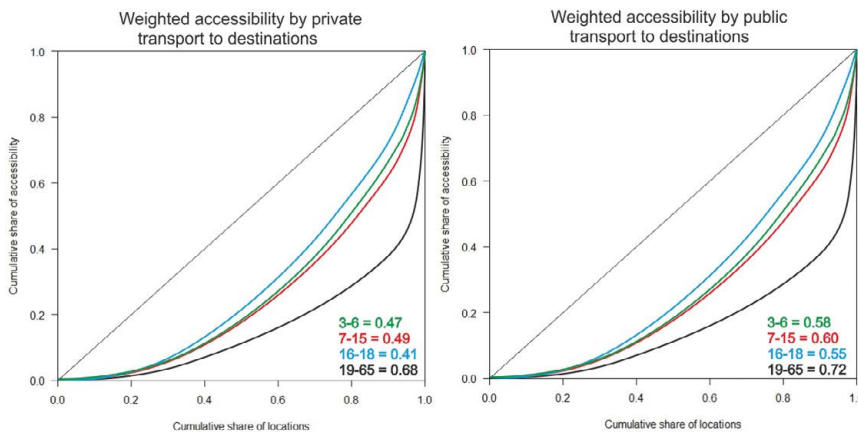


Figure 8. Lorenz curve for private and PT commuting to workplaces and educational institutions in the context of commuter distribution

fully accommodate school-age populations uniformly across the city.

For secondary schools, Gini values are lower: 0.5550 (public) and 0.4122 (private), indicating improved equality in access, possibly due to the centralisation of secondary institutions and their better integration with main PT lines. Nonetheless, a considerable advantage remains for PrT.

The highest disparity in access to workplaces is observed, with a Gini coefficient of 0.7298 for PT, highlighting pronounced spatial inequality. This implies that many workers have limited access to employment opportunities via transit, especially from peripheral areas. PrT significantly reduces this inequality (Gini = 0.6822). Nevertheless, it remains the most unequal category for car users, reflecting the clustering of workplaces in specific urban subcenters and the structural mismatch between residential and employment locations.

In summary, PT is consistently less equitable than PrT, with the most significant disparities in access to employment and primary education. The Lorenz curve analysis underscores the need to improve PT connections, particularly for workplace-rich zones and essential public services, to promote more spatially inclusive urban mobility (Fig. 9).

It is important to note that the Lorenz curve and Gini coefficient reflect the equity, not the efficiency, of transport systems.

The combined results of cumulative accessibility and equity analysis reveal systemic inequalities in transport accessibility in Szczecin. While PrT provides faster and more equitable access across all destination types, PT coverage remains limited, particularly for mid-range trips and peripheral urban areas. These disparities underline the need for targeted improvements in PT infrastructure and service provision to ensure more inclusive access to key urban opportunities.

Discussion

Earlier studies on Szczecin focused primarily on potential-based and cumulative accessibility measures in order to identify the best-connected areas. Although the Gini coefficient was introduced by (Stepniak et al., 2019), it was mainly applied to assess the impact of GTFS temporal resolution on the precision of results. In the present article, the Lorenz curve and the Gini coefficient serve as the principal diagnostic tools for evaluating how equitably the benefits of transport infrastructure are distributed among residents in terms of access to education and employment.

While previous models often operated on total population figures or broad working-age categories, this study introduces a detailed age-group classification linked to specific trip purposes: 3-6 years for kindergartens, 7-15 years for primary schools, 16-18 years

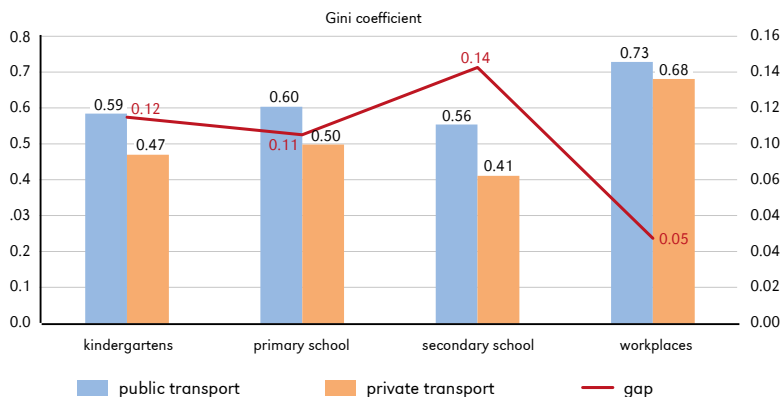


Figure 9. Gini coefficient for private and PT to different destinations (education, workplace)

for secondary schools, and 19-65 years for workplaces. This approach enables a far more precise assessment of spatial equity by accounting for the actual demand of specific social groups for particular services. Earlier published research on Szczecin was largely sectoral in nature: (Goliszek, 2017; Goliszek, 2022b) analysed accessibility primarily to workplaces; Sawińska (2019) focused on recreational spaces for seniors; and Klos-Adamkiewicz and Kowalska (2024) examined the bike-sharing system. In contrast, the present study integrates employment analysis with three levels of education, allowing for a comprehensive evaluation of spatial equity in access to key public services that shape residents' life opportunities.

The innovation of this study lies in its pioneering methodological integration of detailed demographic structures with multi-domain accessibility analysis. By combining age-specific population groups with access to both employment and three educational levels, the study achieves highly precise matching of service supply to the real demand of distinct social groups (Sawińska, 2019; Geurs et al., 2001). Leveraging advanced data sources such as GTFS and Google Maps API, the research uniquely identifies a critical 20-30-minute travel-time window, during which disparities between public and private transport are most pronounced (Fielbaum & Jara-Diaz, 2021). Furthermore, the systematic application of equity metrics – including the Lorenz curve and Gini coefficient – enables a rigorous assessment of fairness in the distribution of transport benefits. By focusing on a mid-sized Central European city context, the study extends the global literature and shifts the paradigm from purely technical efficiency toward planning grounded in social justice, urban ethics, and the “right to the city” (Walker, 2012; Gaglione et al., 2021).

The results of this study highlight persistent and systematic differences in spatial accessibility depending on the mode of transport, with PrT users enjoying a considerable advantage across all destination types. These findings align with previous research

emphasising the modal gap in cumulative accessibility, particularly in cities characterised by dispersed urban structures and limited transit integration (El-Geneidy et al., 2016; Geurs & van Wee, 2004). Such disparities underscore the ongoing challenges in achieving equitable transport systems.

A novel contribution of the article is the demonstration that spatial equity in Szczecin is strongly dependent on the travel time window. A critical 20-30-minute interval was identified, during which inequalities between private car and public transport (PT) users are greatest. The pronounced inequalities in PT accessibility – especially for mid-range trips (20-30 minutes) – reflect both structural limitations of the current transit network and spatial mismatches between residential areas and key destinations. This pattern is consistent with Lucas' (2012) argument that transport disadvantage is most acute when public transit fails to meet the time-space constraints of everyday life, particularly for education and employment-related travel. This temporal and spatial mismatch is a critical barrier to social inclusion.

The Lorenz curve and Gini coefficient analyses provide further insight into the social implications of accessibility disparities. The highest levels of inequality were observed in access to employment opportunities, echoing findings by Boisjoly and El-Geneidy (2017), who noted that workplace accessibility via public transit is often unevenly distributed, especially in peripheral districts with lower service frequency and coverage (Liu & Kwan, 2020). Similarly, the substantial accessibility gap for primary schools may be linked to limited feeder services and low intermodality issues commonly cited as barriers to equitable education access (Pereira et al., 2017).

Interestingly, the lowest inequality levels were found in access to secondary schools, which tend to be more centralised and better served by main transit corridors. This suggests that spatial centralisation, combined with integrated PT, can partially mitigate accessibility gaps – a conclusion supported by comparable studies in Central European

urban contexts (Martens, 2016). This finding highlights the potential for targeted infrastructure and service planning to reduce spatial inequities.

Earlier works by (Goliszek, 2017; Goliszek, 2022a; Goliszek, 2022b) emphasised the competitiveness of public transport relative to private transport and the identification of areas of transport exclusion (gap analysis). The present study shifts the focus toward the ethical dimension of planning, treating accessibility not merely as a matter of technical efficiency but as a foundation for urban justice and the right to the city. Despite the growing use of advanced accessibility indicators in transport planning, this study confirms that cumulative measures remain effective in identifying spatial inequalities when combined with demographic weighting and equity metrics. However, Geurs et al. (2010) note that accessibility indicators must be contextualised within broader planning frameworks to inform inclusive transport policies effectively. In this case, the persistent accessibility disadvantage for PT users points to the need for systemic improvements in service coverage, frequency, and intermodal integration.

Finally, the strong reliance on private vehicles to achieve high levels of accessibility raises concerns about sustainability and social exclusion. As discussed by Bannister (2008) and Hosford et al. (2021), car-oriented accessibility tends to reinforce socio-spatial segregation and undermines climate goals. Therefore, prioritising improvements to PT – especially in underserved peripheral areas – should be central to urban equity and environmental sustainability strategies in Szczecin.

Limitations and future research

While this study offers detailed insights into spatial accessibility patterns in Szczecin, several limitations should be acknowledged. First, the analysis relies on static travel time data, which does not account for variability in service frequency, congestion, or temporal fluctuations. Second, accessibility was measured at the spatial scale of grid cells,

which may obscure important local barriers such as pedestrian infrastructure quality, perceived safety, or micro-level urban form features (Kwan, 1999). Third, the study focused primarily on quantitative measures, without incorporating user perceptions or qualitative aspects of accessibility, which are essential to understanding lived experiences of transport disadvantage.

Future research could integrate dynamic accessibility measures, such as time-dependent travel times or real-time network performance data. Additionally, incorporating participatory approaches and qualitative insights could deepen understanding of how different social groups experience and navigate transport barriers in practice. Finally, extending the analysis to include cycling and micromobility options would provide a more comprehensive view of multimodal accessibility (Guan et al., 2024), reflecting emerging trends in urban mobility and supporting sustainable transport policies.

Conclusion

This study has comprehensively assessed cumulative accessibility to key urban destinations – kindergartens, primary and secondary schools, and workplaces – in Szczecin, using both public and PrT modes. By integrating spatial travel-time analysis with equity measures such as the Lorenz curve and Gini coefficient, the research highlights significant disparities in accessibility across the urban landscape.

The findings demonstrate a clear and consistent advantage of PrT use regarding both the extent and equity of access. In contrast, PT, while improving accessibility over longer time thresholds, remains limited, particularly in peripheral districts and within the critical 20-30 minute travel window. These mid-range trips represent a key spatial challenge, where PT fails to provide adequate connections to educational and employment opportunities for large population segments.

Inequality is most pronounced in access to workplaces and primary schools, as evidenced by the high Gini coefficients, pointing

to systemic spatial mismatches between service locations, residential areas, and the transport network. The comparatively better performance of PrT in all categories further underscores the structural disadvantages faced by individuals reliant on public transit.

The results call for a more equity-oriented transport and urban planning approach in Szczecin. Improving the reach, frequency, and integration of PT – especially in underserved areas – should be prioritised to reduce accessibility gaps and foster more inclusive access to education and employment. Transport accessibility should be viewed as a matter

of efficiency and a fundamental component of social equity and urban justice.

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Editors' note:

Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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