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SPATIAL DIFFERENTIATION OF ACCESS TO BUS TRANSPORT BASED ON THE EXAMPLE OF CORE-IMMEDIATE SURROUNDINGS CONNECTIONS IN THE WROCŁAW AGGLOMERATION

Summary. Accessibility to public transport is a very important factor in determining the general transport accessibility of a given area. Commonly, the bus is the only alternative solution for a car in mobility. However, it is not possible to ensure the same level of possibility of traveling by bus for each location. As a consequence, there may be areas excluded from the service when there are not enough bus connections. On the other hand, the presence of the main transport routes (e.g., regional and national roads), as well as railways, significantly increases the possibilities of mobility with the use of public transport. The aim of the article is to diagnose direct bus connections in the Wrocław agglomeration but only between the immediate surroundings of Wrocław and itself as a core. One of the secondary aims is to identify areas with limited access to those connections and to propose solutions to the diagnosed problems. Two rings of municipalities around the city have been designated as the area of the Wrocław agglomeration as the immediate surroundings of the core. The main research method is the analysis of collected numerical data and using the empirical Bayesian Kriging method to determine areas of different levels of accessibility to bus transport. In addition, the capabilities of PTV Visum made it possible to perform modeling of bus connections. The 2021/2022 timetables of bus connections providing direct access to Wrocław were taken into account. The results of the study are proposals for solutions that may constitute directions for the development of passenger bus transport in the Wrocław agglomeration in order to improve the accessibility of bus transport within the Wrocław agglomeration.

1. INTRODUCTION

Due to the COVID-19 pandemic in 2020, public transport faced the difficult task of encouraging travelers to use alternatives to their own vehicles. The widespread feeling of a low level of safety in travel caused a significant decrease in the number of travelers in both road and rail public transport, as well as in urban transport. While the situation in urban transport (i.e., buses, trams, and light rail) improved relatively quickly, regional bus transport, often based on commercial connections, experienced a noticeable crisis. The number of connections was limited, which resulted in the loss of alternative transport modes. Travelers living in rural areas who were unable to drive a car or did not have a car lost the ability to travel by regional bus. As a consequence, they were not able to travel, for example, to the capital city of the voivodship (NUTS 2 territorial unit in Poland) [1]. Other cases concern

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towns that never had such a connection, or, if it existed, it provided connections only to subregional centers. In order for such a connection to be ensured, however, care should be taken to ensure communication between various transport modes and create proper conditions for changes at nodes.

Nevertheless, it is worth adding that in suburban zones, compared to peripheral zones, the structure of the population is increasing. It is characterized by a higher share of people of pre-working and working age, with particular emphasis on mobile people. In addition, a large part of the population living in the suburban area used to live in this city for a longer time, which is observed, for example, in the example of Wrocław. Their relations on various levels (working, education, services) are still maintained. This automatically implicates greater mobility needs of those inhabitants between rural areas and the city. Due to the lack of connections, mobility needs cannot be met, and if they are, then this is done by using one's own car, which contradicts the mobility policy focusing on decreasing the level of congestion. For this purpose, it is worth analyzing the case of connections in the Wrocław agglomeration, specifically its urban areas and its core, Wrocław. Particular attention should be paid to the possibility of using flexible public transport modes (which means having greater possibilities in terms of space penetration), namely, the bus. If the possibility does not exist, then there is no alternative solution to one's own car, which also excludes some social groups from mobility. Although the train is a more efficient and economical mode of transport, it is the bus that determines the accessibility of the so-called last mile, defined as a service area of transporting passengers between individual towns along the route and a transport node according to the work [2]. An example of the service area discussed in this article may be the area of the Wrocław agglomeration, also defined in [3], which was designated in 2001 in the strategy for the economic and spatial integration of the Wrocław agglomeration. R. Szmytkie and D. Sikorski consider the first two rings of municipalities surrounding the city to be the area of direct influence of Wrocław [4]. In view of the above, it is justified to choose the area of analysis as the municipalities located in the immediate and closer neighborhood of Wrocław. It is a center providing services of a higher order and meeting the criteria of a central center, according to Christaller, including the city's service of its facilities, as mentioned in [5]. The whole agglomeration, including Wrocław and its surroundings, is defined as the first two rings of municipalities and direct bus connections between them will be the subject of further analysis.

2. AIMS, RESEARCH METHODS, AND LITERATURE REVIEW

The main purpose of this study is to diagnose the differentiation of the accessibility to direct bus connections from the locations in the first two rings of municipalities in the Wrocław agglomeration to its core, which is Wrocław. The result of this analysis should be obtained as areas of higher and lower accessibility, which allows us to present possible solutions for improving the efficiency of public transport.

The research methods include a data analysis divided into four steps: establishing the locations in two first rings of municipalities around Wrocław, assigning the number of direct bus connections to Wrocław for each location, determining the level of accessibility of locations for bus connections to Wrocław, and proposing solutions in cases requiring priority intervention. The conducted analyses made it possible to determine the locations with limited access to bus transport, which, in turn, was the basis for determining the areas of limited accessibility. As a a result it was easier to indicate the route of potential routes of new connections, which are supposed to increase the possibility of using bus transport in the analyzed area in commuting to Wroclaw. The results of the research are presented in a later part of the article in the form of cartographic studies prepared with the use of GIS tools (e.g., the highly accurate spatial interpolation kriging method for predicting variable values based on known points) [6]. The number of analyzing locations in this case is 595, which enabled us to use this method. In detail, in order to determine the accessibility differentiation zones, the Bayes Kriging method was used, which is more often used in physical geography than in analyses in the field of socio-economic geography. Examples of the application of the method include the distribution of precipitation [7], the distribution of soil types [8], and the determination of agricultural land prices [9]. In the latter work, the authors used a tool in ArcGIS called empirical Bayesian Kriging (EBK), which was also applied in this work. The

purpose of using the method is to determine the impact ranges of given stops with various numbers of direct connections to Wrocław and, consequently, to establish zones of differentiated accessibility to those bus connections. The Bayesian Kriging method is a variant of geostatistical Kriging methods. This is a group of stochastic methods for interpolating unknown quantities using known quantities. EBK is based on a semivariogram describing the spatial correlation of a phenomenon as a function of the distance and direction of changes in the phenomenon. Among the interpolation methods, it is considered a method with very high accuracy. The stages of EBK are as follows: creating a semivariogram model, simulating unknown values based on the model, and creating a new semivariogram model based on simulated values. The second and third stages are iterative.

While the collection of data on the population in municipalities was not an inconvenience (it is usually publicly available data), in the case of data relating to timetables, they were obtained from various sources, namely, directly from bus stops or from web portals dedicated to travelers. Field research was carried out in selected towns located in the research area in order to verify this data. The field verification was carried out on the example of the largest towns of the first ring of municipalities around Wrocław. This action allowed confirmation of the data previously obtained from operators and publicly available timetable databases. In principle, each bus connection should be marked in an appropriate way on the timetable placed within the bus stop. The data on direct flows between locations and facilities in Wrocław, including locations of work or education, were not included in the analysis due to the inability to obtain data at such a high level of detail. Therefore, the level of demand was determined by the number of inhabitants of the location and based on the assumption that both mobile people and people of pre- and post-working age who do not have an alternative for their own car may have an impact on the demand.

The case of Wrocław as a hub for bus transport was described in detail by, for example, [10]. Public transport and its role in the agglomeration area was naturally emphasized in many works in the field of geography and transport economics. R. Daniels and C. Mulley write in their work about the role of public transport in stimulating economic relations in the agglomeration on the example of the Sydney agglomeration, emphasizing, among other things, significant connections with the use of public transport in daily commuting to the city [11]. D.G. Chatman and R.B. Noland reflect on the interdependence of economic development and improving the quality of the public transport system in the agglomeration, listing numerous factors determining the correlation, including the effectiveness of regional policy [12]. A similar issue is addressed by M. Börjesson et al., who present an example of the impact of transport development on agglomeration processes without distinguishing public transport itself but taking into account the transport system as a whole [13]. A slightly different research approach is presented in [14], who undertake the assessment of the functioning of public transport in the example of rural areas located in the Croatian region of Sisak-Moslavia County. They clearly emphasize that due to the lack of efficient public transport serving rural areas, the population is forced to own a car, but not by their choice. Related situations with transport exclusion are also confirmed by the general research conducted by J.P. Lieszkovszky [15]. P. White divides subsidized public transport services into scheduled and so-called school courses, which are intended to serve children's commutes to school and do not serve the entire population [16]. M.D. Leiren and K. Skollerud present new trends in transport services using the example of rural areas in Norway [17]. In the analyzed areas, the so-called transport on request (on demand) is not based on scheduled connections. The authors indicate the growing popularity of this type of transport, which has replaced traditional bus connections. Another issue is mentioned by A. Lakatos et al., who describe the problem of the "last mile" using the example of rural areas of Hungary [18]. They point to a demand-based transport solution as a way to organize connections, proposing an optimization model that takes into account cost reduction and the advanced use of intelligent transport systems to monitor demand. Ch. Schütze et al. analyze cases of Braunschweig and Tampere and look at ways to increase the number of passengers using public transport [19]. They mainly mention reliability, punctuality, clock-face timetable of connections (frequency including constant intervals between departures), and travel time. A synthetic approach to public transport services in rural areas was undertaken in [20]. This work can still be used primarily to determine the basic problems that often occur today and the challenges related to public transport in rural areas. The authors mention, for example, small service areas, low quality of infrastructure, low quality of service and

rolling stock, and low promotion of public transport. Nowadays, these factors still sometimes prevent public transport in rural areas from being attractive. K. Nosal and U. Duda, in turn, cite an example of a marketing campaign increasing public awareness of the use of public transport services in rural areas using the example of the suburban area of Kraków [21]. Problems related to the frequency of connections are emphasized once again, as is the problem of low-quality passenger infrastructure. In the survey conducted, only 16% of the respondents indicated that they use the bus five times a week. It is emphasized that P&R car parks created on the outskirts of Kraków encourage people to choose their own. J. Hansson et al., in turn, discuss the legitimacy of skipping some stops on routes in rural areas and how to improve transport reliability by operating clearly designated rest areas [22]. On the other hand, in [23] the authors write about the organization of direct public transport connections in rural areas using the example of Prešov. The role of bus connections necessary to serve children, the elderly, and people with reduced mobility who need direct connections to the city is emphasized. For a more detailed analysis related to public transport patterns in the face of demographic change, see [24]. The authors point out that public transport is effective when the motives for traveling in specific areas are known while emphasizing that public transport should maintain its universality. The work also cites Tele-Bus as a transport service ordered at MPK Kraków as an example of transport on request mentioned above. Other research on broadly understood transport behaviors in the example of Bavaria was conducted in [25]. He shows that the travel times of public transport modes are often almost twice as long as the travel times of cars. He also notes the dynamics of change linked to the political situation and demographic changes. The author points to the research of N.R. Velaga et al., recalling the possibility of using information technologies to increase the transmission of transport information in rural areas [26]. Such solutions may allow us to examine transport needs, including the demand for commuting within agglomerations. Other solutions are proposed by T. Petersen [27]. He gives an example of commuting to Zurich from its agglomeration, presenting data from 2000 on commuting to the city from neighboring municipalities. The maximum result was at the level of 29% of the respondents in the case of journeys to work from Henggart municipality to Zurich. More than twice as many people coming to Zurich used their own cars. However, the introduction of a fixed clock-face timetable of connections and the creation of bus connections of the nature of suburban connections allowed a significant increase in the interest in public transport. The involvement of municipalities in the agglomeration is, therefore, very important. At the same time, as T. Kwarciński points out, public awareness of the problem of the importance of public transport in servicing agglomeration municipalities is increasing [28]. It happens that some municipalities have a transport system that allows people to commute to the subregional center, where they can change to bus connections in the direction of the regional center. Research conducted in [29] indicates, however, that the accessibility of rural areas to their own county city is poor and that 40% of rural areas are characterized by low accessibility to public transport. It seems that the key to the effective use of public transport by the inhabitants of agglomerations is to ensure the reliability of public transport connections by implementing a high frequency of connections with fixed clock-face timetable. However, this requires significant financial outlays in the first phase of operation. However, in the future, it may bring positive effects, which may permanently encourage the inhabitants of the agglomeration to choose public transport in their daily mobility.

3. DIAGNOSIS OF EXISTING BUS CONNECTIONS IMMEDIATE SURROUNDINGS − CORE

The diagnosis of the condition of bus connections between Wrocław and it is immediate surroundings was carried out based on data from late 2021 and early 2022. In the adopted research procedure, all bus transport connections on weekdays and holidays were included. Given the situation regarding the COVID-19 pandemic, it should be emphasized that this was a period of ongoing restrictions, including the obligation to wear protective masks in public transport. Nevertheless, there was also a time after many connections were suspended due to the pandemic, which occurred in March 2020, and these connections have not necessarily been restored. The study allowed us to identify seventeen bus and minibus operators that provide connections in the analyzed area. One of them was the MPK Wrocław company, which is the most important urban operator, partially also serving suburban lines and having

two subcontractors (i.e., ITS Michalczewski and Mobilis). A very important role was also played by three operators with, above all, large-capacity buses – namely, Dolnośląskie Linie Autobusowe (DLA), Polbus PKS, and Beskid. These operators' service areas include at least four municipalities on the way to and from Wrocław, while the remaining 14 operators serve three municipalities at most, often limiting the spatial scope of their operations to one municipality. The analysis included 595 villages and towns located in the municipalities of the first ring around Wrocław: Miękinia, Oborniki Śląskie, Wisznia Mała, Długołęka, Czernica, Siechnice, Żórawina, Kobierzyce and Kąty Wrocławskie. The municipalities of the second ring are Brzeg Dolny, Prusice, Trzebnica, Zawonia, Dobroszyce, Oleśnica, Jelcz-Laskowice, Oława, Domaniów, Borów, Jordanów Śląski, Sobótka, Mietków, Kostomłoty, and Środa Śląska. In total, the subjects of the study were bus connections to Wrocław from locations in 24 municipalities. The urban areas of Oława and Oleśnica, characterized by high transport accessibility in connections to Wrocław provided by buses and trains, were not included. For each of the analyzed locations, the number of operators' service routes on working and weekdays was determined, and then the number of routes of each operator was determined. Only direct connections from each location to Wrocław were analyzed. Through the appropriate collection of data, it was possible to determine the total number of connections per working day, the total number of connections per day off, the average number of connections during the day in total, and the total number of connections within a week. Tab. 1 presents the share of towns without direct bus connections to Wrocław in individual municipalities.

Table 1

Share of locations in the analyzed municipalities without bus connections to Wrocław

Municipalities	Number of locations without any bus connections to Wrocław	Number of locations	Share of locations without bus connections to Wrocław
Brzeg Dolny	14	14	100.0%
Kostomłoty	27	27	100.0%
Oborniki Śląskie	24	24	100.0%
Prusice	28	28	100.0%
Zawonia	25	25	100.0%
Trzebnica	40	43	93.0%
Środa Śląska	26	28	92.9%
Borów	24	26	92.3%
Jelcz-Laskowice	16	18	88.9%
Dobroszyce	12	14	85.7%
Oława	27	35	77.1%
Jordanów Śląski	9	13	69.2%
Oleśnica	19	29	65.5%
Domaniów	15	24	62.5%
Mietków	8	14	57.1%
Sobótka	12	23	52.2%
Kąty Wrocławskie	19	40	47.5%
Wisznia Mała	7	16	43.8%
Miękinia	9	29	31.0%
Siechnice	5	21	23.8%
Żórawina	6	32	18.8%
Długołęka	1	41	2.4%
Czernica	0	13	0.0%
Kobierzyce	0	33	0.0%

Source: Own study on the basis of timetable study.

Among the remaining municipalities of the first ring, the situation is the least favorable in the case of the municipality of Oborniki Śląskie, where none of the localities of the municipality have bus connections to Wrocław. Oborniki Śląskie is served by numerous railway connections ensuring efficient access to the agglomeration core. Bus transport is limited only to buses to Trzebnica serving the towns located on the provincial road no. 340. The situation in the municipality of Prusice, located north of the municipality of Oborniki Śląskie, is clearly different, as only Skokowa has any rail connections and no bus connections with Wrocław. According to data available on the website of the Prusice municipality, there are practically no morning connections from Prusice to Skokowa, which makes it impossible to use multimodal solutions when commuting to Wrocław with a change of transport modes, in this case, in Skokowa. Other municipalities with very low accessibility of bus transport are the municipalities of Trzebnica and Zawonia, located on the east of the Oborniki Śląskie municipality.

Trzebnica is one of the subregional nodes of bus connections from Prusice, Oborniki Śląskie, and Zawonia. Small buses depart from Trzebnica to Wrocław approximately every 20 minutes, and trains run hourly. Buses from Zawonia to Trzebnica stop along the way only in Cerkwica in the Trzebnica municipality. In practice, the municipality of Zawonia, which neighbors the Trzebnica municipality, has no connections to Trzebnica. That means traveling from Zawonia to Wrocław with one change is practically impossible. As a result, many potential passengers of this route are excluded from passenger flows to Wrocław. Almost all towns in the Trzebnica municipality also lack direct connections to Wrocław, and Będkowo is the only stop on the Trzebnica–Wrocław bus route from this municipality. In view of the above, a fairly extensive area with very limited access to bus transport is clearly visible north of Wrocław. This area covers the municipalities of Oborniki Śląskie, Trzebnica, Prusice, and Zawonia. The second area with limited access to bus connections to Wrocław comprises a string of municipalities from the municipality of Kostomłoty through the municipality of Środa Śląska to the municipality of Brzeg Dolny (i.e., areas generally located to the west of the core). Other areas without connections to Wrocław are located in the municipality of Kąty Wrocławskie. While Brzeg Dolny, the largest city in the study area, has train connections to Wrocław (although it clearly has fewer connections than, for example, Oborniki Śląskie), Kostomłoty has neither bus nor train connections because there is no railway in the area of the municipality. An important role in transport within the municipality is played by the A4 motorway, but it has no significance in public transport inside the agglomeration. The situation in the municipality of Środa Śląska is not suitable. The number of bus connections is very limited, and there are no connections to Wrocław, for example, in cases of large villages like Ciechów (which has over 1,500 inhabitants) and Szczepanów (in this case, the nearby location of Środa Śląska station compensates for the situation to some extent). It is worth emphasizing that the Środa Śląska railway station is located about 3 km from the city center, and the distance from Szczepanów is about 800 m, which allows inhabitants of the village to travel by train comfortably.

The municipalities located further from Wrocław in the second ring of municipalities have even lower possibilities of using direct bus to Wrocław. On the other hand, there is sometimes an efficient alternative like train connections (e.g., in Oława). However, more than half of the locations of the neighboring rural municipality, Domaniów, have no connections with Wrocław. The municipality of Borów, located south of the municipality of Żórawina, which is well served by direct buses, is also without connections. Another example is Borów, the center location of the Borów municipality, which also has many locations without bus connections to Wrocław. The center is without railway connections, and the only rail stop is in Boreczek, which has less than 200 inhabitants. About 70% of locations in the municipalities of Oleśnica, Jelcz-Laskowice, and Dobroszyce do not have access to connections to Wrocław. Although the centers of these municipalities are connected to Wrocław by rail transport, Dobroszyce (the center of the municipality of the same name), for example, has no bus connections. The remaining municipalities where the majority of locations do not have direct access to the agglomeration core are Jordanów Śląski, Mietków, and Sobótka. The proximity of these municipalities may allow a possible improvement of accessibility by creating new connection routes. The municipalities of Kąty Wrocławskie, Wisznia Mała, Miękinia, Siechnice, Żórawina, and Długołęka are well-connected with Wrocław, although not each location has direct bus connections to the core. Many locations in these municipalities are close to Wrocław, which indicates that closer proximity with a core generally implicates better communication with the core. Exceptions include locations in the municipality of

Oborniki Śląskie, where the proximity to Wrocław in bus connections is not noticed and the transport system to Wrocław is based solely on rail connections.

4. AREAS WITH LIMITED ACCESS TO BUS CONNECTIONS TO WROCŁAW

When examining the accessibility of towns located in the research area, certain assumptions regarding the interpretation of the obtained results should be made. It is trivial to make assumptions about the general availability of bus transport, which is expressed by the possibility of traveling by bus. It is obvious that the lack of bus connections to Wrocław means a lack of access to this transport mode. The number of such localities is 372, which, given the total of 595 localities, means that 62.5% of localities in the analyzed area do not have direct bus connections to Wrocław, while 83% of locations in the second ring of municipalities do not have such connections. It is worth looking at the spatial distribution of the locations in view of the number of direct bus and minibus connections to Wrocław. In principle, this number corresponds to the number of connections from the main stop in a given location (i.e., the stop that is a transfer node in a given city and is served by all connections from a given city). Fig. 1 presents the spatial differentiation of the number of connections based on the above assumptions. Excluded from the analysis, as mentioned above, are Oława and Oleśnica.

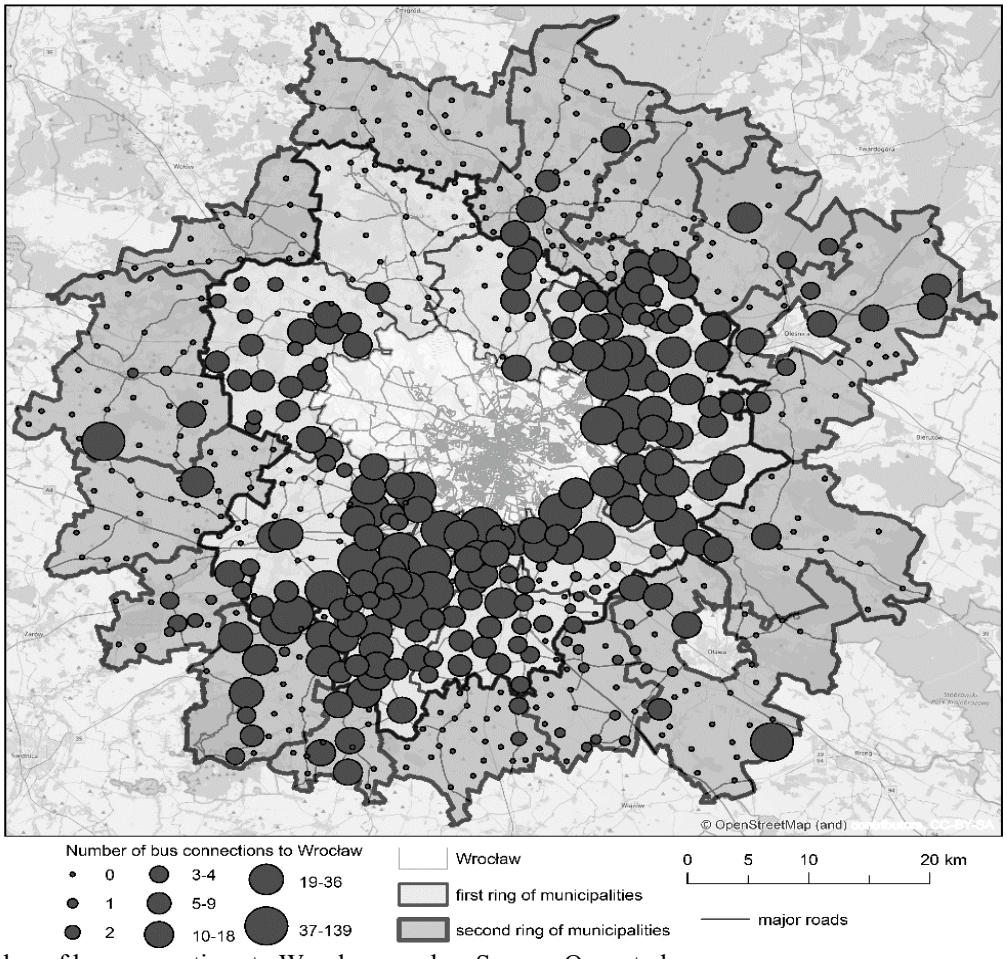

Fig. 1. Number of bus connections to Wrocław per day. Source: Own study

The designated ranges for the number of connections per day refers to the frequency of connections and assumptions described above. A number of connections below five illustrates a situation in which the average frequency of connections is less than one service every three hours, which de facto makes the traveler highly dependent on timetable assumptions. If there are five to nine connections, there is a

possibility to travel in intervals of between two and three hours, which, under the right conditions, may be sufficient. A number of connections between 10 and 18 means a frequency of about one service every 1.5 hours, with 18 connections indicating an hourly clock-face timetable between 05:00 and 23:00. A greater number of connections corresponds to the clock-face timetable of, for example, 36 connections (every 30 minutes) and 72 connections (every 15 minutes).

The delimitation of zones of limited access to bus connections to Wrocław may be done through regionalization based on the number of connections. This, in turn, is possible owing to interpolation methods that estimate the theoretical level of accessibility on the example of known numerical values. The EBK method is helpful in determining areas with various levels of accessibility to direct buses to Wrocław based on the number of connections. Fig. 2. presents the zones determined in the interpolation by the this method with the assumption that the level of accessibility is measured by the number of connections.

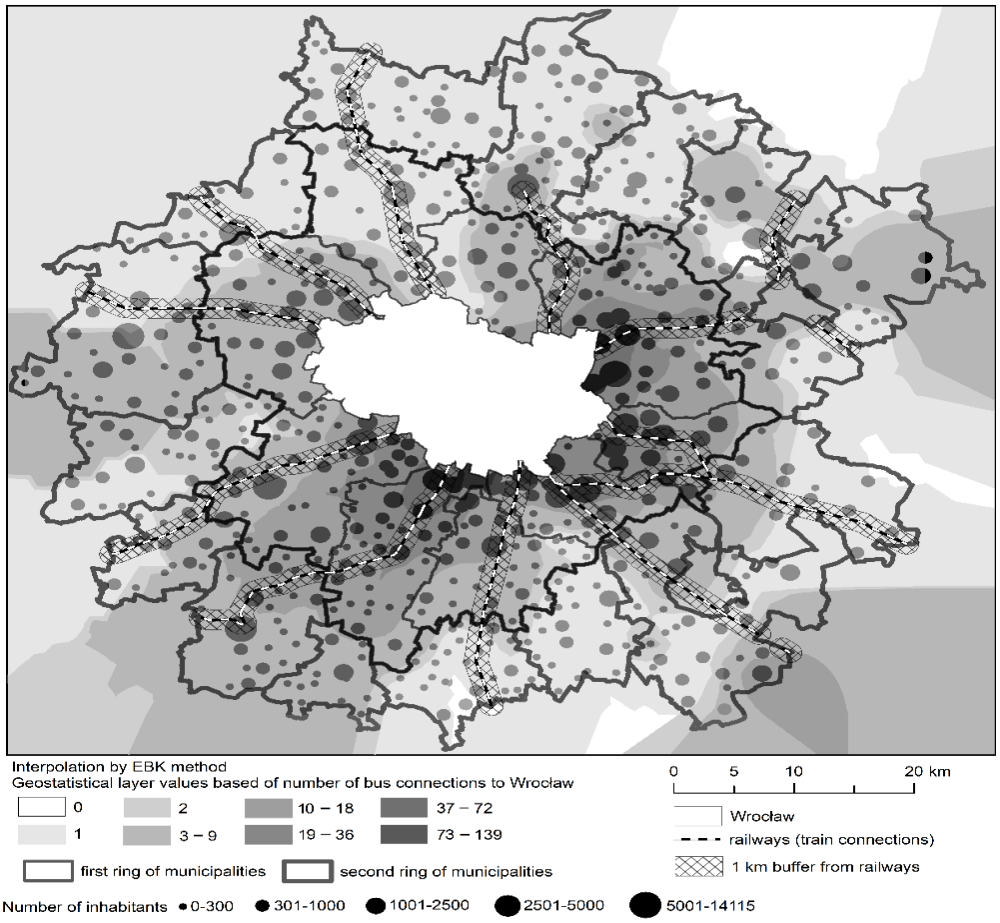

Fig. 2. Transport accessibility zones determined on the basis of the number of connections using the empirical Bayesian Kriging (EBK) method

The above assumptions are based on Tobler's law of geography, which states that objects are located in a certain vicinity are similar, so the level of accessibility to bus connections in areas located closer to stops with more connections will be higher [30]. The leader in terms of the average number of connections per day is Bielany Wrocławskie. This town benefits from its location near the borders of Wrocław as a transport node, for example, for the A4 motorway and the motorway bypass of Wrocław (A8). In addition, one of the largest shopping and production centers in Central Europe operates in this location. Several thousand employees are employed here and come to this area to work every day. This village is served by, among other transportation modes, MPK Wrocław buses, ensuring very good connection times. In addition, the municipality of Kobierzyce, where Bielany Wrocławskie is located, is served by several operators, including only those serving this municipality. This allows for an average

of 139 connections to Wrocław, which translates to one connection every 10 minutes during the day and night and one connection every seven minutes between 06:00 and 22:00. The second-ranked area in this respect, Długołęka, boasts 66 connections per day, which means one connection every 15 minutes on average during the day. Only towns located directly south of Wrocław have a similar frequency of connections. On the other hand, they are provided every hour on average for the inhabitants of Święta Katarzyna, Smardzów, Iwiny, Karwiany, Komorowice, and Trzebnica. However, the number of connections is very weakly correlated with the number of inhabitants of the town. The Pearson correlation coefficient for these features is 0.24, which, in practice, manifests itself in the fact that both large and smaller towns have similar levels of accessibility to bus transport.

The interpolation shows areas where, in general, towns and cities show insufficient access to bus transport, as well as those from which many buses depart to Wrocław. In addition, the different sizes of symbols representing towns indicate population potential. Fig. 2 should be interpreted as follows: areas marked with a dark color are characterized by high accessibility, as indicated by one connection more often than every hour between 05:00 and 23:00 (from value class 19-36 to a maximum of 139 connections in the case of Bielany Wrocławskie). The brighter the color, the fewer connections are possible. In the case of the first three low classes, where the maximum number of connections is two, there is no flexibility in traveling to Wrocław by bus. The fourth class is characterized by connections no more often than every two hours, which does not allow us to determine the availability at a level that ensures reliability resulting from the existence of alternative connections in short time intervals. The figure also shows the differentiation of localities in terms of the number of inhabitants, with larger symbols signifying a greater population potential. Therefore, a comprehensive interpretation of the figure consists of separating areas based on four possible situations: when a small locality is characterized by low accessibility (a symbol of small size and an area marked in a light color), a location with few inhabitants is characterized by high accessibility (symbol of small size and an area marked in a dark color), a large locality is characterized by low accessibility (large size symbol and an area marked with a light color) and a large locality is characterized by higher accessibility (large size symbol and an area marked with a lighter color). In addition, the location close to the railway and train stops should be taken into account, which gives an alternative to the bus in the form of a train and allows access to Wrocław. In Fig. 2, the zones of locations close to the railway are in the 1-km-long buffer zone. In summary, while zones marked with a dark color have good connections with Wrocław, there are cases when locations with quite a large number of inhabitants are located in areas with low accessibility to direct bus connections to Wrocław. Moreover, they do not have direct railway connections.

From among the first ring of municipalities characterized by the greatest problems with the availability of bus transport in commuting to Wrocław, Oborniki Śląskie should be mentioned. It is the only municipality located in the neighborhood of Wrocław. The locations which are not located on railways do not have direct connections to the core of the agglomeration. The situation is similar in the western part of the Wisznia Mała municipality, the north-western part of the Kąty Wrocławskie municipality, and the southern part of the Siechnice municipality. The centers of these municipalities have connections with Wrocław (only by train in Oborniki Śląskie). Due to the proximity of these municipalities to Wrocław, the low level of accessibility forces a priority intervention to improve this negative situation. It is also worth noting that the municipalities of Czernica, Kobierzyce, and Długołęka are very well connected, which is confirmed by the area differentiation in Fig. 2.

In the second ring of municipalities, there are municipalities with more or less access to bus connections. Evidently, lower accessibility occurs in the municipalities located in the northern part of the analyzed area, including Prusice, Trzebnica (excluding Trzebnica), Zawonia, Brzeg Dolny, the northern part of the Środa Śląska municipality; the municipalities of Domaniów, Borów, Kostomłoty; and the most remote parts of the municipalities of Mietków, Oława, Jelcz-Laskowice, and Oleśnica. The municipalities of Sobótka and Jordanów Śląski, as well as the southern part of the municipality of Środa Śląska, are characterized by good accessibility. However, attention should be paid to the limitations of the EBK method, which, as a method of describing the transport accessibility of a given area based on the number of connections, has not been described in the literature so far. Like other interpolation methods, it is vulnerable to extrapolation, which can cause misinterpretation. Therefore, the above attempt to determine zones based on point data for localities is not an exact delimitation but an example

of such zones. Nevertheless, the analysis makes it possible to correctly determine the general areas where travelers to Wrocław have worse or better chances to travel by bus. Therefore, it is advisable to create public service connections that serve as many locations as possible in areas with lower accessibility. At the same time, their routes should be planned in the most optimal and economically justified way possible.

5. SOLUTIONS FOR EXTENDING CONNECTIONS TO THE AGGLOMERATION CORE

The organization of bus transport is a challenge that requires balancing many factors determining the attractiveness and economic justification of a given connection. It is never possible to provide direct connections between all locations of a settlement system. The spatial structure of buildings located in the immediate surroundings of Wrocław is described in detail [31]. In the minds of many people, a change of transport mode is still an effort, and the elderly and people with limited mobility may not choose a connection with a change due to inconvenience. The main problem is planning routes in such a way that they serve locations without alternative means of access. However, the road network and its constraints should naturally be taken into account. Other important issues are the cost-effectiveness of the connection (including the number of vehicles used, the length of the route, and the time allocated for commuting) and the need for an adequate supply of places and connections. A very important factor is financing, which is often one of the biggest barriers to implementing connections. The transport organizer is usually a municipal or a municipal-county association. Legal regulations in this area are discussed in more detail [32]. In case of areas with low accessibility to bus connections it would be advisable for public transport connections to be organized by municipal and county associations in cooperation. In the case of bus transport, it is quite common to double route sections to serve an additional location. However, it is recommended that the route be as short as possible and the number of locations, especially those with a higher population potential, be as great as possible. The time between the start of the journey and arrival at the destination should not exceed a certain set level. According to timetables, existing bus connections in city agglomerations rarely need more than 90 minutes to reach their destination, so this example can be taken into account in the case of this study.

The factors mentioned above were included in the solutions, the target of which is to increase the efficiency of bus transport in areas with low accessibility to direct connections to Wrocław. The solutions include proposed routes of new bus connections, which would be the main sources of improving the level of accessibility to direct connections to Wrocław for the first two rings of municipalities around it. The routes were developed in the PTV Visum program, in which the routes, travel times, number of vehicles, and frequency of connections were determined in the GIS environment. As a result, three exemplary connections were created, serving the areas with the lowest accessibility in the most balanced way and providing direct connections to Wrocław with an average travel time of the entire route in 75 minutes. The potential number of new passengers should be considered to be inhabitants of the mobile age of towns completely deprived of direct connections to Wrocław, both by bus and train (40% of the total population). The proposals are presented in Tab. 2.

The ideas included in Tab. 2 would ensure adequate accessibility to direct connections to Wrocław, including a clock-face timetable no less frequent than every two hours. As a result, it should be expected that two vehicles serving each other would be used to service the connections. In addition, the routes would ensure inter-municipal multimodal communication with access to transfer nodes within railway stations in, for example, Skokowa, Szczepanów (Śróda Śląska), and Dobroszyce. As a result, passengers would be able to travel not only directly to Wrocław but also in various directions by train. An example of a fairly important route connecting Prusice to Wrocław is presented in Fig. 3.

The Fig. 3 shows the route of the connection, the traffic graph for the connection to Wrocław, and the return route generated in PTV Visum. It is visible that the travel time from Strupina to Wrocław would be approximately 80 minutes, with a 10-minute break after the end of the journey, followed by a return journey. As a result, two vehicles would operate the connection every 100 minutes between 05:00 and 21:15, which would give 11 connections per day. As a result, inhabitants of Prusice would be able to travel to Wrocław directly and access Skokowa, where it would be possible to change to a train to, for example, Wrocław or Poznań. In addition, multimodal solutions would significantly increase the

possibilities of using public transport in general mobility beyond the Wrocław agglomeration. This connection could be organized in cooperation between the municipalities of Prusice and Oborniki Śląskie. As the second municipality is fully dependent on trains and has by far the lowest accessibility among the municipalities of the first ring, special attention should be paid to solving the problems of accessibility to public transport in this area. The idea above is an example for public transport organizers to consider and analyze. Multimodal passenger transport could also be used on other routes, such as Kostomłoty/Ciechów – Środa Śląska/Szczepanów and Zawonia – Dobroszyce. These routes would primarily serve to connect with Wrocław and the centers of municipalities located in the second ring of municipalities of the agglomeration, including Kostomłoty and Zawonia. The routes could be planned to ensure access from the largest towns of a given municipality to its seat, to the nearest important railway stations (multimodal nodes), and, as a result, to Wrocław.

Table 2

Proposed routes of new bus connections between the immediate surroundings and the core

Starting point	Route	Number of maximum potential passengers
Strupina	Strupina – Skokowa – Prusice – Kuraszków – Oborniki Śląskie – Rościsławice – Uraz – Paniowice – Wrocław	2,600
Rzeczyca	Rzeczyca – Brodno – Szczepanów – Środa Śląska – Ciechów – Piersno – Kostomłoty – Piotrowice – Rakoszyce – Bogdaszowice – Krzeptów – Wrocław	2,400
Złotów	Złotów – Czeszów – Zawonia – Łuczyna – Dobroszyce – Dobrzeń - Wrocław	3,300

Source: Own study.

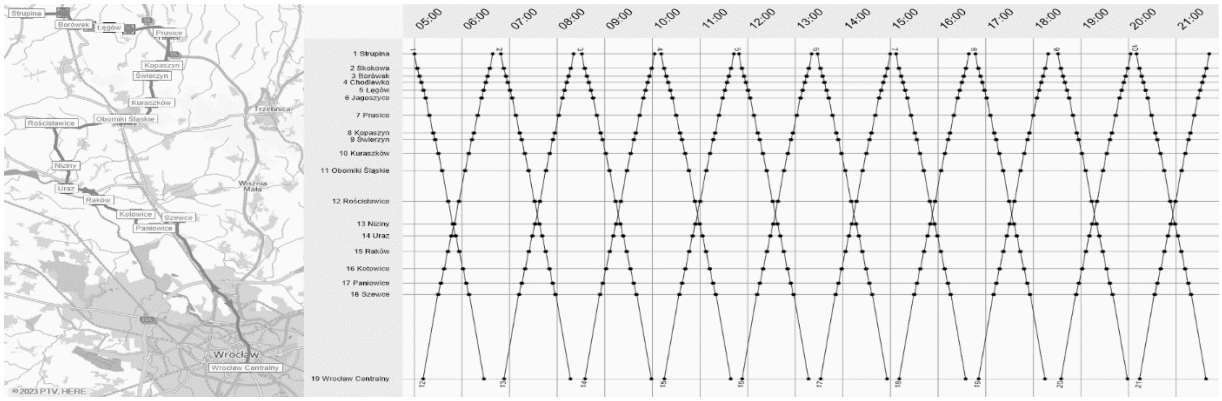

Fig. 3. An example of the route of the proposed new bus connection to Wrocław for Prusice as a city without direct connections. Source: Own study at PTV Visum

Also, among the existing connections from Trzebnica to Wrocław, it is worth noting the already functioning multimodal passenger transport, as buses end their runs at the Wrocław Nadodrze multimodal node, where it is possible to change the transport mode. This node is one of the examples of a well-functioning interchange of this type in Wrocław [33]. Perhaps it is also worth considering the cooperation of the municipalities of the Wrocław agglomeration and Wrocław in the context of multimodal nodes in Wrocław and their service by newly established bus connections. It is worth emphasizing that, as a result, according to calculations, more than 20,000 inhabitants of the agglomeration would gain access to bus connections, and 40% of them could have features conducive to mobility within the analyzed area, including commuting to Wrocław.

6. CONCLUSIONS

The accessibility of the municipalities of the Wrocław agglomeration to direct bus connections to the agglomeration core is highly varied. While the municipalities located to the south and east of Wrocław

are very well connected with the core, its neighboring municipality of Oborniki Śląskie, located to the north, is completely devoid of direct buses to the agglomeration core, and the only mode of public transport is a regional train. Several municipalities have no public transport connections to Wrocław, including the municipalities of Kostomłoty and Zawonia, as well as Brzeg Dolny and Prusice, where only some locations have direct trains to Wrocław. The population of the towns located in the analysis area that do not have direct bus connections to Wrocław exceeds 130,000. Overall, 58% of all towns are characterized by an unacceptable level of access to bus connections to Wrocław due to their absence or very small number. Spatial analyses, including the use of the EBK interpolation method to identify areas with varied accessibility, allowed us to specifically identify areas of various levels of accessibility based on the number of connections from a given stop to individual zones in the Wrocław agglomeration. This made it possible to identify areas with higher and lower accessibility. In some municipalities, there are organized transport connections to the center of the municipality (e.g., in Trzebnica and Środa Śląska). However, the required change between two connections or even modes is still a significant barrier, which is confirmed by the research of both the authors and other researchers. Therefore, it is advisable to solve the identified low accessibility problems. The authors propose several solutions, including bus routes, which would provide direct access to Wrocław for over 10,000 mobile people. While this solution would be relatively inexpensive, it would require agreement between local government units. Another opportunity is the Bus Transport Development Fund and central support, which could enable practical solutions to the problems identified in the study and enable tens of thousands of inhabitants to use reliable bus connections on the way to Wrocław.

The spatial distribution of the availability of bus connections clearly refers to the course of the most important communication routes. The largest amount of bus traffic is generated along DK8, which crosses Wrocław from the southwest to the northeast and covers the municipalities assigned to the so-called second ring. In addition, it can be noticed that the most favorable access to this means of transport is characteristic of the most affluent municipalities, whose budgets allow them to launch their own communal bus transport systems. The continuous and above-average increase in the number of inhabitants of municipalities (mainly in the first ring), which is the result of the constantly advancing suburbanization process, is also significant for the number of bus connections provided.

It should be emphasized, however, that the organization of public transport is increasingly efficient in the Wrocław agglomeration and is associated with rail transport (there are 11 possible railway directions from Wrocław, and the offer of passenger rail connections is constantly expanding). However, bus transport, due to its specificity (there are definitely greater possibilities in penetrating space), will continue to decisively eliminate the phenomenon of transport exclusion. Skillful management supported by a well-thought-out economic calculation; far-sighted policy at the state, regional, and subregional levels; and the popularization of zero or low-emission vehicles provide a chance that some (but certainly not all) of the problems related to the functioning of bus connections may be solved.

The proposed method for determining accessibility zones (in this case, the availability of public bus transport) based on the Bayesian Kriging method may find wider application in the development of similar accessibility zones for other agglomeration centers. However, the use of this method must take into account the specificity of a given research area, which requires the identification of certain conditions (e.g., determining the route of railway lines with the use of a distance buffer, which is an important alternative to public transport, taking into account the population or infrastructure potential) characteristic of a given center. It has to be highlighted that the EBK method is not commonly used as a geostatistical tool in the case of transport analysis; thus, the above work is also a proposal to use this method to determine zones of differentiated accessibility based on point data. In summary, the obtained results make it possible to determine zones with higher and lower accessibility, and in the case of problem zones, sample connections were proposed, the implementation of which could allow for better communication within the research area. The solutions presented above may inspire discussions in the effective planning of public transport in the Wrocław agglomeration.

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