Transport accessibility of Warsaw

Citation for published version (APA):

DOI:
10.3390/su11195536

Document status and date:
Published: 01/10/2019

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.
Article

Transport Accessibility of Warsaw: A Case Study

Albina Mościcka 1,*, Krzysztof Pokonieczny 1, Anna Wilbik 2 and Jakub Wabiński 1

1 Faculty of Civil Engineering and Geodesy, Military University of Technology, 00-908 Warsaw, Poland; krzysztof.pokonieczny@wat.edu.pl (K.P.); jakub.wabinski@wat.edu.pl (J.W.)
2 Department of Industrial Engineering and Innovation Sciences, Eindhoven University of Technology, 5612 AZ Eindhoven, The Netherlands; A.M.Wilbik@tue.nl
* Correspondence: albina.moscicka@wat.edu.pl; Tel.: +48-503-510-470

Received: 15 August 2019; Accepted: 4 October 2019; Published: 8 October 2019

Abstract: In this study, we detected which means of transportation is beneficial from a travel time perspective in specific districts of Warsaw, Poland. To achieve this goal, we proposed a framework to perform a spatial analysis to describe the as-is situation in the city (the state that the situation is in at the present time). The framework contains the following elements: attractiveness analysis, travel time and speed analysis, and potential accessibility analysis. The relationship between the averaged nominal travel speed and the number of residents was also investigated. We used data from a journey planner, as well as land use and population statistics, and employed descriptive analytics. The results are presented as maps of travel times, travel speed, and potential accessibility, as well as scatter plots of dependencies between travel speed and number of residents. Unfortunately, public transportation ranks behind car and bike transport in terms of travel time, speed, and potential accessibility. The largest positive influence on effectiveness of traveling by public transportation is the metro and railway system; also, bikes can perfectly complement the public transportation system. The obtained results can be used to indicate directions of changes in the transportation system of Warsaw.

Keywords: spatial analysis; means of transport; potential accessibility; Warsaw transportation system

1. Introduction

Due to the increasing number of residents in cities, local authorities are trying to provide effective and efficient public transportation [1] in order to reduce the number of private cars in cities and to facilitate the functioning of residents, thus minimizing problems related to city transport [2]. For this purpose, a number of solutions have been implemented which are based on, for example, information about resident mobility obtained from mobile phones [3,4] and urban vehicle traffic data obtained from GPS-based location systems [5,6]. Intelligent transport solutions (ITS) are also being developed [7], including those dedicated to public transport [8].

Most solutions aimed at improving the quality of transport, including urban transport, are based on data analysis. Data selection and applied research methods are probably the most important and commonly used research instruments. Transport data are most often modeled using two types of methods: statistics [9] and computational intelligence (CI) [10]. Karlaftis and Vlahogianni discussed the differences and similarities between these two approaches, taking into account neural networks (NN), an extremely popular class of CI models, which has been widely applied to various transportation problems [11]. They also provided a broad summary of the research done in this area as well as some insights for selecting the appropriate approach.

Additionally, there is a new trend in using open data platforms for solving daily life problems including transportation. An example is the OpenStreetMap (OSM) project [12], which provides open
geospatial data for routing and navigation. OSM is used for planning of urban public transportation networks [13], assessing the completeness of bicycle trails and designated lane features [14], as the base for testing advanced journey planning visualization [15], as well as in research on the availability of transportation for people with mobility restrictions [16,17]. Despite complaints about the quality of OSM data, there are studies about methods for improvement of the quality of data in OSM, also used in the European transportation [18], which provides an opportunity for extensive use of OSM in the future.

The above-mentioned studies are connected with data related to the travel directions of travelers, as well as routes, and the frequency of public transportation. Most of them are based on data obtained during the travel of city residents using buses, trams, or the underground. However, before a passenger uses public transportation, he has to first choose the route and the means of transport. Moreover, whenever a passenger has to go somewhere, he must decide if it is better to choose a private car or public transport. The decision is often based on the available transport connections at the locations from which the passenger departs and to which the passenger is traveling. The decision depends on many factors, such as travel time, means of transport, as well as the number of changes. This is information that a passenger can obtain using online travel planning services such as Google Maps [19]. Recognizing and understanding the reasons why a passenger often chooses a private car instead of buses or trams is one of the key issues for improving the functioning of public transport.

Such issues are factors in accessibility analysis, which has many different definitions in the literature. In abstract terms, accessibility is defined as the ability of multiple elements in a set to engage in a functional relationship. Komornicki et al.’s [20] definition is associated with two characteristic features from the point of view of determining the subject of accessibility. Firstly, there are at least two elements in space that can unilaterally or mutually reach each other (i.e., in one direction or in both directions), and so, that can interact with each other (e.g., source and destination). Secondly, there is a carrier of this relationship (e.g., means of transport). In the real world, these relationships are hindered by many physical, political, social, and economic barriers. In a similar way, one of the most frequently cited definitions in the literature describes accessibility as the potential for the possibility of interaction [21]. Handy and Niemeier [22] underline that interactions should be understood in a broad sense as being both economic and social. According to Ingram’s definition [23], accessibility is an inherent property of a place, associated with a certain form of overcoming the resistance of space (e.g., physical or temporal distance). According to Dalvi and Martin [24], accessibility is the ease of accomplishing any activity, from any place, using a specific transport system. Bruinsma and Rietveld [25] provide another definition, pointing to the “ease of spatial interaction” or the “attractiveness of the network node taking into account the mass of other nodes and the costs of reaching these nodes using the network”. Wegener et al. [26] use a definition similar to that of Dalvi and Martin, which states that accessibility indicators describe a specific location in relation to opportunities, activities, or resources in other locations, where the term “location” can be understood as a region, city, or transport corridor.

Accessibility involves the interdependence of many concepts, such as transport; communication; spatial, social, economic, physical, or temporal accessibility; and so forth. The greatest consensus exists as to the relationship between the notions of communication accessibility and transport accessibility. Communication can be understood as a combination of two components: transport and connectivity [27]; therefore, transport accessibility can be defined as transport availability and connectivity (telecommunications) availability. Social and economic forms of accessibility are associated with individual user characteristics (financial resources, status, and social location), which in turn determine the “reachability” of an attractive object or destination [28]. According to Taylor, spatial accessibility involves overcoming space, regardless of the user’s financial resources. Transport accessibility can be equated with spatial accessibility, assuming that [20]:

- the distance measure is interpreted as the amount of time or cost required to overcome the distance, not just the physical distance;
it is possible to analyze the differences in accessibility resulting from the individual characteristics of the user of the transport network; and

accessibility can also be measured by the infrastructure of a given area.

Regardless of the adopted definition, most of the authors mentioned above indicate two basic components that are integral components of transport accessibility: transport and land use [20]. The transport component reflects the ease of traveling between two points in a space determined by the type of transport. The ease of traveling is determined by the nature and quality of the transport services provided by the transport system. The land use component refers to the attractiveness (importance) of a given destination in the transport system [22]. According to Geurs and van Wee [29], the land use component can be determined according to, for example, the spatial diversity of the supply of destinations and their characteristics (places of work, hospitals, or schools). The inclusion of both components allows feedback between transport policy and land use policy. Thanks to this, transport accessibility can be an efficient tool to indicate the needs and to assess the effectiveness of individual investments related to the construction or modernization of transport networks [22]. In addition to the two basic components listed, some authors also provide temporal and individual components [30].

Many cities in highly developed countries have long researched the causes and factors affecting the choice of public transport instead of a private car. They have made many efforts to boost the use of public transport, such as improving the quality of transportation services, the capacity of lines and service frequency, the coverage, reliability, and comfort, as well as enhancing traffic safety, environmental sustainability and energy efficiency. Such activities can have the greatest effect in those areas of a city where a private car is more attractive to residents than public transport.

Taking the above into consideration, our aim in this study is to determine which means of transportation is beneficial from a travel time perspective in which parts of a city. To achieve this goal, we have developed a framework to perform the spatial analysis to describe the as-is situation in a city, which is the state that the situation is in at the present time. The analysis is based on the time accessibility from each place in the city to each possible destination in the same city, calculated by an Internet journey planner. The scope of analysis described in this paper belongs to the category of descriptive analytics in Gartner’s maturity model of business intelligence [31], which answers the question “what happened?”. Development of more mature analytics in the category of prescriptive analytics, which can recommend improvements and optimizations for a travel system, is the end goal of this research.

Therefore, our research goal for the current paper can be formulated by the following three research questions:

• Which means of transportation is the most efficient for each location in the city?
• Which districts have the best transportation to the most attractive locations in the city?
• Are there such areas in the city where many people live and using a car is better than using public transport from a travel time perspective?

The answers to these questions lead to several important observations. Firstly, they show whether transport in the city is optimized based on places of residence or attractiveness of locations. Secondly, they indicate parts of a city where many people live but public transport is not well planned. Thirdly, they show whether public transport is organized such that it reduces the need to use private cars. The results of the analysis determine the places in the city where it is not profitable to use public transport because transport by private car is usually faster. On this basis, it is possible to demonstrate where modifying an existing or adding a new city bus/tram line is needed to improve access to places inhabited by many potential passengers. The detailed methodology of our research to answer the above three questions is described in Section 2.

So far, no comprehensive research on transport in Warsaw has been carried out, especially considering the transport and land use components and the spatial distribution of people. It is not
known whether existing public transport is optimal and whether it is possible to reduce car traffic in the city by improving public transport.

2. Methodology

To achieve the aim of the analysis, we have used the methodology depicted in Figure 1. The arrows indicate the sequence of the steps.

![Figure 1. Methodology of the analysis.](image)

We started the analysis with data acquisition. The collected data include information about travel times, populations, land use, and attractiveness indicators of certain locations, as described in Section 2.1. The aim of the attractiveness analysis (Section 2.2) is to estimate the attractiveness level of travel destinations. For this purpose, an objective attractiveness measure was proposed. In the travel time analysis (Section 2.3), we processed the gathered travel times and plotted the obtained results on maps of the city. A different view was obtained when analyzing travel speed (Section 2.4). The last step in our analysis was the potential accessibility analysis (Section 2.5), which helped us to illustrate the concentration of the attractive places in Warsaw.

In the following, we describe each of the research steps in more detail.

2.1. Data Acquisition

As a study area, Warsaw, the capital of Poland, was selected. It is a rapidly growing city, in which public transport is chosen daily by more than 50% of residents and is well-rated by 87% of them [32]. Despite this, Warsaw, like many other Polish cities, has one of the highest rates of air pollution in Europe and struggles with a considerable amount of smog, which is often caused by road transport [33]. Therefore, Warsaw authorities are making efforts to encourage more people to give up their private cars and use public transport. However, public transport services [34] do not use advanced data analysis to improve the quality of public transport and do not have objective data regarding the parts of the city where such activities are most necessary, expected, and beneficial.

Moreover, there is substantial age diversity among Warsaw’s residents in its various districts. Some districts are inhabited by almost only (90%) young people (up to 40 years old: Wilanów and Białołęka) and other are pensioner’s districts (Śródmieście, Praga-Północ, and Wola). There is also considerable diversity in population density among the districts. There are post-industrial areas close to the city center with a low number of inhabitants (post-war areas in Ochota and post-industrial areas in Mokotów), as well as areas that are further from the city center but with quite dense buildings that house many people (Wilanów) [35].

For the territory of Warsaw, 601 measurement points were defined on a 1000-meter grid, as shown in Figure 2. Previous works have shown that such a distribution of points is sufficiently fine-grained...
for obtaining reliable results when developing travel time maps and performing time accessibility analysis [36]. For each measurement point, the travel times to the other 600 points were calculated along with the distances and speeds. Travel times, by foot, bike, car, and public transport were determined. The travel times for public transportation and driving by car were measured at 02:00, 08:00, 12:00, 17:00, and 21:00 to get a complete picture throughout the day. The travel times for walking and bicycling were measured only at one moment during the day (at 10:00), because they were assumed to be the same at any other time of day as neither congestion nor schedules play a significant role for these modes of transport. We decided to collect the travel times only at these times because there were only small changes in travel times between subsequent hours. The moments of 08:00 and 17:00 were chosen as representation of the rush hours, i.e., the hours at which most traffic on the roads in Warsaw occurs. The moments of 12:00 and 21:00 were chosen as off-peak hours [37]. The moment of 02:00 represents a night schedule: it was chosen based on the analysis of Warsaw public transport timetables [34] as the time when day lines no longer run and only night bus lines operate. The latest daytime lines in Warsaw are metro lines that operate until 01:00. Maps of public transport lines can be found on the public transport service website [34], under the “maps” menu.

![Figure 2. Measurement points, cells, and district borders in Warsaw.](image)

Travel times were determined using the functionality of Google Maps. Our previous research [36] shows that results from this service are accurate enough for this kind of research. The absolute error of travel time measurement did not exceed 3 minutes. The accuracy of determining travel times from Google Maps using a regular grid of points is at a level comparable with other services [38].

This analysis also used Warsaw population data. The number of residents was acquired from the Main Statistical Office of Poland [35] in a grid with 1 × 1 km cells (primary fields). Centroids of those cells coincide with the measurement points used for travel times calculation. The available population data contains the general number of residents in each cell defined by the grid, as well as classifications
by gender and age groups (0–14, 15–64, and 65+ years). In the case of houses located on the border of two cells, the centroid of the polygon representing the house was taken into consideration.

As the source of land use, the database of topographic objects (BDOT) was used to designate the destination attractiveness of each cell, that is, the places with different communication needs depending on how often and how many people may need to get to such places. The database of topographic objects is a spatial database containing features with a level of detail corresponding to a topographical map on scale of 1:10,000. This database was established in 2012–2013 as part of the state geodetic and cartographic resources in Poland. It was developed on the basis of technical guidelines included in the Regulation of the Minister of Interior and Administration of 17 November 2011 on the database of topographic objects and the database of general geographic objects, as well as standard cartographic studies [39]. It covers the following topics, each of which is described in several layers: the water network, the communication network, the land utilities network, land cover, buildings, structures and equipment, land use complexes, protected areas, territorial division units, and other objects.

2.2. Attractiveness Analysis

For each cell, we calculated its attractiveness (destination attractiveness) in the form of a coefficient. The coefficient of destination attractiveness is based on the destination attractiveness from the user’s point of view, which can be understood as the potential usefulness of the opportunities located in the travel destination [40]. The most common choice for the attractiveness measure is the population (demographic potential) and the income (economic potential) measured by the GDP [41]. Other studies have also included travel motivations [42], such as commuting to work, business and business trips, shopping, trips for health services, education and other services (commuting to school, university, or hospital), recreational and tourist trips, and visits (social, family, etc.). The latter approach was applied in our research. In our study, each of the above-mentioned travel motivations was used for a different kind of destination (in the sense of a different kind of place in space). For commuting to work, we determined the attractiveness of the travel destinations on the basis of the number of workplaces. For business trips, these were communication connections with other cities and/or countries. For shopping trips, we determined the attractiveness of the travel destination on the basis of the size of the retail spaces in the cell (area) of destination. In the case of trips for health services, the purpose of travel was based on the number of doctors and beds in the hospitals. For educational services, the essence was the number of pupils and students.

To designate the destination attractiveness, we used feature classes from the BDOT data set to select different kinds of places where people can travel. Using statistical data [35], we determined how many people can go to each of these kinds of places and how often they do so. Based on this, we determined the weights of each BDOT feature class in the range of 0–20. They were assigned to the specific objects as shown in Table 1.

<table>
<thead>
<tr>
<th>No.</th>
<th>Object Name</th>
<th>Weight</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stations and terminals</td>
<td>20</td>
<td>Point</td>
</tr>
<tr>
<td>2</td>
<td>Offices</td>
<td>5</td>
<td>Point</td>
</tr>
<tr>
<td>2</td>
<td>Commercial and service buildings</td>
<td>5</td>
<td>Area</td>
</tr>
<tr>
<td>3</td>
<td>Schools and research institutions</td>
<td>5</td>
<td>Point</td>
</tr>
<tr>
<td>4</td>
<td>Hospitals and medical care buildings</td>
<td>5</td>
<td>Area</td>
</tr>
<tr>
<td>5</td>
<td>Parking lots</td>
<td>4</td>
<td>Area</td>
</tr>
<tr>
<td>6</td>
<td>Museums, libraries, and other cultural places</td>
<td>3</td>
<td>Point</td>
</tr>
<tr>
<td>7</td>
<td>Physical culture buildings</td>
<td>3</td>
<td>Point</td>
</tr>
<tr>
<td>8</td>
<td>Hotels</td>
<td>2</td>
<td>Point</td>
</tr>
<tr>
<td>9</td>
<td>Industrial buildings</td>
<td>2</td>
<td>Area</td>
</tr>
<tr>
<td>10</td>
<td>Religious buildings</td>
<td>2</td>
<td>Point</td>
</tr>
<tr>
<td>11</td>
<td>Botanical gardens and zoos</td>
<td>2</td>
<td>Point</td>
</tr>
</tbody>
</table>
Table 1. Cont.

<table>
<thead>
<tr>
<th>No.</th>
<th>Object Name</th>
<th>Weight</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>Residential buildings with three or more flats</td>
<td>1</td>
<td>Point</td>
</tr>
<tr>
<td>13</td>
<td>Garages</td>
<td>1</td>
<td>Area</td>
</tr>
<tr>
<td>14</td>
<td>Swimming pools, stadiums, and other sports places</td>
<td>1</td>
<td>Point</td>
</tr>
<tr>
<td>15</td>
<td>Cemeteries, parks, and garden plots</td>
<td>1</td>
<td>Area</td>
</tr>
<tr>
<td>16</td>
<td>Historic buildings</td>
<td>0.5</td>
<td>Point</td>
</tr>
<tr>
<td>17</td>
<td>Tennis courts</td>
<td>0.5</td>
<td>Point</td>
</tr>
<tr>
<td>18</td>
<td>Residential buildings with two flats</td>
<td>0.2</td>
<td>Point</td>
</tr>
<tr>
<td>19</td>
<td>Single-family residential buildings</td>
<td>0.1</td>
<td>Point</td>
</tr>
<tr>
<td>20</td>
<td>Play and sports grounds</td>
<td>0.1</td>
<td>Point</td>
</tr>
<tr>
<td>21</td>
<td>Other</td>
<td>0</td>
<td>Point</td>
</tr>
</tbody>
</table>

The coefficient of the destination attractiveness for each cell was calculated using Equation (1) [43]:

\[
CVC_i = \sum_{k=1}^{n} A_k I_{Ak} + \sum_{l=1}^{m} P_l I_{Pl}
\]  

(1)

where \(CVC_i\) is the coefficient of the destination attractiveness of the \(i\)th primary field, \(A_k\) is the normalized area of a polygon object (located within the \(i\) primary field) of the \(k\) BDOT polygon feature class, \(I_{Ak}\) is the normalized attractiveness of the \(k\) BDOT feature class, \(P_l\) is the normalized number of point objects (located within the \(i\) primary field) of the \(m\) BDOT point feature class, and \(I_{Pl}\) is the normalized attractiveness of the \(m\) BDOT feature class.

The results were normalized to take values from the range of 0–1 according to Equation (2):

\[
x' = \frac{x - x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}} (\text{new}_\text{max} - \text{new}_\text{min}) + \text{new}_\text{min}
\]  

(2)

where \(x'\) is the normalized value, \(x\) is the input value, \(x_{\text{min}}\) is the minimum value in the set, \(x_{\text{max}}\) is the maximum value in the set, \(\text{new}_\text{max} = 1\), and \(\text{new}_\text{min} = 0\).

2.3. Travel Time Analysis

For each cell of the map the data includes the travel times to all other cells (destinations). The data was gathered in June 2018 and was collected for a working day. For public transportation and car travels, we collected these data for five different moments of the day. For walking and biking, we collected only one measurement. This means that for each cell for public transportation, we gathered 3000 measurements (600 measurements for each point; 5 times a day). The same number of measurements was gathered for transportation by car. For walking and bicycle rides, we gathered 600 measurements each (600 measurements for each point, one time a day). So, in total, we have 7200 measured travel times for one measurement point (\(2 \times 3000 + 2 \times 600\)). Multiplied by the number of cells, this gives us almost 4.5 million travel time measurements. We determined one average time for each measurement point. It is the average time calculated on the basis of the travel times for different moments of the day to all other measurement points. The results are illustrated on the maps (Section 3). Naturally, we were aware of the bias due to this type of analysis, as the average travel time to the city center is always shorter than to a point at the outskirts of the city. To overcome this drawback, we decided to also look at the travel speed, as described in the next subsection.

2.4. Travel Speed Analysis

In this work, we analyze the nominal travel speed, that is, the minimal distance between two points (i.e., in a straight line) divided by the travel time. The nominal travel speed is in many cases slower than the actual travel speed because the actual distance is longer. However, using the minimal distance allows for comparison of those speeds independently of the chosen route. The nominal travel speeds
to all other destinations (and for five moments of the day for public transportation and car travel) were averaged using attractiveness weights (Equations (3) and (4)), so that we obtained one single value for each cell:

\[
V_i = \frac{\sum_{j=1,j\neq i}^{601} \frac{\text{CVC}_j \sum_{k=1}^{5} V_{ijk}}{\sum_{j=1,j\neq i}^{601} \text{CVC}_j}}{\sum_{j=1,j\neq i}^{601} \text{CVC}_j}
\]

(3)

\[
\bar{V}_j = \frac{\sum_{j=1,j\neq i}^{601} \frac{\text{CVC}_j \bar{V}_{ij}}{\sum_{j=1,j\neq i}^{601} \text{CVC}_j}}{\sum_{j=1,j\neq i}^{601} \text{CVC}_j}
\]

(4)

where \(\text{CVC}_j\) is the attractiveness of a cell \(j\), and \(V_{ijk}\) is the nominal travel speed the \(i\)th cell to the \(j\)th cell at time \(k\).

Moreover, we used this averaged nominal travel speed as the proxy of the quality of the means of transport, because the faster the speed, the shorter the travel time. Therefore, the relationship between the averaged nominal travel speed and the population in each cell is interesting to investigate.

We also calculated Pearson and Spearman statistics to quantify this dependency or lack thereof [44]. The Pearson correlation measures the linear correlation between two variables. Spearman’s rank correlation is more robust than the Pearson correlation because it assesses how well the relationship between two variables can be described using a monotonic (not necessarily linear) function. We used both of them to ensure a comprehensive analysis.

2.5. Potential Accessibility Analysis

The adopted methodology is based on a potential-based accessibility measure to compare the possibility (or necessity) of using private or public transport throughout the whole territory of Warsaw. Designating the potential accessibility of each place in the city for different transport modes enables identifying places in which the potential of travel by car is greater than that of travel by public transport.

The potential accessibility is the most common approach used in the study of transport accessibility. In the group of models referred to as “potential accessibility models”, many variants of accessibility are measured using indicators of potential or gravity models. The potential model for spatial economy was introduced by Isard [45]. The first author, and at the same time the most frequently quoted in the literature, who referred directly to accessibility is Hansen [21]. He considered accessibility as the sum of the quotients of attractions (masses) of destinations and travel times (costs) for these purposes. Later, the formula was also used by Keeble et al. [46], Rich [47], and Linneker and Spence [48].

In our research, we employ the most often used exponential function (on the basis of the natural logarithm) and the potential accessibility index, also taking into account internal accessibility. Potential accessibility is calculated for each primary field and for each transportation means with the use of Equation (5) [20]:

\[
A_i = M_i \exp(-\beta c_{ii}) + \sum_{j=1}^{j} \text{CVC}_j \exp(-\beta c_{ij})
\]

(5)

where \(A_i\) is the accessibility of the \(i\)th primary field, \(M_i\) is the number of residents in the \(i\)th primary field, \(\text{CVC}_j\) is the coefficient of the destination attractiveness of the \(j\)th primary field, \(c_{ii}\) is the time of an internal trip within the \(i\)th primary field, \(c_{ij}\) is the travel time between \(i\) and \(j\) primary fields, and \(\beta\) is the sensitivity of the network user to the increase in physical, temporal or economic travel distance.

3. Results

In this section, we discuss the results of the analysis performed according to the steps described in Section 2. We present the results by means of a number of figures. Figure 3 shows the population distribution in each primary field. More people live on the west side of the river and most people live in the central part of the city. The northern and southeastern parts of the city, as well as the outskirts, are sparsely populated.
Figures 4–8 present the results of our analysis. On each of the maps, there are some points indicated with gray color which denote missing data. For those points, the used journey planner was not able to find a route.

Figure 4 shows the travel times depending on the transportation means, namely: car, public transport, or bike. The greater the distance from the city center, the higher the average travel time. This was an expected result because the city center has the shortest distance to all other places in Warsaw. In Figure 4a (travel time by car), we show the main roads and district borders. The proximity of the main roads (most of which have speed limits greater than 50 km/h) decreases the travel time by car. Travel time by public transport (Figure 4b) clearly shows the positive impact of the metro and the railway network (the railway network is shown in Figure 7b for better visibility). The travel time by bike (Figure 4c) is only affected by areas with restricted access.

Figure 5 shows the weighted nominal travel speed for different transportation means. For each of them, there was less traffic in the city periphery. In these areas, often there are no traffic lights and building density is relatively low, which is why, especially with transport on foot and by bike, the algorithm was able to find routes that were close to straight lines, which translated into higher nominal speeds. The weighted nominal travel speed is the highest for car travel (Figure 5a). It starts at 34 km/h in the city center and reaches 54 km/h in the suburbs. Such a speed is much greater than that of all the other transportation means. The weighted nominal speeds for public transport and bikes are similar and reached a maximum of about 21 km/h, but Figure 5b,c shows that for bikes, it starts at 16 km/h, while for public transport, it starts at 12 km/h. The weighted nominal speed for walking (Figure 5d) is the most stable and varies from about 5 to 6 km/h.

Looking at Figure 6 and Table 2 one can conclude that there is no correlation between the number of residents and weighted nominal speed of any transportation means. Public transportation, bike, and walking speeds seem to be independent of the number of residents. However, this is not true in the case of car travel. In areas of high population density, the nominal speed is low, while in other areas it can take any value.
Figure 7 shows the potential accessibility of Warsaw calculated according to Equation (1), for different transportation means. The city center has the highest potential accessibility, regardless of the transportation mode. The potential accessibility value for transport by car (Figure 7a) is the highest (up to 290), which covers not only the strict city center but also the neighboring districts (score above 170). Almost the entire analyzed area has higher scores of potential accessibility by car than the best potential accessibility by public transport (Figure 7b). The potential accessibility for public transport again clearly shows the advantage of using the metro and the railway network. Figure 5c shows the potential accessibility by bike, which obtained scores between those of car travel and public transport. It is interesting to note that the lack of a bridge across the Vistula River in the southern part of Warsaw implies lower potential accessibility scores for bike transport in this area. Figure 7d shows the potential accessibility by walking. Due to the constant and slow walking speeds, this map basically presents the attractiveness of each primary field.

Figure 4. Travel time.
Figure 5. Cont.
Figure 5. Weighted nominal travel speed.
Table 2. Correlation coefficients between weighted nominal speed and number of residents.

<table>
<thead>
<tr>
<th>Weighted Nominal Speed</th>
<th>Number of Residents</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pearson’s correlation coefficient</td>
</tr>
<tr>
<td>Walking</td>
<td>0.092208</td>
</tr>
<tr>
<td>Bicycle</td>
<td>−0.185442</td>
</tr>
<tr>
<td>Driving</td>
<td>−0.332788</td>
</tr>
<tr>
<td>Transit</td>
<td>0.143926</td>
</tr>
</tbody>
</table>

Figure 6. Scatter plot weighted average travel speed versus number of residents.

Figure 8 shows the differences in the potential accessibility between particular transportation means. The potential accessibility for car travel with respect to public transport (Figure 8a) is always higher and the greatest differences are observed in the districts adjacent to the strict city center. The potential accessibility for bike travel with respect to public transport (Figure 8b) is usually higher, and the greatest differences occur in the city center. This is also influenced by the higher density of bus stops in the city center, which generally causes slower communication, despite more frequent connections. The value of the coefficient adopted by us ($\beta = 0.109161$) was selected so that the median potential accessibility for public transport (averaged over the 5 moments of the day mentioned above) was equal to 10 and that the impact of the two components of the equation, i.e. the number of people living in a given primary field and the attractiveness of the target primary fields were as much as possible, equally important.
Figure 7. Cont.
Figure 7. Potential accessibility.
Figure 8. Differences in potential accessibility.

(a) bicycle vs. public transportation

(b) car vs. public transportation

Figure 8. Differences in potential accessibility.
4. Discussion

The results of the analysis described above aim at capturing the as-is situation. Many interesting observations can be made. One such observation is that a car is faster than any other transportation means. The common perception is that people use cars because they are more comfortable, not because they are necessarily faster (“it is better to sit in a car than stand in a tram”). According to our analysis, the car is the most efficient means of transportation in Warsaw. This is clearly visible taking into consideration the travel times, average speed, and potential accessibility. The car has the greatest advantage in the districts adjacent to the city center. However, in our analysis, we only considered travel time, excluding time needed for parking, availability of parking places and the related costs. Paid parking is found mostly in the city center, which is a relatively small area compared to the area of the whole city. This sort of economic analysis is beyond the scope of the work reported in this paper.

Another unobvious observation is about bike commuting being better than public transportation. The observed increase in bike rides was perceived as people biking for fun, not for a daily commute. Bike commuters were regarded as “bike bigots” and their opinions about travel time and efficiency were considered as exaggerated. Our research shows that the bike is the second-most efficient way of transportation in Warsaw. It is most advantageous in the city center. Bikes can be used in combination with public transportation. Traveling with bikes by metro, trains and buses is possible and at the same time very efficient. The potential of bike transport can be observed, for example, by the success of the city bike system called Veturilo. It was introduced in 2012 and has recently been developing quite rapidly. In the first year of the system’s operation (2012), there were fewer than 300,000 bike rentals, while in 2018, there were almost 6.5 million. Now, it is the fifth largest city bike system in Europe, with 380 stations, 5500 bikes, and almost 800,000 registered users [49]. The only disadvantage of using bikes in Warsaw is the weather, because the biking season typically only lasts for seven months a year (April–October).

In recent months, electric scooters have become very popular in Warsaw. Currently, there are at least three companies that offer short-term rentals (for minutes). This creates an opportunity for very fast, short trips in the city. Unfortunately, this opportunity is quite expensive (€0.25–0.5 per minute). Also, regulations are still lacking which define the style of driving (e.g., on pavements, bike paths, or roads). There are still no data available regarding this means of transportation; therefore, we excluded it from our analysis.

The greatest positive influence on travel time by public transportation is the metro and railway system. This is clearly visible when considering the travel times, average speed, and potential accessibility. This way of transportation allows for fast travel across long distances throughout the city and traveling “the last mile” with a slower bus or tram.

The advantage of the metro is its speed and frequency (every 2–3 min during rush hours, every 6–10 min during weekends), which allows fast travel for many passengers. The disadvantage is that Warsaw currently only has two lines, one of which is under construction (so effectively 1.5 lines). The line under construction currently only has 10 stops. Three additional stops are planned to be finished by the end of 2019. It will be further extended later and is currently expected to be finished in 2022. The size of the metro network is for now insufficient to significantly improve overall travel times in the city.

Warsaw also has four lines of fast city rail (in Polish called Szybka Kolej Miejska (SKM)), which are integrated with Warsaw’s public transport system. SKM complements the metro network but also provides good connections with suburban towns, from which people commute to Warsaw on a daily basis. However, the problem is the low frequency of SKM trains, which run every hour on average. Recent track repairs on these routes also have an impact on this, as normally, trains run every 30 minutes. SKM has a huge impact on travel time, which is clearly visible especially in the Wawer district, despite its low frequency. Increasing the frequency of SKM trains, which could be achieved at a relatively low cost, can significantly improve traveling times, especially in districts further from the city center.
For comparison, in other European metropolitan areas, the frequency of local trains is much higher (e.g., RER trains in Paris run every 3–10 min).

The results of our analysis show a lack of correlation between travel speeds and number of residents in the given area. In order to increase the attractiveness of public transportation, the travel speed should be increased. This could be especially beneficial in areas with a high population density (e.g., Śródmieście, Praga Południe i Północ, Ochota, Mokotów, and Ursus). Extended metro and railway systems, new tram lines, and traffic lanes intended for buses only could help in achieving this goal. Traffic lanes intended for buses only increase the bus speed and simultaneously decrease the car speed, closing the gap in travel speed between public transport and car travel.

However, the safety of pedestrians and cyclists has to be taken into account while planning modifications within built environments and determining road design characteristics. According to the World Health Organization [50], 50 million people are injured every year due to traffic accidents worldwide. The most common factors that cause collisions are related to characteristics of the built environment, e.g., roadway speeding or lack of lighting.

Despite the fact that in urban areas (e.g., Warsaw) more facilities for pedestrians and cyclists usually exist, the number of accidents involving them and motor vehicles can be up to 5 times higher than in rural areas [51]. As pedestrian infrastructure can reduce the risk of accidents involving pedestrians [52], further actions in this field have to be undertaken by stakeholders in Warsaw. Extension of low speed limit areas in the city, reduction of the carriageway widths or relocation of parking lots are exemplary modifications that are easy to implement and that can improve pedestrian and cyclist safety [53].

Using the concept of potential accessibility in transport analysis has many advantages. Potential accessibility takes into account the relationship between the land use and the transport components. In addition, it requires less data than methods that consider an individual component (i.e., accessibility measured in time geography or maximization of utility). Potential accessibility is a relatively easy approach in calculations and is often used at both national and international levels, including the European level. Thus, potential accessibility is a score that can be interpreted as “adjusted attractiveness”, adjusted with the “attractiveness” of the easily accessible “neighbors”. The higher the primary field’s potential accessibility value, the more easily accessible and “attractive” this primary field is. The primary fields with low value of potential accessibility or that are further away result in a smaller increase of the potential accessibility of that primary field.

In this paper, we present the topic of transport accessibility of a large city—Warsaw in particular. In our opinion, the presented topic is of interest because it presents research in the area of the spatial dimension of transport and underlines the meaning of geospatial analysis in sustainable transport planning. Moreover, it joins methods of spatial analysis with statistical methods as well as cartographic visualization, providing a multi-aspect analysis of transport and its environment.

The presented spatial analysis is a novel way of looking at transportation data in a city as a whole. Unfortunately, in Warsaw public transportation ranks behind car and bike transportation in terms of travel time and speed. In this study, the grid that was used was 1 x 1 km. Because of this relatively low level of granularity, this analysis focuses on the main trends. A more detailed analysis can be performed for smaller neighborhoods, for example, with unexpectedly high or low travel times. In our analysis, we did not include real traveling destinations which could result in better estimations of temporal attractiveness of the primary fields (e.g., workplaces and schools during working hours). Unfortunately, so far, such data are unavailable. Partial data for specific points of interest do exist; however, this is not sufficient to perform an analysis for the whole city.

In future work, we plan to incorporate in our analysis the availability of parking places and the related costs. This can lead to the design of a multi-criteria decision-making engine, which can recommend the best way of traveling between certain destinations. This analysis will also incorporate the influence of the metro. Warsaw is the perfect opportunity for such an assessment, as new metro stops are planned to be opened in the near future. Moreover, we would like to analyze the differences in accessibility resulting from the individual characteristics of transport network users (e.g., people of
different ages: teenagers, students, and older people) and their destination needs. A comparison analysis with other European cities or metropolitan areas can also be interesting. In future we plan to compare cities and/or metropolitan areas with similar area and population.

**Author Contributions:** Conceptualization and methodology, A.M. and A.W.; data gathering, performing analyses, K.P. and J.W.; maps preparation, J.W.; writing—original draft preparation, A.M. and A.W.; writing—review and editing, J.W. and K.P.

**Funding:** This research was funded by the Military University of Technology in Warsaw, Poland under the statutory project “Acquisition and processing of geodata for the needs of geospatial recognition systems”, task “Processing spatial data for the purpose of terrain assessment”, grant number PBS 23-885/2019, realized in 2019 at the Military University of Technology in Warsaw.

**Acknowledgments:** We would like to express our thanks to the reviewers for their feedback and valuable comments, which has allowed us to improve the quality of this article.

**Conflicts of Interest:** We report no conflict of interest. The funding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; nor in the decision to publish the results.

**References**


26. Wegener, M.; Eskelinen, H.; Fürst, F; Schürmann, C.; Spiekermann, K. *Criteria for the spatial differentiation of the EU territory: Geographical position.* Study Programme on European Spatial Planning; Federal Ministry of Transport, Building and Housing: Bonn, Germany, 2001; p. 79.


43. Pokonieczny, K.; Mościcka, A. The Influence of the Shape and Size of the Cell on Developing Military Passability Maps. *ISPRS Int. J. Geo-Inf.* 2018, 7, 261. [CrossRef]


