COMPARATIVE ANALYSIS OF THE ACCESSIBILITY AND CONNECTIVITY OF PUBLIC TRANSPORT IN THE CITY DISTRICTS OF KRAKOW

Analiza porównawcza dostępności i łączności transportu publicznego w dzielnicach Krakowa

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Abstract:
A properly functioning public transport is one of the most important components of urban mobility for the population. Due to spatial inhomogeneity and overall socio-economic differences within a city, there are often considerable disproportions in the quality of transport services within its districts. Also, the city of Krakow is no exception in this case. For a comparison of public transport accessibility in 18 Krakow districts, 7 major quantitative and 5 minor indicators were created. These indicators include the most important characteristics of transport services such as accessibility, frequency, connectivity of connections, and ratios of tram public transport subsystem. The resulting values give a fairly comprehensive picture of the quality of the transport services. Overall higher values for most indicators occur in the central districts of the city. However, due to the complexity of the observed characteristics, it is possible to discover significant differences in the structure of individual indicators. Peripheral districts reach higher amplitudes, which means that in some aspect they have even better transport services than the city center. Yet, at the same time, we also find opposite extremes here, highly below-average values for most other indicators. A detailed analysis of the results provides a unique perspective on the disparities among districts. It can also serve for specific identification of strengths and weaknesses of transport services and its possible optimization.

Keywords: comparative analysis, Krakow, public transport indicators, connectivity, accessibility

1. Introduction

Urban public transport can be divided into bus, trolleybus, tram, cable car, (sub)urban rail, and unconventional transport subsystems (Drdla, 2018). This study deals exclusively with the tram and bus subsystem. The main source data for the analysis is taken from (MPK Kraków, 2019). The research area covers the city of Krakow within its administrative boundaries. The delimitation of the area for comparative purposes is based on the administrative division of the city into 18 districts. The very nature of the whole analysis is thus closely connected with a very general division, which does not allow a completely accurate objective comparison for public transport data. However, it is the generality of the administrative division that makes it easier to compare the results of the analysis with other socio-economic data, which are often only available for city districts. The main goal of this article is to present a new analysis method of selected geographical indicators based mainly on urban transport accessibility and connections, important factors of transport services. The study also aims to answer two summary questions. How are the individual values of selected indicators distributed in Krakow and How do the ratios of indicators differ within the given city districts? In addition to these basic questions, there is an effort to briefly mention similarly focused studies and compare their methodologies.

2. Studies of public transport accessibility

If we want to compare territory units in terms of the quality of their transport network and service, the cornerstone of such research is an analysis of transport accessibility. In general, studies can be categorized by research area and methodology used. This chapter aims to briefly outline the diversity of studies related to transport accessibility. Due to the large number of publications on a similar topic, only a representative sample was selected. (Puławska, 2014) deals with the evaluation of transport accessibility in specially defined subdistricts of Krakow. The accessibility level is described by 8 relative indicators, which are divided into two groups, firstly the indicators related to the infrastructure and secondly indicators related to service quality. The possibility of practical use of accessibility modelling in the form of valuation of a selected area is documented by the doctoral thesis of Puławska (2018). Another attempt to analyze the accessibility of connections within public transport is represented by Kisielewski, Skóra (2016). They work separately with time and spatial accessibility. A particular emphasis is put on access to public transport stops within the city of Poznań in Gadziński, Beim (2010). Moreover, due to

the similar structure of urban transport and the size of Poznan, there can be used the same methodology of this article for the city of Krakow too. (Soczówka, 2013) concerns the accessibility within the specific region Upper-Silesian conurbation, which includes among other 9 cities above 100 000 inhabitants. The analysis is mainly based on the percentage of community areas within walking distance to stops zones. The area of the capital of Warsaw is the focus of interest for Mościcka, et al. (2019). Their methodology consists of three principal components: travel time analysis, travel speed analyses and potential accessibility analysis. Completely different methodologies are applied in articles dealing with the use of GIS tools for analysis and evaluation of public transport services. An example of such an article may be Horak, et al. (2017), who for the analysis of public transport conditions uses simulations of commuting to important employers with cluster analysis. Yan-yan, et al. (2016) evaluates the transport value by a relatively new method APTA (Area Public Transit Accessibility). With this concept, the passenger travel behavior, travel psychology hypothesis and the service range of transit network and road network are examined. The possibility to connect the topic of land use changes given the spatial accessibility of all transport systems presents (Fuglsang, Mansen, Münier, 2011). From a wide range of researches dedicated to public transport accessibility, it is worth mentioning further (Saghapour, Moridpour, Thompson, 2016) with their approach incorporating population density in metropolitan areas, Bok, Kwon (2016) concerning using method GTFS feed and demographic data, Jackiva, Budiloviča, Gromule (2017), who deal with transport characteristics more broadly, relating urban, regional and international transport system by case study the city of Riga and the key destinations in Baltic states, or Murray et al. (1998) with their examination of public transportation access in South East Queensland region of Australia.

3. Research area

As of June 30, 2019, the city of Krakow was the second-largest city in Poland with 774.800 inhabitants (GUS-Kraków, 2020). According to Resolution XXI/143/91, available on (BIP-Miasto Kraków, 2020), Krakow has been divided into 18 districts. Table 1 summarizes the complete list of districts with their basic characteristics. The city districts serve not only as administrative units but also as main statistical units for which it is possible to compare individual large parts of the city an effective way. The main advantage of such a division of the city is a delimitation of relatively homogeneous large units for which comparative analyzes can already be made. The most important

attributes of demarcated units are population and area, respectively population density. In this respect, the most important districts in Krakow are Prądnik Biały, the largest one in terms of population, and Nowa Huta, the largest one in terms of area. In terms of population density, the highest value is related to Bieńczyce. The central districts rank rather to average and below-average parts of the city. However, to compare the overall significance of a given unit within a city, it is necessary to include in the attributes also the centrality, availability of services, and many others. One of the more complex attributes is also the quality of transport services, which we can measure by various types of indicators.

In Krakow, there is a relatively extensive public transport system consisting primarily of a bus and tram subsystem. Another important transport subsystem, the suburban railway, together with trams and buses, forms an integrated transport system serving the entire Krakow metropolitan area. We can also find water tram transport in Krakow. It is not operated all year round though, but only during the main tourist season from 1 May to 30 September (Krakowski Tramwaj Wodny, 2020). The vast majority of the public transport network is managed by a transport company MPK Kraków. According to (MPK Kraków, 2019), as of June 6, 2019, there were a total of 196 lines in operation (172 bus and 24 tram lines) and 736 stops within the boundaries of Krakow municipality. In 2011, there were 693 stops in Krakow (Bryniarska, 2012). Naturally, the number of lines and stops is constantly changing, not only in the long-term development but also during medium and short-term reconstructions of transport infrastructure. The continuous change concerns all possible characteristics of the transport system. Therefore it is essential to take the results of any analysis of traffic data very circumspect concerning its period of origin.

Tab. 1. Basic characteristics of Krakow's districts in 2019.

Number of district	Name of district	Area (km^2)	Population	Population density
I	Stare Miasto	5.57	31 359	5 632.4
II	Grzegórzki	5.85	29 474	5 042.4
III	Prądnik Czerwony	6.44	46 627	7 242.6
IV	Prądnik Biały	23.42	70 647	3 016.7
V	Krowodrza	5.62	30 223	5 378.7
VI	Bronowice	9.56	23 678	2 476.9
VII	Zwierzyniec	28.73	20 392	709.8
VIII	Dębniki	46.19	61 637	1 334.5
IX	Łagiewniki-Borek Fałęcki	5.42	15 259	2 817.9
X	Swoszowice	25.60	27 493	1 073.8
XI	Podgórze Duchackie	9.54	53 747	5 633.9
XII	Bieżanów-Prokocim	18.47	62 830	3 401.0
XIII	Podgórze	25.67	36 885	1 437.1
XIV	Czyżyny	12.26	29 635	2 417.8
XV	Mistrzejowice	5.59	52 011	9 304.3
XVI	Bieńczyce	3.70	41 112	11 114.4
XVII	Wzgórza Krzesławickie	23.82	20 205	848.4
XVIII	Nowa Huta	65.41	51 234	783.3
	Kraków	**326.84**	**704 448**	**2 155.3**

Source: Own elaboration from (BIP-Miasto Kraków, 2019).

4. Methodology

The analysis is based on 7 major relative indicators and 5 minor relative indicators. These indicators represent main public transport statistics, which enable comparison of all the city districts with relative ease. Here is the list of 7 used major indicators along with an explanation of the variables:

$$I_1 = \left(\frac{CS_w}{P} \right) \cdot 1000$$

$$I_3 = \left(\frac{S}{A_{ha}} \right) \cdot 1000$$

$$I_5 = \left(\frac{CL_w}{P} \right) \cdot 10\,000$$

$$I_2 = \left(\frac{CS_h}{P} \right) \cdot 1000$$

$$I_4 = \left(\frac{L}{S} \right) \cdot 10$$

$$I_6 = \left(\frac{CL_h}{P} \right) \cdot 10\,000$$

$$I_7 = \frac{\left[\left(\frac{CST_w}{CS_w} \right) + \left(\frac{CST_h}{CS_h} \right) + \left(\frac{L_t}{L} \right) \right] \cdot 100}{3}$$

CS_w = average number of connections per stops during one working day (W)

CS_h = average number of connections per stops during Sunday or public holiday (H)

P = number of inhabitants (population)

S = number of stops

A_{ha} = area in hectares

L = number of lines

CL_w = average number of connections per lines during one working day (W)

CL_h = average number of connections per lines during Sunday or public holiday (H)

CST_w = number of tram connections per stops during one working day (W)

CST_h = number of tram connections per stops during Sunday or public holiday (H)

L_t = number of tram lines

The structure of the indicators was intentionally selected so that the resulting values are within a certain amplitude. The first two indicators, followed by the fifth and sixth indicators, express the frequency of connections, separately during the working days of a week and Sundays or public holidays. The frequency of connections is also relativized to both stops and lines. Data for Saturdays are not included in the statistics in this case. The reason is only a slight difference in values compared to Sundays and public holidays. The third indicator characterizes the density of stops within the defined area of a given urban district

and thus the spatial accessibility of urban transport. A total of 736 stops were included in the analysis. All points (stops) with the same name are considered to be one specific stop. The problem of uncertainty in the allocation of stops at the border of urban areas was solved by a simple ad hoc rule. This consists in assigning border stops always to the outer district, further from the city center. Another important factor in the quality of the transport network is the connectivity of lines, which is linked to the fourth indicator. The last observed traffic characteristic is a synthetic indicator comparing the ratio of the tram subsystem in the overall public transport system. Each of the 7 indicators is designed so that its higher value means a higher level of transport services. All used statistics were obtained from the main website of the transport company of the City of Krakow (MPK Kraków, 2019). The cut-off date was June 6, 2019.

The other 5 minor indicators provide additional pieces of information on the level of transport services for each district of the city. Unlike the main indicators, they do not serve as a complementary part of statistics to the overall sum of the selected characteristics. They can be described as follows:

1) Number of stops per 1000 inhabitants
2) Number of connections (W) per one person
3) Number of connections (H) per one person
4) Number of connections (W) per one stop
5) Number of connections (H) per one stop

5. Results of analysis

Given the nature of a large amount of traffic data, some compression is required to highlight the statistics sought and vice versa to reduce the quantity of redundant information. The results of the analyzes can be divided according to the above methodology into major and minor indicators.

5.1. Major indicators

In order to compare the sums of indicators in individual districts, it has been necessary to relativize the output data. In this case, all values within a given indicator have been related to the highest value achieved. The maximum score of a district has been 100 % and the total max. a possible score of all indicators has so meant 700. Fig. 1 gives a comprehensive picture of the distribution of all indicator values. The higher the value lies, the better is the transport service.

in the center or close neighborhood of the city center. A range of moderately high values between 400 and 500 includes districts Bieńczyce, Łagiewniki-Borek Fałęcki, and Czyżyny. From the opposite point of view, the worst results with a value below 200 have been recorded in districts Prądnik Biały (IV), Dębniki (VIII), Swoszowice (X) and Nowa Huta (XVIII). If we look at the structure of the values within indicators, the most visible differences are connected with the seventh indicator (ratio of tram transport). In Swoszowice and Bronowice there was no tram service in operation in
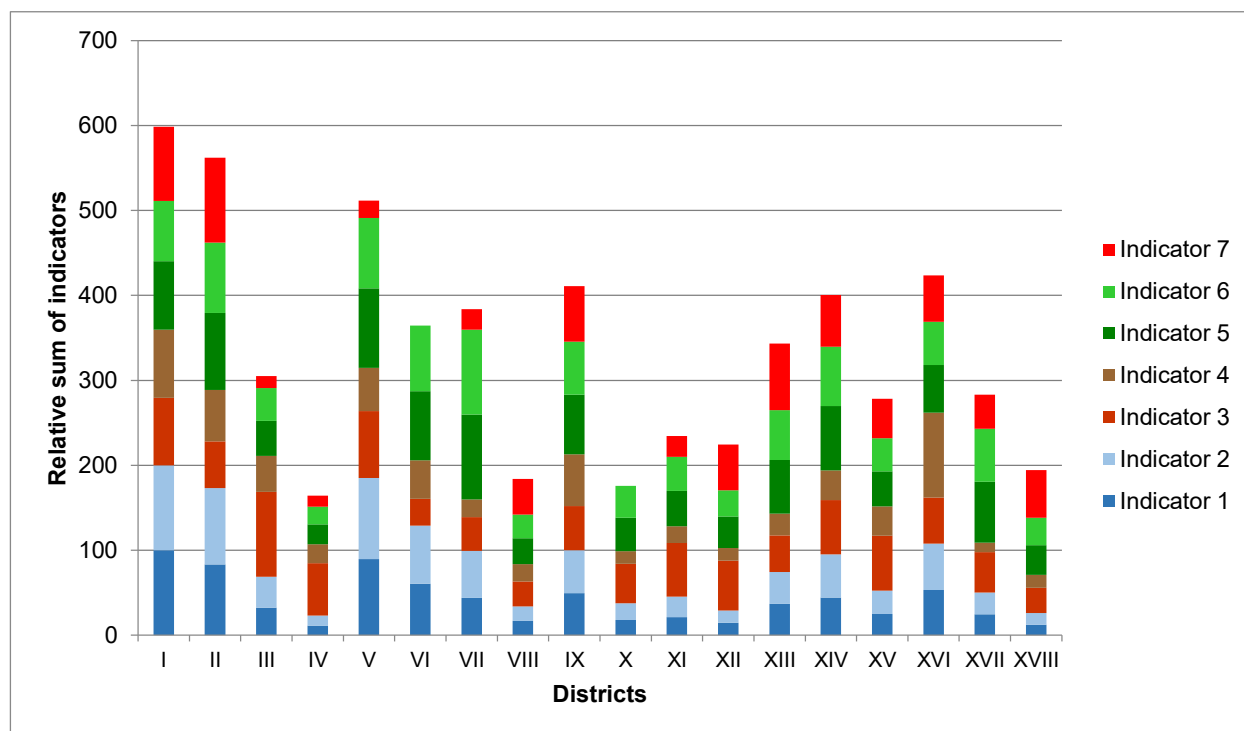

Fig. 1. Distribution of 7 indicators within the Krakow districts in June 2019.

Source: Own elaboration from (MPK Kraków, 2019).

As can be seen, the highest sum of values has been reached by the first two districts, Stare Miasto (I) and Grzegórzki (II). Above the significant value of 500 is district Krowodrza as well, which means, that the best transport services are concentrated mainly

June 2019. But only in the case of Swoszowice it is a permanent state without any tram infrastructure. At the time of processing the traffic data, the tram service was shut down in Bronovice. For a better overview, tab. 2 shows the range of values of each indicator.

Tab. 2. Range of the highest and lowest values of indicators, together with the average value.

Indicators	Max value (district)	Min value (district)	Average value
1	35.11 (I)	3.89 (IV)	14.37
2	19.26 (I)	2.30 (IV)	8.48
3	49.71 (III)	14.72 (VIII)	27.62
4	34.00 (XVI)	3.75 (XVII)	12.72
5	40.64 (VII)	9.50 (IV)	24.22
6	25.74 (VII)	5.37 (IV)	14.09
7	59.15 (II)	0.00 (VI); (X)	25.65

Source: Own elaboration from (MPK Kraków, 2019).

It is worth mentioning, in particular, the value of the third indicator. Spatial accessibility of public transport is best managed in Prądnik Czerwony and creates almost one third of its total value. The fourth indicator, connectivity of lines, in turn, represents a substantial component of the total value in Bieńczyce. The only used synthetic seventh indicator is illustrated in more detail in fig. 2. The low values of the tram line ratios compared to the relatively higher ratios of tram connections on weekdays and holidays confirm the significant capacity importance of the tram subsystem, unlike the bus subsystem. In other

districts have turned out Swoszowice (50,2 %) and Prądnik Biały (52,7 %).

5.2. Minor indicators

Additional statistics of minor indicators further refine the picture of the spatial distribution of the transport services quality. The Number of stops per 1000 inhabitants serves as another characteristic of transport accessibility. However, it can often be distorted by high population density values, such as central districts or Bieńczyce. In the case of the Number of
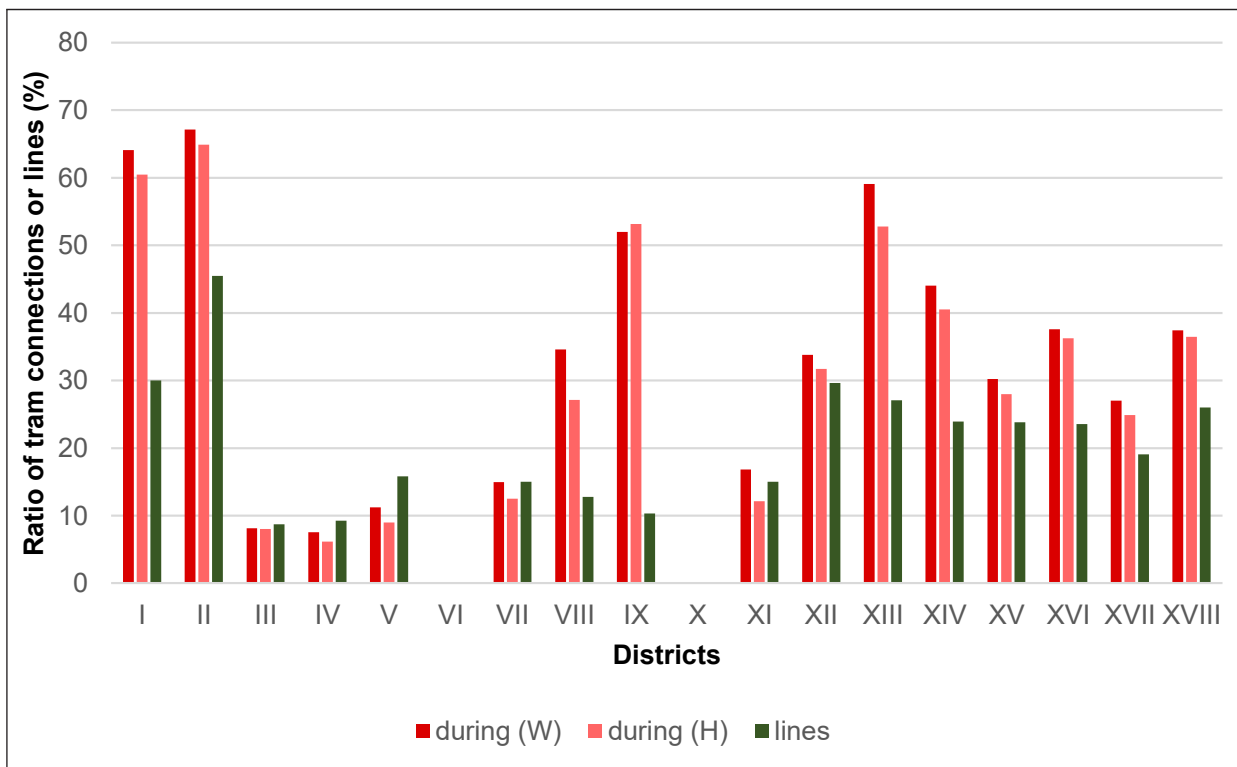

Fig. 2. Detailed statistic of the seventh indicator within the Kraków districts in June 2019.

Source: Own elaboration from (MPK Kraków, 2019).

words, one tram line serves significantly more passengers than a bus line.

Choropleth map in fig. 3 displays both spatial distribution of Krakow districts and the sum of all indicators related to the average value in percent. The limits of the intervals have been set to indicate the main number divides (75, 100, 125 and 150 %). The districts with the highest quality transport services are Stare Miasto (176 %) and Grzegórzki (167 %). 8 out of 18 districts have more than above average transport services. On the contrary, as the worst served

connections per one person (both W and H types), the possibility of misinterpretation is considerably lower. Nevertheless, in all three indicators, the highest value is linked with the district of Zwierzyniec. The Number of connections (W and H types) per one stop effectively complements previous statistics as it adds significant weight to each stop. Here again, the central parts of the city dominate. Taken together, the aforementioned indicators form a complementary combination of significant characteristics within different types of transport services (tab. 3).
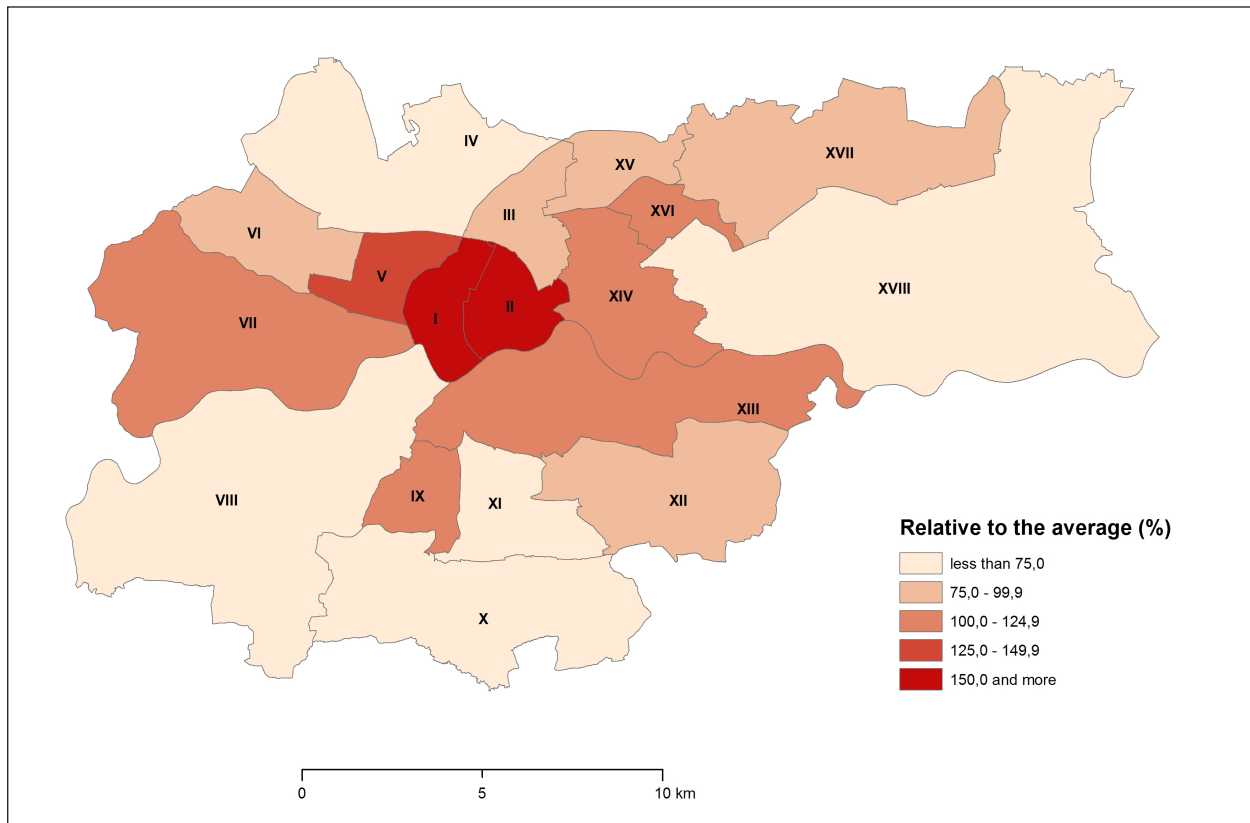
Fig. 3. Percentages of th e sum of 7 indicators in individual districts of Krakow to the average value for the whole city of Kraków in June 2019.

Source: Own elaboration from (GIS-Support, 2020), (MPK Kraków, 2019).

Tab. 3. Complete statistics of minor indicators in June 2019.

Number of district	Number of stops per 1000 inhabitants	Number of connections (W) per one person	Number of connections (H) per one person	Number of connections (W) per one stop	Number of connections (H) per one stop
I	0.70	0.77	0.42	1101.0	604.0
II	0.54	0.47	0.28	861.1	509.9
III	0.69	0.37	0.22	532.5	324.9
IV	1.02	0.28	0.17	275.0	162.6
V	0.73	0.69	0.40	951.0	555.8
VI	0.63	0.32	0.20	504.1	312.3
VII	2.80	0.88	0.61	315.2	216.7
VIII	1.10	0.40	0.22	360.8	202.8
IX	0.92	0.24	0.14	265.0	148.4
X	2.15	0.37	0.23	172.4	105.3
XI	0.56	0.22	0.14	401.7	247.9
XII	0.86	0.28	0.15	321.6	173,9
XIII	1.49	0.71	0.40	475.2	266.6
XIV	1.32	0.61	0.38	461.1	289.8
XV	0.35	0.16	0.10	455.8	275.7
XVI	0.24	0.19	0.11	765.9	432.7
XVII	2.77	0.48	0.28	173.8	100.7
XVIII	1.89	0.42	0.25	223.3	134.6
Kraków	**1.04**	**0.40**	**0.24**	**381.1**	**225.1**

Source: Own elaboration from (MPK Kraków, 2019).

Discussion and conclusion

The author's methodology with own system of indicators has not aimed to create a comprehensive way of evaluating urban public transport. The core of the research has lied in the analysis of transport services. Particular emphasis has been placed on spatial accessibility of stops, frequency of connections, line connectivity and the ratio of tram transport subsystem. From the aforementioned studies on the accessibility of public transport, the author's methodology is closest to Puławska (2014). The main positive differences consist in the inclusion of the total relative sum of used indicators and also in the calculation of more variable transport characteristics. However, the work of Puławska (2014) has the advantage of analyzing the quality of transport services in specially delimited 60 subdistricts. Compared to the official division of Krakow into 18 city districts, it is a far more detailed and accurate study. Concerning the two summary questions for the author's comparative analysis of urban public transport, the results practically confirm the distribution of higher values for all indicators in the central districts of the city. The most distinguished in this respect are the indicators related to the frequency of connections per stops and ratios of tram transport subsystem. Most peripheral districts feature, with a few exceptions, much worse transport services. The level of line connectivity and frequency of connections per line is distributed around the city relatively evenly. More detailed results of the analysis, both the major and minor indicators can be further extended and used either as a partial component of a comprehensive assessment of socio-economic disparities within districts of the city or separately as a study detailing the current state of selected characteristics of transport services.

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