Spatio-Temporal Variation of Accessibility by Public Transport—The Equity Perspective

Marcin Stępniak and Sławomir Goliszek

Abstract The growth of large, open datasets coupled with an acceleration of technical developments, including GIS solutions, opens the door to new challenges in transport research. One of the emerging fields of research is the temporal dynamics of accessibility. The increase in availability of General Transit Feed Specification (GTFS) data permits the inclusion of very detailed, schedule-based travel time information. In the study presented we focus on the spatial and temporal variation in accessibility by public transport in the city of Szczecin (Poland). This paper advocates the necessity of incorporating a temporal component in accessibility analysis. We conducted a full day analysis for 1 day using averaged 15-min-long time periods at a very detailed spatial scale (enumeration districts). Based on the calculated origin-destination matrix in 96 time-profiles we calculated the potential accessibility indicator. Then we investigated spatial disparities and their variability during the day-long observation. Apart from the well-known spatial disparities in accessibility level, our findings underline the uncertainty of the accessibility pattern. Moreover, the results show that less accessible areas are also more affected by the daily variation in accessibility level. The findings provide a more realistic insight into accessibility patterns which will be useful for transport planners and policy makers.

Keywords Accessibility · Public transport · Open data · GTFS · Spatial and temporal analysis · Szczecin

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1 Introduction

Accessibility plays a decisive role in shaping our contemporary cities and regions. Its evaluation has become a key issue in spatial planning and modelling. For several decades urban planners, transportation experts and researchers use accessibility in order to examine transport efficiency (Benenson et al. 2011; O'Sullivan et al. 2000), risk of social exclusion (Church et al. 2000; Lucas 2011) and the potential for equitable transport systems (Delmelle and Casas 2012; Foth et al. 2013) or the assessment of new transport investments (Golub and Martens 2014; Manaugh and El-Geneidy 2012; Martens and Hurvitz 2011).

The emergence of new, large datasets and progress in computational capacities offers new opportunities, and enables researchers to increase the temporal and spatial resolution of accessibility analyses. The rapid development of open databases has provided valuable open data sources which are critically useful, especially for transport analyses. For example the OpenStreetMap database collects a huge number of gigabytes of data on transport networks, while GTFS datasets contain all the information required for analyses that investigate public transport. Taking all these new capabilities into account, we can face new research challenges, or investigate established ones from a new perspective.

One of the new fields of research is related to the temporal dynamics of accessibility (Geurs et al. 2015; van Wee 2016), which may provide a valuable, previously hidden input for policy makers and practitioners. Given that the level of accessibility (Farber et al. 2014) and its equity vary through the day (El-Geneidy et al. 2015), it is inequitable to include a temporal dimension into accessibility analysis (Baradaran and Ramjerdi 2001). The present study is focused on the temporal variation of the spatial pattern of accessibility by public transport in the city of Szczecin, Poland. We investigate this variability from the equity perspective focusing on its spatial and temporal dimensions. Thus, in the next section we describe two core issues that are used as a point of departure for the research conducted: accessibility and equity. Next, we present a selected case study, data sources and the methods applied. The results of our analyses, illustrated by maps, graphs and tables, are then presented. The final section presents our conclusions.

2 Accessibility and Equity—A Multidimensional Perspective

Accessibility, following the classical definition by Hansen (1959), is commonly understood as the potential of opportunities for interaction. Limited accessibility may therefore be considered as one of the main limitations of full participation in the social and economic activity of a given society, and in consequence—as one of the main factors responsible for social exclusion (Church et al. 2000; Lucas 2011; Preston and Rajé 2007). Given that the link between accessibility and exclusion is receiving growing attention, the focus of transport studies is evolving towards equity approach (Manaugh et al. 2015; Martens 2012; van Wee and Geurs 2011) and this is becoming more frequently included in accessibility instruments for planning practice (Papa et al. 2016).

Accessibility is a multidimensional phenomenon which covers a wide range of issues. Geurs and van Wee (2004) established fourfold typology of accessibility components, which includes: land use, transport, temporal and individual components. In a given study, we focus on the first three components, leaving an individual one behind the scope of this study. Thus, we assume, that accessibility level is a by-product of spatial distribution of potential origins and destinations (i.e. land use component, hereby population distribution), reflected by an existing transport system (i.e. transport component, hereby public transport service), which varies in time (i.e. temporal component, hereby daily variability). As accessibility determines human opportunities—for jobs, for economic or social interaction, for access to goods, or for the use of social or economic resources—the differentiation in the level of accessibility creates variations in opportunities and when differentiation comes onto the stage, equity should also be considered. The discussion about accessibility should therefore include an equity perspective, with equity understood as equality in accessibility level.

Equity in transport appears to be a very complex phenomenon, which results from the fact that there is no standard definition for it (Martens et al. 2012). Nevertheless, a common framework established to analyse equity from the accessibility perspective does exist, and this is based on two main dimensions: the vertical and the horizontal (Litman 2002). The vertical focuses on the differences between individuals, including their social and economic status as well as their mobility, with regard to their needs and abilities. The horizontal dimension has its roots in egalitarian theories of social justice (El-Geneidy et al. 2015; van Wee and Geurs 2011), i.e. it assumes that no one should be disfavoured, no matter who they are and where they live. Common practice usually identifies the horizontal dimension as spatial disparities (El-Geneidy et al. 2016) underlying the importance of a uniform distribution of accessibility levels across space (Chang and Liao 2011; Thomopoulos et al. 2009). The equal level of access is obviously an utopia, as a spatial pattern of any city or region creates conditions for unequal distribution of potential destinations, e.g. due to their centre-peripheral division, as stated by Martens et al. (2012). Nevertheless, we assume that one of the main aim of transport system is to diminish existing differences, by providing a proper level of public transport service.

Another equity dimension, which is investigated with regard to accessibility is modal equity, i.e. the comparison between accessibility by private car and public transport modes (Benenson et al. 2011; Golub and Martens 2014; Martens et al. 2012). The scale of disparities of accessibility level between both transport modes, called public transport gaps (Fransen et al. 2015), can be used as a proxy of car dependency and results in higher inequality levels (Martens 2012). Furthermore, in recent studies a next, intergenerational dimension of equity is identified (El-Geneidy et al. 2015; Foth et al. 2013; Kaplan et al. 2014), but this seems to be a special type of Litman's vertical dimension, where demographic groups take the place of social classes, rather than a separate equity dimension. Finally, apart from the spatial (identified with the horizontal) dimension and the socio-demographic (related to the vertical) dimension, the third, temporal dimension is beginning to attract more attention (Jones and Lucas 2012; Kawabata 2009), and this can be linked to the increasing availability of real-time data on traffic conditions and General Transit Feed Specification (GTFS) data (Geurs et al. 2015).

Given the complexity of the equity issues, we are limiting our interest to two of its dimensions: the horizontal and temporal ones. We consider spatial disparities to be applying the horizontal dimension of equity. We have investigated these disparities in accessibility level by public transport in the city area. Additionally, we have included temporal equity in our analysis. With regard to the latter, our analysis is twofold: First, we investigate the extent to which accessibility and equity levels vary during the day. Second, we estimate temporal disparities in accessibility level in given spatial units (enumeration districts). Taking the joint perspective of concepts of accessibility and resilience (Östh et al. 2015) as a point of departure, we argue that, for a given areal unit, it is not only low accessibility that may be considered 'problematic'. The constancy of travel time to a given destination, independent of the time period, also determines quality of life and travel behaviour.

3 Data and Methods

3.1 Case Study

The study covers the area of the city of Szczecin, north-west Poland. It is a subregional centre, one of the capitals of the Polish regions (voivodship, NUTS-2 region). The city area of 300 km^2 has a population of about 410,000. The city is divided by the River Oder and the two river banks are connected by only two main bridges. The main settlements of the city are located on the left-bank of the river, including the city and regional administration, main railway station as well as most of the population (Fig. 1) and employment. Moreover, almost a quarter of the city area consists of uninhabited natural zones, mainly wetlands. The public transport network consists of a radial tramway network (12 routes, mainly in the city centre) supplemented by a bus network, which connects most of the residential areas with the city centre (Fig. 2). The night-time public transport is operated by 16 dedicated night-bus routes. Only a few routes connect both river banks (including 3 night-time ones).

The study covers a complete day long accessibility analysis, applied for a typical weekday. We have used a complete day measurement (timespan 00:00–23:59) using 15-min intervals, i.e. we obtained 96 origin-destination travel time matrixes. Given that the total number of origin-destination nodes in the accessibility model is equal to 1745, each of the 96 averaged travel time origin-destination matrices

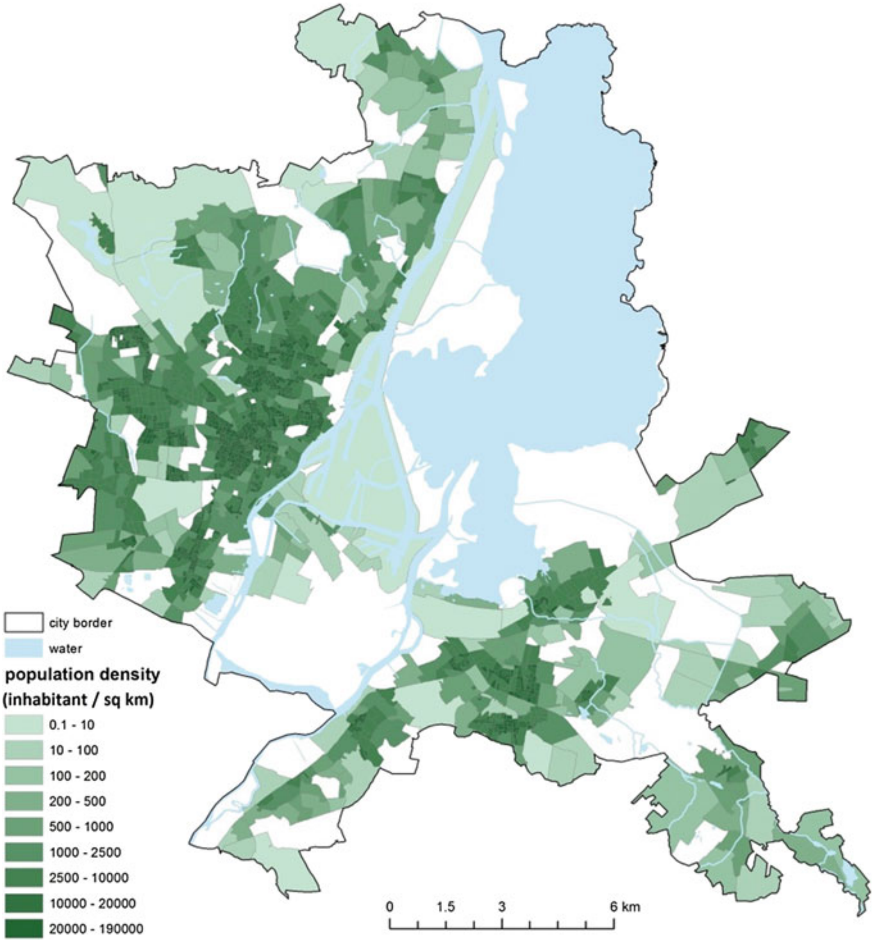

Fig. 1 Population density in Szczecin (according to National Census 2011)

contains about 3 million records, and the whole dataset contains almost 300 million individual travel time measurements. All of these are used to estimate the accessibility level and its daily variability for each individual spatial unit.

3.2 Open Data

The assumption that lies behind this study is that it should be fully replicable, requiring only data (including any spatial data) that are available in open access. We take advantage of the growing potential of the GTFS data format, and the freely available datasets containing the pedestrian network (derived from the

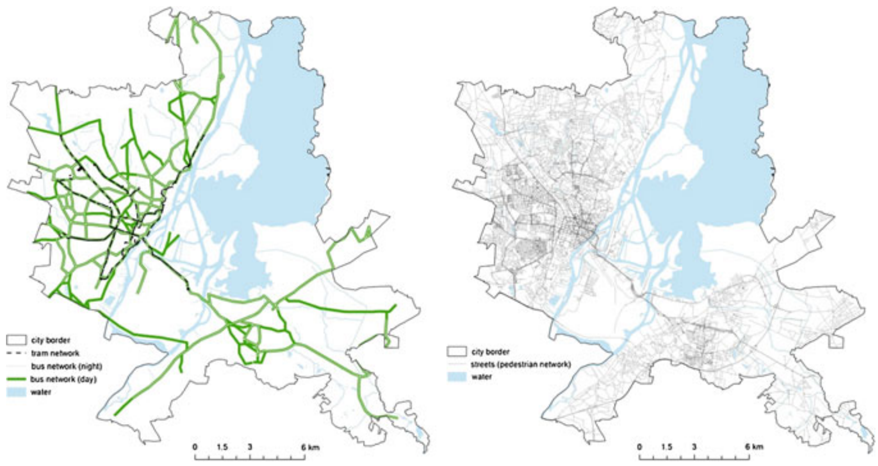

Fig. 2 Public transport and pedestrian network in Szczecin (July 2015)

OpenStreetMap dataset) and population data available from the Information Portal of the Central Statistical Office of Poland.

The GTFS is a data standard which is used to describe the public transport system and it contains the public transport stops (including their geographical location), routes and schedules. The subsequent GTFS files used in this study include stops (i.e. their individual geographical location), routes (i.e. the set of stops which constitutes a particular public transport line), trips (i.e. a sequence of two or more stops that occurs at specific time), stop-times (i.e. times that a vehicle arrives at and departs from individual stops for each trip) and calendar (i.e. dates for service IDs using a weekly schedule) (https://developers.google.com/transit/gtfs/reference). In result, it enables to calculate a precise, real travel time by public transport between any pair of origin-destination points. Due to the fact it enables one to investigate real-time accessibility by public transport, it is attracting growing attention from practitioners and the scientific community. It is used to evaluate the efficiency of the public transport network in general (Hadas 2013) and in comparison with travel times by private car (Benenson et al. 2011; Salonen and Toivonen 2013), providing practical conclusions that enhance the effectiveness of public transport systems (Tao et al. 2014). In addition, GTFS data enables a more precise assessment to be made of the level of socio-spatial disparities in the metropolitan area (El-Geneidy et al. 2016) with special attention being paid to socially disadvantaged groups (El-Geneidy et al. 2015). The precise information on the public transport schedules permits a better understanding of temporal changes of accessibility patterns, e.g. in the case of accessibility to health-care services (Fransen et al. 2015) or supermarkets (Farber et al. 2014).

The original GTFS dataset, which is applied in the present study, is published by the Szczecin public transport authority (http://zditm.szczecin.pl/rozklady/GTFS/latest/) and it covers the whole city area. We have used the most current dataset available at the time of the study (i.e. July, 2015). The dataset contains detailed information on 88 transit lines (60 daytime and 16 night buses, supplemented by 12 tram lines), 1888 edges in the geodatabase and 1394 points that represent particular public transport stops (more about GTFS standard may be found here: https://developers.google.com/transit/gtfs/reference), among them 1112 located within the city borders and the rest in adjoining areas. The Add GTFS datasets to a Network tool for ArcGIS (available at: http://www.transit.melindamorang.com/overview_AddGTFStoND.html) is then applied to create a routable network and the ArcGIS Network Analyst extension (10.2) is used for travel time calculations [Similar calculations may be also executed using open software instead of commercial one provided by ESRI, e.g. Open-TripPlanner (http://www.opentripplanner.org/)]. The travel time from origin i to destination j is calculated for a specific departure time and includes: walking to and from the public transport stop, waiting, boarding (0.25 min) and duration of the ride. The last of these includes intermediate boarding and waiting times, as well as walking between particular stops (where this applies).

The OpenStreetMap data are used to characterise the pedestrian network, required to connect enumeration district centroids to the nearest public transport stop, as well as to connect different public transport stops in the case of transfer. The full dataset consists of almost 139,000 edges. The distance travelled is derived from GIS data using the shortest path algorithm along the pedestrian network. Previous studies apply a wide range of walking speeds, starting from 3.2 up to 5.4 km/h (Table 1). Based on these examples we have applied an average walking

Table 1 Examples of walking speeds applied

Study	Walking speed (km/h)	Comment
Reyes et al. (2014)	3.2	Minimum typical speed for children aged 5–11
Fransen et al. (2015)	4.0	Adult's average
Ritsema van Eck et al. (2005)	4.0	Distance as the crow flies
Hadas (2013)	4.0	–
Nettleton et al. (2007)	4.8	–
Farber et al. (2014)	4.8	–
Willis et al. (2004)	5.3	Mean walking speed of individuals
Reyes et al. (2014)	5.4	Maximum typical speed for children aged 5–11
Krizek et al. (2012)	5.4	Average walking speed for 14–64 year old

travel speed of 4.5 km/h. Both of the datasets, i.e. GTFS data on the public transport network and OpenStreetMap create a very complex, multimodal transit network, which enables connections to be made between any pair of origin-destination nodes.

The nodes are located in the centroids of all the inhabited enumeration districts (census tracks) in the case study area (1745 units connected to the multimodal transport network). The average area of these units is equal to 98.8 ha and they are inhabited by 235 persons on average (in a range 3–899 persons). Such detailed, spatially disaggregated data are available from the geoportal of the Central Statistical Office of Poland (see http://geo.stat.gov.pl/inspire), established in the framework of the European INSPIRE directive (2007).

3.3 Accessibility calculations

As accessibility is a multidimensional phenomenon, there exist many measures of accessibility. The one applied in the present study is potential accessibility. Geurs and van Wee (2004) note that the gravity-based measure of potential accessibility provides a suitable framework as it combines two essential elements: land use and transportation. The measure is based on travel time calculations between all pairs of origin-destination nodes within the case study area. It is based on the framework established by the 'first law of geography' (Tobler 1970) and the Huff model (Griffith 1982; Huff 1963). According to the former, everything is related to everything else, but near things have a stronger relationship than distant ones. This means that closer destinations have more influence than distantly located ones, hence they appear as more 'attractive' destinations. According to the latter, the more important (e.g. larger) the destination, the farther its influence extends. Thus, accessibility level is determined by travel time to a diverse range of destinations and it assigns more importance to larger centres than to smaller ones with diminishing attractiveness with increasing travel time. Let M_j be the attractiveness of destination j and $f(t_{ij})$ be the impedance component. From this the accessibility A_i of the spatial unit i is then calculated using the following formula:

$$A_i = M_i f(t_{ii}) + \sum_j M_j f(t_{ij})$$

The first component of the formula is the self-potential of a given enumeration district, i.e. the potential produced by the area itself. Its value is estimated based on the area of a given spatial unit, following the method proposed by Rich (1978) (cf. Bröcker 1989; Frost and Spence 1995), i.e. internal travel distance is equal to half the radius of the area and the average internal travel speed is the typical walking speed applied in the study (4.5 km/h). The second component is then the 'external' potential, i.e. the potential produced by all other destinations included in the study.

We use population size, which is assumed to be a proxy of destination attractiveness. The impedance component is determined by time, with the negative exponential function as an impedance form (for a review on the selection of the proper distance decay function consult: De Vries et al. 2009; Kwan 1998; Martínez and Viegas 2013; Reggiani et al. 2011; Rosik et al. 2015). In order to estimate the β parameter which influences the slope of the distance decay function, we apply the 'half-life' approach (Östh et al. 2014), i.e. we assume that the destination loses half its attractiveness at the observed median travel time for a given trip purpose. According to the data derived from the Comprehensive Traffic Study conducted in Szczecin (2010) the average travel time is 27 min which gives a β equal to 0.02567.

Daily accessibility values are calculated using the weighted average, where the share in daily flows by public transport is used as a weighting factor. As a result, the accessibility level during the peak-hours has more influence on the aggregated daily value than night-time accessibility. The same weighting procedure is applied to five time-periods during the day. The share of flows in a given time period is derived from the Comprehensive Traffic Study of Szczecin (2010). The extract from the Study is based on individual travel patterns during a weekday. It does not differentiate trip motivations (i.e. it includes work- as well as non-work-related trips) and it is limited only to the walking and public transport modes (buses and tramways), while private cars, taxis and regional trains are excluded from the weighting procedure. Nevertheless, the variability of the share of the departure times of journeys during the subsequent periods of the day is quite similar for different transport modes (Table 2).

3.4 Equity and Spatio-Temporal Variation

Similar to the broad range of accessibility measures, there also exist several equity measures. Due to the fact that each of these reflects a different perception of (in) equality, it may be difficult to assess the degree of equality on the basis of a single measure (Ramjerdi 2006). Nevertheless, all the equality indicators already devised and tested (i.e. Gini coefficient, coefficient of variation, standard deviation and Theil's entropy index) are strongly correlated with each other, as underlined in the cited paper (Ramjerdi 2006), as well as in our case study area (Table 3). thus we selected the Gini coefficient for further analysis (cf. Kaplan et al. 2014; Neutens et al. 2010; van Wee and Geurs 2011). The Gini coefficient is based on the Lorenz curve, and it is calculated as a ratio between the line of the perfect equality and an observed Lorenz curve. It can assume values between 0 (a perfectly even distribution) and 1 (a maximal concentration). We use 'ineq' package for RStudio environment (ineq package: Measuring Inequality, Concentration, and Poverty https://cran.r-project.org/web/packages/ineq/index.html) to calculate Gini coefficient.

Taking advantage of the completeness of the GTFS data, we investigated the daily variability of both accessibility levels and equity measures. In the case of the latter we can investigate both of its dimensions, i.e. the horizontal dimension, using

Table 2 Share of trips by time-of-day (journeys started, all trip motivations)

%	0:01–6:00	6:01–7:00	7:01–8:00	8:01–9:00	9:01–11:00	11:01–12:00	12:01–13:00	13:01–14:00	14:01–15:00	15:01–16:00	16:01–17:00	17:01–18:00	18:01–20:00	20:01–24:00
Total (n = 8039)	3.2	7.5	13.5	6.8	12.9	5.1	4.7	5.9	8.0	10.7	7.7	5.1	6.2	2.7
Walking (n = 1511)	1.8	3.6	11.6	8.8	17.8	7.4	6.0	7.5	8.3	7.6	5.8	4.0	6.6	3.2
Public transport (n = 2696)	3.5	8.1	12.0	6.8	14.6	5.5	5.7	6.5	8.4	10.2	7.4	3.9	5.2	2.2
Walking and public transport	**2.9**	**6.5**	**11.8**	**7.5**	**15.7**	**6.2**	**5.8**	**6.9**	**8.4**	**9.3**	**6.8**	**4.0**	**5.7**	**2.5**

Source Comprehensive Traffic Study of Szczecin (2010)

Table 3 Correlation matrix for the calculated equity measures

	SD	Coefficient of variation	Gini	Theil
SD	1.00	0.91	0.91	0.85
Coefficient of variation	0.91	1.00	1.00	0.98
Gini	0.91	1.00	1.00	0.98
Theil	0.85	0.98	0.98	1.00

the Gini coefficient calculated for all spatial units (enumeration districts), and the temporal dimension, focusing on the daily variability of the accessibility level noted in particular spatial units.

4 Results

4.1 Spatial Disparities

The spatial pattern of the daily weighted average of potential accessibility level replicates the distribution of population including the modification resulting from the central-peripheral division of the city (Fig. 3). Further located areas are obviously less accessible (Martens 2012), but those located on the right bank are even less accessible than left-bank peripheries. The separation of the city produced by the river crossing from south to north and limited connectivity of both parts of the city is then clearly visible. Moreover, the fact that almost 80 % of city's population inhabits residential areas located in the western part of the city is also reflected by the spatial pattern of accessibility values, which are significantly higher on the left bank of the River Oder.

Nevertheless, we argue that public transport, to some extent, fulfils its role in diminishing disparities in accessibility level. The spatial disparities in walking accessibility (Fig. 4a) are far more intense than those resulting from public transport accessibility. Ai values in the western part of the city are significantly higher than those in the other part and these differences are more extreme than in the case of accessibility by public transport. The evenness of the spatial distribution of potential accessibility values is also significantly higher for accessibility by public transport—in the case of the latter the Gini coefficient is equal to 0.13, while the Gini coefficient of potential accessibility through the pedestrian network increases up to 0.28. In case of walking accessibility, the most accessible areas have Ai values almost 45 times higher than the lowest ones, comparing to 5.5 in the case of public transport accessibility. The public transport system compensates, to some extent at least, the accessibility imbalance resulted from the spatial distribution of population and terrain constraints. The areas that gain the most from public transport are located on the east-bank as well as in the city's peripheries in general (Fig. 4b).

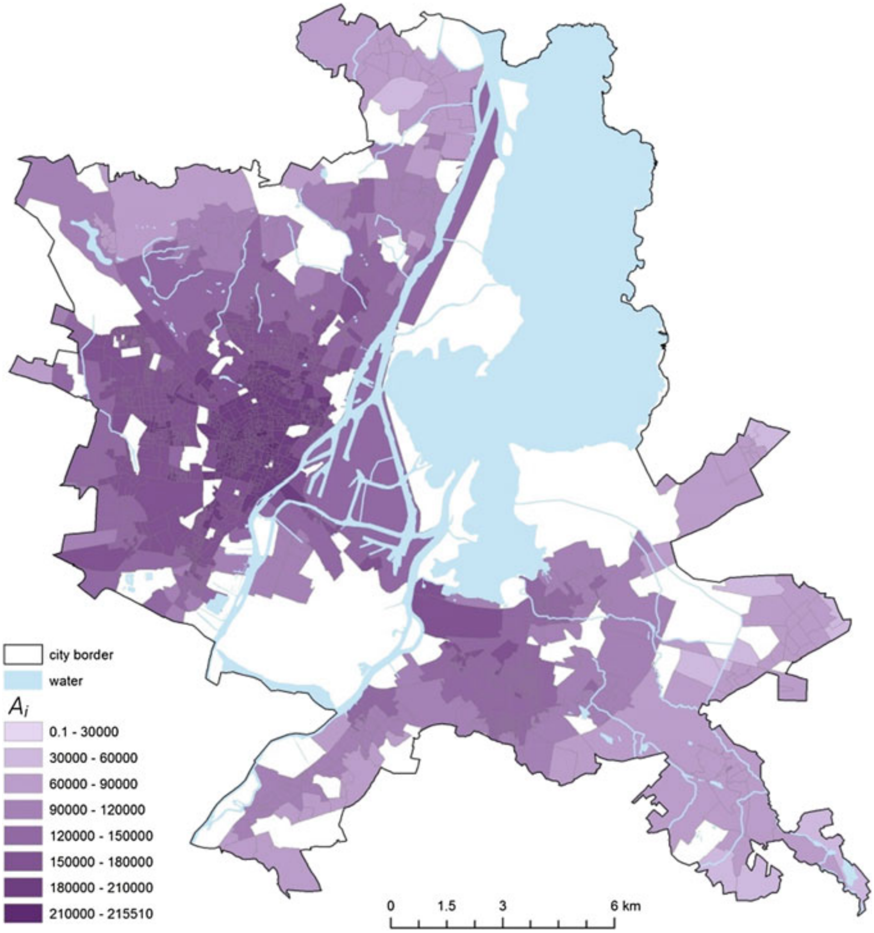

Fig. 3 Weighted daily average of potential accessibility by public transport

4.2 Temporal Variability

One would expect potential accessibility to vary during the day, and that the lowest values would be noted during the night (Fig. 5). The night-time service is less frequent and does not cover the whole city area, thus some neighbourhoods are reachable only by walking. However, it is surprising that the peak hours (especially the afternoon ones), when the public transport frequency is the highest, are almost invisible. The difference in the overall potential accessibility values between morning peak-hours and the daily off-peak does not exceed 4 %, and for the less-concentrated evening peak the difference is even smaller. If we look at the averaged potential accessibility values during successive periods during the day, we find hardly any differences (Fig. 6). The only exception is night-time accessibility.

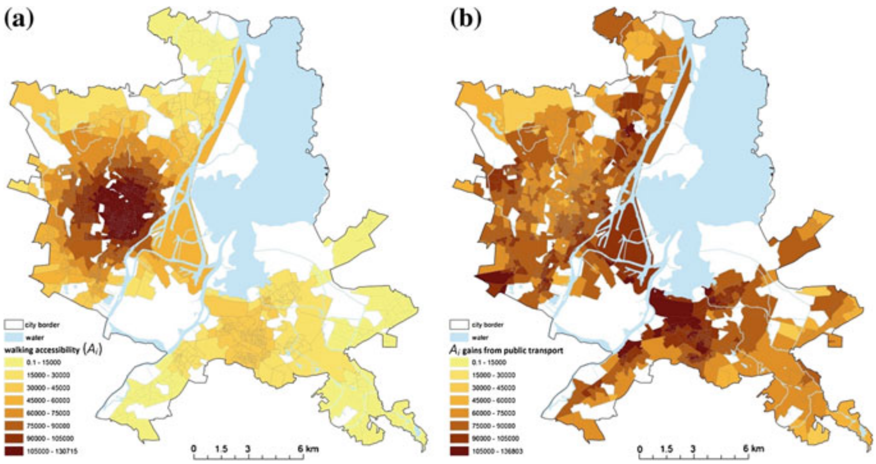

Fig. 4 Weighted daily average of potential accessibility by walking (**a**) and gains from public transport (**b**)

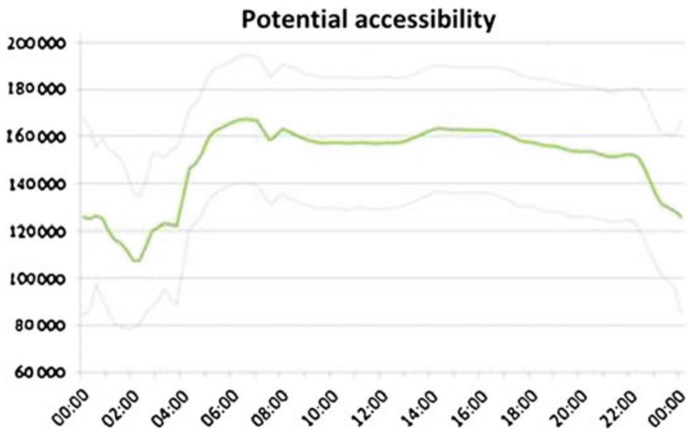

Fig. 5 Daily temporal fluctuations (30-min averages) of population weighted accessibility level at the city scale

The growth of spatial disparities during the night-time is reflected by an increase in standard deviation values (Fig. 5). Night-time inequality is also illustrated by an almost doubled Gini coefficient (Fig. 7). The higher the accessibility is by public transport, the lower the level of inequalities that is noted. This supports the statement that efficient public transport plays a decisive role in reducing spatial disparities in accessibility level.

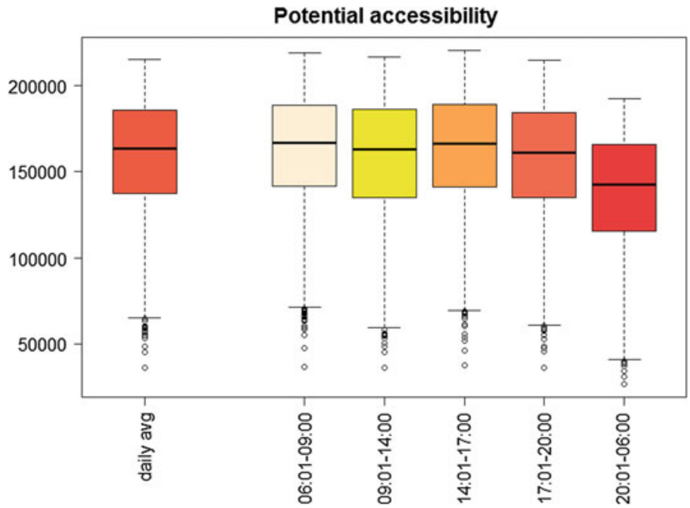

Fig. 6 Boxplots of potential accessibility values

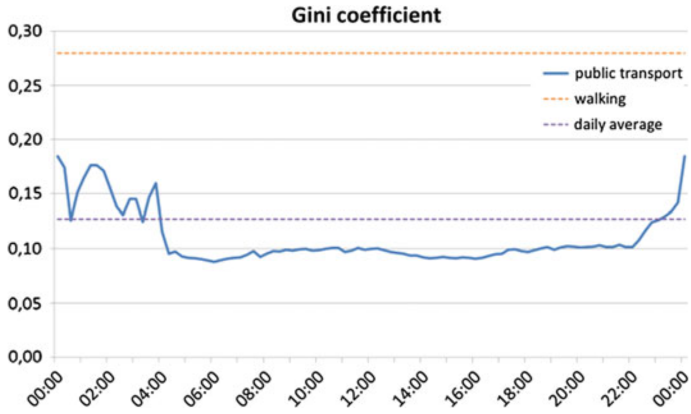

Fig. 7 Daily temporal fluctuations (30-min averages) of Gini coefficient at the city scale

4.3 Spatio-Temporal Arrangements

Potential accessibility values calculated for particular enumeration districts during different periods of a the day are still highly correlated to each other, as well as to the daily average (Table 4). The comap shows the changes of absolute values and their spatial pattern between different periods of the day (Fig. 8). Although the picture underlines slightly higher accessibility values during the morning peak-hours, the spatial patterns remain generally the same throughout the day. Again, the only exception is found in the night-time period and the most affected

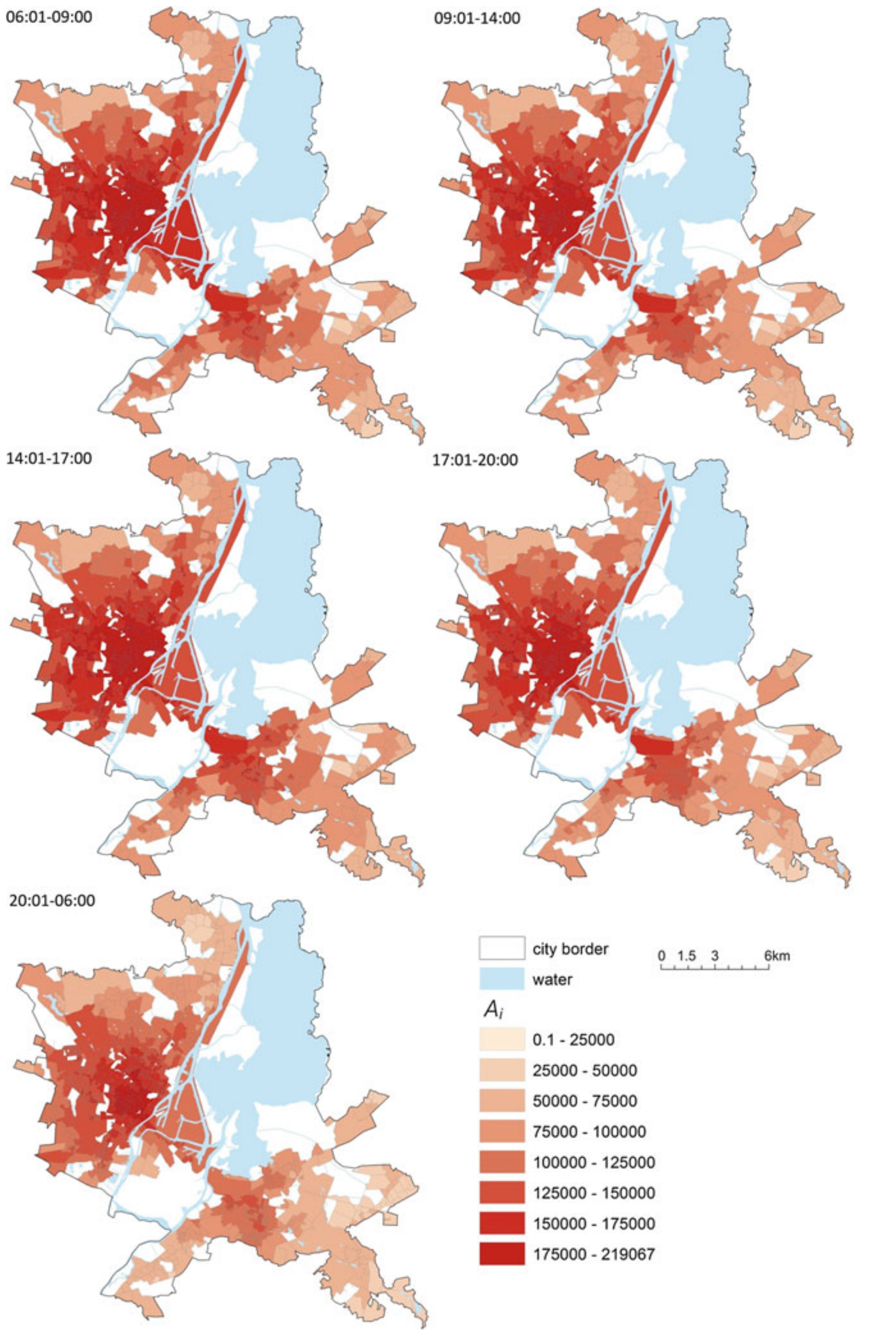

Fig. 8 Comap for potential accessibility values (by times of day)

Table 4 Correlation matrix of weighted averages of potential accessibility for different times of a day

	Daily	06:01–09:00	09:01–14:00	14:01–17:00	17:01–20:00	20:01–06:00
Daily	1.000					
06:01–09:00	0.999	1.000				
09:01–14:00	0.998	0.996	1.000			
14:01–17:00	0.998	0.996	0.994	1.000		
17:01–20:00	0.998	0.995	0.996	0.994	1.000	
20:01–06:00	0.990	0.989	0.986	0.987	0.989	1.000

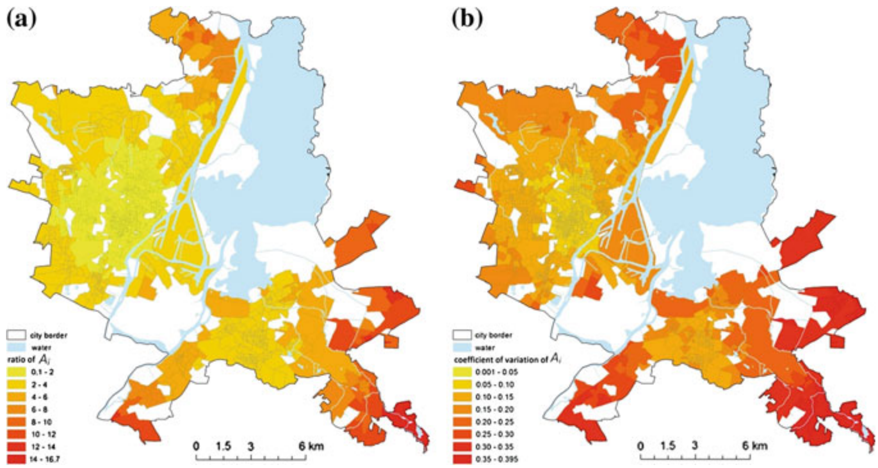

Fig. 9 Ratio of potential accessibility values (**a**) and coefficient of variation (**b**)

area is the right-bank part of the city. The crucial role of the terrain and infrastructure constraints is again underlined.

The spatial pattern of daily variability of accessibility level indicates that less accessible areas are simultaneously the areas most affected by the inconstancy of accessibility level. The ratio between the extreme values of accessibility levels reflects this inconstancy in absolute terms, while the coefficient of variation of accessibility level during the day indicates the same relationship in relative terms. In the case of the former, the relationship between the lowest and the highest accessibility level in some, peripheral areas exceeds a factor of ten, while in the case of the highly accessible city centre the ratio is lower than two (Fig. 9a). Similarly, the latter underlines the same areas as the most imbalanced ones (Fig. 9b). The scatterplots depict a strong relationship between a daily average accessibility level and its daily variation in both absolute and relative terms (Fig. 10).

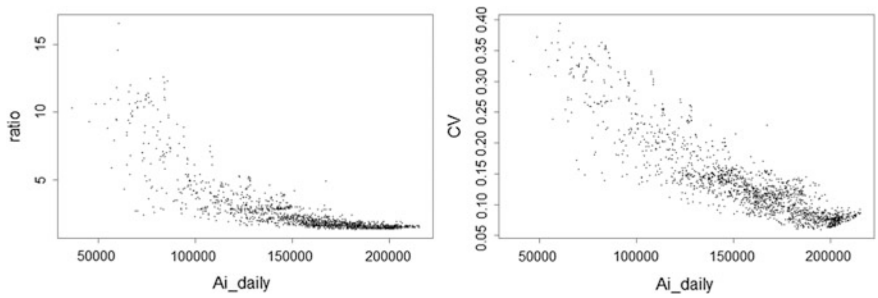

Fig. 10 Scatterplot of weighted average of potential accessibility versus ratio and coefficient of variation

5 Conclusions

The present study tends to shed more light on the less investigated, temporal dimension of equity in the distribution of accessibility level across the city. Increasing computational efficiency, and the rise of large-scale open data, including GTFS standard, enables an unprecedentedly detailed analysis of accessibility disparities. Using real travel times by public transport calculated on the basis of up-to-date schedules, we built up an original, time-varying origin-destination matrix which is then converted into potential accessibility values. Highly disaggregated spatial units (1745 enumeration districts) provide very detailed information about spatial disparities in Szczecin. The effectiveness of combination of GTFS large datasets and GIS solutions, provides tools for highly detail accessibility analysis for a large case study areas, which have been unavailable before.

Our results show, that the public transport system in Szczecin at least partly compensates the accessibility imbalance resulted from the unusual spatial pattern of land use. The spatial disparities in accessibility levels by public transport are not as heavily affected by the city's division by Oder river, as it might be expected. The accessibility by walking in the eastern part of the city is significantly lower than in case of daily average of accessibility by public transport. The central-peripheral division of accessibility disparities is still visible, but it is quite typical for any urban area (cf. Martens et al. 2012).

We acknowledge the previous findings about the existence of great temporal variability in accessibility level by public transport (Farber et al. 2014), even though the dissimilarities decrease when using temporally aggregated values (Fransen et al. 2015). Investigating equity indicators during the course of the day, we add a better understanding to previous studies regarding the temporal component of spatial disparities in terms of accessibility. The average accessibility level does not vary significantly between peak and off-peak hours, nor does the equity indicator (Gini coefficient). Nevertheless, the limited service during the night-time period strongly affects both the overall accessibility level and its degree of equity. It should be clearly pointed out that public transport frequency and coverage not only has an influence on the population accessibility level, but also has a significant impact on spatial inequalities. Accessibility inequality is strongly inversely related to accessibility level.

A major finding of this study is that a low accessibility level is associated with a higher inconstancy of accessibility level. In the results some areas, mainly the peripheral ones, are doubly affected by the limited public transport service. Not only do their inhabitants need more time to reach their desired destination, but also their expected travel time is strongly influenced by uncertainty and greatly depends on a particular time of a departure. Apart from public transit gaps, this uncertainty may be the most important factor in car dependency and transport inequalities.

In this study we focus on the spatial and temporal dimension of equity in accessibility level. Neither the distribution of accessibility between the different population groups (vertical equity), nor modal equity remain unaffected and they should be included in further investigations. We identify a compelling need for a complex, multidimensional analysis of equity, which includes all of its identified dimensions (i.e. horizontal, vertical, temporal and modal). Such an approach requires comprehensive data which describe several fields of population characteristics and travel behaviour including their very detailed spatial representation. Further, in the presented study we apply an average walking speed, equal for the whole population. The combination of vertical and horizontal dimension of equity and availability of supporting data provides an opportunity to include, among others, variability of walking speed depending of the characteristic of individual (e.g. age, potential disabilities etc.). We believe that our findings on the temporal and equity dimensions supplement the existing body of knowledge, and the rise of 'big data', supported by increasing technical capacities, provides a stable ground reference for future investigations. The proposed methodology enables to combine various equity dimensions into one analysis, which can be easily adapted for any other case study area. Moreover, similar approach may be implemented when comparing any other equity dimensions (e.g. vertical and/ or modal equity dimensions). Thus, the described research procedure may be easily implemented e.g. for an ex-ante evaluation of changes in organization of public transport services.

Finally, our analysis suggests, that some of neighbourhoods (and their inhabitants) are "double-affected", i.e. not only by low average level of accessibility by public transport, but also—by the high daily variation in accessibility level. It should be further evaluated, whether this multiplication of a negative impact of temporal and horizontal inequalities is something typical or it is a by-product of the unusual spatial pattern of the land use (city divided into two parts by natural constraints) in the particular case study.

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