International Journal of *Geo-Information*

MDPI

Article

Multi-Mode Two-Step Floating Catchment Area (2SFCA) Method to Measure the Potential Spatial Accessibility of Healthcare Services

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Received: 22 April 2019; Accepted: 15 May 2019; Published: 21 May 2019

Abstract: While great progress in the development of a methodological approach to measure the accessibility of healthcare services has been made, the exclusion of the complex multi-mode travel behavior of urban residents and a rough calculation of travel costs from the origin to the destination limit its potential for making a detailed assessment, especially in urban areas. In this paper, we aim to describe and implement an enhanced method that enables the integration of multiple transportation modes into a two-step floating catchment area (2SFCA) method to estimate accessibility. We used a travel-mode choice survey, based on distance sections, to determine the complex multi-mode travel behavior of urban residents. Taking Nanjing as a study area, we proposed complete door-to-door approaches to determine every aspect of basic transportation modes. Additionally, we processed open data to implement an accurate computing of the origin-destination (OD) time cost. We applied the enhanced method to estimate the accessibility of residents to hospitals and compared it with three single-mode 2SFCA methods. The results showed that the proposed method effectively identified more accessibility details and provided more realistic accessibility values.

Keywords: spatial accessibility; multiple transportation modes; 2SFCA; door-to-door approach; healthcare service

1. Introduction

Despite investing heavily into its health service system, China still faces a largely unbalanced spatial distribution of health resources. Unbalanced access to health services has led to an overall poorer health status and increased demand for healthcare facilities in poorer areas, thus destabilizing the social harmony in China. Unrestricted access to healthcare for all populations remains a key goal of governments and societies. To ensure adequate access to primary care, health service planners and policy makers need accurate and reliable measures of accessibility so that areas with true physician shortages can be accurately identified and allocated resources to alleviate the problem.

The potential accessibility method, based on the gravity-type, is the most popular method to measure the ease with which residents of a given area can reach medical services and facilities. Various methods for calculating potential spatial accessibility have been proposed, including the gravity model and the two-step floating catchment area (2SFCA) method, as well as their variants [1–10]. In general, potential accessibility is mainly influenced by three factors: supply of service facilities, population demand for the service facilities, and travel costs between the demanding populations and service facilities. The calculation of travel costs plays an important role in estimating accessibility, when data concerning supply and demand are constant.

Previous studies have faced a major limitation in regard to calculating travel costs: the interaction between the supply location and demand location is based on a uniform transportation mode, a single-car mode in most cases [11,12]. In reality, there are many multiple-transportation modes available in cities, and the travel costs calculated by different transportation modes vary greatly. People may choose one or more appropriate transportation modes, according to their travel needs, to seek service. For example, people may prefer walking or cycling to driving to a nearby healthcare center. When they live far away, they may choose a car or public transportation mode to the center, instead of walking or cycling. It is obvious that time cost results will vary widely when using different transportation modes from the same origin to the same destination.

There has been a growing interest in transport accessibility and potential spatial accessibility in multiple transportation modes. Mavoa et al. [13] computed destination accessibility when people were restricted to public transit and walking modes of travel. Salonen and Toivonen [14] evaluated the comparability of different methods for calculating the travel time by different travel modes. Dony et al. [15] compared the resulting park accessibility landscapes for four different modes of transportation: bicycling, driving, public transit, and walking. Based on the framework of the two-step floating catchment area method, both Mao et al. [11] and Langford et al. [12] incorporated multiple transport modes into potential accessibility to increase the sophistication of the 2SFCA framework. However, their research only considered simple or independent transport modes, which are not consistent with the factual multiple transport modes.

Besides, due to both data availability and computing limitations, most studies have used rather rough estimates of travel time when calculating potential accessibility [16]. The problem with such an approach is that it ignores traffic congestion, transfer time, necessary walking time, etc., which may substantially alter the travel time results [14,17–19]. The majority of previous studies measure accessibility aggregately, at a rather coarse scale [20,21]. With the increased availability of more disaggregate data, some studies have recently taken into account every part of a journey between its origin and destination by creating a multimodal network model [13,14,18,22–25]. However, building a multimodal network faces several issues, such as obtaining detailed data, setting many parameters, integrating it with factual time schedules of public transit, etc. Salonen and Toivonen [14] used the Journey Planner Application Program Interface (API) to calculate the transportation accessibility based on the official up-to-date public transport schedules, which greatly reduced the cost of the calculation of accessibility and made results more representative of actual scenarios. However, they did not consider travel behavior and related travel-mode choices from a human-centered view. Additionally, open API data supply fewer transportation mode queries for the public [26–29].

To address these issues, this paper describes and implements an enhanced method that enables the integration of multiple transportation modes into the 2SFCA method to more realistically assess the potential spatial accessibility of healthcare. A travel-mode choice survey, based on distance sections, was used to reflect the complex multi-mode travel behavior of urban residents. The previous door-to-door approach was extended to illustrate every aspect of basic transportation modes. Open API data were downloaded and processed to compute the door-to-door travel cost for different transportation modes. The rest of the paper is organized in the following manner: Section 2 extends the previous door-to-door approaches and proposes the multi-mode 2SFCA method. Section 3 illustrates the study area and data sources, implements the proposed method, and analyzes the experiment results. The last section concludes the article and discusses our future work.

2. Methods

2.1. Multi-Mode Two-Step Floating Catchment Area Method

Travel distance is an important factor affecting people's choice of transportation mode. We propose an enhanced method that enables the integration of travel-mode choice probability, based on distance sections, into a two-step floating catchment area method. If we assume that there are n ($n \geq 1$) transportation modes in the study area, multi-mode accessibility can be implemented in the following two steps:

Step 1: For each service facility location j, search all population locations k that are within a distance threshold d_0 from location j (d_0 is the catchment of the service location j), and compute the service capacity to the weighted-population ratio R_j within the catchment area:

$$R_j = \frac{S_j}{\sum_{k \in d_{kj,M_k} \leq d_0} \left(P_k P(M_1) f\left(d_{kj,M_1}\right) + P_k P(M_2) f\left(d_{kj,M_2}\right) + \cdots + P_k P(M_n) f\left(d_{kj,M_n}\right)\right)} \quad (1)$$

where S_j is the service capacity of the facility at location j, P_k is the population at location k, and $P(M_1)$ is the probability of P_k choosing M_1 within the distance ranges from 0 to d_1. $P(M_2)$ is the probability of P_k choosing M_2 within the distance ranges from d_1 to d_2. Correspondingly, $P(M_n)$ is the probability of P_k choosing M_n within the distance ranges from d_{n-1} to d_n. The value of $d_1, d_2, \ldots, d_n$ can be estimated from a factual survey. $\sum_1^n P(M_k)$ is equal to 1, which represents the sum of the probability of P_k choosing each transportation mode. $f\left(d_{kj,M_k}\right)$ is the distance decay function between the population location k and physician location j traveling by M_k mode.

Step 2: For each population location i, search all service facility locations j that are within the distance threshold d_0 from location i (d_0 is catchment area i), and sum up the weighted facility-to-population ratios (derived in step 1) R_j at these facility locations as follows:

$$A_i^F = \sum_{j \in d_{ij,M_k} \leq d_0} \left(R_j P(M_1) f\left(d_{ij,M_1}\right) + R_j P(M_2) f\left(d_{ij,M_2}\right) + \cdots + R_j P(M_n) f\left(d_{ij,M_n}\right)\right) \quad (2)$$

where A_i^F represents the accessibility of the population at location i to physicians. $f\left(d_{ij,M_k}\right)$ is the distance decay function between the population location i and physician location j, traveling by M_k mode.

2.2. Door-to-Door Approaches of Multiple Transportation Modes

Four basic transportation models can be used to express many complex transportation modes that exist in the Chinese metropolis: by walking, by riding, by driving, and by public transit. That means any kind of transportation mode can be composed of these four basic models alone or a combination of them, as defined in Figure 1. To illustrate every part of the OD travel route, we propose complete door-to-door approaches to illustrate these basic transportation models, which are shown as Figure 1. As shown in Figure 1, square bracket is optional, '*tc*' denotes traffic congestion, and '*wt*' denotes waiting at transit stations.

By the walking mode, the journey only includes walking from the origin to the destination, which is the simplest mode. By the riding mode, a door-to-door journey includes: (1) Walking from the origin to the place where the bicycle is parked; (2) cycling from the bicycle parking to the next bicycle parking; and (3) walking from the parking to the destination. By the driving mode, a door-to-door journey includes: (1) Walking from the origin to place where the car is parked; (2) driving from the parking to the next car parking; and (3) walking from the parking to the destination. By the public transit mode, the journey may be very complicated. The door-to-door journey includes: (1) Walking from the origin to a transit stop, which possibly implies additional riding and walking travel; (2) waiting for a bus or metro to arrive and to depart; (3) sitting in the bus or metro until the final stop, which possibly implies transferring from one stop to another; and (4) walking from the last stop to the final destination, which possibly implies additional riding travel. As shown in Figure 1, each journey contains traffic congestion-related delays, including traffic jams, traffic lights, traffic control, which are called "tc (traffic congestion)" for short in Figure 1. The traffic congestion extends the travel time in the metropolis but is often ignored in other studies.

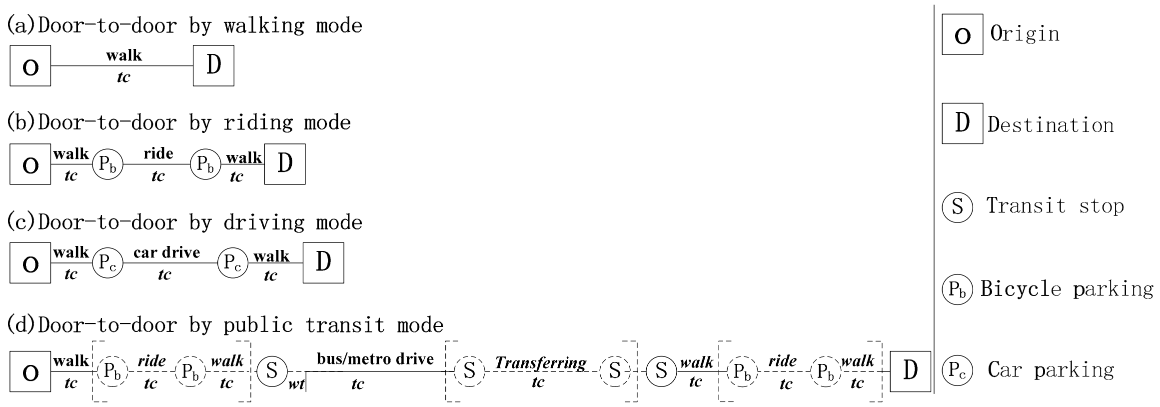

Figure 1. Door-to-door approaches of the four basic transportation models.

3. Case Study

3.1. Study Area and Datasets

Nanjing, the capital of Jiangsu province, is located slightly inland from the coast of China. It is the second largest city in the East China region after Shanghai and has long been one of China's most important cities. It has an urban population of 6.43 million in 2013, according to the Statistical Yearbook of Nanjing 2014. The study areas include the main urban areas and three sub-urban areas of Nanjing (Jiang Bei, Xian Lin, Dong Shan), which are passed through by the Yangtze River.

In the study area, 62 of the large hospitals were chosen as the healthcare service facilities. Therefore, the number of beds is used as the service capacity in this paper. There are 24,192 inpatient hospital beds in the study area, as shown as brown circle-shaped point symbols in Figure 2. To avoid excessive population concentrated at one point, the administrative population is spread in the grid cells according to the population density and land use. The data set was provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn) and is aggregated in 1000 m × 1000 m cells regarding the terrain and population density. According to the overall planning of Nanjing city, two grid levels are adopted to divide the regions of the Nanjing metropolitan area, as shown in Figure 3. One has 1000 m × 1000 m cells for the three sub-urban areas, which are downloaded from RESDC. The other has 500 m × 500 m cells for the main urban areas, which are processed by 1000 m × 1000 m population cells. The total number of population cells is 1512, of which the population of the main urban area is 964. The total number of grid cells in Jiang Bei is 282, in Xian Lin, 156, and in the Dong Shan area, 109.

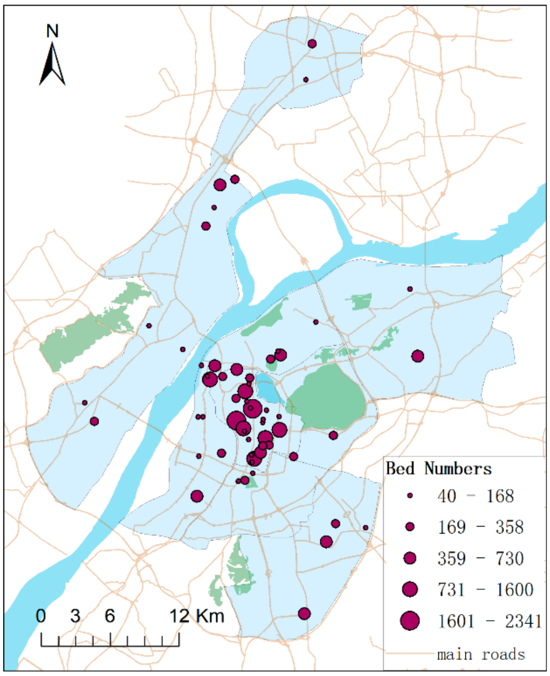

Figure 2. Healthcare service facilities in the study area.

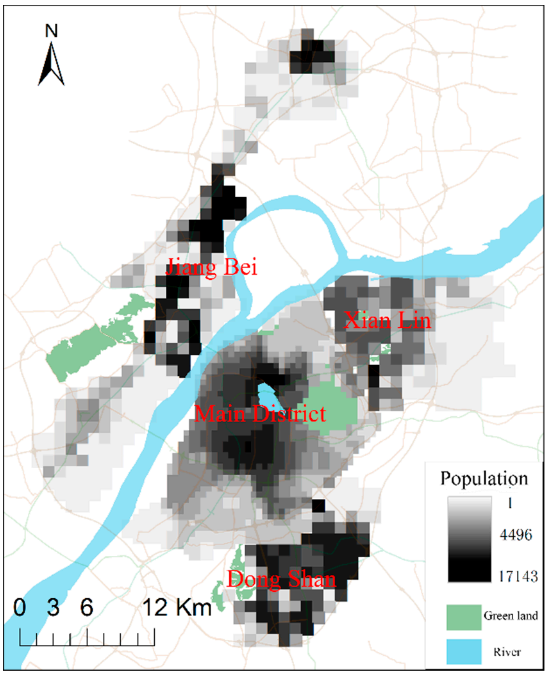

Figure 3. Population in the study area.

It is almost impossible to collect the factual population of each transportation mode at all the population cell locations. As local survey data can reveal global phenomena, a survey questionnaire was designed for a transport mode survey based on different distance sections. Today, the online survey website makes the survey research much easier and faster. Therefore, the questionnaire was conducted by the online survey method around the Nanjing urban areas [30]. We invited the patients of these large hospitals to fill in the information about transportation mode from home to hospital through online questionnaire survey website. We received 3527 responses to this anonymous survey, and after eliminating unusable data records. In addition, we obtained a final sample of 2674 participants. The questionnaire includes age, gender, income, job type, address, education level, and the main transportation mode to hospital of five distance sections (see Table 1). While, in reality, there are many transportation modes for Nanjing's residents to hospitals, six of them are the most popular modes, which account for more than 98 percent, according to a previous survey [31,32]. The six transportation modes are: walking (W), riding by bicycle (B), driving (D), public transit (PT), riding by electric bicycle (EB), and riding by motorcycle (MB). Thus, six transportation modes have been taken into account in our questionnaire. The survey results of the travel-mode choice survey, based on distance sections, are shown in Table 1. The travel distance from origin to destination plays an important role in affecting people's choice of travel mode. We set the maximum catchment area threshold of the population and hospitals at 25 km, which is the distance from the northernmost to the southernmost point by the public transport mode.

Table 1. Travel-mode choice survey results, based on distance sections.

Distance Sections	W	B	D	PT	EB	MB	Total
0–1 km	51	11	7	3	20	8	100%
1–3 km	21	14	16	17	23	9	100%
3–5 km	1	8	32	28	19	12	100%
5–15 km	0	2	41	36	10	11	100%
15–25 km	0	0	48	37	6	9	100%

This paper introduces online map APIs to improve the estimation of travel time. Baidu map APIs build a multi-mode road network model based on door-to-door approaches, which are consistent with our approaches, as described in Section 2. The APIs not only take into account travel costs related to roads, but also other relevant necessary travel costs, including traffic congestion-related delays, transfer time, and walking time, which are more accurate, compared with the traditional calculation method, which uses the weighting of the roads. It supplies the travel costs of the four modes (walking, driving, riding by bicycle, and public transit) with the door-to-door approach. Thus, we use Baidu map APIs to compute the travel costs of walking, riding by bicycle, driving, and public transit in this study. The calculating procedures of the OD travel cost by Baidu map APIs are shown in Figure 4. However, we take into account six transportation modes in calculating the accessibility of the new method. The transportation modes of electric bicycles and motorcycles are out of the scope of Baidu map APIs. As electric bicycles and motorcycles have similar travel routes to those of bicycles, their travel costs can be obtained by processing the route results of bicycles in the calculating procedures of the OD travel cost by Baidu map APIs. We use Microsoft Visual C++ (Microsoft, Redmond, WA. USA) and ESRI ArcObjects (ESRI, Redlands, CA. USA) to implement this procedure.

3.2. Results

Taking Nanjing as a study area, we implemented an estimate of the spatial accessibility of residents to hospitals using the proposed new method. To illustrate the new proposed method, we compared the results of new method (called MGa2SFCA) with those of three other methods, which use the same 2SFCA framework but a different transportation mode. The first method is the driving mode with the door-to-door approach (called DGa2SFCA). Here, door-to-door approach means the OD route considers every part of the travel. The second method is also the driving mode but without the door-to-door approach (called SGa2SFCA); and the third method is the public transit mode with the door-to-door approach (called PGa2SFCA). The travel costs of the DGa2SFCA method and PGa2SFCA method are all calculated by Baidu map APIs. The SGa2SFCA method is the most popular method for calculating spatial accessibility in the traditional 2SFCA framework, which sets the speed of cars based on the levels of the roads. When calculating the travel cost of the SGa2SFCA method in this paper, we used the same processing mode. Based on different levels of the roads in the study area, the standard speed was set at 60 km/h for expressways, 50 km/h for main roads, 40 km/h for secondary roads, and 30 km/h for other roads (Rui, 2014; Mao and Nekorchuk, 2013). In this paper, the ArcGIS OD Cost

Matrix was used as the tool to calculate the travel cost of the SGa2SFCA method. The catchment of the hospital location and population is defined as an area within 45 minutes in DGa2SFCA and SGa2SFCA. Additionally, the catchment of the hospital location and population is defined as an area within 60 minutes in PGa2SFCA [33].

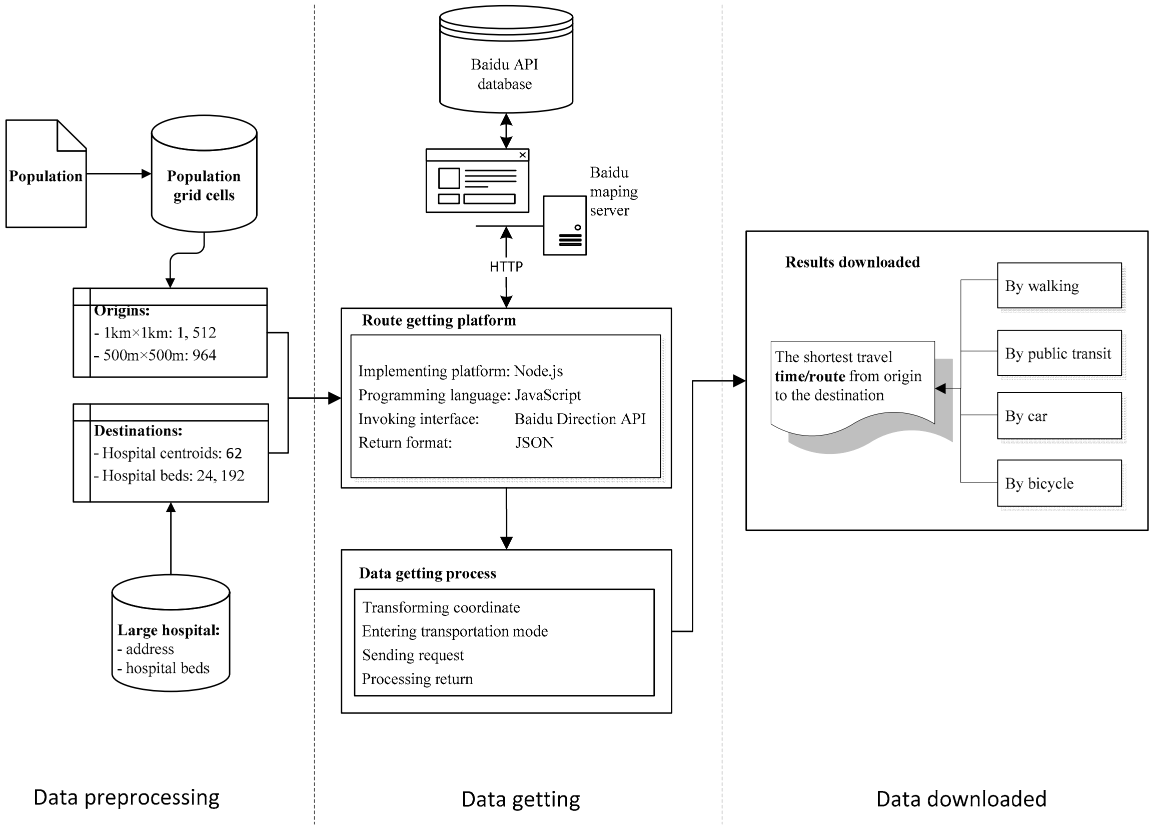

Figure 4. The calculating procedures of the OD travel cost by Baidu map application program interfaces (APIs).

Table 2 shows the statistical results of accessibility, calculated using 4 different methods. As shown in Table 1, the accessibility scores of MGa2SFCA range from 0.000347 to 0.007337, with an average of 0.004290 and standard deviation of 0.001722. The accessibility scores of DGa2SFCA have a narrower range, from 0.000539 to 0.007718, with an average of 0.004491 and standard deviation 0.001578. A potential reason is that some residents prefer a transportation mode (bike, walk, and bicycle etc.) with a lower speed in the MGa2SFCA method. Therefore, the overall accessibility value calculated by the DGa2SFCA method is higher, and the standard deviation of accessibility is lower than that of the MGa2SFCA method. Due to the scattered distribution of residents and the concentrated layout of public transportation facilities, the accessibility values are small in general, and their accessibility differences in different areas are very large, relative to other methods. The SGa2SFCA method assumed that all people seek healthcare by car, without considering the door-to-door situation, thus further increasing their ability to access health services. Meanwhile, this uniform assumption smoothed the variability of estimates, leading to a lower standard deviation. That is why the accessibility scores of SGa2SFCA have the narrowest ranges, with the largest average and smallest standard deviation of the 4 methods.

Table 2. Statistics of accessibility, calculated using 4 methods.

Methods	Min.	Max.	Avg.	Std. Dev.
MGa2SFCA	0.000347	0.007337	0.004290	0.001722
DGa2SFCA	0.000539	0.007718	0.004491	0.001578
PGa2SFCA	0.000012	0.011121	0.003821	0.002716
SGa2SFCA	0.000542	0.005347	0.004639	0.000744

Figure 5 shows the spatial distribution of the accessibility results, calculated using the four methods. Overall, the four methods generate similar accessibility distribution patterns, with a high accessibility value in the main urban area and low accessibility value in the sub-urban area. However, there are significant local differences among these four accessibility results. From Figure 5a, using the MGa2SFCA method, the higher accessibility values are mainly concentrated around the city center, and the majority of these areas are above 0.006. As the distance from the city center gradually increases, there is an evident tendency toward decreasing accessibility, the highest of which is near the population center, and the lowest is farther away. This is mainly due to two potential factors: on the one hand, almost all large hospitals gather in the city center area, and thus people there have a much easier access to these resources; on the other hand, people there can make the best use of the advantages and bypass the disadvantages of transportation. For example, they can choose an e-bicycle or walk, for the short distance travel, and choose the metro or car for further distance travel (see Table 1). The areas with the poorest accessibility are distributed in the sub-city of Xian Lin, the south of Jiang Bei and the periphery of Dong Shan, where the majority of accessibility values are below 0.0005. Thus, clearer hierarchy structures can be observed in the study areas in the MGa2SFCA accessibility results (compare Figure 5a with Figure 5b–d), which is more logical and reasonable, considering the facts.

In the northern part of Jiang Bei, the MGa2SFCA method has higher accessibility values than DGa2SFCA and SGa2SFCA. Because these two single-mode methods increase the ability of residents to access hospital beds, residents in the central and south-central areas of Jiang Bei can obtain medical resources in these areas within the catchment area, although they are located in marginal areas, further from the center. However, in fact, this might not always be true, because people at the southern outer rim might not prefer to search for hospital resources beyond their catchment area. While the MGa2SFCA method overcomes this shortcoming, many people in southern areas might not travel further distances and longer times to obtain care from the northern areas, causing the accessibility values in these regions to be generally high. The travel-mode choice survey results, based on distance sections, indicate the facts relating to residents' travel behavior, so the accessibility result distribution of the MGa2SFCA method is more consistent with the facts.

To further compare the difference between the MGa2SFCA method and other methods, Figures 6–8 show the plot of accessibility at each population grid cell, as generated by the MGa2SFCA and DGa2SFCA, PGa2SFCA and SGa2SFCA methods, respectively. As shown in Figure 6, the DGa2SFCA method generally tends to overestimate accessibility compared with the MGa2SFCA method, with the higher accessibility values near the Jiang Bei and Xian Lin city areas (see Figure 5a,b). However, in the center of the old urban area, the DGa2SFCA method generally tends to underestimate accessibility. This might be due to the fact that the Door-To-Door road network model is taken into account in the DGa2SFCA method. People in the old urban area are very close to hospital; when using the DGa2SFCA method, people need more time to find cars, park cars and wait in traffic jams, leading to a greater OD time cost than that of MGa2SFCA method on the whole. The highest accessibility values are mainly located in the beltway expressway, the junction of G312 and G26, and near the Jiang Bei Expressway, where there are small areas and a discrete distribution of these high value areas. This is might be because the people there are fully served by the physicians, not only from the main urban area, but also from the sub-urban areas, where facilities for driving transportation have been developed.

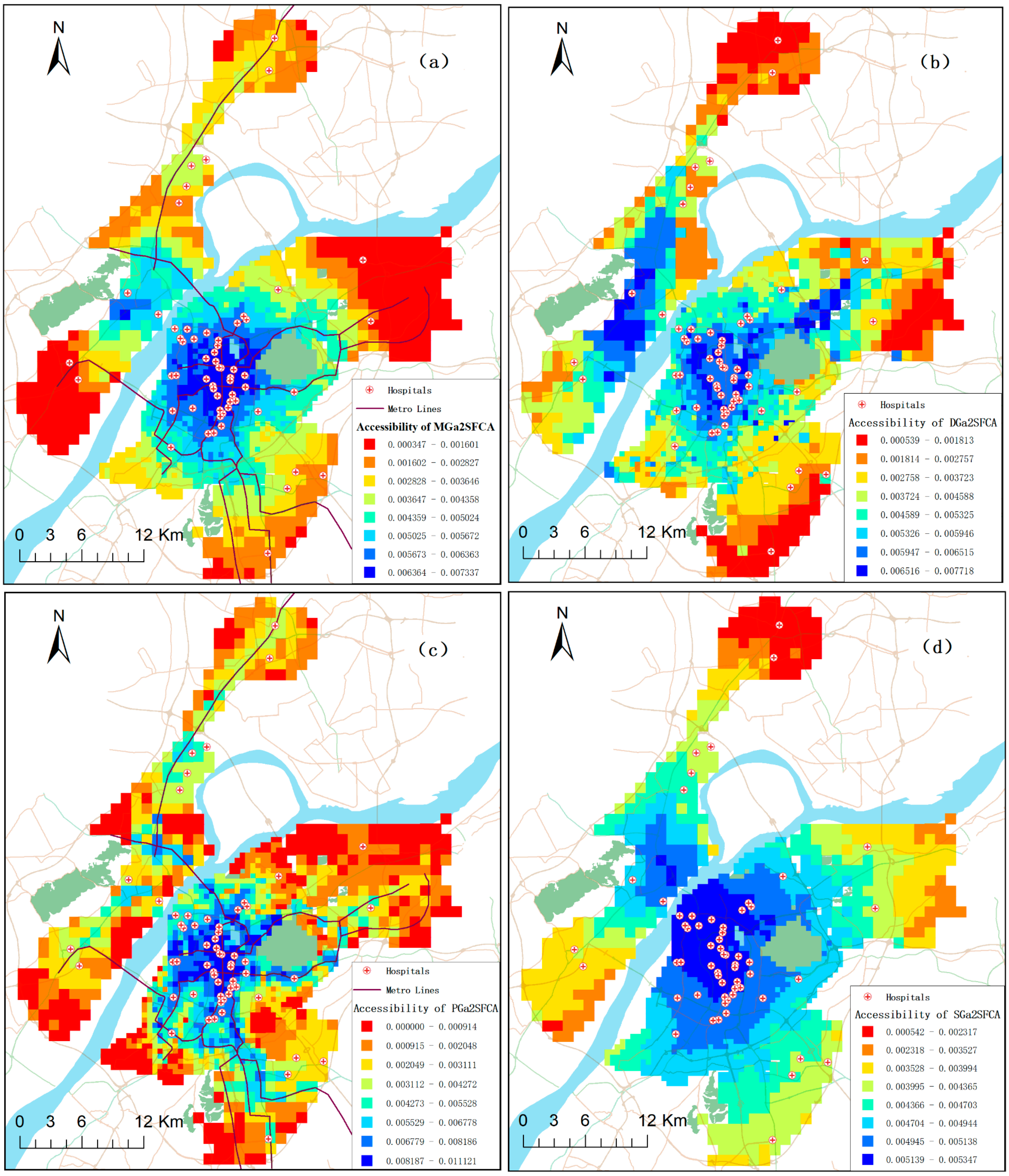

Figure 5. Spatial distribution of accessibility using 4 methods.

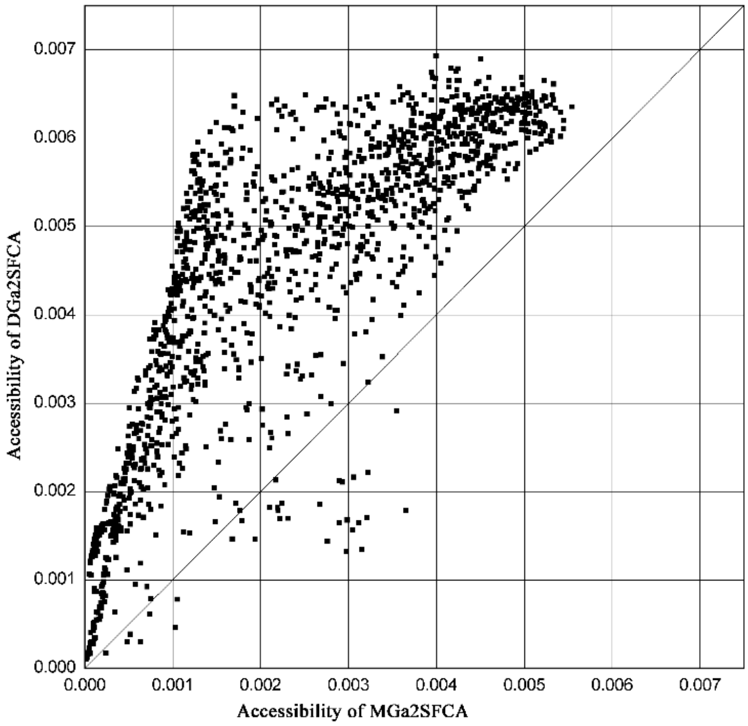

Figure 6. Accessibility comparison of the DGa2SFCA method and the MGa2SFCA method.

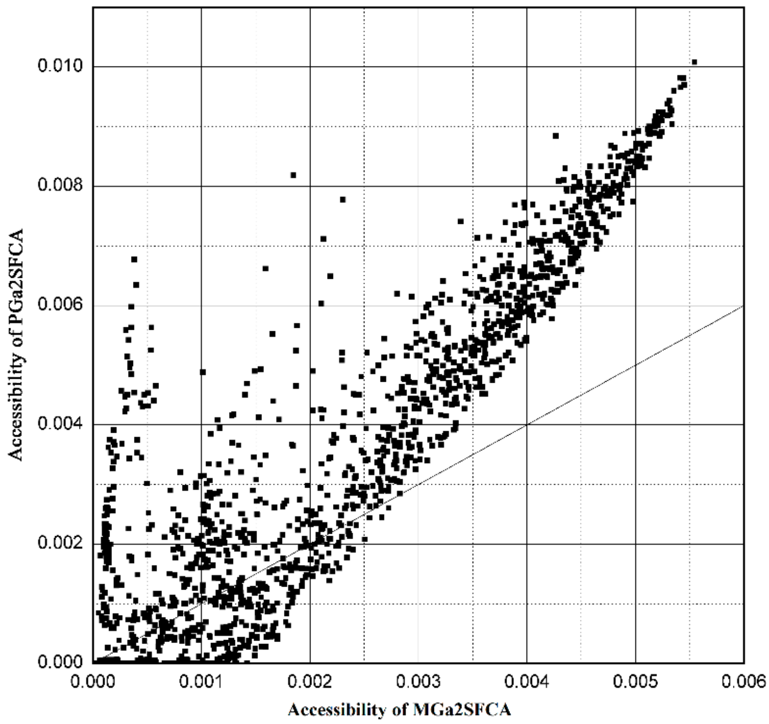

Figure 7. Accessibility comparison of the PGa2SFCA method and the MGa2SFCA method.

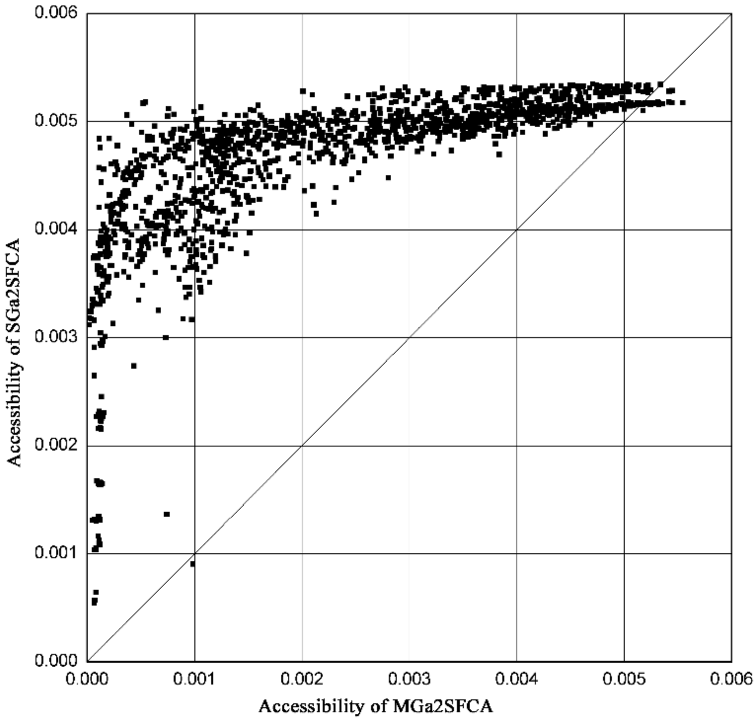

Figure 8. Accessibility comparison of the SGa2SFCA method and the MGa2SFCA method.

As shown in Figure 7, when using the DGa2SFCA method, over- and underestimation of accessibility exist widely in the whole study area, compared with the MGa2SFCA method. The serious underestimation is mainly concentrated in the sub-urban areas, especially in the Xian Lin sub-urban areas. When using the PGa2SFCA method, the calculated OD time cost for seeking health service is higher than when using the other three Ga2SFCA methods. Residents in sub-urban areas have less opportunity to obtain superior medical resources from the old urban areas and are affected by a decay function, which results in a low accessibility value of the sub-urban areas. The areas with serious overestimation are mainly located in the old urban areas, and the maximum overestimation difference is more than 0.006. Due to the perfect public transit system, the accumulation of medical resources, and the underestimation of accessibility in the sub-urban areas, the accessibility of the old urban areas, calculated by the DGa2SFCA method, has been seriously overestimated. The accessibility along the railway lines in the main urban area is also very high. With the distance from the metro lines gradually increasing, the decaying accessibility tendency is very serious.

As shown in Figure 5d, the accessibility result of the SGa2SFCA method shows the spatial distribution pattern of a rating-circle structure, centered on the main urban area, which is related to the circle distribution of the hospital and the fixed setting of the road speed. Compared with the MGa2SFCA method, the SGa2SFCA method always overestimates the spatial accessibility in the majority of the study area, especially in the three sub-urban areas, as shown in Figure 8. When using the SGa2SFCA method, most urban medical resources are within the catchment area of the residents of the sub-urban area, leading to an overestimation of their propensity to seek services. Therefore, overestimated areas are mainly located in the sub-urban areas, and underestimated areas are mainly located in the main urban area, especially in the central area. Meanwhile, the SGa2SFCA method tends to weaken the spatial accessibility differences of different population grid cells, and the standard deviation is only 0.000744, which is only half of the result of the MGa2SFCA method. Generally, the SGa2SFCA method underestimates the spatial accessibility and, more seriously, overestimates it in the study area.

4. Conclusions

Despite the many advantages of the original 2SFCA method in measuring potential spatial accessibility, the exclusion of the complex multi-mode travel behavior of urban residents and the rough calculation of travel costs from origin to destination greatly limit its potential for accurately estimating the spatial accessibility of healthcare, especially in urban areas. We described and implemented an enhanced method that enables the integration of multiple transportation modes into the accessibility estimation. We used a travel-mode choice survey, based on distance sections, to determine the complex multi-mode travel behavior of urban residents, which could not reflect the real and detailed spatial variations of various transportation modes. We extended the previous door-to-door approaches to illustrate every aspect of these transportation modes. Additionally, we processed open data to implement the computing of the OD time cost, the estimation of which could be more accurate, because it is based on the door-to-door network model and big data analysis results.

Taking Nanjing as a study area, we implemented an estimate of the spatial accessibility of residents to hospitals using the proposed new method and compared the accessibility estimates with those using the traditional single-mode 2SFCA methods, including the driving door-to-door approach (called DGa2SFCA), simple driving door-to-door approach (called SGa2SFCA), and public transit door-to-door approach (called PGa2SFCA). The DGa2SFCA method tends to underestimate accessibility in the old urban areas, but overestimate accessibility in the sub-urban areas. When using the SGa2SFCA method, a great amount of overestimation, and very little underestimation, is found. Meanwhile, the two driving door-to-door approaches smoothed the variability of the accessibility estimates, because their ability to access health services was overestimated. The PGa2SFCA method tends to overestimate accessibility in the old-city areas and areas along the metro lines and bus lines, but underestimate accessibility in the sub-urban areas, especially in the Xian Lin area. These methods would inevitably introduce misestimates into the accessibility because of the uniform assumption of one transportation mode. By accounting for multiple transportation modes within populations, our multi-mode method has great potential for the calculation of the precise spatial accessibility and provides guidance for the layout and optimization of health facilities.

Author Contributions: Jianhua Ni proposed the idea of the new method and analyzed the experiment results. Ming Liang conducted the primary experiments and cartographic visualization. Yan Lin processed the data, downloaded from Baidu map APIs. Yanlan Wu provided the original idea for this paper and wrote the original draft. Chen Wang offered data support for this work.

Funding: This project was supported by the Natural Science Foundation of Anhui Province [1908085QD164], Anhui Science and Technology Major Project (18030801111), and Anhui University Ph.D. Foundation(J01003317).

Conflicts of Interest: The authors declare no conflict of interest.

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