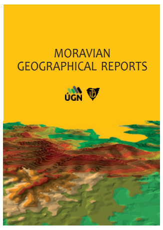

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Long-term impact of railway transport on morphological development of the largest urban agglomerations in Poland

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Abstract

Railway transport accessibility is widely recognized as one of the key factors stimulating spatial development. This dependency was particularly evident during periods of its greatest significance before the era of mass motorization. Despite growing research interest in the issue of relationship between transport and land use, few studies have considered this subject in long-term perspective and in quantitative terms. The primary objective of this study is to determine historical, long-term impact of railway transport on the dynamics of morphological changes in the settlement network. This study was conducted in the eight largest urban agglomerations in Poland, serving as an example of the Central and Eastern European region. The general temporal scope of the study spans the period from 1842 to 1989. The research revealed a strong correlation between railway transport and morphological changes in analyzed urban agglomerations. The most significant changes observed within 1,600 meters of railway stations and up to 20 kilometers from central stations. This quantitative analysis contributed to understanding the long-term impact of railways on spatial development, offering valuable insights for planning and policymaking. The research emphasized the importance of historical context in comprehending current spatial processes, particularly in the context of new railway investments.

Keywords: *Long-term analysis, railway transport, urban agglomerations, urban morphology*

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1. Introduction

The emergence of railway transport has played a crucial role in shaping space at global, regional, and local levels. On a global scale, the possibilities offered by railways have helped overcome distance barriers, contributing to the ongoing process of time-space convergence (Janelle, 1968; Schivelbusch, 1978). Regionally, access to railway transport has accelerated economic development in many towns and cities (Mumford, 1961; O'Brien, 1983; Antrop, 2004; Divall & Bond, 2017). At the local level, railway infrastructure has acted as catalysts for spatial development in their immediate surroundings (Ward, 1964; Janelle, 1966; Adams, 1970; Pels & Rietveld, 2007).

From the perspective of research on the issue of transport and land use, the key concern is understanding the mechanism of the railway transport impact on spatial development at a local scale. Although this issue has been addressed in the literature, the spatial and temporal variations in this regard remain relatively poorly understood. There is a lack of long-term, comprehensive, and quantitative analysis, particularly in regions with specific geopolitical conditions. The reference point in this regard remains the analyses conducted by Kaasrain et al. (2016) for the period of 1850–2010 in the Netherlands. However, these studies confined spatial development to the lens of built-up areas, neglecting to examine morphological changes within the studied area.

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Valuable contributions have been made by studies analyzing the long-term influence of railway transport on broadly understood spatial development by the prism of population growth. Such studies have been conducted, among others, for the Netherlands (Koopmans et al., 2012), Switzerland (Büchel & Kyburz, 2020), as well as for England and Wales (Bogart et al., 2022). However, these analyses did not have a spatial nature, which prevents a sufficiently detailed understanding of the relationship between transport and land use.

The primary objective of this study is to determine historical, long-term impact of railway transport on the dynamics of morphological changes in the settlement network. The analysis is conducted in the eight largest agglomerations in Poland, serving as representatives of the Central and Eastern European (CEE) region[1]. In this study, railway transport is approached comprehensively, considering both the infrastructural and functional aspects. The reference point of analysis will be the railway station as infrastructure object, yet its value stems from the possibilities of reaching various destinations. Morphological changes, in turn, serve as package of indicators related to the settlement structure complexity, which is a significant element of broadly understood spatial development. The analytical part of this study was based on use of GIS techniques, utilizing multi-temporal datasets that encompass historical maps, and aerial photographs. In the process of quantitative analysis, the authors aimed to address two interconnected key research questions:

- Do areas located closer to railway stations exhibit greater dynamics of morphological changes compared to areas located farther away, and to what extent?
- Can differences be identified in the dynamics of morphological changes among the analyzed agglomerations that are characterized by different historical and geopolitical conditions?

The analysis of the dynamics of morphological changes was conducted within designated distance zones, calculated both from all railway stations and from the central railway station. This dual approach enabled the authors to assess the effect of the railway itself and the effect of the strength of the core agglomeration

Based on this research approach, two hypotheses were formulated:

- H1: The intensity of morphological changes will decrease with distance from the railway station.
- H2: The intensity of morphological changes will decrease with distance from the central station within the agglomeration.

This research goal is important for understanding the regularities in the morphological changes of the largest urban agglomerations in Poland. The results contributed to the overall recognition of the relationship between transport and land use in several ways: it analyzes a region that has been poorly recognized, provides a long-term perspective, and employs a quantitative approach using GIS methods to assess the scale of morphology changes (described in more detail in the Section 3). Verifying these patterns will enhance our knowledge of potential development trajectories and highlight the historical conditions influencing spatial urbanization in present-day Poland. These precisely defined research assumptions will provide clear evidence for current policymakers addressing the issue of uncontrolled urban growth, not only in Poland but also in other CEE urban agglomerations. Particularly significant is the consideration of the transportation factor, which is one of the fundamental determinants of spatial development. Understanding the mechanisms of the relationship between transport and land use in a historical context can contribute to better future planning in this regard, especially in the context of achieving the goals of sustainable development. The added value of this study lies in its quantitative assessment of the impact of railways on spatial development. The rigid research design enables comparability across all major urban agglomerations within Poland's current borders. Furthermore, the method's universality allows for its application in other regions and its subsequent validation in different administrative and political systems.

2. Theoretical background

2.1 Rail transport and spatial development

The minimization of transportation costs achieved through railway transport has significantly contributed to the reorganization of existing spatial structures. First and foremost, it is important to note that historically railway transport led to the spatial redistribution of employment and residential places. The location of workplaces no longer needed to be near residential areas; instead, the proximity of railway stations became more significant because it facilitated daily commuting between these places (Assink & Groenendijk, 2009). This could be observed through the placement of industrial factories near railway infrastructure in 19th century England and Wales (Bogart et al., 2022). As a result, industrial factory workers began constructing their houses near railway stations, seeking better employment opportunities, thereby stimulating spatial development processes in these areas (Wegener, 1994).

The possibility of fast rail access to the agglomeration core has also become one of the key factors in the garden city concept (Howard, 1902). Moreover, the course of the railroad not only favored the location of garden cities, but also influenced the formation of their spatial layouts, treating the station as one of the main elements of morphological development. Howard's concept, and basically the development of the rail network, initiated a trend toward suburban development (Ward, 1998). With railroads providing quick access to the core of metropolitan areas, as well as relatively lower prices, suburban zones became an attractive place to live for people working in cities (Capuzzo, 2017; Divall & Bond, 2017). According to Barras (2009), the development of railroads was crucial to housing construction in the late 19th century, shaping one of the major building cycles. Railway transport has contributed to the creation of linear patterns of spatial development (Aljoufie et al., 2011; Kheyroddin & Ghaderi, 2023). Many studies highlighted the formation of a star-shaped urban pattern along railway lines in suburban areas at the end of the 19th and beginning of the 20th century (Kellet, 1969; Adams, 1970). Kheyroddin and Ghaderi (2023) even suggest that railway network development shapes the spatial structure of metropolitan areas to a greater extent than other criteria.

The strength of the impact of railway transport on spatial development can vary in specific geographical regions and change over time, especially due to mass motorization (Axhausen et al., 2011; Kotavaara et al., 2011; Knowles & Ferbrache, 2014). The greatest significance of railway transport as a stimulant for spatial development was observed at the turn of the 19th and 20th centuries, as exemplified by cases in Europe and the United States (Carr & Whitehand, 2014; Keating, 2015). After World

[1] Central and Eastern Europe in this study is delineated according to Hamilton (1999, 2005) and the OECD's delimitation (2024), emphasizing the post-socialist character of the region. These countries are considered part of the eastern section of Central Europe, shaped by distinct historical and socio-political influences. This designation should not be understood as a region combining both Central and Eastern parts of Europe. The delimitation of Central and Eastern Europe remains inherently controversial and ambiguous, as the region lacks clear geographical borders, stretching from the Baltic Sea to the Adriatic and southeastward toward the Black Sea (Batt, 1998).

War II, American suburbs experienced urban sprawl driven by mass motorization, diminishing the significant role of railway transport in shaping spatial structures. In Europe, post-war population growth and consequent spatial expansion also led to the development of suburban areas. However, in many cases, this development was planned and oriented towards transit, as seen in examples like the Five Finger Plan in Copenhagen from 1947, the General Plan of 1952 in Stockholm, or the Île-de-France Regional Masterplan of 1965 in Paris (Knowles et al., 2020). Despite significant pressure from road transport in Western Europe, railway transport remained a significant factor shaping the space of suburban areas. This was demonstrated, for example, in studies conducted for the Barcelona Metropolitan Region between 1991 and 2006 (Garcia-López, 2012). However, different trends have been observed in CEE countries, especially after the socio-economic transformation since 1989. A negative feedback loop between the development of individual motorization and suburbanization led to the emergence of spontaneous forms of spatial development in suburban areas, poorly integrated with, and sometimes isolated from, railway infrastructure (Komornicki, 2011; Jurkowski, 2019).

2.2 The role of railway transport in historical urbanization in Poland

A case study of Poland presents a unique opportunity to trace back the long-term impact of railway transport on spatial development under varying geopolitical conditions. Notably, Poland is characterized by a well-developed railway network, with a significant portion of the analyzed lines constructed in the second half of the 19th century, within a period known in Polish history as the time of the partitions (Dylewski, 2022). During this period, the present territory of Poland was divided among three powers: the Kingdom of Prussia, the Russian Empire, and the Empire of Austria (see Section 3.1). As a result, the relationships between railway transport and land use in local scale in analyzed territories were shaping by diverse political decisions made by three distinct countries. Each of these territories pursued distinct visions for the development of railway transport, influencing the timing of construction, network density, and the location of stations and, finally, the level of integration of rail system with the existing settlement network (Fig. 1).

Firstly, the Kingdom of Prussia placed considerable emphasis on developing the railway network and connecting all towns, thereby stimulating urbanization processes. The railway development plan aimed to link major cities by 1845 and complete a full standard-gauge system by 1880, allowing for additional branching for local lines (Hornung, 2015). At railway junctions, numerous railway towns, such as Jaworzyna Śląska, Węgliniec, Krzyż Wielkopolski or Zbąszynek were established during this period (Urbaniak, 2018; Dragan, 2017; Balińska-Ciężki, 2018). As a result, the western and northern part of Poland up to current day is characterized by a dense railway network that is well-integrated with the settlement network.

Secondly, the eastern part of Poland under the dominion of the Russian Empire witnessed a significantly slower pace in railway network construction, due to the Russians' initial reluctance toward this issue. The Russian Empire's approach

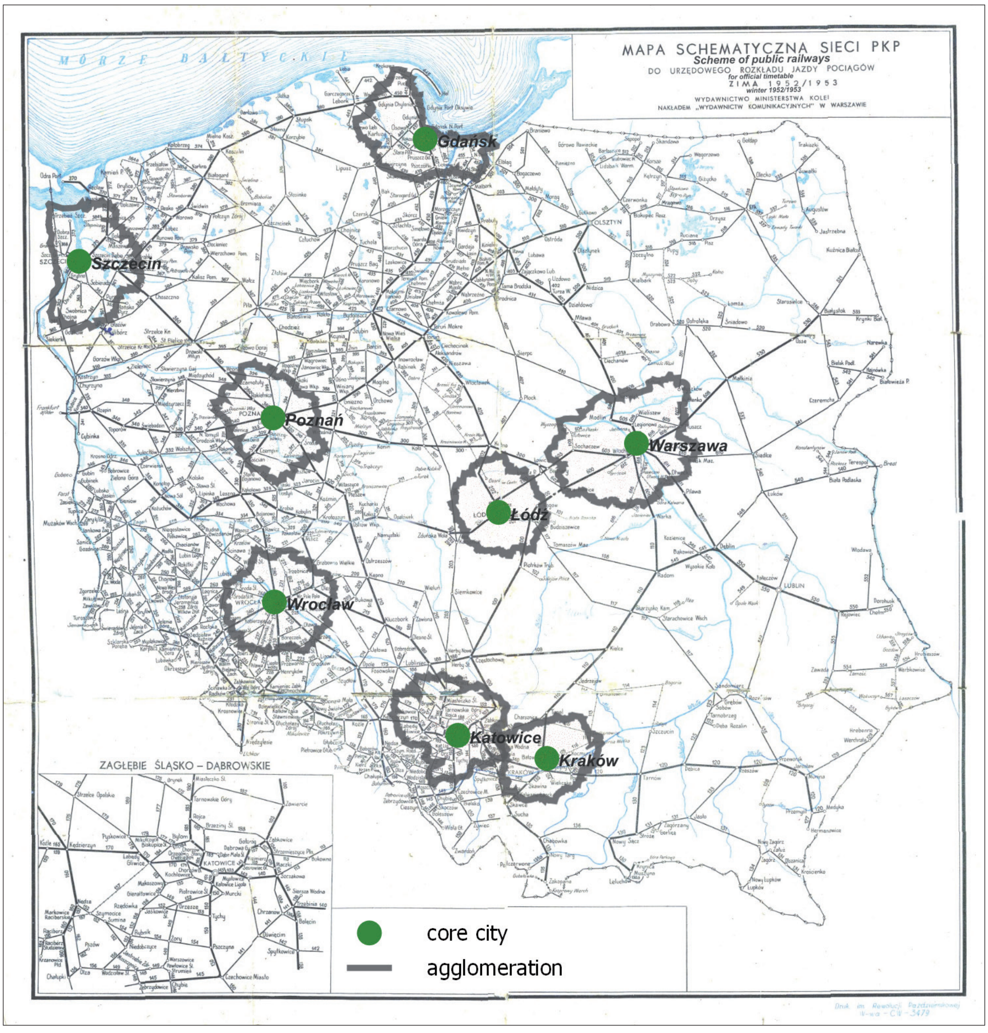


Fig. 1: Map of the railway network in Poland around 1950
Source: Authors' elaboration based on map provided by historical Ministry of Railways

to railway network construction prioritized military objectives, resulting in the placement of lines away from town centers and adopting configurations geared towards defense (Siddall, 1969; Jacolin, 2016). This strategic intent influenced the specific routes of later railways, reflecting the imperial concept of dispersing the network in sparsely developed areas, often bypassing towns (Dylewski, 2012). To this day, railway stations in many cities are located away from the city center (e.g. Ostrołęka, Tarczyn) and are often situated outside the city limits (e.g. Garwolin, Nałęczów).

Finally, the southern Polish territories, situated within the Empire of Austria, did not receive priority attention from the Habsburg Monarchy. Nevertheless, a reasonably well-integrated railway network was successfully developed, with the most significant investment directed towards the construction of the Transversal Line. This line, spanning the Carpathians longitudinally, connected various important towns such as Jasło, Gorlice, and Nowy Sącz, providing access to oil fields in the Carpathian Mountains (Lijewski, 1959). Another crucial investment involved a railway line connecting coal mines and steel mills in Ostrava, as well as salt and crude oil mines in Wieliczka and Bochnia (Kaim et al., 2020). On the one hand, topography presented additional challenges to investments; however, in many mountain towns, the railway infrastructure was relatively well-integrated into the settlement network. Railway lines often followed river valleys, serving as both the communication axis and the axis for the spatial development of built-up areas.

Previous studies conducted in the Polish context have primarily taken the form of network development monographs (Lijewski & Koziarski, 1995; Taylor, 2007; Jerczyński & Koziarski, 1992; Dylewski, 2022), recognizing the overall city-forming role of railways (Dragan, 2017; Urbaniak, 2018), and architectural perspectives of railway infrastructure (Balińska-Ciężki, 2018; Dominas, 2014). However, railway transport impact on morphological changes has never been clearly defined in a quantitative manner, nor do we know how areas located in different parts of Poland differ in this respect.

3. Materials and methods

3.1 Study area and time range

The study was conducted on the example of Poland, which serves as an interesting and representative case for Central and Eastern Europe, which has not been previously analyzed within such a timeframe. Authors have analyzed Poland's eight largest urban agglomerations: Gdansk, Katowice, Krakow, Lodz, Poznan, Szczecin, Warszawa, and Wroclaw (Tab. 1). In the case of Gdansk and Katowice, it should be noted that these agglomerations have a polycentric character (reffered to as Tricity and Silesia respectively), meaning they have several centers that serve as cores for spatial development. The suburban zone for selected urban agglomerations was defined as two rings of municipalities surrounding the core cities. Exceptions include the Warszawa agglomeration and the Katowice conurbation. For the Warszawa agglomeration, the boundaries were determined based on the criteria established by the Mazowieckie Biuro Planowania Regionalnego (2011) for the Warszawa Metropolitan Area. In the case of the Katowice conurbation, the boundaries were adopted according to the delimitation proposed by Krzysztofik (2007) and Krzysztofik et al. (2011).

The general temporal scope of the study spans from around the mid-19th century (the inception of railway lines) to the years preceding 1989 (the period of socio-economic transformation and the symbolic beginning of mass motorization in Poland). Establishing precise time frames in this study was unfeasible due to the dependence on the availability of cartographic materials, resulting in slight variations for individual years across the studied agglomerations (see Section 3.2). The adoption of this time frame is rooted in the authors' aim to minimize the influence of other factors, with road transport accessibility being the most notable among them. Consequently, the authors focused on analyzing the period when railways held a dominant role as the primary mode of transport. The year 1989 was chosen as the endpoint of the study period because it signifies not only the onset of socio-economic transformation in Poland, marking the beginning of mass motorization, a decline in railway transport, but also uncontrolled suburbanization. Thus, analyzing the period up to 1989 provides better insights into the decisive role of railway transport accessibility railway transport accessibility as a primary factor in shaping spatial development in the urban agglomeration areas. Despite the presence of other disruptive factors, the authors assumed that analyzing a large number of research units (localities) would help mitigate incorrect interpretations resulting from the influence of these factors

3.2 Data sources

The predominant obstacle in the investigation of spatial development in historical approach resides in data accessibility and comparability. Consequently, the imposition of data collection and standardization emerges as a requisite element for facilitating substantive analyses. To address these challenges, we compiled cartographic materials categorized into two groups. First, pre-1989 detailed topographic maps at the scales of 1:10,000 and 1:25,000, and general topographic maps at the scales of 1:50,000, 1:75,000, and 1:100,000 (see Appendix A: List of historical maps). Second, to streamline the georeferencing process, we also amassed contemporary (post-1989) vector-spatial open data (such as administrative boundaries, cadastral plots, and a database of topographic features) provided by the Head Office of Geodesy and Cartography in Poland.

Utilizing GIS software, specifically as detailed by Affek (2012, 2013), we executed the calibration of historical maps through a polynomial transformation, employing a minimum of four control points per map. The reference image for this process consisted of previously georeferenced Polish topographic maps

Agglomeration	Number of political affiliation changes	Number of localities	Number of railway stations
Gdansk agglomeration	8	1,031	72
Katowice conurbation	Eastern part: 6 Western part: 3 Eastern and Western part: 1	665	128
Krakow agglomeration	7	625	56
Lodz agglomeration	7	996	39
Poznan agglomeration	5	772	74
Szczecin agglomeration	4	472	80
Warszawa agglomeration	7	1,735	152
Wroclaw agglomeration	4	901	92

Tab. 1: Changes in political affiliation of analyzed urban agglomerations between 1800 and 1989
Source: Authors' calculations

from the 1965 system. Georeferencing procedures were conducted within the PL-ETRF2000 CS92 geodetic system (EPSG: 2180). The data collection process conducted in this manner enabled the acquisition of insights into historical urbanization processes, as well as information pertaining to railway infrastructure, which underwent digitization based on collected maps. Subsequently, a detailed analysis of the data was undertaken to identify the specific railway stations that were operational during the historical period. To maintain the topological correctness of the analyzed spatial objects, manually vectorized data based on historical maps were compared with contemporary spatial objects in order to maintain their geometric correctness in the appropriate geographical reference system.

3.3 Research design

The analyses were conducted for individual research units, referred to in the study as localities. Localities can be defined as settlement units or other settled areas, distinguished from other localities by a separate name (Statistics Poland, 2024), including housing estates, villages, or hamlets. The impact of railway transport was analyzed linearly in the Euclidean plane in the context of access to (1) each station located in urban agglomerations and (2) the eight central stations within the analyzed agglomerations. The first approach (1) made it possible to verify the overall impact of morphological changes of localities in the vicinity of stations located in various places within the agglomerations, while the second approach (2) made it possible to verify the impact of morphological changes in the context of gradual movement away from the central areas of the agglomerations.

The research design comprised several sequential phases, as illustrated in Figure 2. The first step involved identifying morphological changes during the analyzed period. To assess these changes, we employed a comparative approach utilizing topographic maps from the relevant years (refer to subsection 3.2. Data sources). Quantitative evaluations of morphology changes for all localities were conducted, focusing on spatial shrinkage (values ranging from – 3 to – 1), spatial stability (assigned a value of 0), and spatial growth (values ranging from + 1 to + 3).

The assessment involved employing the graph method (Szmytkie, 2017), whereby localities were observed and every morphological changes were quantitatively analyzed. For simplicity, the settlement network was treated as a set of edges and nodes, in accordance with the guidelines of graph methods. Edges represented a continuous line of buildings along a road, and nodes were either crossroads or individual buildings located more than 150 meters from others. The adopted categories of changes (values 1–3) directly corresponded to changes in graphs: the appearance of a new node, edge or the formation of a new cycle. The precise methodological approach of the morphological changes assessment is presented in Table 2 The assignment of values was applied to GIS project and represented by centroids in the central point of each locality.

Having established pre-1989 morphological changes, our focus shifted to evaluating the correlation between these changes and the proximity of railway stations. This analysis unfolded across two thematic threads. As previously mentioned, the first thread (1) involved the assessment of urbanization changes within aggregated buffers surrounding railway stations. Dissolved buffers were systematically generated around all railway stations, delineating 10 rings at 400-meter intervals, as illustrated in Figure 3. Subsequently, the count of localities and their associated morphological change values (ranging from – 3 to 3) were tallied within each ring. Average values were computed for each buffer, with values beyond the 11th ring aggregated into a

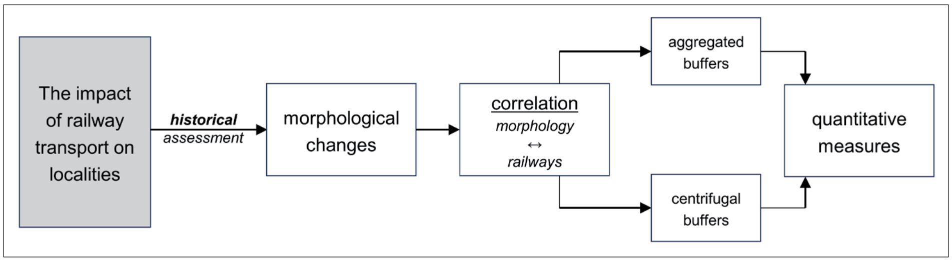


Fig. 2: Flowchart of the research procedure
Source: Authors' conceptualization

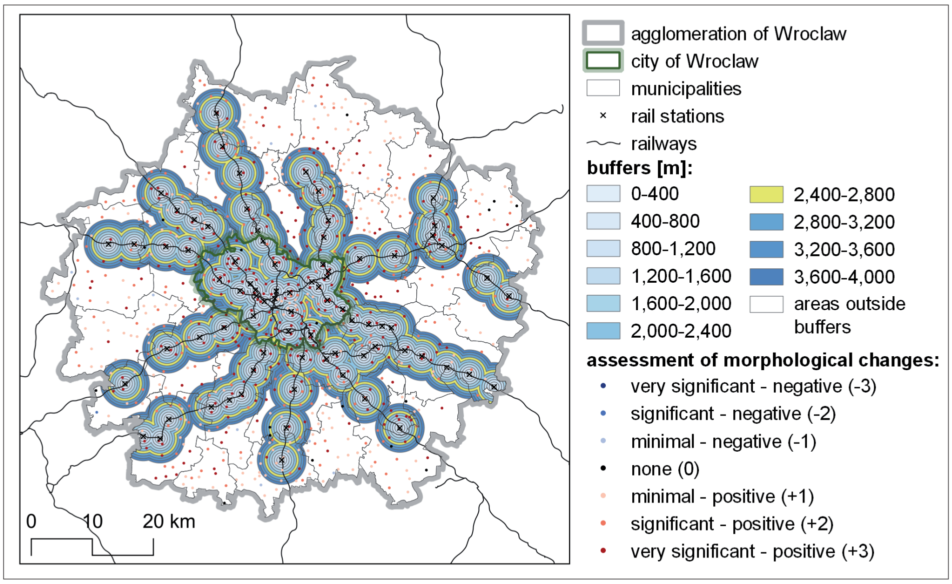
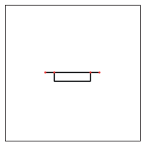
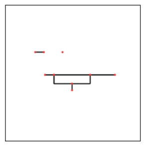
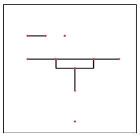
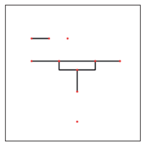
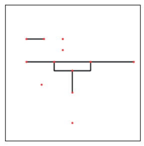
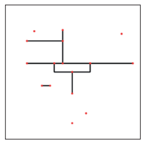
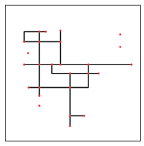


Fig. 3: Methodological approach to the analysis of spatial urbanization in aggregated buffers from railway stations on the example of Wroclaw agglomeration. Source: Authors' elaboration

Initial stage (example)	Type of morphological change		Rank	Description	Final stage (example)
	Negative (spatial shrinkage)	Very significant	– 3	Complete disappearance of the locality	
		Significant	– 2	Disappearance of a edge(s)	
		Minimal	– 1	Disappearance of single nodes Shortening the length of edges Disappearance of individual buildings without changing the graph structure	
	None	None	0	No changes between the original and final spatial structure	
	Positive (spatial growth)	Minimal	1	Appearance of single nodes Lengthening the edges Densification of the existing spatial fabric without changing the graph structure	
		Significant	2	Appearance of a new edge(s) (regardless of whether the edge is connected to the original graph or separated)	
		Very significant	3	Appearance of new edges and at least one cycle, which cause the original graph to become more complicated	

Tab. 2: Methodological approach of the morphological changes assessment
Source: Authors' conceptualization

single interval exceeding 4,000 meters. This meticulous approach enabled the discernment of the railway stations' impact on spatial development processes within the broader agglomeration structure.

In the second thread (2), we aimed to ascertain the general impact of railway transport on spatial morphological changes in the analyzed urban agglomerations. The basic issue was to investigate whether proximity to the central stations in each urban agglomeration correlates with higher dynamics of morphological changes or if such proximity is inconsequential in the agglomeration context. In this setting, the central stations are considered the primary destination or point of reference for measuring the accessibility of railway transport in the urban agglomeration. This was, therefore, an attempt to compare the overall accessibility offered by railway transport, understanding it as the possibility of reaching the main travel destination, rather than access to the railway itself (by the prism of railway station), which was examined in the previous stage.

To address this objective, we systematically divided the entire agglomerations into 5-km rings based on distance from the central station, as depicted on the example in Figure 5 (blue rings). Within each 5-km ring, the respective railway stations were identified, and centrifugal buffers with a radius of 4 km were delineated around them (refer to Fig. 4, burgundy buffers). In the centrifugal buffers, once again we quantified the values of morphological changes assigned to points within their boundaries. The chosen distance values for all buffers were selected with consideration for the size and scale of the analyzed urban agglomerations, as well as adhering to the principles associated with Transit Oriented Development (Dittmar & Ohland, 2012; Ibraeva et al., 2020).

To conduct this analysis, we applied different buffer distances, each functioning as an independent element. The largest buffers, set at a distance of 5 km (blue lines in Fig. 4), were utilized to divide the agglomerations into broader sectors and facilitate the search for railway stations within them. Given the necessity for greater data aggregation compared to analysis described in Figure 2, we generated a merged buffer with a distance of 4 km (represented by red polygons in Fig. 4) around each station within these sectors. The 4 km buffer corresponds to 10 individual buffers of 400 m each, as used in our previous analysis, thereby ensuring consistency and comparability across the applied distances.

For both analyses, we determined the maximum value of the individual buffers and examined their correlation with the average value of morphological changes, defined as the ratio of the sum of values to the number of localities. Simultaneously, we verified the statistical significance to ensure that the dataset was significant at a level at least of $p < 0.05$. This verification enabled us to establish the robustness and reliability of the observed correlations.

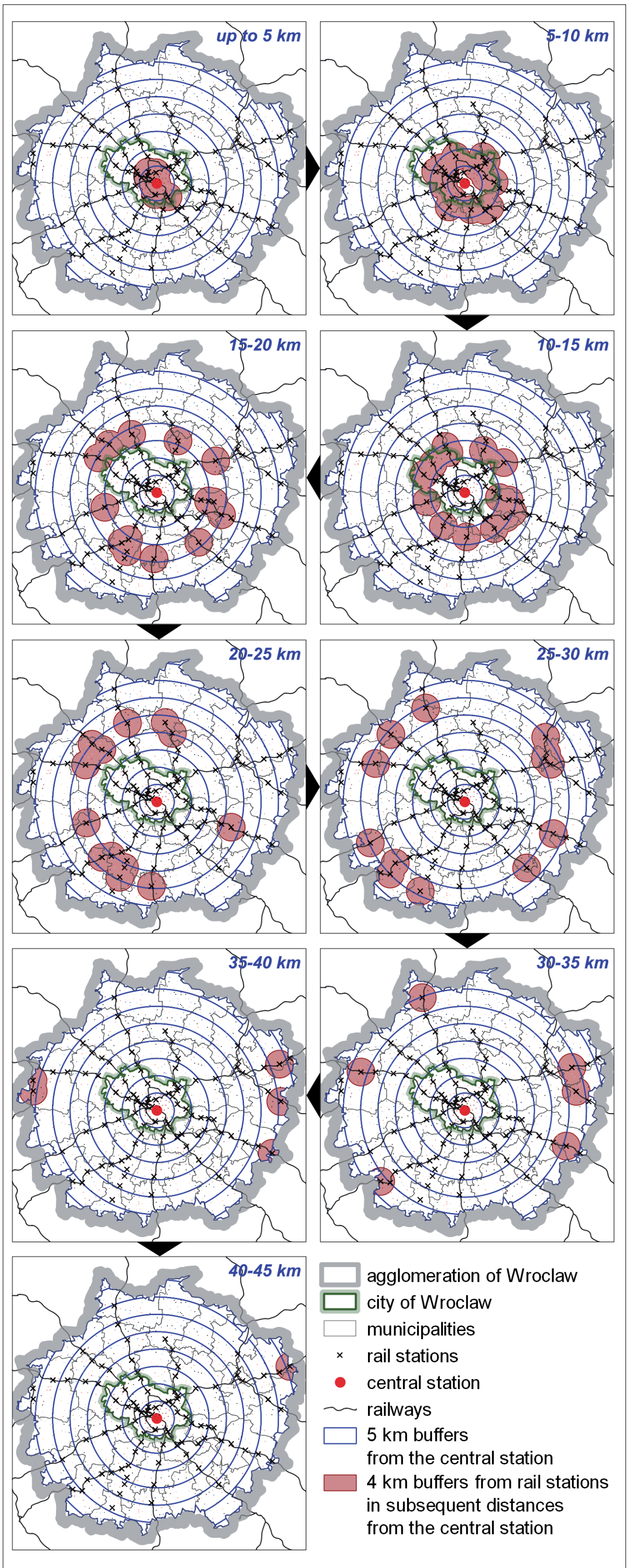


Fig. 4: Methodological approach to the analysis of spatial urbanization in the vicinity of railway stations depending on their location to the central station on the example of Wroclaw agglomeration
Source: Authors' elaboration

4. Results

In the first part of conducted analysis, the spatial distribution of localities characterized by varying intensities of morphological changes during the analyzed period was identified against the backdrop of railway transport accessibility zones. Accessibility was considered from both the perspective of access to the particular stations, and the perspective of access to the central railway station in the analyzed urban agglomeration, regarded as the most important destination for passengers. Therefore, the distance from every station in agglomerations and the distance from the central station were adopted as reference points to determine distance zones on the presented chart (Fig. 5).

The initial analysis for aggregated data indicated a general pattern, where there is an increase in the proportion of localities characterized by significant and very significant changes as the distance decreases to both all stations in aggregated buffers and central railway stations in centrifugal buffers. Significantly, it is evident that morphological changes of the greatest magnitude (+ 3) are predominantly observed within localities situated in close proximity to railway stations (especially within a radius of up to 1,600 meters) and localities in the immediate vicinity of the central station of each urban agglomeration (within a range of up to 10 kilometers). However, this relationship did not exhibit perfect regularity; it is more accurate to distinguish two distance zones grouping localities with more and less intensive dynamics of changes during the studied period.

In both groups, the highest share of localities with the greatest dynamics of morphological changes during the studied period was observed in the immediate vicinity of the railway station (within the 0–400 meters and 0–5 km zones from the stations and central railway station, respectively). It is worth noting that no distinct spatial regularities were found in the distribution of localities characterized by a negative morphological change during the studied period. These localities generally constituted a clear minority and were usually distributed relatively randomly across various distance zones from the railway station. The absence of changes during the studied period was typically influenced by local, specific factors, and their identification would require in-depth analyses. A noteworthy observation is the occurrence of morphological changes with minimal intensity (+ 1) at further distances from both nearest railway stations and the central railway station.

In the second part of the analysis, a comparison of results was conducted in division of eight urban agglomerations to identify variations in the examined relationship across different geographical areas. Considering the overall nature of the relationship between average morphological changes and distances to both all stations and central railway stations, a negative correlation was observed in all analysed urban agglomerations (Tab. 3). The results of the examined relationship do not vary across urban agglomerations located in different parts of Poland and shaped by different historical conditions. The value of the Pearson linear correlation coefficient ranged from – 0.40 to – 0.92 concerning the distance to railway stations and from – 0.61 to – 0.91 regarding the distance to the central railway station. It is essential to emphasize that in the majority of cases, the value of the Pearson linear correlation coefficient exceeded 0.75, which can be classified as a strong or even very strong correlation. Thirteen out of sixteen results were statistically significant at a significant level of $p < 0.05$, and fourteen out of sixteen at $p < 0.10$. The statistically insignificant results pertained to both cases of Krakow and centrifugal buffers in the case of Szczecin. These findings align with lower R values and the authors' initial intuition, which were influenced by local geographic condition; further developed later in the study.

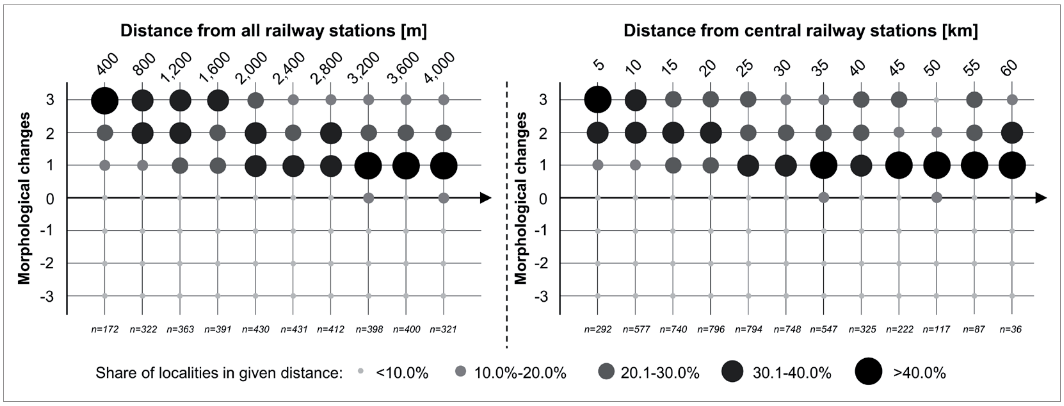


Fig. 5: The share of the number of localities characterized by a specific type of morphological changes within the adopted distance zones from all railway stations (left) and central railway stations (right) during the period of 19th century to 1989
Source: Authors' calculations

Agglomeration	R: distance to all railway stations	R: distance from central station
Gdansk	– 0.915	– 0.806
	0.000206	*0.002737*
Katowice	– 0.809	– 0.914
	0.004591	*0.000215*
Krakow	– 0.400	– 0.710
	0.252072	*0.073861*
Lodz	– 0.824	– 0.857
	0.003375	*0.01373*
Poznan	– 0.808	– 0.884
	0.004682	*0.003571*
Szczecin	– 0.652	– 0.612
	0.041062	*0.060037*
Wroclaw	– 0.978	– 0.788
	0.00001	*0.011658*
Warszawa	– 0.922	– 0.884
	0.000147	*0.000136*

Tab. 3: Pearson correlation coefficient (R) of average values of urbanization changes in the largest urban agglomerations in Poland (Notes: In italics the P-values at $p < 0.05$; in red background, the values are not significant at $p < 0.05$). Source: Authors' calculations

It is worth noting that almost in all the studied urban agglomerations, rail transport can be identified as a stimulant of morphological changes, although the correlation values varied across the different units. The impact of railway transport on morphological changes was most pronounced in the case of the Warszawa and Gdansk agglomerations, and weakest in the Krakow and Szczecin agglomerations. However, considering only the distance to railway stations, the highest value of the Pearson linear correlation coefficient was observed in the case of the Wroclaw agglomeration. These results do not provide sufficient grounds to claim that the political affiliation of individual agglomerations to different state entities had an impact on the strength of the studied relationship. High values were achieved by agglomerations that initially belonged to both the Kingdom of Prussia and the Russian Empire, which were characterized by differing approaches to railway development. Additionally, the study examines morphological changes within historically established railway stations. It can be concluded that the presence of a railway station directly influenced the intensification of spatial growth. However, the development of railways under various political regimes is a different issue that extends significantly beyond the scope of this study.

In the case of Wroclaw and Warszawa, a facilitating factor for integrating development with railway infrastructure was likely the absence of terrain barriers; both agglomerations are situated in low-lying areas. In the case of Gdansk, the influence of the coastline is evident, contributing to more linear spatial arrangements running parallel to the shoreline. The restricted capacity for expansion in other directions reinforced the correlation between urban development patterns and proximity to railway stations. The lowest and finally insignificant values in case of Krakow and Szczecin agglomerations is due to the specific geographic and historical conditions of these two cities. The density of the rail network in the surroundings of the two cities is significantly lower than in the other analyzed urban agglomerations, which influenced the low degree of spatial correlation between the rail network and the development of suburban villages. At the time of the formation of the rail network, Krakow was located on the border of the three partition Empires, that participated in the partition of Poland. In addition, the city is located in the Brama Krakowska, which separates the Carpathian Foothills in the south and the Krakow-Częstochowa Upland in the north. The relief of the land around the city determines the direction of the development of transportation lines in the river valleys, and north of Krakow, where suburban development has been most dynamic, is basically limited to a single train line (Line 8). Szczecin, on the other hand, is located in the delta of the Oder River and near Dąbie Lake, surrounded by extensive forest areas, making the settlement network sparse and underdeveloped. Moreover, the Pomeranian region, as one of the less developed regions within the borders of Prussia, experienced in the 19th and 20th centuries the phenomenon of Ostflucht, i.e. migration outflow to the more prosperous western areas of the Reich (Praszałowicz, 2006). In both cases, geographical and historical conditions could likely significantly disrupt the influence of railway transport on spatial development, as the settlement network had to adapt to the topography and land cover forms.

The distribution of average values of morphological changes in designated distance zones from the railway stations, as presented in Figure 6, enables the tracing of spatial regularities regarding the analyzed issue for each urban agglomeration in a more detailed approach. The charts revealed that, although there is a general trend of a gradual decrease in the average values of morphological changes during the period under study, its regularity was more or less noticeable depending on the examined urban agglomerations. The identified trend was nearly perfectly reflected in the Warszawa and Wroclaw agglomerations and quite clearly in the cases of the Gdansk and Lodz agglomerations. Although the relationship is somewhat less obvious in the remaining urban agglomerations, in all of the examined urban agglomerations, the highest values of average morphological changes were observed in one of the zones within a distance of up to 1,600 m from railway stations. This corresponds to the zone of stronger influence from the railway station identified in the first stage of the analysis. It is also worth noting the last collective distance category above 4,000 m, where significantly more localities are located than in the previous groups; however, these localities do not exhibit high dynamics of morphological changes during the studied period.

The distribution of the average value of morphological changes in defined distance zones from the central railway station showed relative similarity across the eight examined urban agglomerations (Fig. 7). The highest average values of morphological changes for six out of eight urban agglomerations were noted in the zone up to 5 km, while in the remaining two cases, it was the 5–10 km zone. In the subsequent zones, there was more or less regular decrease in the average morphological changes during the studied period. In general, the 20 km distance can be marked as a reference point beyond which a decline in the average intensity of morphological changes occurred, compared to subsequent zones, aligning with the overall trend identified in Figure 6.

5. Discussion

Spatial development in the long-term perspective depends on various factors, however, there is no doubt that one of the key factors stimulating this process on a local scale is transport, (Marsh & March, 1977; Frost, 2001; Whitehand, 2001; Garcia-López, 2012; Carr & Whitehand, 2014; Kasraian et al., 2016; Divall & Bond, 2017). The patterns identified in this study provide a quantitative complement to existing theories on the relationship between transport and land use, specifically in the context of rail transport. The influence of rail transport on surrounding areas should primarily be considered through the lens of opportunities provided by increased transport accessibility. This issue has been well-established in geographic theories that emphasize accessibility as a key factor in spatial development (Hansen, 1959), especially in the idea of new transit town (Dittmar & Ohland, 2003), enhancing the attractiveness of land, ultimately leading to more intensive land use (Alonso, 1964; Horner, 2004). The findings also show that the impact of rail transport decreases with increasing distance, which is strongly supported by gravity-based models, such as those by Lowry (1964) and Erlander and Stewart (1990). In terms of form, the identified urbanization processes align with the concept of sub-centers at railway stations described by Newman and Kenworthy (1996) in relation to the development patterns of transit cities during the late 19th and early 20th centuries.

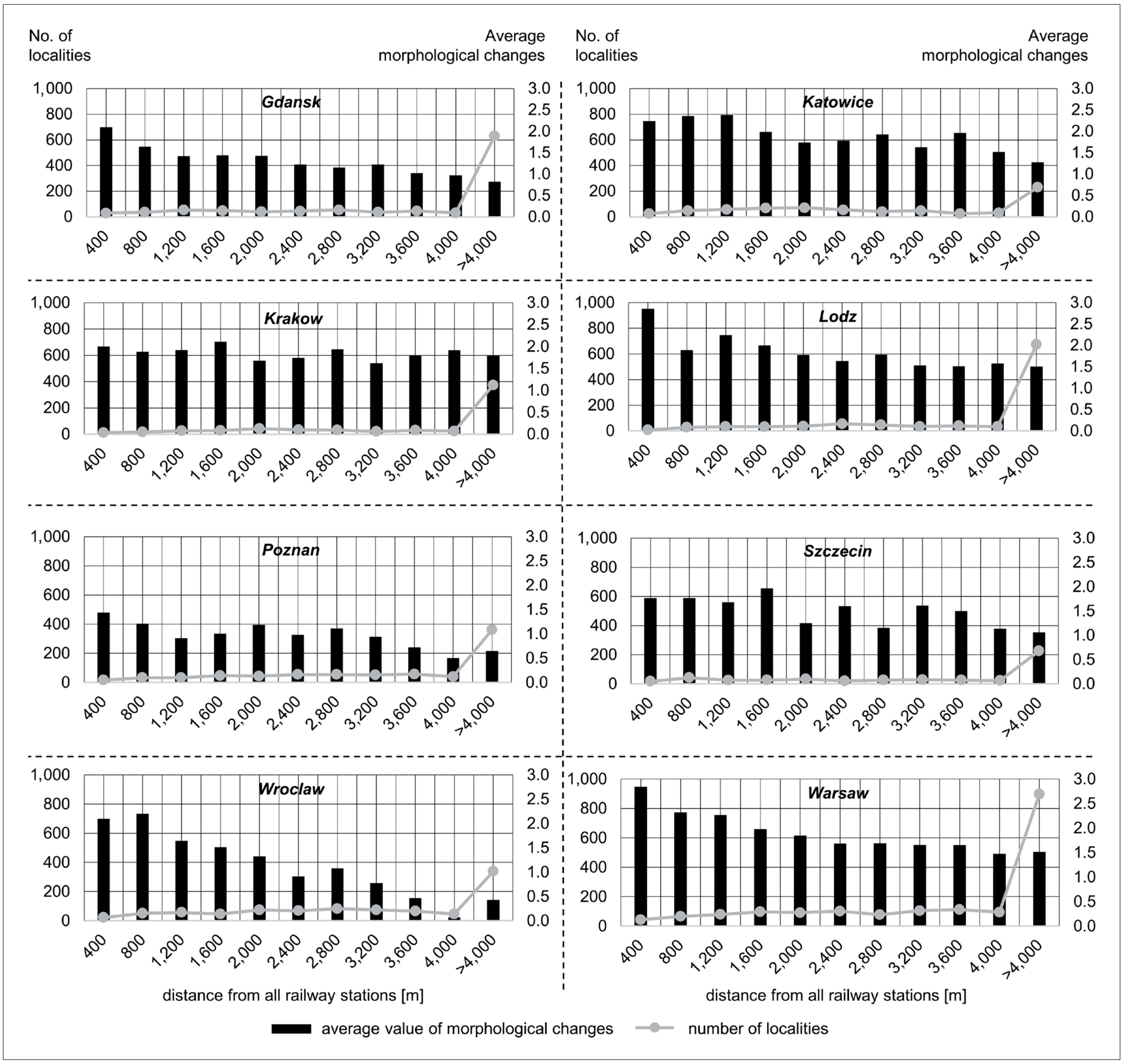


Fig. 6: Average values of morphological changes in relation to the distance from all railway stations in the largest urban agglomerations in Poland during the period of 19th century to 1989
Source: Authors' calculations and elaboration

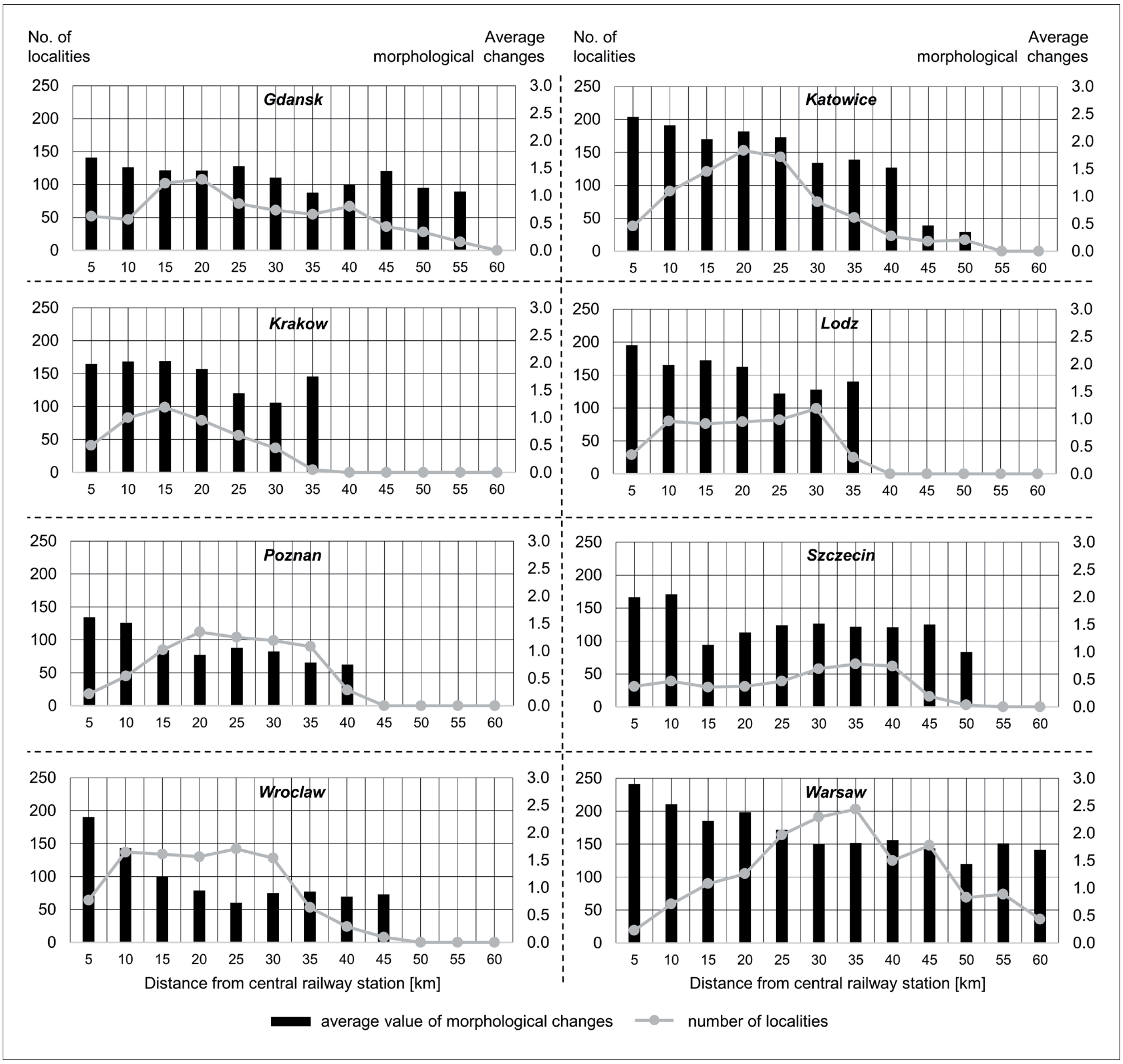


Fig. 7: Average values of urbanization changes in relation to the distance from central railway stations in the largest urban agglomerations in Poland during the period of 19th century to 1989
Source: Authors' calculations and elaboration

This study, in a quantitative and comprehensive manner, confirmed the general observations regarding the spatial development by railway transport in agglomerations of Central and Eastern Europe. These include, among others, the formation of commuter villages along the suburban light railway line (HÉV) in Budapest (Kovács & Tosics, 2014), summer cottages (dachas) near railway stations in Moscow suburbs (Brade et al., 2014), or mix-type buildings in Prague agglomeration (Sýkora & Mulíček, 1999).

The study also provides a significant complement to existing studies focused on the specific urban-forming role of railway transport, serving as a case study for individual towns and cities (Dragan, 2017; Urbaniak, 2018). Based on the conducted analysis, it can be clearly stated that the role of railway transport in shaping the settlement network had a more general nature and was not limited solely to towns located at junction points, but also within wider agglomeration scope. Although the spatial configuration of development near railway stations was not examined in this study, our findings align with the research of Knowles et al. (2020) and Banister (2012), who verified that railway development influences the formation of linear and radial development patterns. Our research confirms that historically, railway stations were focal points of spatial growth, particularly in the rings closest to these stations.

While the authors were unable to compare the influence of railway transport against other factors, the scale of analysis and the adopted period allow us to assert that the formulated dependencies are not coincidental. The authors analyzed over 7,000 localities in 8 urban agglomerations located in different parts of Poland within the timeframe before the mass motorization period. Through the utilization of a morphological approach to analysis, we were able to observe varying correlation values between spatial development and the presence of railways. These results likely stem from geographic and topographic factors such as hills, sea, rivers, and lagoons, rather than the density of the transportation network, shaped by the diverse investment strategies of historical annexationists in current areas of Poland.

The identified zones of stronger railway impact somewhat relate to distances recognized in the literature. In the case of the distance from the railway station (1,600 m), this suggests that over an extended time horizon, the influence of the railway station was typically twice as significant as it is currently, as indicated by the 800 meters according to the concept of Transit-Oriented Development (TOD) (Dittmar & Ohland, 2012; Guerra & Cervero, 2013). However, TOD is specified as a pedestrian travel distance, and even by considering the potential for increased service range through commuting by bicycle or scooter (popular during the socialist period in Poland), it seems to confirm the general rule. This zone was primarily influenced by the accessibility of railway transport, as 20 km corresponds to a travel time of 30 minutes, depending on the period, thus totaling approximately 1 hour for commuting to work – Marchetti's constant (Marchetti, 1994).

The noteworthy significance of the obtained results should be underscored within the current research landscape due to their quantitative relevance. However, it is essential to acknowledge certain limitations in our study, primarily pertaining to the analytical methodology utilizing simple distance buffers. While employing buffers of different distances could yield different outcomes, our approach was predominantly rooted in distance assumptions derived from TOD principles and observations of social behavior in the context of transport accessibility. Conversely, the utilization of simple buffers as an analytical parameter neglects the influence of topography and potential spatial barriers impacting the accessibility of analyzed facilities (Chrobak & Kryczka, 2018). The authors are aware of this limitation, yet its impact was minimized at the study's inception. It was posited that the analysis of morphological changes encompasses all developmental factors embedded in the spatial evolution of the localities. Spatial barriers and other constraints directly influencing development are inherently integrated into urbanization processes, thereby accounting for potential modifications arising from spatial accessibility. Opting for an alternative buffer type, such as employing network analysis tools on the road network, would redundantly consider the same factor, leading to the determination that employing a simple research tool was the most advantageous choice.

Despite its limitations, the study, however, confirmed the value of the long-term, historical perspective in the analysis of the relationship between transport and land cover. The conducted research may serve as a contribution to further studies on this issue, including comparisons with other countries, especially in CEE, or regarding the role of road transport as a stimulant of urbanization processes. Adopting a historical perspective is crucial for a better understanding of the railway network in Europe, especially considering that 70% of currently operational lines were established before the year 1900 (Martí-Henneberg, 2013). The recognition of the relationship between location of railway stations and spatial development from a historical perspective is crucial, especially in the context of future railway development, especially considering the growing interest in High-Speed Rail and Light Rail Transit investment and their potential impact on spatial and economic development. The absence of a comprehensive understanding of this mechanism in historical approach poses a barrier to understanding the nature of current processes in the context of analyzing the conditions for new investments.

The analyzed topic is quite limited in scope, and it is intertwined with additional considerations that would require further investigation in subsequent stages. This includes not only the accessibility to central stations but also their placement within the morphological setting. A significant supplement to the findings would also involve comparing the impact of railway and road transport on morphological changes. Moreover, the presented analysis provides a certain framework for conducting micro-scale analyses, such as case studies of individual areas. Future research could explore the geopolitical influences on urban morphology by comparing the impact of railway infrastructure in regions with varying degrees of political fragmentation. A promising direction for this investigation would be to include a European state with more stable boundaries during the same period, which could provide a valuable comparison to the current sample and help isolate the effects of political dynamics on urban development. The authors acknowledge many other conditions, i.e. economic development, internal migrations, as well as industrialization processes, as factors influencing urban form (van den Berg et al., 1982, Cross, 1990; Fujita & Mori, 1997); however, specific scope of this study is focused on spatial development in chosen largest agglomerations in Poland. This approach helps us to provide deeper insight into spatial transformation occurred in the historical period.

6. Conclusions

The conducted study provided quantitative confirmation that railway transport accessibility stimulates spatial development in their immediate area. Localities located closer to railway stations exhibit greater dynamics of positive morphological changes compared to those located farther away. Despite minor deviations in the case of Szczecin and Krakow, this confirmed both of the formulated hypotheses: that the intensity of morphological changes decreases with increasing distance from railway stations as well as from the central railway station within an urban agglomeration.

This generally dependency was observed in relation to all examined urban agglomerations, both in terms of accessibility to the stations as well as to the central station. Nevertheless, analyzed urban agglomerations showed differences in the strength of correlation and the regularity of the decrease in the value of morphological changes with increasing distance. However, contrary to the initial assumptions, it appears that variations in this regard were not strongly influenced by different historical and geopolitical conditions. It is likely that these differences were mitigated over time through the process of railway network integration. It should therefore be recognized that the railway was a universal factor resulting in spatial growth in its vicinity. Geographical factors, such as terrain features and hydrological networks, seem to be more significant in explaining the observed local variations. However, the authors only suggest potential explanations that require further verification. To definitively identify the influence of geographical factors, more detailed studies analyzing specific features of the natural environment are necessary.

The results should be associated with two perspectives of perceiving rail transport accessibility: access to the rail station from the place of residence and the possibility of reaching the core of the agglomeration, which serves as the main destination. From the perspective of detailed results of quantitative analysis, the study helped to identify approximate ranges for the highest intensity of morphological changes within these two specified perspectives. They refer to distances that have long served as reference points for many analyses, such as 800 meters in the concept of Transit Oriented Development, or the Marchetti constant when estimating the maximum commuting time to work. It is confirmation that even in such a long-term, historical perspective, certain universal regularities regarding the role of time and distance in transport and land use relationships can be identified.

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Appendices

Appendix A: List of historical maps

1. detailed topographic maps at the scales of 1:10,000, 1:25,000
   - maps of the Military Geographical Institute (WIG)
   - maps of the General Staff
   - Messtischblatt, Urmesstischblatt
   - Flötzarte des Oberschlesischen Steinkohlenbeckens
   - Bodenschäzungskarte
   - Sonderausgabe (German enlargement of maps of the Military Geographical Institute)
   - Festungs-Umgebungsplan von Krakau
   - German maps of the Russian partition
   - maps of the Workers' and Peasants' Red Army
   - Polish topographic maps in the 1965 system
2. general topographic maps at the scales of 1:50,000, 1:75,000, 1:100,000
   - maps of the General Staff
   - Deutsche Karte
   - Spezialkarte der Österreichisch – ungarischen Monarchie
   - British-American maps (Army Map Service – AMS)
   - Russian topographic map (scaled to 1:42,000)