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The impact of public transport accessibility on the Polish labour market – an econometric approach

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Abstract: This paper uses geographically weighted regression to examine the impact of transport accessibility on the registered unemployment rate. It utilises a transport accessibility index that was previously developed for municipalities in Poland. Analysis of three econometric models revealed that transport accessibility has a significant negative impact on the unemployment rate, which varies across the regions studied. The model using the average transport accessibility of municipalities within a given county showed a stronger relationship with the unemployment rate. This suggests that accessibility at the county level is more important than local accessibility. Furthermore, it was found that the type of municipality had no impact on the strength or direction of the examined relationship. The research confirms that public transport availability significantly influences unemployment levels in Poland, with considerable spatial variation in this relationship. The results emphasise the importance of considering the regional context of transport accessibility when devising anti-unemployment policies.

Keywords: transport accessibility, unemployment rate, geographically weighted regression, transport exclusion, spatial mismatch

JEL codes: C21, R40, O18

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1. Introduction

Public transport plays a key role in ensuring mobility and access to services and employment opportunities. Following the political transformation in Poland in 1989, the transport system underwent significant changes which, in many cases, contributed to a deterioration in accessibility, particularly in rural and peripheral areas. As Dubicki (2019) points out, the state's withdrawal from most activities in the transport sector led not only to a reduction in bus connections, but also to the elimination of some passenger rail connections. This resulted in the phenomenon of transport exclusion deepening in Poland. Wolański, Mrozowski and Pieróg (2016) emphasise that negative changes to public transport outside cities result not only from economic changes, but also from the lack of coherent transport policies that take into account the needs of residents of less urbanised areas.

Transport exclusion is one of the manifestations of the broader phenomenon of social exclusion. It involves limiting access to public transport and can lead to marginalisation in various aspects of social and economic life. A lack of, or limited access to, transport hinders access to key services such as work, education and healthcare. As Lucas (2012) points out, transport exclusion is a complex phenomenon that can stem from individual factors, such as age, disability or low income, as well as structural factors, such as inadequate transport infrastructure or the inefficient organisation of transport services. In Poland, this issue is particularly evident in rural areas, where access to public transport is often limited, forcing residents to use their own cars and generating additional costs that exacerbate social inequalities. These mobility restrictions are especially challenging for groups without access to private cars, including the elderly, young people, and children.

Previous studies of transport exclusion in Poland have mainly focused on the local level, relying primarily on survey data and interviews with residents. While this approach has allowed for an in-depth understanding of specific transport accessibility problems in particular municipalities or regions, it has had limited scope and has not always allowed the results to be generalised to the whole country. Nationwide studies conducted to date have primarily analysed transport accessibility and attempted to identify areas at risk of transport exclusion. However, despite significant progress in identifying such areas, there has been little research into the impact of transport exclusion on key socio-economic indicators such as the unemployment rate.

This study aims to address this issue by examining the impact of public transport availability on the labour market in Poland. Geographically weighted regression (GWR) will be used to examine the spatial variability of this relationship and identify areas of Poland that could benefit most from increased accessibility. The study's goal is to provide new, relevant insights that contribute to a better understanding of transport exclusion and the development of more effective transport policies.

First, a transport accessibility index will be developed for each municipality in Poland. This will form the basis for analysing variations in transport accessibility at a local level. Next, three GWR models will be constructed based on this index and other variables. The first model will examine the relationship between local accessibility and unemployment within each municipality. The second model will consider the regional context, analysing the relationship between average accessibility in the county and unemployment in individual municipalities. This will enable us to establish whether transport accessibility is important not only at the local level, but also within the broader regional transport system. The third model will assess whether this relationship differs between urban and rural areas by using interaction variables for municipality types.

The following research hypotheses were formulated based on the objective of the study and refer to the expected results of the three designed regression models:

- Local models using GWR better describe the relationship between transport accessibility and unemployment than local models based on the least squares method (OLS);
- The relationship between the transport accessibility variable and the unemployment rate is significant and negative;
- The relationship under study varies greatly geographically, with transport accessibility being more important in certain areas;
- The quality of the wider regional transport network is more important than individual transport accessibility in a municipality;
- Transport accessibility is more important in rural areas, while in cities this relationship is weaker.

The paper will consist of four sections. First, the literature relevant to the paper's topic will be discussed (Chapter 2), with a focus on works analysing the relationship between accessibility and unemployment, both on local and global levels. It will also present Polish works on transport exclusion and studies examining regional transport accessibility in Poland. Chapter 3 will describe how the transport accessibility index was prepared and the methods that will be used to analyse the relationship under study. The fourth chapter will present the constructed accessibility index and conduct a preliminary analysis of its relationship with the unemployment rate in municipalities. Chapter 5 will present the results of the econometric analysis, forming the basis for answering the study's key questions. The paper finishes with the summary of the study's most important findings.

2. Literature review

2.1. Relation between accessibility and employment on the local level

John F. Kain (1968) was the first to highlight the link between accessibility and employment. In his work, he examined how segregation in the housing market impacted the employment of black people in American cities. Kain argued that higher unemployment among Black people was due to factors other than racial discrimination alone. By analysing empirical data from Chicago and Detroit, he showed that housing market segregation distanced the black population from jobs, thereby reducing their employment prospects. This concept, later termed the Spatial Mismatch Hypothesis (hereafter SMH), formed the basis for numerous empirical studies linking unemployment to limited job access.

Ihlanfeldt and Sjoquist (1990) analysed the differences in employment rates between black and white young people in Philadelphia. Their research revealed a significant correlation between proximity to job opportunities and employment prospects among young people. The results suggested that the Black population lives in areas with limited access to jobs, which may account for much of the disparity in employment between these groups. Similar conclusions can be drawn from Raphael's (1998) research, which analysed the San Francisco area in terms of the SMH. He argued that neighbourhoods inhabited by Black people are characterised by weak or negative employment growth. The study found that differences in access to areas with high employment growth explain 30–50% of the disparity in employment levels between black and white youth.

Initially, the work on the SMH centred on analysing the discrepancy between workers' residences and places of employment. Accessibility to jobs was primarily measured in terms of the physical distance and travel time between locations. Subsequent studies built on this, considering the role of public transport. Sanchez (1999), for example, analysed the relationship between public transport accessibility and employment in Portland and Atlanta. Using spatial data, the author examined access to public transport in different areas of the cities. This data was then used in a regression model to estimate the impact of public transport accessibility on the labour force participation rate. The results indicated that accessibility significantly impacted the average labour force participation rate in both cities.

Research on the impact of accessibility on employment began with an analysis of the effects of racial segregation. Over time, however, researchers became interested in the impact on other marginalised social groups. Ong and Houston (2002) analysed the effect that access to public transport had on the employment of women receiving social assistance in Los Angeles. Their study revealed that improved access to public transport increases this group's likelihood of being employed. Yi (2006), focusing on the city of Houston, demonstrated that accessibility of jobs by public transport is important for employment levels, particularly among low-income individuals. The author argues that high unemployment among ethnic minorities may result not only from racial discrimination, but also from reduced mobility stemming from poorer access to public and private transport.

As in the United States, a number of studies have been conducted in Europe analysing the impact of job accessibility on employment, particularly among disadvantaged groups in the labour market. Korsu and Wenglenski (2010) investigated the idea that unemployment among the least privileged social groups is partly due to spatial factors. Their research, conducted in Paris, showed that living in the poorest districts of the city, and more broadly in areas with lower accessibility, can increase the risk of long-term unemployment. The results revealed that a significant proportion of low-skilled workers in Paris experienced significantly below-average job accessibility, negatively affecting their employment prospects. Matas, Raymond and Roig (2010) examined the effect of access to public transport on employment prospects for women in Barcelona and Madrid. Their findings suggest that poor job accessibility negatively affects employment prospects, particularly among those with lower levels of education.

An interesting approach to studying the impact of accessibility is to conduct empirical research analysing the effects of the construction of new transport infrastructure. Sari (2015), for instance, examined the impact of a tram line being built in the Bordeaux metropolitan area, which connected previously isolated neighbourhoods with the city centre. Better access to employment areas led to an overall fall in unemployment in the city. However, areas in the vicinity of the new tram stations experienced a significantly greater decline in unemployment. These findings imply that investing in public transport can help reduce socio-economic inequalities by providing access to higher-paid employment opportunities.

A similar analysis was conducted by Rotger and Nielsen (2015) in Copenhagen. They examined the impact of constructing a new metro line connecting the southern part of the city with the centre. The results of the study suggest that the investment had a negligible impact on employment rates among residents in areas near the new stations. However, analysis of the data showed that wages increased as residents moved to more lucrative jobs in the city centre. Similarly, Åslund, Blind and Dahlberg (2017) found no significant relationship between the development of transport infrastructure and the employment of the people surveyed when analysing the effects of the introduction of a new suburban railway line in Sweden. This suggests that improved transport accessibility alone may not be a sufficient factor in determining changes in the labour market.

2.2. Relation between accessibility and employment on the global level

In the context of the United Kingdom, Johnson, Ercolani and Mackie (2017) examined whether differences in employment levels could be explained by the quality of the local transport network across the whole of the UK at a local level. Using data from the 2011 English census, they developed an econometric model to investigate this. Areas were divided according to population density in order to determine whether accessibility is as important in large cities as it is in rural areas. The results indicate that areas with shorter public transport commuting times are characterised by higher employment levels. They found that a 10% difference in bus travel time between areas corresponded to a 0.13% change in employment levels in rural areas and a 0.3% change in the most urbanised areas.

Research in Sweden also confirms the existence of a link between transport accessibility and employment levels. In their work, Norman, Börjesson and Anderstig (2017) focus on the relationship between changes in unemployment and changes in labour market accessibility. They use a measure of accessibility based on a national transport model that considers consumer behaviour, all modes of transport and various components of travel time. This makes their analysis more precise than previous studies. They demonstrate that improving accessibility to the labour market leads to a reduction in unemployment, particularly among those with lower levels of education.

Bastiaanssen, Johnson and Lucas (2022) conducted a nationwide study in the United Kingdom. Unlike an earlier study by Johnson, Ercolani and Mackie (2017), this study examined the impact of accessibility on the probability of individual employment rather than on overall employment levels. This approach enabled the researchers to examine the impact of accessibility on specific social groups. The results suggest that improving transport accessibility increases employment opportunities, albeit only in certain circumstances. The greatest beneficiaries of better accessibility are people living in cities with low car ownership rates, young people, and those with lower levels of education. The most significant impact of accessibility on employment opportunities is observed in the lowest-income areas, which also have the poorest transport accessibility.

2.3. Studies on transport accessibility vs unemployment in Poland

There are no statistical studies in Poland linking transport accessibility to employment. However, there are many studies that analyse transport accessibility in specific regions of the country in detail. While these studies identify areas with poor transport accessibility, they do not analyse its effects. Rosik et al. (2017), however, carried out such an analysis as part of a study by the Institute of Geography and Spatial Management of the Polish Academy of Sciences. In this study, they created an index to determine the transport accessibility of municipalities in Poland. This index was developed using timetable data and takes various means of transport and the possibility of changing between them into account. Rosik et al. (2018) carried out a similar analysis of transport accessibility on a national scale, focusing on bus transport. This study assessed the accessibility of municipalities taking transfers into account and compared it with individual transport, highlighting significant spatial disparities.

Another study analysing transport accessibility in Poland was presented by Stępniak et al. (2017). In their study, the researchers focused on modelling accessibility and analysing spatial differences in access to various public services. They used GIS data and travel time modelling methods to accurately determine these differences between regions. The study revealed significant disparities in access to public services such as education, healthcare and administration between Polish regions, particularly in peripheral areas. The authors emphasised the importance of adapting spatial policy to the specific characteristics of individual service sectors and local conditions. Similarly, Guzik (2003) analysed accessibility in relation to key services, focusing on access to educational institutions. They demonstrated spatial variation in accessibility to schools, emphasising the importance of location and transport infrastructure.

In addition to nationwide studies, many works analyse transport accessibility on a regional and local scale. Guzik and Kołoś (2021) and Parol (2021), for example, conducted studies focusing on specific regions of Poland. Both studies examined accessibility between smaller towns and regional centres, where services and jobs tend to be concentrated. The results of these studies confirmed that transport accessibility varies significantly depending on proximity to major urban centres and road and rail infrastructure. Guzik and Kołoś (2021) highlighted the particularly challenging circumstances faced by smaller towns situated outside major transport corridors, while Parol (2021) emphasised the discrepancy between public transport services and the actual requirements of residents. Both studies emphasise the need for regional interventions and for transport planning to adapt to functional spatial links.

The issue of the effects of insufficient transport accessibility is addressed in the extensive literature on social exclusion in Poland. Key studies include an article by Zmuda-Trzebiatowski (2016), which analyses transport exclusion in terms of service accessibility and forced motorisation, and a study by Kaczorowski (2019), which documents the specific effects of eliminating bus connections in villages and small towns. While the former author focuses on the systemic determinants of the problem, the latter illustrates its real-life impact on residents, ranging from difficulties in commuting and attending school to the degradation of local communities. Together, these works reveal the theoretical foundations and practical manifestations of transport exclusion in Poland.

There is a lot of research on the effects of transport exclusion. However, these studies tend to be local and are mainly based on analyses of survey data or interviews with residents. For instance, Ciechański (2020) examines the consequences of the sudden withdrawal of the primary transport company from the Komańcza region; Orchowska (2022) explores various facets of transport exclusion from the viewpoint of inhabitants of specific towns in the Mazowieckie Province; and Szczecina and Ziółko (2023) investigate the ramifications of transport exclusion in Nowy Sącz County.

In recent years, an increasing number of studies have examined the effects of transport exclusion on specific social groups. For instance, Białobrzeska's (2022) research on the mobility issues faced by older people highlights limited access to healthcare and social isolation among seniors in regions with inadequate transport infrastructure. A UNICEF report edited by Komornicki (2024) also provides a comprehensive overview of the problem, documenting the scale of transport exclusion of children and young people in Poland and emphasising the differences between rural and urban areas.

Yet there is a dearth of studies in Poland that examine in detail the relationship between transport accessibility and unemployment. The only similar study is that by Beim et al. (2014), which analysed the impact of accessibility on various socio-economic development indicators, including the unemployment rate. However, this study was limited to the Wielkopolskie province. Furthermore, the analysis only used correlation coefficients and simple linear regression, which are less effective than GWR models in studying spatial relationships. While there are studies examining local unemployment using GWR (e.g. Lewandowska-Gwarda, 2018), these do not consider transport accessibility as an independent variable.

3. Methodology

3.1 Development of the accessibility index

The transport accessibility index was created for each municipality and city at the county level in Poland in order to assess the quality of local public transport. The index is intended for examining the relationship between transport accessibility and unemployment at the municipal level.

3.1.1 Data for the index

The index was developed using data from the Local Data Bank of Statistics Poland for 2023. Data from the passenger exchange analysis carried out by the Railway Transport Office and the list of passenger transport operators compiled by the General Inspectorate of Road Traffic were also used. Data at municipal, county and provincial levels were used to construct the indicator. The indicator is composed of several variables:

- Number of bus stops in the municipality per square kilometre (*PA*)

Data on the number of stops and the municipality's area come from the Local Data Bank. Dividing the number of stops by the municipality's area allows us to determine the density of the transport network and, indirectly, the distance to the nearest stop for residents. Although the number of stops per capita was considered, this distorted the value of the indicator, artificially inflating the result for sparsely populated municipalities and underestimating it for densely populated ones. Due to a lack of data, the frequency of buses at stops and the number of lines at specific stops are not considered, meaning all stops are treated as identical.

- Municipal transport expenditure per capita (*WT*)

Data on municipal transport expenditure comes from the Local Data Bank. The quality and volume of public transport in a municipality can be reflected by dividing municipal expenditure in the transport sector by the municipality's population. Higher transport expenditure may indicate a larger number of drivers and vehicles employed, as well as investment in transport infrastructure development. To avoid overestimating the indicator in the case of one-off large investments, expenditure has been averaged for the years 2014–2023.

- Number of carriers registered in the province per 100,000 inhabitants (*PZ*)

The data on the number of carriers was taken from the list of entrepreneurs providing passenger transport services, which was compiled by the General Inspectorate of Road Traffic. Data on provincial populations comes from the Local Data Bank. It is assumed that carriers provide their services in multiple municipalities, and sometimes even in multiple provinces. The number of carriers in a province indicates the potential supply of transport services and the variety of transport options available to the population within and outside the province.

- Transport network density in the province (*GS*)

The density was obtained by dividing the number of transport lines in the province by its area in square kilometres. Data on the number of transport lines and provincial areas come from the Local Data Bank. The density of the transport network reflects the degree of its development. This variable considers both the number of connections and the density of the transport network. A higher value indicates that the province has a more extensive network of connections. Even if transport lines do not pass through a municipality directly, the number of transport lines in the province affects its transport accessibility, as residents can use transport in neighbouring areas.

- Rail network density in the county (*GK*)

The density was obtained by dividing the number of railway stops in the county by its area in square kilometres. The number of stops was obtained from a passenger exchange analysis carried out by the Railway Transport Office. Data on provincial areas come from the Local Data Bank. The density of the railway network in the county reflects the intensity of the regional railway infrastructure, which indirectly affects transport accessibility in municipalities. A higher density of railway stops indicates better coverage of the county by the transport network, increasing the mobility of residents both within and beyond the region. Even if a given municipality has no railway stops, the presence of stops in other municipalities in the county facilitates access to transport. While this indicator does not consider the location of stops or connection frequency, it provides a rough assessment of the state of rail transport in the region and its impact on residents' mobility.

3.1.2 Construction of the indicator

The transport accessibility indicator was constructed by aggregating the individual values of the above variables for each municipality in Poland. This process consisted of three stages: data collection and preparation; variable normalisation; and variable aggregation using appropriate weights. The methods used to develop the indicator and prepare the data are based on the OECD's (2008) recommendations for constructing composite indicators.

To enable comparability between variables with different ranges, each variable was normalised using percentiles. This involved assigning each variable its percentile position in the empirical distribution, reducing the data to a common scale of 0–100. Here, 0 corresponds to the smallest variable value in the set and 100 to the largest. This solution is advantageous because it is resistant to outliers and enables variables with different scales to be easily compared, facilitating their aggregation into a single indicator. Additionally, percentile transformation preserves the rank order of the data, ensuring the resulting indicator accurately reflects relationships between units.

The exact mechanism of variable normalisation can be best illustrated using the example of several characteristic municipalities. During the period under study, the urban municipality of Bolesławiec had approximately seven bus stops per square kilometre, a very high figure that gave this municipality a variable value of 99.47. By contrast, the rural municipality of Bolesławiec had just 0.339 stops per square kilometre — slightly below average — giving it a variable value of 39.35. Another municipality in the same county had a bus stop density of 0.086, a low result giving a variable value of 3.07. Five more variables were calculated in this way for all municipalities and then summed with the appropriate weights, as shown in eq. 1:

$$DT_i = 0.5PA_i + 0.3WT_i + 0.15PZ_i + 0.15GS_i + 0.3GK_i \quad (1)$$

The weights assigned to the individual variables reflect their importance for overall transport accessibility. The variable concerning the number of bus stops was assigned the highest weight, as this variable most accurately reflects the state of public transport in the municipality. A slightly lower weight was assigned to the variable concerning municipal transport expenditure because it only indirectly reflects the state of transport. Nevertheless, it is a municipality-level variable and more accurately reflects differences between municipalities. The same weight was given to the variable concerning the county's railway network. While this variable clearly shows the level of transport infrastructure in the county, access to railways may vary between municipalities within the same county. This is why it was given a lower weight than the variable concerning the number of bus stops. The lowest weight was given to the variables concerning the number of carriers and transport lines in the province. As both variables are based on provincial-level data, they may not accurately reflect the situation at a municipal level. Nevertheless, these variables directly demonstrate the differences in potential transport options available to residents of different provinces, making them an important element in assessing a municipality's local transport accessibility.

After aggregating the variables, the index was normalised using percentiles to make the results easier to interpret, in a manner analogous to that previously presented for individual variables. The transport accessibility index also has values ranging from 0 to 100, based on percentiles: 0 represents the municipality with the worst transport links, and 100 represents the municipality with the best transport links. These values correspond to the percentile at which a municipality's transport links are located. For example, a municipality with an index value of 60 has better transport connections than 60 percent of municipalities in Poland.

3.2 Regression model

Econometric methods were employed to analyse the effect of public transport accessibility on the unemployment rate, based on data from the Local Data Bank from 2023 at the municipal level. The dependent variable in the study is the proportion of the working-age population in the municipality that is registered as unemployed. The analysis focuses on the previously constructed transport accessibility index as the main independent variable. A key element of the analysis is to examine how this variable affects the unemployment rate. It is expected that there will be a negative relationship between accessibility and the unemployment rate. Control variables were also included in the model to avoid the error of omitting important variables: demographic variables (percentage of the working-age population and percentage of the population with higher and higher or secondary education) and economic variables (municipality income and investment expenditure per capita), as well as a division into types of municipality (urban - base level, urban-rural and rural). However, these control variables will not be analysed in detail. These variables were selected based on recommendations from literature examining local unemployment variation in Poland (Ciżkowicz, Kowalczuk & Rzońca, 2016; Ingham, Ingham & Herbst, 2011).

The analysis employed a Geographically Weighted Regression (GWR) model, which was introduced by Brunsdon, Fotheringham and Charlton (1996), to analyse spatial heterogeneity. Unlike ordinary least squares (OLS) regression, which assumes global relationships between variables, GWR enables regression coefficients to be estimated locally for each observation. In the GWR model, the regression function takes the following form:

$$y_i = \beta_{i0} + \sum_{k=1}^{m} \beta_{ik} x_{ik} + \varepsilon_i \quad \text{(Brunsdon, Fotheringham \& Charlton, 1996)}, \qquad (2)$$

where y_i is the dependent variable at location i; x_{ik} is the k-th independent variable at location i; m is the number of independent variables; β_{i0} is the intercept at location i; β_{ik} is the local regression coefficient for the k-th independent variable at location i; and ϵ_i is the random error at location i.

The estimator in this model takes the form:

$$\beta_i = [X^T W_i X]^{-1} X^T W_i Y \qquad \text{(Brunsdon, Fotheringham \& Charlton, 1996)}, \qquad (3)$$

where W_i is a matrix containing geographical weights w_{ij} assigned to observations in location j for regression in location i on the main diagonal, and values equal to 0 on elements outside the diagonal. The method used to assign weights to individual observations is of key importance in the model. In GWR models, greater weight is assigned to observations closer to the point under analysis and less weight is assigned to observations that are further away. These weights are calculated using a kernel function that considers the distance of points from the location in question and the bandwidth, which determines the range of points taken into account in the regression (Lu et al., 2014). Various kernel functions can be used; this study used the bi-square function, which has the following form:

$$w_{ij} = \left[1 - \left(\frac{d_{ij}}{b}\right)^2\right]^2 \qquad \text{(Brunsdon, Fotheringham \& Charlton, 1996)}, \qquad (4)$$

where d_{ij} is the distance between the observed point j and the point i for which we perform regression; parameter b is the bandwidth.

Selecting the optimal bandwidth value is crucial in GWR modelling. This value is determined using LOOCV (leave-one-out cross-validation), whereby different bandwidth values are tested and the one that provides the best model fit is selected. The bandwidth can be either fixed, taking into account points at a specific distance from the location under study, or adaptive, in which case a specific number of neighbours is selected. The adaptive method is more useful when the density of observations varies spatially. It will therefore be used to construct a GWR model based on municipalities in Poland, where the density is not uniform across all regions.

Three GWR models will be analysed. The **first** model will take the form:

$$SB_i = \beta_{i0} + \beta_{i1}DT_i + \beta_{i2}D_i + \beta_{i3}I_i + \beta_{i4}LP_i + \beta_{i5}WW_i + \beta_{i6}WS_i + \beta_{i7}MW_i + \beta_{i8}W_i + \varepsilon_i, \quad (5)$$

where β_{i0} is a free term, β_{ik} are successive regression coefficients in the municipality i. SB_i is the registered unemployment rate in municipality i, DT_i is the value of the accessibility index of a given municipality i, D_i is the income of a given municipality i per capita, I_i is the value of investment expenditure in enterprises in the county per capita for a given municipality i, LP_i is the percentage of the working-age population in municipality i, WW_i is the percentage of the population with higher education in municipality i, WS_i is the percentage of the population with secondary or higher education in municipality i, MW_i and W_i are binary variables for urban-rural and rural municipalities, respectively, and finally ϵ_i is a random element for municipality i.

The **second** model will differ only in the variable concerning accessibility (variable DT_i) – it will use a variable determining the average transport accessibility of the county in which a given municipality is located. Comparing these models will answer the question of whether transport accessibility in a broader regional context is as important as, or more important than, local accessibility. Using the average transport accessibility of the county may better reflect actual conditions, since residents often work outside their municipality and use public transport available throughout the county:

$$SB_i = \beta_{i0} + \beta_{i1}DP_i + \beta_{i2}D_i + \beta_{i3}I_i + \beta_{i4}LP_i + \beta_{i5}WW_i + \beta_{i6}WS_i + \beta_{i7}MW_i + \beta_{i8}W_i + \varepsilon_i, \quad (6)$$

where DP_i is a variable that determines the average accessibility of municipalities within a given county. The other variables remain the same as in the model (5).

The **third** model will introduce interaction variables between transport accessibility (variable DT_i) and municipality type (variables MW_i and W_i), enabling us to assess whether the impact of accessibility differs depending on the degree of urbanisation:

$$SB_i = \beta_{i0} + \beta_{i1}DT_i + \beta_{i2}D_i + \beta_{i3}I_i + \beta_{i4}LP_i + \beta_{i5}WW_i + \beta_{i6}WS_i + \beta_{i7}MW_i + \beta_{i8}W_i + \beta_{i9}DT_i * MW_i + \beta_{i10}DT_i * W_i + \varepsilon_i, \quad (7)$$

This model will have the same form as the first model (eq. 5), except that it will include two interaction variables relating to transport accessibility and the type of municipality. Analysis of this model will reveal whether the type of municipality affects the direction and strength of accessibility's impact on the unemployment rate.

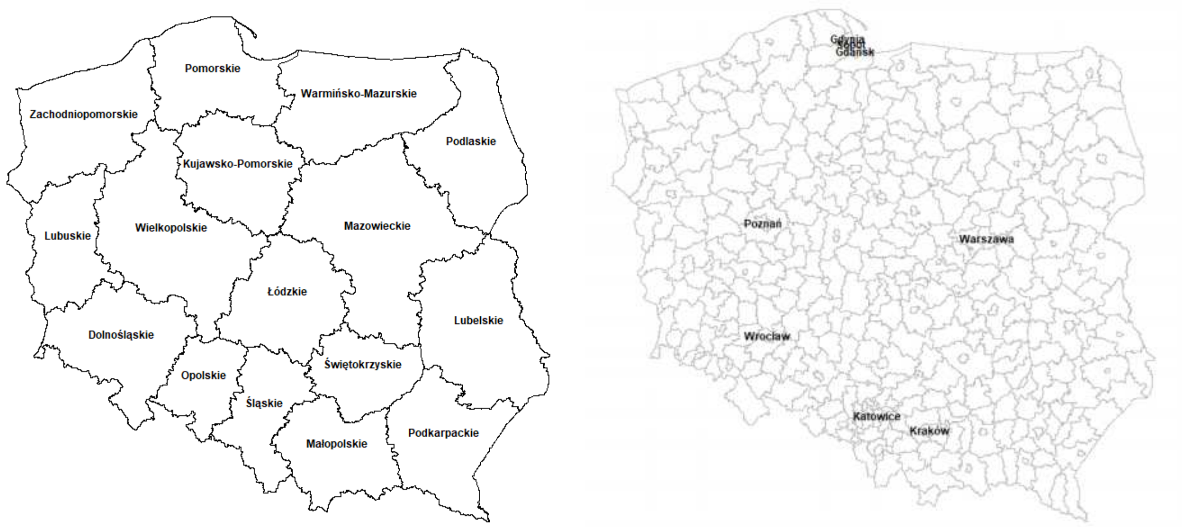
A negative relationship between transport accessibility and the unemployment rate is expected for both the first and second models. However, it is difficult to determine which model will better describe this relationship. The results of the third model are even more difficult to predict. It appears that the relationship in rural and rural-urban municipalities will be stronger than in cities, though it is also possible that no such differentiation will occur.

The models were constructed and the results analysed using the R programming language, which offers advanced spatial analysis tools. Specialised libraries such as spgwr:: and GWmodel:: were used, containing functions dedicated to GWR modelling. These libraries enable local regression coefficients to be estimated, the optimal bandwidth to be selected, models to be tested, and results to be visualised (Gollini et al., 2015; Ćwiakowski, 2020). The ggplot2 library was also used to visualise the data and results.

4. Analysis of the public transport accessibility index

Having developed the transport accessibility index for municipalities and cities with county rights in Poland, the next key step is to analyse it in detail. This section presents maps showing spatial variations in the index. This will be followed by a preliminary interpretation of the obtained results before more advanced analysis methods are used in the next part of the study. This analysis will enable us to identify the areas with the best and worst transport accessibility, and make a preliminary assessment of the relationship between accessibility and unemployment. First, we provide a map of Polish provinces (Fig. 1, left) and the biggest Polish cities (Fig. 1, right) to help readers understand the comments that follow.

Figure 1. Polish geography: left – provinces, right – biggest cities

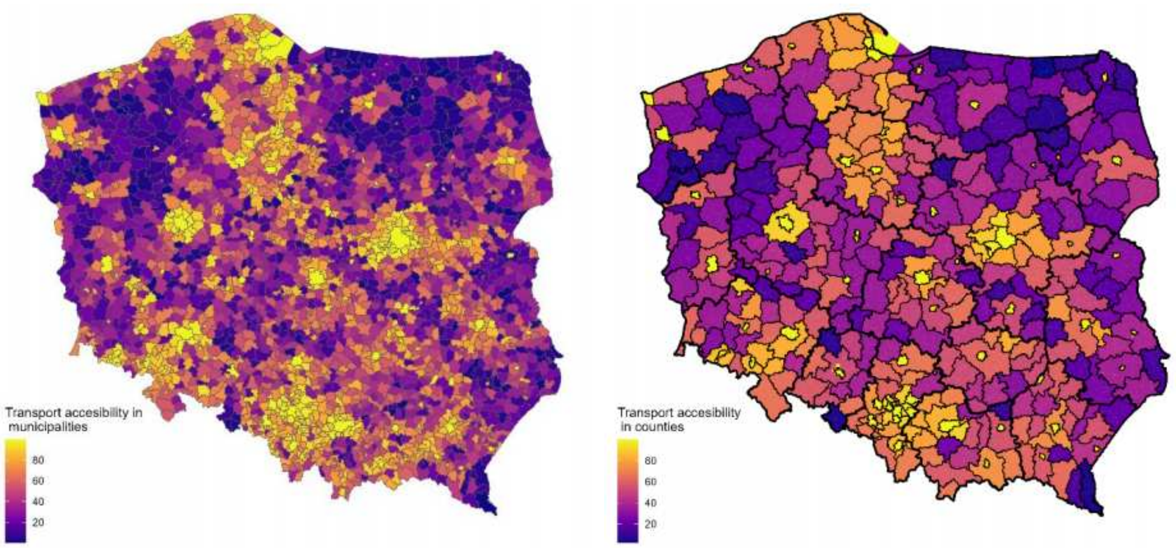


Source: own work with use of ggplot2:: library in R
Note: Silesian agglomeration consists of several cities; only Katowice is given for orientation

The developed transport accessibility index enables regional differences in the level of public transport accessibility to be assessed. Figure 2a shows a map of public transport accessibility in Polish municipalities. The map reveals significant regional disparities in transport accessibility across Poland. The highest values of the indicator, marked in yellow, are concentrated around large cities, primarily provincial capitals and urban agglomerations. Municipalities located slightly further away from the largest metropolitan areas have average values, marked in orange and pink. The lowest values, marked in purple, occur in peripheral areas distant from regional centres.

Figure 2b shows a map of the average transport accessibility of municipalities within a given county. The analysis of this variable produced similar results to those of the analysis of individual municipality accessibility.

Figure 2. Transport accessibility index map in Poland, 2023: a – in municipalities, b – in counties

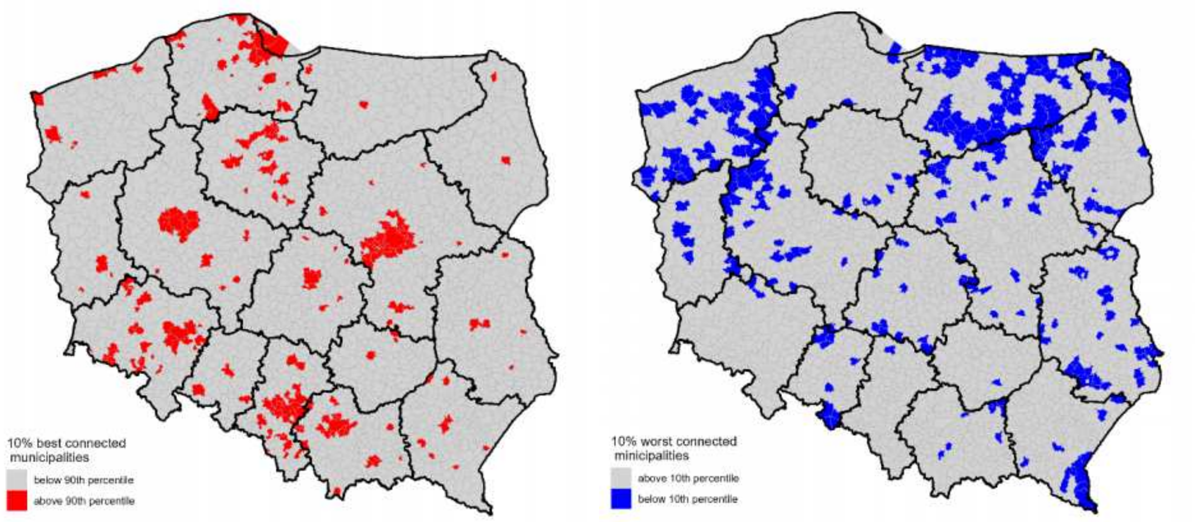


Source: own work with use of ggplot2:: library in R

In order to more easily identify extreme cases, Figure 3 presents maps showing the municipalities in the top 10 percent (Fig.3a) and bottom 10 percent (Fig.3b) in terms of transport connectivity.

As can be seen on the maps from Figure 3, the best-connected municipalities are mainly the agglomerations of the largest cities – Warsaw, Krakow, Wrocław, Poznań, the Tri-City (Gdańsk, Gdynia and Sopot), and the Silesian agglomeration. The municipalities with the lowest accessibility index values are mostly located near province borders and are largely municipalities in areas with lower population density. Most of these municipalities are located in the Warmińsko-Mazurskie and Zachodniopomorskie provinces. Over 30% of municipalities in these provinces are in the group of 10% of municipalities with the worst accessibility. In the case of the best-connected municipalities, none of the provinces have such significant values.

Figure 3. Municipalities with highest (a) and lowest (b) transport accessibility



Source: own work with use of ggplot2:: library in R

Turning to our area of interest, Table 1 shows the average registered unemployment rate for percentile groups of municipalities according to the transport accessibility index. As expected, we see that unemployment decreases with increasing accessibility.

Table 1. Average registered unemployment rates for groups of municipalities classified by percentile groups of the transport accessibility index

Transport Accessibility Index	Average registered unemployment rate
90-100	3.098
75-100	3.545
50-100	3.911
0-50	4.997
0-25	5.294
0-10	5.725

Source: Compiled by the author based on data from the Local Data Bank of the Statistics Poland

Reversing this relationship also makes it possible to calculate the average transport accessibility index for different percentile groups of municipalities, divided according to their registered unemployment rate. As can be seen in Table 2, there is also a relationship between the transport accessibility index and the unemployment rate. On average, the accessibility index is over 80% higher in the group of municipalities with the lowest unemployment than in the group with the highest unemployment.

Table 2. Average values of the transport accessibility index for groups of municipalities classified by percentile groups of the registered unemployment rate

Unemployment rate percentile groups	Average availability rate
90-100	63.05
75-100	59.18
50-100	56.38
0-50	43.58
0-25	39.63
0-10	34.17

Source: Compiled by the author based on data from the Local Data Bank of the Statistics Poland

Another element of the analysis is the variation in unemployment and accessibility according to municipality type. The lowest indicator value is found in urban-rural municipalities, at an average of 44.73 – almost identical to rural municipalities' average of 46.64. Transport accessibility is naturally highest in urban municipalities, where the index value is 78.51. In county towns, the index value was 95.88. As can be seen, transport accessibility is significantly greater in more urbanised areas. There is no significant variation in the average unemployment rate depending on the type of municipality. This average for rural and urban-rural municipalities coincides with the national average. In urban municipalities, the unemployment rate is, on average, approximately 0.3 percentage points lower than the national average. The largest difference is found in county towns, where the average is approximately 1.2 percentage points lower. Finally, the relationship between unemployment rates and accessibility was also examined visually using maps (see Appendix A).

5. Analysis of regression model results

5.1. Results of global model (OLS) and changes in GWR functional form

To determine the impact of transport accessibility on the local unemployment rate, a geographically weighted regression method was employed to examine the variability of regression coefficients in space. A preliminary model was first created using the ordinary least squares (OLS) method to select the appropriate variables for the final model. Taking into account the significance of these variables and the level of collinearity, as assessed using the variance inflation factor (VIF), the final set of independent variables in the model was selected, with variables with excessively high VIF values excluded from the analysis. Even in the preliminary results of this model, which still requires corrections, we can see confirmation of the hypothesis regarding the value of the coefficient relating to transport accessibility. It is statistically significant, with a negative value as predicted. The detailed results of the OLS model and the VIF values are presented in Appendix B.

After selecting the most appropriate variables (see Appendix B), the first GWR model (eq. 5) takes a following form:

$$SB_i = \beta_{i0} + \beta_{i1}DT_i + \beta_{i2}D_i + \beta_{i3}I_i + \beta_{i4}WW_i + \beta_{i5}MW_i + \beta_{i6}W_i + \epsilon_i, \quad (8)$$

where β_{i0} is a free term, β_{ik} are successive regression coefficients in the municipality i. SB_i is the registered unemployment rate in municipality i, DT_i is the value of the accessibility index of a given municipality i, D_i is the income of a given municipality i per capita, I_i is the value of investment expenditure in enterprises in the county per capita for a given municipality i, WW_i is the percentage of the population with higher education in municipality i, MW_i and W_i are binary variables for urban-rural and rural municipalities, respectively, and finally ϵ_i is a random element for municipality i. An adaptive bandwidth and a bi-square weight function were employed to determine the optimal bandwidth, thereby ensuring the best possible model fit.

The second model (eq. 6) differs from the previous – it uses a different accessibility variable to determine the average accessibility of municipalities within a given county. The final version of this model is expressed as follows:

$$SB_i = \beta_{i0} + \beta_{i1}DP_i + \beta_{i2}D_i + \beta_{i3}I_i + \beta_{i4}WW_i + \beta_{i5}MW_i + \beta_{i6}W_i + \varepsilon_i, \quad (9)$$

where DP_i is a variable that determines the average accessibility of municipalities within a given county. The other variables remain the same as in the formula (8) model.

Lastly, third GWR model (eq. 7) takes a following form:

$$SB_i = \beta_{i0} + \beta_{i1}DT_i + \beta_{i2}D_i + \beta_{i3}I_i + \beta_{i4}WW_i + \beta_{i5}MW_i + \beta_{i6}W_i + $$
$$+\beta_{i7}DT_i * MW_i + \beta_{i8}DT_i * W_i\epsilon_i, \quad (10)$$

5.2. GWR estimation results

We start first with comparison of models (8)-(9) with global model. The goodness-of-fit measures in Table 3 show that the GWR regression models fit the data significantly better than the global models. Comparing the model using municipal accessibility with the second model shows that changing the variable to average municipal accessibility in the county slightly improves the fit. The model from equation (8) has an adjusted coefficient of determination of 0.635, whereas the model from equation (9) has an adjusted coefficient of determination of 0.666. The AIC criterion is also lower for this model at 8,291.49 compared to 8,516.1 for the first model. Figure 4 shows the local values of the coefficient of determination for municipalities for both models.

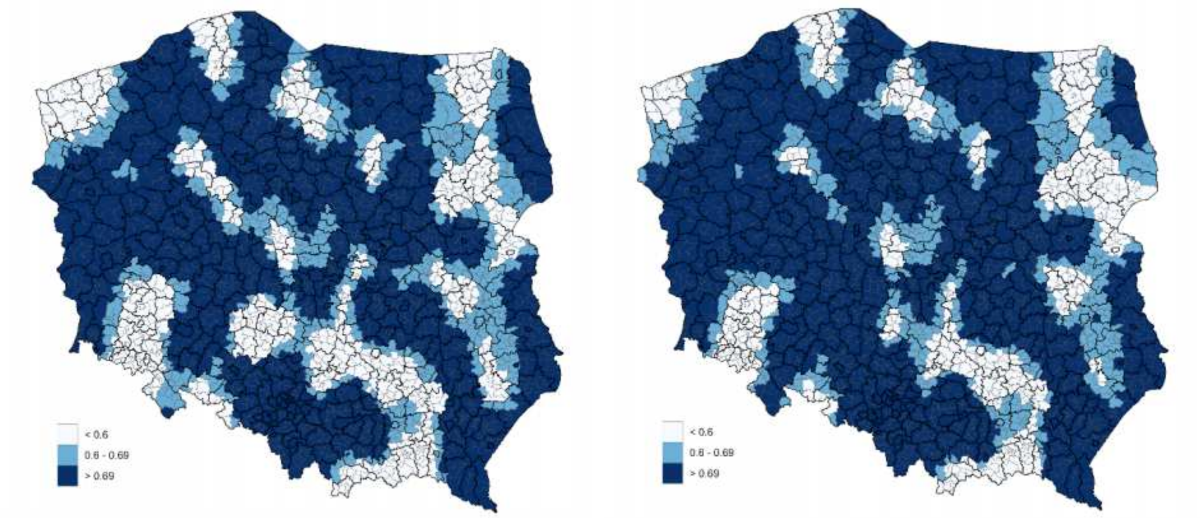
Table 3. Comparison of the fit of local (GWR) and global (OLS) models, for models based on municipal transport accessibility and average county accessibility

	GWR - municipality	**OLS - municipality**	**GWR - county**	**OLS - county**
R^2	0.7421	0.1703	0.7627	0.1724
R^2_{adj}	0.6347	0.1682	0.6662	0.1704
AIC	8,516.107	10,856.2	8,291.492	10,849.67

Source: own work with use of GWmodel:: library in R

As shown in Figure 4, both models accurately describe unemployment variability in most areas of Poland. The worst fit to the data for both models is in the Świętokrzyskie, Dolnośląskie, and Podlaskie provinces, as well as parts of the Warmińsko-Mazurskie and Zachodniopomorskie provinces. The model using the average accessibility of municipalities in a county as a variable has a high fit over a larger area than the model using individual municipality accessibility.

Figure 4. Local R^2 values: left – model (8), right – model (9)



Source: own work with use of ggplot2:: library in R

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To assess the fit of the models, the tests proposed by Leung et al. (2000a) were performed. The first two tests (F1 and F2) assess whether the GWR model describes the data better than the global model in different ways. The p-value was close to 0 in all tests performed, clearly indicating that, for both models studied, local models describe the relationships between variables much better than their global counterparts. The results of these tests are shown in Table 4.

Table 4. Leung et al. (2000a) F1 and F2 tests performed for models (8) and (9)

	Test F1	**Test F2**
GWR - municipality	0.3643***	1.667***
GWR - county	0.3264***	1.774***

Source: own work with use of spgwr:: library in R
*Note: p-value <10% - *, <5% - **, <1% - ****

Another test that was performed was the F3 test, which is also based on the work of Leung et al. (2000a). In this test, the null hypothesis is that the regression coefficients for the variables are identical in all locations. In this test, each variable in the model is tested individually. All the variables in both models had p-values close to zero, which indicates that the regression coefficients for each variable differ depending on location. As can be seen in Table 5, the test results indicate significant spatial variation in the variables, suggesting the validity of using GWR regression models to capture local relationships between variables in space.

Table 5. Leung et al. (2000a) F3 test performed for models (8) and (9)

	Model 8	**Model 9**
Intercept	1.7528***	2.1864***
Transport accessibility	1.9035***	4.6245***
Income	1.1954**	1.1202**
Urban-rural	1.200***	1.3231***
Rural	1.1948***	1.2700***
Investments	5.1796***	7.7085***
log(Higher educ)	2.0058***	2.3265***

Source: own work with use of spgwr:: library in R
*Note: p-value <10% - *, <5% - **, <1% - ****

The last test conducted was a test of autocorrelation of models' residuals based on Moran's I statistic from Leung et al. (2000b). In this test, the null hypothesis is the absence of autocorrelation of residuals. The tests yielded a p-value of 0.1295 and 0.066 for models (8) and (9), respectively, which does not allow us to reject the null hypothesis of no autocorrelation (accepting alpha=5%). This means that the residuals are randomly distributed in space and the model has effectively eliminated the influence of spatial dependencies.

Table 6 shows the distribution of regression coefficient values for the accessibility variable obtained for local models, as well as the global value of this coefficient. In GWR models, each location is assigned an individual regression coefficient, which is why the results of the regression are shown in the form of a distribution. In contrast, the global model has a single averaged value. As can be seen, the coefficient values vary greatly in both models, as evidenced by the difference between their respective maximum and minimum values. This variation indicates the complexity of the relationship between unemployment and transport accessibility, which the global model is unable to capture. The full results, showing the values of all variables for both models, are presented in Appendix C below.

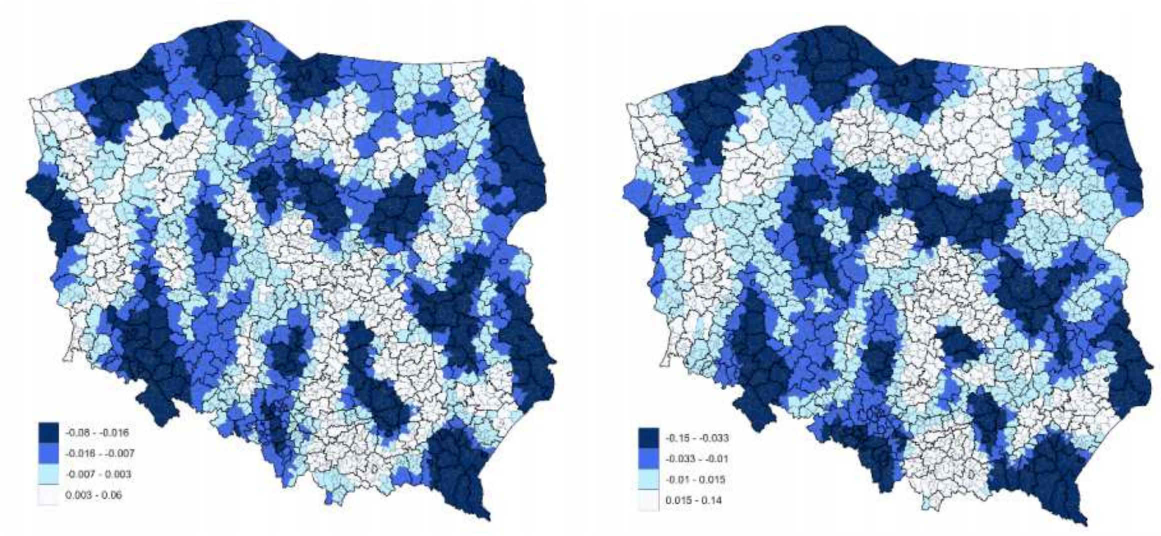
Based on the analysis of the maps presented in Figure 5 and the data contained in Tables C1 and C2 (Appendix C), it can be concluded that the spatial distribution of the regression coefficient values for the transport accessibility variable shows significant variation in both local models analysed – both for the model with accessibility in the municipality and the model with average accessibility in the county. In both models, the median coefficient is negative, which allows us to conclude that for most municipalities, improved transport accessibility is associated with a decrease in the unemployment rate. In the case of the GWR model based on transport accessibility in the municipality (left map), the coefficient values range from -0.08 to 0.06. The areas with the lowest coefficient values, marked in dark blue, are mainly concentrated in the border areas of the Dolnośląskie, Śląskie, Podkarpackie, Lubelskie, Podlaskie, Warmińsko-Mazurskie, Pomorskie, and Zachodniopomorskie provinces, as well as in the northern part of the Mazowieckie province and in the Kujawsko-Pomorskie province.

Table 6. Transport accessibility coefficient values summary for models (8) and (9)

	Min.	1st Qu.	Median	3rd Qu.	Max.	Global
GWR – municipality	-0.08	-0.016	-0.007	0.003	0.06	-0.017
GWR - county	-0.15	-0.033	-0.01	0.015	0.14	-0.022

Source: own work with use of GWmodel:: library in R

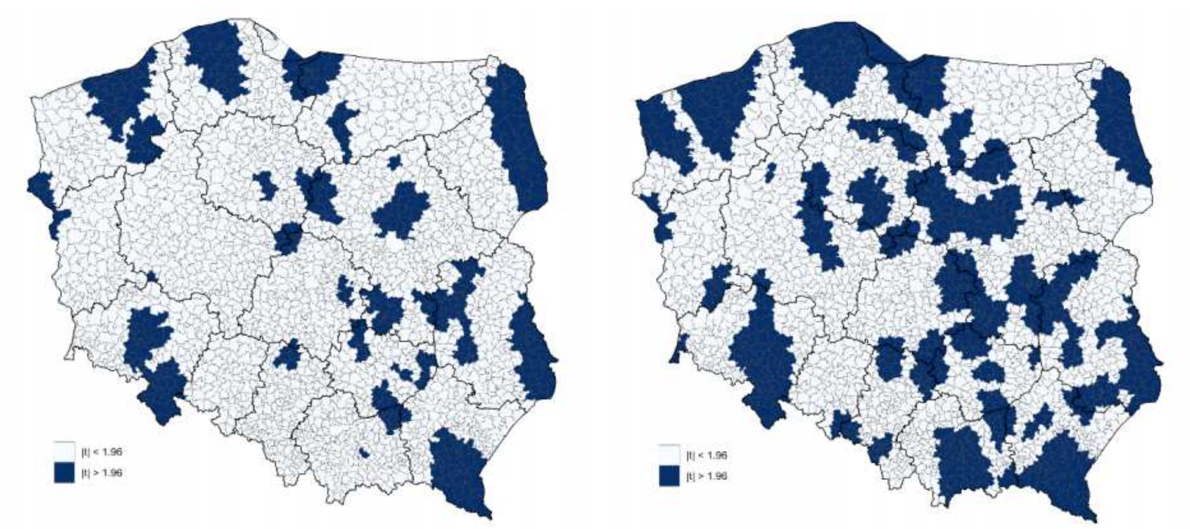
Figure 5. Map of transport accessibility coefficient values summary for models (8) and (9)



Source: own work with use of ggplot2:: library in R

The local coefficient values for both models have a similar spatial distribution. However, for the model that uses the average accessibility of municipalities in the county as a variable, these values are higher. This model is characterised by even greater spatial diversity – the range of coefficient values extends from -0.15 to 0.14 – which is also reflected in the map's more intense colour diversity. Municipalities with similar local regression coefficient values are not randomly distributed, but rather tend to cluster together. Many of these clusters are located in the peripheral areas of provinces with poor transport links to other regions, which is consistent with the theories of transport exclusion discussed in the literature review. However, many areas with low coefficient values are located in regions with relatively well-developed transport links, such as the Tri-City area and the Śląskie and Dolnośląskie provinces. This suggests that improving transport accessibility has a significant positive impact in well-developed areas as well as in those that are isolated in terms of transport. It is also worth noting that spatial clusters of similar regression coefficient values in local models partially overlap with the administrative grid of counties. This may indicate institutional or organisational effects operating at the county level that influence the relationship between transport accessibility and unemployment levels. As units responsible for the organisation of public transport, labour market policy and spatial planning, among other things, counties may play a role in shaping these relationships. Conversely, this convergence may be technical in nature, for example in a model where the accessibility variable is the average accessibility of municipalities in a county, or in a model with individual municipality accessibility, since the accessibility indicator itself is partly based on county-level data. Nevertheless, it is reasonable to assume that municipalities within the same counties may share characteristics that influence the relationship between transport accessibility and the unemployment rate.

Figure 6. Local significance of the transport accessibility variable coefficient for models (8) and (9)



Source: own work with use of ggplot2:: library in R

Figure 6 shows how the significance of the transport accessibility variable varies across space for the two models examined. Municipalities where the Student's t-statistic exceeded the critical value at a 5% significance level are marked in dark colours. The maps clearly demonstrate that the variable is not statistically significant across Poland as a whole. Accessibility only impacted selected regions, indicating local diversity within the country and providing further support for the use of spatial methods when analysing the relationship under study. As can be seen in Figure 6, the variable was significant in the global model, but it had a significant impact only in certain areas.

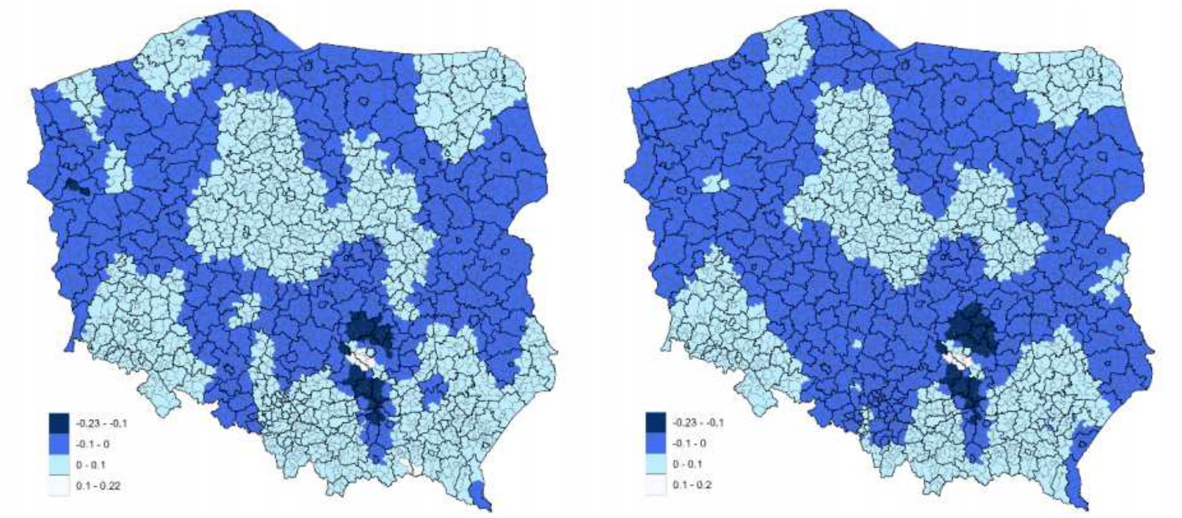
For the model with individual municipality accessibility (see Figure 6, left), the accessibility variable has a significant impact on a relatively limited number of municipalities. These areas are scattered and most of the municipalities are located in border areas or on the outskirts of provinces. In theory, municipalities located in remote and isolated areas should be more vulnerable to transport exclusion, a phenomenon that the model results seem to confirm. This suggests that transport accessibility at the local level does not play a significant role in explaining the national-scale phenomenon, but its importance depends on local spatial and social characteristics. Notably, some provinces, such as Lubuskie and Wielkopolskie, have virtually no municipalities where the variable is statistically significant, which corroborates the hypotheses presented in the previous chapter.

The results for the second model, which uses average accessibility within the county, are very similar to those for the first model. This suggests that if individual municipality accessibility is a significant variable, then average county accessibility is also significant. However, the second model covers a noticeably larger range of municipalities in which the accessibility variable is significant. The areas where the variable is significant are concentrated in larger clusters. Some of these clusters occupy significant portions of certain provinces, including Podkarpackie, Lubelskie, Małopolskie, Dolnośląskie, Mazowieckie, Pomorskie and Zachodniopomorskie. Additionally, many smaller groups of municipalities are located close to provincial borders.

By comparing the significance maps for both models in Figure 6 with the earlier results in Figure 5 and Table 6, we can conclude that average transport accessibility in a county appears to impact the unemployment rate more than individual accessibility in a given municipality. Figure 5 and Table 6 show that county-level accessibility has lower regression coefficients, indicating that accessibility has a stronger impact on reducing unemployment. Additionally, the area in which this impact is considered significant is larger than in the model with municipal accessibility. Figure 6 shows that the variable of average accessibility in the county is significant over a much larger area. These results enable us to address the question raised earlier in the paper concerning the scale of accessibility's impact. In light of these findings, regional transport accessibility appears to have a greater impact on reducing unemployment than local accessibility.

The results of the third model (Equation 10), which used interaction variables to examine whether the impact of transport accessibility varies depending on the type of municipality, were inconclusive. In both the global and local models, interaction variables proved to be insignificant for the variable determining transport accessibility at municipality level and for average transport accessibility at county level (see Table B2). Also, in the local models (see Table C3 and Figures 7-8), interaction variables between accessibility and municipality type did not produce interpretable and objective results. Therefore, it can be concluded that the type of municipality does not significantly alter the strength or direction of the impact of transport accessibility on the unemployment rate. An analysis of the municipalities that were significant in the previous two models showed that the distribution of municipality types in the significant group is similar to the actual distribution in Poland.

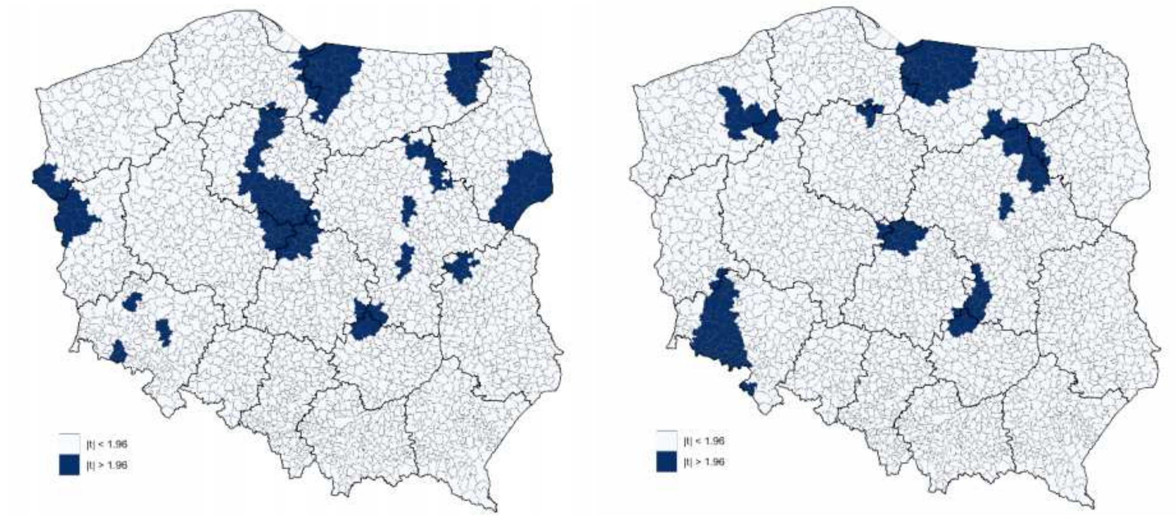
Figure 7. Local interaction coefficients in model (10): left – for urban-rural*accessibility, right – for rural*accessibility



Source: own work with use of ggplot2:: library in R

These model results suggest that there are no significant differences in the relationship between transport accessibility and unemployment rates for different types of municipality. However, this does not mean that the degree of urbanisation is unimportant in this relationship. Perhaps municipality type is too general an indicator of a municipality's level of development, and more precise indicators should be used to determine whether there are differences in the relationship between rural and highly urbanised areas.

Figure 8. Local significance of the interaction coefficients in model (10): left – for urban-rural*accessibility, right – for rural*accessibility



Source: own work with use of ggplot2:: library in R

6. Summary

This study examined the impact of public transport accessibility on unemployment level in Poland, taking into account the territorial diversity of this relationship. Geographically weighted regression (GWR) was used alongside other econometric methods to analyse the spatial heterogeneity of the relationship under study. The study provided answers to key research questions, improving our understanding of the role of transport accessibility in shaping Poland's labour market.

The results of the analysis clearly show that the GWR model more accurately reflects the relationship between transport accessibility and unemployment than the global model (OLS). This is evidenced by the GWR model's higher coefficient of determination and lower AIC values. Furthermore, statistical tests confirmed significant spatial variation in regression coefficients, meaning that the strength and direction of the impact of transport accessibility on unemployment varies depending on the municipality's location. Therefore, it can be concluded that the impact of transport accessibility on the labour market in Poland is spatially diverse, meaning that transport policy needs to be tailored to the specific characteristics of individual regions.

Although its impact was not uniform across the country, transport accessibility proved to be a significant variable explaining the level of unemployment. In most municipalities, the regression coefficient for accessibility was negative, confirming the anticipated negative correlation between transport accessibility and unemployment rates. However, this variable was statistically significant only in selected regions, primarily on the outskirts of provinces and particularly in border regions. In many other areas, this relationship was weaker or insignificant. This suggests that improving transport accessibility could be an effective way of reducing unemployment in areas most vulnerable to transport exclusion.

A comparative analysis of models using individual municipality and average county accessibility showed that regional transport accessibility has a stronger impact on unemployment than local accessibility. The model using average county accessibility fit the data better and had higher values of the coefficient of determination. Additionally, the variable of average accessibility in the county was statistically significant over a larger area than the variable of individual municipality accessibility. These results suggest that reducing unemployment requires not only local transport infrastructure, but also a coherent regional transport system. As residents often travel outside their municipality in search of work, transport accessibility in a broader regional context plays an important role.

Introducing interaction variables into the model did not reveal any significant differences in the impact of transport accessibility on unemployment, depending on the type of municipality (urban, rural or urban-rural). Interaction variables were found to be statistically insignificant in both the global and local models. This suggests that the strength of the impact of accessibility on unemployment is not significantly affected by the degree of urbanisation of the municipality, but rather by local spatial and social factors. Therefore, transport policy should focus on the diverse needs of individual regions rather than general categories such as municipality type. It would perhaps be worthwhile examining a similar relationship that takes population density or another indicator of urbanisation into account, as the type of municipality is too general and often does not correspond to the municipality's actual level of development.

The study confirms that access to public transport is a significant factor in determining unemployment levels in Poland, with this relationship showing significant spatial variation. The findings highlight the importance of considering regional variations in transport accessibility when designing labour market policies to reduce unemployment, especially in peripheral and less developed regions. Due to the significant variation in the impact of transport on labour market outcomes across the country, policy responses must be flexible and adapted to local circumstances.

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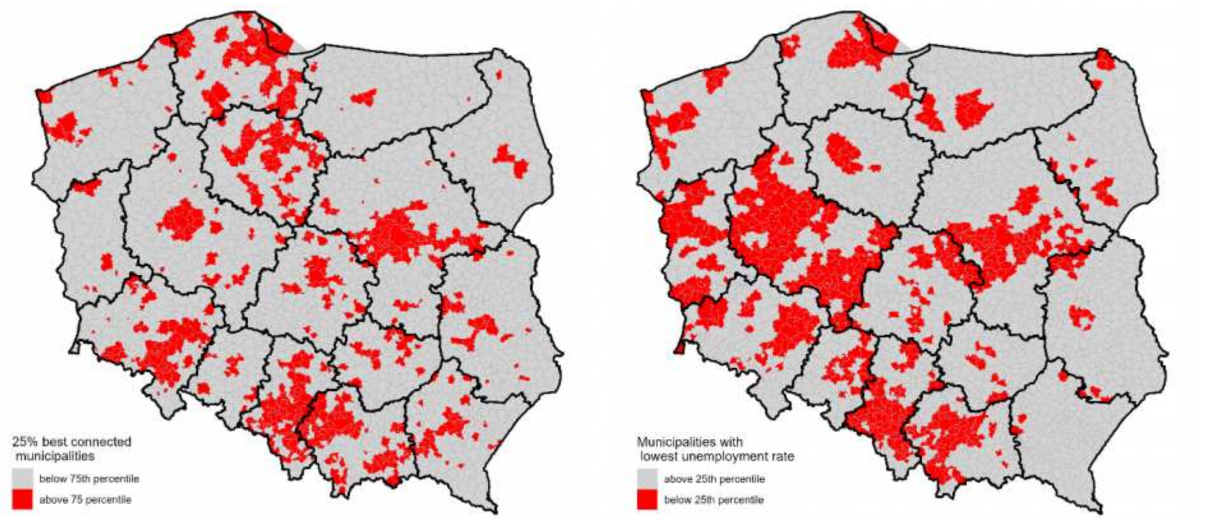
Appendixes

Appendix A. Relationship between transport accessibility and unemployment rate

If we consider the group of 25% of the best-connected municipalities, the Dolnośląskie and Małopolskie provinces, with about 40% of municipalities belonging to this group. The best-connected provinces are Pomorskie, where 47% of municipalities are in the group of 25% of the best-connected municipalities, and Śląskie, with a value of 52%. The worst-connected province is Podlaskie, where 45% of municipalities belong to the group of 25% of municipalities with the lowest transport accessibility index. However, the worst performers are the Zachodniopomorskie and Warmińsko-Mazurskie provinces, with values of 52% and 60%, respectively.

Figure A1 shows two maps, the first showing the group of 25% of municipalities with the best transport links, and the second showing the group of 25% of municipalities with the lowest unemployment rates. The regions with low unemployment are more clustered, which may be due to structural and historical factors. Municipalities with the highest accessibility, like the narrower group discussed earlier, are concentrated around urban agglomerations.

Figure A1. Municipalities with high transport accessibility, 75-100 percentile (a) and municipalities with low unemployment rate, 0-25 percentile (b)

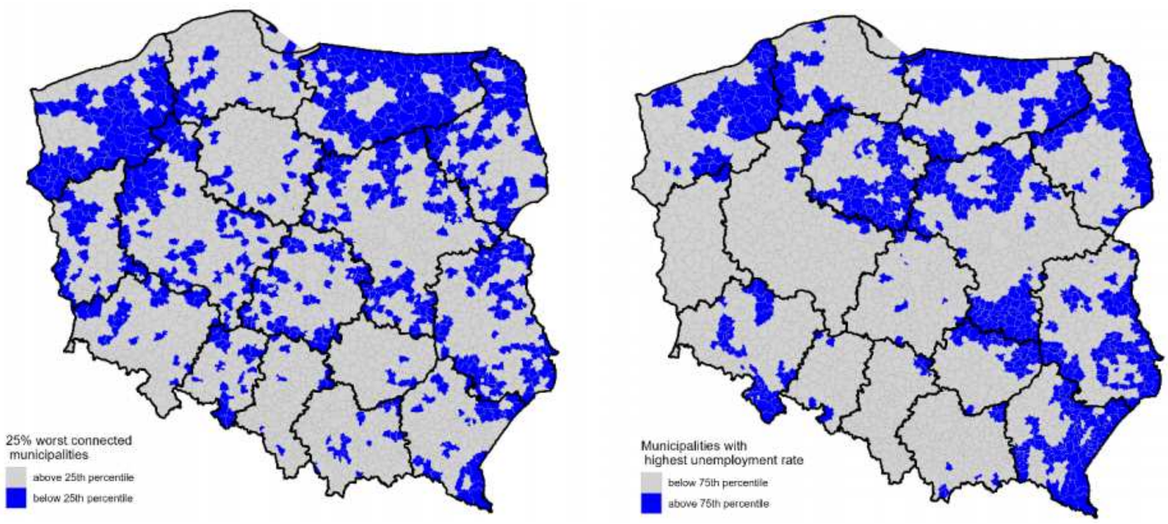


Source: own work with use of ggplot2:: library in R

Analysis of the maps indicates a partial overlap of areas, with 39% of municipalities actually overlapping. The greatest differences are visible in the Lubuskie and Wielkopolskie provinces, where large areas that do not stand out in terms of transport accessibility have low unemployment rates. Perhaps this observation will prove important in a later analysis of this relationship. It may suggest the existence of other factors that may play a key role in shaping the labour market situation, regardless of transport accessibility.

A similar analysis can be performed for municipalities with the highest unemployment rates and the worst transport links. The maps in Figure A2 show the group of 25% of municipalities with the worst transport links and 25% of municipalities with the highest registered unemployment rates. For a larger group of municipalities, the aforementioned correlation is even more evident: the municipalities with the worst transport links are usually located on the outskirts of provinces. Similarly, unemployment is concentrated in peripheral areas, and again it can be seen that municipalities with high unemployment are less dispersed than municipalities with low accessibility. At first glance, the areas on both maps do not differ significantly from each other, with 36% of municipalities actually overlapping. The greatest discrepancies are visible on the border between the Świętokrzyskie and Mazowieckie provinces and in the Kujawsko-Pomorskie province, where unemployment is high even though transport accessibility is at least average. Once again, the situation in the Lubuskie and Wielkopolskie provinces is visible, this time municipalities with low transport accessibility do not show any problems related to unemployment.

Figure A2. Municipalities with low transport accessibility, 0-25 percentile (a) and municipalities with high unemployment rate, 75-100 percentile (b)



Source: own work with use of ggplot2:: library in R

The provinces in which the relationship between the accessibility index and the unemployment rate is least apparent are Lubuskie and Wielkopolskie. When the unemployment rate maps are compared with the map of average county accessibility, the discrepancies in the Kujawsko-Pomorskie and Świętokrzyskie provinces appear slightly smaller than in previous cases.

Appendix B. OLS regression results and VIF analysis

Table B1 presents estimation of global model (eq. 5).

Table B1. Results of the least squares model (eq.5) and variance inflation factor (VIF) values for the proposed variables

	Coefficient	Std. error	t-value	p-value	VIF
Intercept	1.1062	1.6433	0.673	0.5009	-
Transport accessibility	-0.0157	0.0017	-8.984	0.0000	1.398
Income	0.0001	0.00002	3.916	0.0000	1.092
Population in productive age	2.7537	2.7528	1	0.3172	1.373
Urban-rural	-0.4171	0.1706	-2.445	0.0145	3.153
Rural	-0.5405	0.1739	-3.107	0.0019	3.943
Investments	-0.0002	0.00001	-1.524	0.0000	1.09
Secondary or higher education	5.8699	0.7108	8.257	0.0000	6.918
Higher education	-3.9540	0.3654	-10.819	0.0000	6.32

Source: own work with use of GWmodel:: and car:: libraries in R

The variables concerning the percentage of the working-age population and the percentage of the population with secondary or higher education were rejected as irrelevant. The latter showed collinearity with the variable concerning the percentage of the population with higher education (VIF value above 5). After correcting the model by removing these two variables, the p-value for each of the remaining variables decreased and became close to 0. The VIF values also decreased, with the binary variable for rural municipalities having a value of 3.25 in the final model. The education variable was also log-transformed because it takes percentage values.

Table B2 shows estimation of global model for equation (10).

Table B2. Results of the least squares model (eq. 10)

	Coefficient	Std. error	t-value	p-value
Intercept	7.3116	0.5025	14.548	0.0000
Transport accessibility	-0.0208	0.0054	-3.790	0.0000
Income	0.0001	0.00002	5.668	0.0000
Urban-rural	-1.2593	0.4711	-2.673	0.0077
Rural	-1.2086	0.4607	-2.623	0.0087
Investments	-0.0002	0.00001	-11.904	0.0000
Higher education	-7.9467	1.1591	-6.856	0.0000
Urban-rural*Transport accessibility	0.0090	0.0061	1.474	0.1407
Rural* Transport accessibility	0.0014	0.0057	0.242	0.8090

Source: own work with use of GWmodel:: library in R

Appendix C. Full results of the local regression models (GWR)

Table C1. Full results for model (8)

	Min.	1st Qu.	Median	3rd Qu.	Max.
Intercept	-15.3263	0.6180	2.7037	5.2745	15.5733
Transport accessibility, municipality	-0.07958	-0.01640	-0.0067	0.0036	0.0580
Income	-0.0008	-0.00008	0.00003	0.0001	0.0009
Urban-rural	-29.0429	-1.3432	-0.5839	0.1447	3.4070
Rural	-12.6402	-1.9218	-1.0690	-0.4401	4.9109
Investments	-0.0028	-0.0005	-0.00017	0.000016	0.0027
log(Higher educ)	-8.7260	-2.7046	-1.4306	-0.3000	5.1709

Source: own work with use of GWmodel:: library in R

Table C2. Full results for model (9)

	Min.	1st Qu.	Median	3rd Qu.	Max.
Intercept	-12.2284	0.4559	2.7032	5.3101	17.3539
Transport accessibility, county	-0.1503	-0.0330	-0.0097	0.0150	0.1416
Income	-0.0008	-0.00009	0.00001	0.0001	0.0009
Urban-rural	-8.5277	-1.2644	-0.5498	0.0932	3.1326
Rural	-7.8630	-1.8091	-1.0720	-0.5028	3.8984
Investments	-0.0028	-0.0005	-0.0001	0.00004	0.0040
log(Higher educ)	-7.7706	-2.9420	-1.6635	-0.4905	5.1776

Source: own work with use of GWmodel:: library in R

Table C3. Full results for model (10)

	Min.	1st Qu.	Median	3rd Qu.	Max.
Intercept	-12.6979	4.1726	6.6124	10.3616	30.2580
Transport accessibility, county	-0.2257	-0.0221	-0.0040	0.0104	0.2121
Income	-0.0004	-0.00003	0.00007	0.00016	0.0007
Urban-rural	-23.3424	-2.4322	-0.4312	1.1121	18.8797
Rural	-22.1736	-2.6947	-0.7174	0.6037	17.7160
Investments	-0.0019	-0.0005	-0.0002	-0.00004	0.0008
Higher educ	-38.0706	-15.7666	-8.9292	-2.7684	16.0840
Urban-rural*Transport accessibility	-0.2207	-0.0217	0.0004	0.0209	0.2137
Rural* Transport accessibility	-0.2243	-0.0240	0.0062	0.0137	0.1940

Source: own work with use of GWmodel:: library in R

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