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Research article

Comparison of the transportation network for public transit and private vehicles in Shanghai: An accessibility approach

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ABSTRACT

This study examines the differences in service level and coverage of public transit (PT) and private vehicles (PV) with multi-source data in Shanghai. To construct computable networks and address visual results, the constrained shortest path algorithm and a spatial grid accessibility model are employed to seek the optimal path for travelers to city key points. Travel time ratio of PV and PT is applied to reflect the competitiveness of the two modes over different areas of Shanghai. Results show that for PV, although the average travel time meets the needs of car travel, 51 % of the population cannot get to graded city centers within 45 min. In addition, the PV accessibility gradually weakens from the central city to the outside, highways and expressways may be feasible solutions. For PT, half of the population can't reach any city key points within two transfers, and almost all of these people live in the suburbs. Less than 30 % of the population can reach the city key points within 1 h, of which rail transit contributes more than conventional buses. Furthermore, the travel accessibility of PV is much better than that of PT. The average travel time ratio in all comparable grids is 2.04 for hubs, and 2.10 for graded city centers. For travels to graded city centers, the travel time ratio of suburbs is 35 % higher than that of central city, indicating that the inequity distribution of public transportation resources is worse in the suburbs than in the central city. This study also measures equity performance of groups based on spatial location and income level, and we find out that more core locations and higher income lead to higher accessibility. The gap among groups is significant, with a Gini coefficient over 0.5.

1. Introduction

China has witnessed substantial urbanization since the 1980s, resulting in pronounced population concentration and rapid urban land expansion [1]. As living standards have improved, an increasing number of travelers now prefer private vehicles (PV) over public transit (PT) [2]. Although private vehicles were initially seen as a supplementary mode of transportation, their continuous growth has brought challenges to the sustainable development of public transit. What's more, time and resources are required for developing transportation infrastructure to meet demands of greater traffic flow, and this result in transportation supply shortage in short term [3]. However, urban transport, which is understood as "central to actualizing the right to the city" [4], is one of the most significant

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factors that influence social equity [5]. Public transit is usually planned and invested by city governments, so it acts as a redistribution of wealth and a fundamental social service [6]. When strategizing for newly developed areas, it is incumbent upon governments to ensure complementary public transit and social services [7]. Moreover, the socio-economic fabric of a city is directly influenced by the effectiveness and accessibility of its public transportation systems. This is especially true in the peripheral areas of the city. Unlike the United States, low-income families in China tend not to buy cars and rely on public transit for daily travel [8]. The Public transit system should meet the basic travel needs of travelers, which is one of the keys to making public transit competitive compared with private vehicles. This also emphasizes the importance of residents' accessibility to opportunities and activities, and the equalization of public services.

Since urban area keeps growing, the distance between regions causes deep social inequality, group segregation, and exclusion [9]. In China, the majority of suburban residents work downtown, but most non-work travels of them take place in the suburbs [10]. As China's major cities evolve, their suburbs are transitioning from mere residential zones to holistic living spaces, necessitating improved connectivity to city sub-centers and key transportation hubs. City sub-centers, as well as new towns and new development areas, can share the burden of city centers and increase the efficiency of suburban life [11]. For instance, the government of Shanghai published the "Shanghai Urban Master Plan (2017–2035)", and a core point is to construct graded space [12]. In this context, assessing the difficulty for urban residents to access different "city key points" becomes especially crucial. "City key points" are urban public activity centers essential for daily travels of residents. They consolidate urban spatial opportunities and vital facilities while driving urban development and enhancing community interactions. What's even more significant is that researching the accessibility to "city key points" serves as a pivotal means to support the layout of urban functional centers and to regulate public service resources. This has a profound impact on narrowing disparities among different groups, mitigating spatial exclusion, and achieving a balanced distribution of spatial opportunities.

This study aims to explore spatial opportunity disparities between different regions and the development status of transportation infrastructure from an equity perspective, and to assess the ability of various groups to access key urban functional areas through the public transportation network. The remainder of this paper is organized as follows: Section 2 reviews the literature on relevant topics. Section 3 provides a detailed description of the data source and preprocessing, and the methodologies we use. Detailed explanations of the obtained results are presented in Section 4. Finally, Section 5 outlines the discussion, conclusions, limitations, and future research directions of this study.

2. Literature review

The transportation system has a great influence and impact on regional patterns of development, economic viability, environmental impacts, and maintaining socially acceptable levels of quality of life [13]. The goal of urban transportation planning and management should provide travelers with more transportation options, especially in a city with a large area and a great amount of population like Shanghai, China. However, it seems unlikely that public transit will be able to increase its overall market share compared to private vehicles, even if society and the economy can benefit from it [14]. In recent years, to improve public transit and coordinate the whole network system with urban space, many researchers put their interests in transportation accessibility, examining the competitive relationship between PT and PV, and the analysis of transportation to public services.

2.1. Using accessibility to evaluate transportation systems

Historically, mobility is used to evaluate transportation systems, which reflects the capacity of transportation systems to deal with the number of transportation objects in a unit period [15]. Compared to mobility, accessibility can describe the spatial distribution and difficult degree of travel, the possibility of specific activities, or the potential of interaction. It is an intuitive method to represent travelers' access to travel opportunities and the relationship between the origin-destination points. Existing studies have various understandings and definitions of accessibility, which result in different ways of calculation and modeling. Hansen created the concept of accessibility on transportation as the size of interaction opportunities of nodes in traffic networks, and the Hansen Gravity Model was established in the process of distributing the forecasted metropolitan population to small areas within the metropolitan region [16]. Since then, many new definitions have been derived, including minimum travel time and the shortest travel distance [17], the difficulty for the OD points to overcome the space separation contact [18], the number of opportunities that can be obtained in the range of unit time or unit distance [19], the number and diversity of destinations that travelers can reach [20], and the potentials of interaction or contact between OD points [21]. In recent years, studies focusing on public transportation using accessibility model have been greatly attended. Researchers put their main emphasis on the relationship between public transit and spatial equilibrium [22,23], land use and house prices [24], travel vulnerable groups [25], and social service facilities [26]. More research examined the public transportation system and made service capability classification using comprehensive evaluation [27,28].

2.2. The competitiveness between PT and PV

Existing studies usually use one or more quantifiable indicators to compare the competitiveness of public transport and cars. Travel time is always the most important factor that affects travelers' choices. PT tends to cost a longer time than PV because of the time consumed by walking to stations and transferring, and the difference in vehicle speed [29,30]. The travel time ratio is used as a key index to measure the relative competitiveness of public transport, and is the most intuitive index to reflect the service level gap. Hitge and Salone compared travel times between public transport and private cars in Cape Town and Helsinki, respectively, and proposed

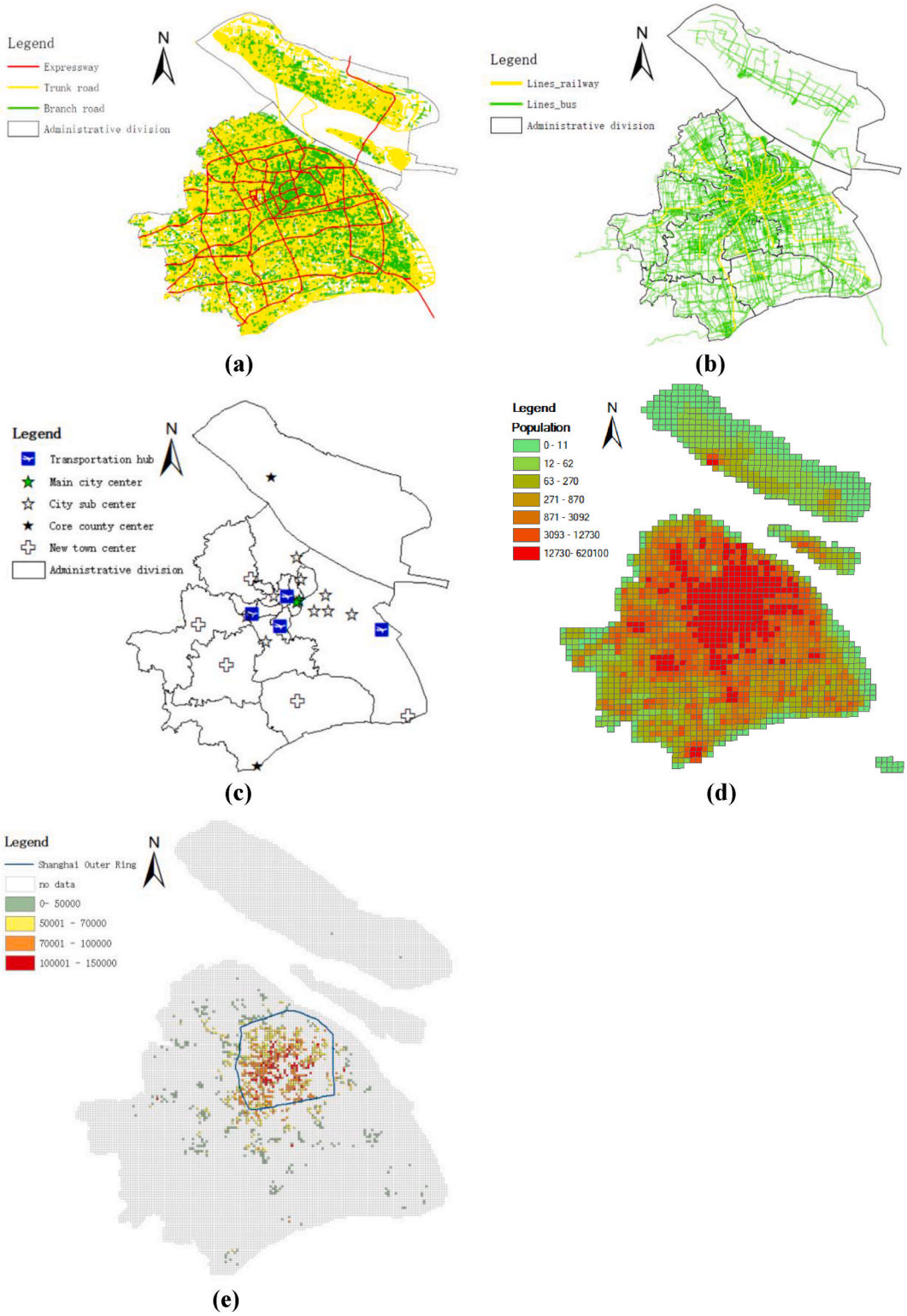


Fig. 1. (a) The network of roads in Shanghai; (b) the network of public transit in Shanghai; (c) the city key points in Shanghai; (d) the population of Shanghai; (e) the second-hand housing on sale.

measures to improve the competitiveness of public transport [31,32]. Evidence from the Stockholm region and Singapore reveals that when the travel time ratio between PT and PV is less than 1.5, public transit will become a relatively more competitive travel mode [33]. People also identified this indicator as the main development goal of Singapore's transport system, aiming to provide public transport services that can compete with private vehicles. However, PV does not have many advantages over PT in big cities [34]. PT has lower travel costs considering the price and energy consumption, and is more reliable because it has to follow the timetable [35,36]. Another research finds that the implementation of priority bus lanes and the increment of railway speed can increase the passenger flow of PT [37], which also improves the competitiveness of PT by reducing the travel time difference between PT and PV.

2.3. Access to key urban areas and public services

Key urban areas and public services refer to all kinds of public facilities that provide services for residents, such as city centers, hospitals, hubs, schools, or markets. They are an indispensable vital element in people's life and work. Accessibility is an effective way to measure whether the spatial layout of public facilities and transportation network is reasonable, which intuitively reflects the services and opportunities available in regional space through the transportation system [38].

Some studies reveal the travel convenience of residents in a certain area to obtain public services, which is greatly affected by the spatial distribution of facilities, roads, and public transit [39]. For example, The method based on accessibility can find out the areas with insufficient medical services and provide suggestions for the optimal allocation of medical resources [40]. As hospitals and subway lines are always concentrated in the central area of the city, urbanites can always have better access to medical facilities [41], while it is difficult for suburbanites to obtain necessary resources. Education facilities are also cored influential impacts on people's daily travel generation. In terms of facility weight factors, existing studies mainly take school type, the number of teachers, student capacity, and school reputation as the coefficients of the accessibility method [42,43]. Aside from basic social services, the accessibility of residents to hubs is of great significance for obtaining regional economic and cultural exchange activities. Current research mainly focuses on a single hub to analyze the efficiency or difficulty of reaching the hub through the public transport network [44,45].

In sum, this study focuses on some knowledge flaws in the field. First, although some of the accessibility research mentioned travel equity, few of them compared public transit with private vehicles from the perspective of integrated networks and space service, which were closely related to the reasonable and balanced development of the transportation system. Second, most research on public transit focused only on either buses or the railway. Transfers between different modes of transportation were ignored. Third, much research didn't relate PT and PV with population information, which could reflect the spatial demographic discrepancies in different regions. Moreover, lots of Chinese people in big cities travel to city sub-centers for entertainment almost every week. Existing research always focused on the accessibility to public services such as hospitals and schools as mentioned above, while the accessibility to city sub-centers and all transportation hubs in a city has not received much attention. Accessibility to city sub-centers and hubs could illustrate the main part of non-work travels.

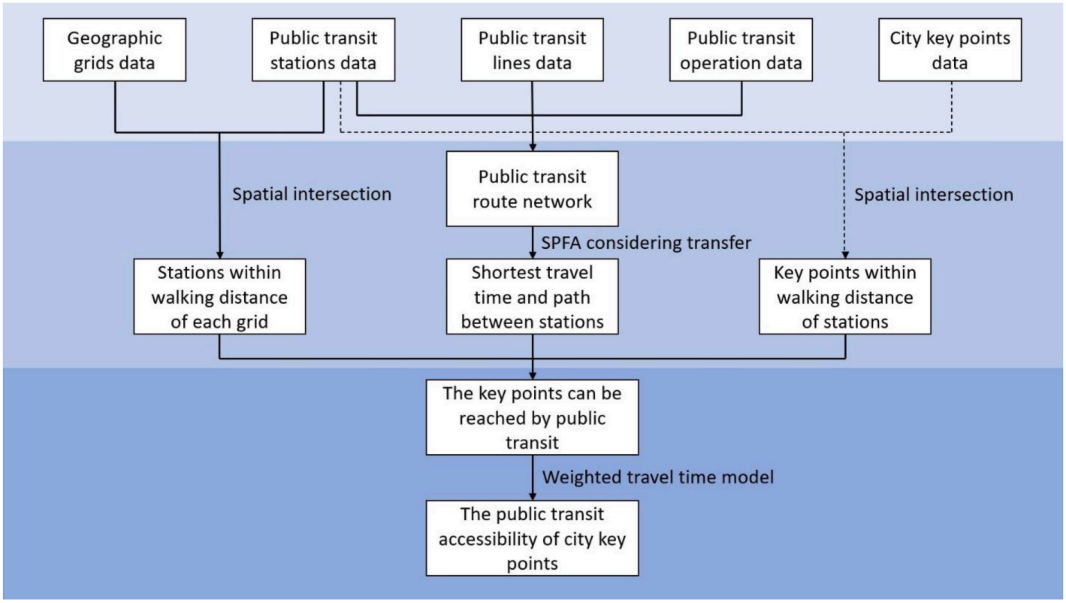
Table 1
Public Transit data field of Gaode Map.

Field Name	Example	Description
id	310100015853	Id of bus line.
type	regular bus	Line type, including ordinary bus, subway, ferry, tram and trolley bus, airport bus, and tourist line.
name	bus 157 (Yonglian Village - Shanghai Stadium)	Line name (by direction).
polyline	121.445602,31.106503; 121.445625,31.106333; 121.445847,31.106224 …	Track coordinates of road section (in WG 1985 format).
start_stop	Yonglian Village	Starting station of the line.
end_stop	Shanghai Stadium	Final station of the line.
start_time	530	Departure time of the first train.
end_time	2200	Departure time of the last train.
direc	310100015852	Id of the reverse bus line.
company	Shanghai bus (Group) Co., Ltd	Operating company.
distance	12.01697	Line length (km).
basic_price	2	Basic ticket price/RMB.
total_price	2	Maximum ticket price/RMB.
stations_ids	BV10384079; BV10032385; BV10032448 …	Station ID along the line.
stations_locatioins	121.445602,31.106503; 121.438568,31.10471; 121.433407,31.103802 …	Coordinates of stations along the line.
stations_names	Yonglian village; Jinghong road; Hongmei South Road …	Name of stations along the line.

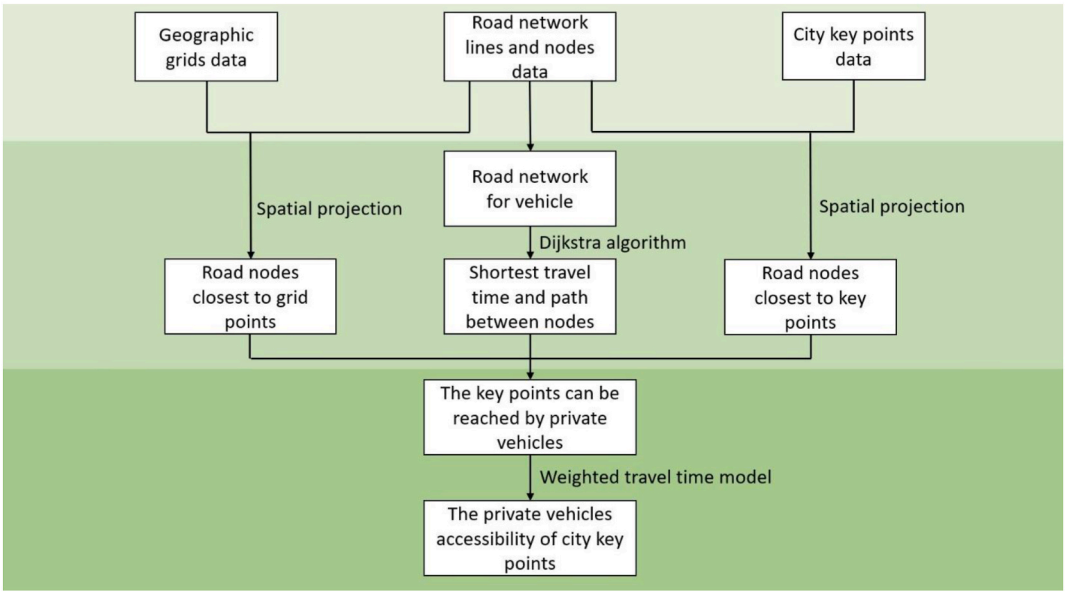
3. Research design

3.1. Study area and data resource

This study focuses on Shanghai, China, and sources the required data from official reports and geographic information websites. The network of public transit and private vehicles are demonstrated in Fig. 1 (a) and Fig. 1 (b). The data of the integrated transportation network was accessed from four resources. Among them, the public transit network data was composed of bus line lists and



(a)



(b)

Fig. 2. Research framework of traffic network accessibility: (a)public transits; (b)private vehicles.

lines & station coordinates, which were obtained from Shanghai 2020 Public Transit Passenger Flow Report and Gaode Map website respectively [46]. A total of 1613 bus and subway lines in Shanghai were obtained, and 1557 lines remained after excluding night lines and shutdown lines. The details of information acquired from the Gaode Map are shown in Table 1. The public transit operation data used in our study was extracted from the Shanghai Transit APP, including the information on departure intervals, transfer times, and travel times between stations. The transfer time was obtained from the "Collection of Transfer Walking Time Parameters" provided by the Shanghai Rail Transit Operation Management Center. The road network data consisted of coordinates, design speed, and topology of roads at all levels, which were obtained from the OpenStreetMap website. We also considered the actual vehicle speed on various grades of roads shown in the Shanghai Traffic Annual Report. In addition, as shown in Fig. 1 (c), this research focuses on 22 graded "city key points" in Shanghai that were planned in the "Shanghai Urban Master Plan (2017–2035)" [12], including two main city centers, nine city sub-centers, two core county centers, four new town centers, and four transportation hubs. Transportation hubs contain two railway and long-distance travel bus mixed hubs Shanghai Station and Shanghai South Station, and two airport and railway mixed hubs Hongqiao Station (Airport) and Pudong Station (Airport). In addition, as presented in Fig. 1 (d), census data is used to combine the spatial distribution of the population with accessibility analysis to analyze the proportion of the population covered by each accessibility level. To analyze the relationship between family income and accessibility, as shown in Fig. 1 (e), we also collected 3000 s-hand housing data from "lianjia.com", which is one of the largest second-hand house transaction web-sites. In this study, we use the average price per square meter of housing to stand for the household income level, because the vast majority of household main wealth is housing in China.

3.2. Methodology

This study applies transportation network construction, spatial intersection and search, path optimization calculation, and an improved accessibility model to deal with the multi-source data, as shown in Fig. 2 (a) and **(b)**.

3.2.1. Network construction and calculation

For the reason of measuring geospatial data in more detail, this study divides Shanghai into 15,767 square grids of the same size. Based on the calculation of line data, the average distance between bus stations is 790 m. To ensure that at least one bus stop is distributed in an analysis unit, we set the side length of a grid as 800 m. The grid center point represents the starting point of a resident's travel in the grid. According to the "Standard for Urban Comprehensive Transport System Planning" published by the Ministry of Housing and Urban-Rural Development [47], the proper service radius of a subway station is 800 m, and that of a bus station is 500 m. These can be used to intersect a public transit station with the grids it can serve.

This paper constructs a route network based on public transit network data, including 18,639 stations and 1557 lines. The bus operation relationship between nodes is expressed by "public transit links", with a total of 59,965. For bus lines, the travel time between stations is obtained by dividing the line length between stations by the average speed. Based on the research by the Shanghai Traffic Research Center on GPS data of buses, the average speed of the ground bus is set at 17.39 km/h [48]. For subway lines, the inter-station travel time is obtained from the subway operation schedule. The walking transfer relationship between nodes is expressed by "walking transfer links", with a total of 132,765. For example, as indicated in Fig. 3, we make a buffer zone for station A. In China, research based on surveys found that the tolerable walking distance to transfer to a bus station is 200 m, and to a subway station is 862 m [49,50]. Therefore, in this study, we set a radius of 200 m for bus stations and 800 m for subway stations. Then we establish the walking transfer link from other stations B and C to station A within the buffer zone. Based on the result of the GaoDe Map big data analysis, the walking speed is set to 1.2 m/s [51]. The link length is the sum of walking time and waiting time, as shown in **Equation**

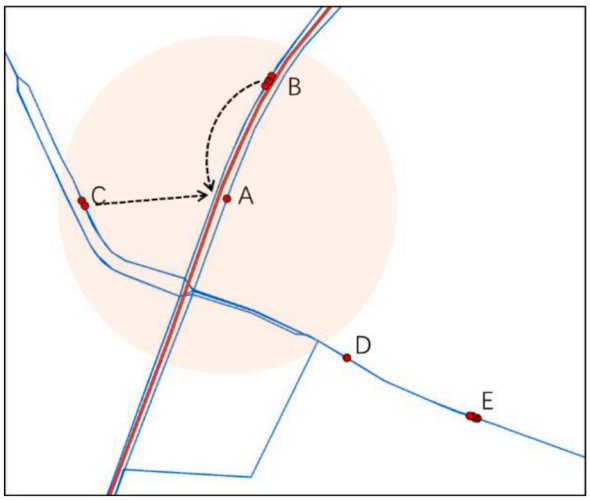


Fig. 3. Construction of the walking transfer links.

(1).

$$t_{BA} = \frac{\beta d_{BA}}{v_{walk}} + 0.5 * T_{line_A} \tag{1}$$

where β is the non-linear coefficient of straight line BA; d_{BA} is the straight line distance from station B to station A; v_{walk} refers to the average walking speed; and T_{line_A} is the average departure interval of the line to which station A belongs.

Based on the characteristics of the travel matrix and their respective application scenarios, this study employs different shortest path algorithms for public transit network and road network. According to the research by Singh and Tripathi, SPFA (Shortest Path Faster Algorithm) is more efficient when dealing with a small number of nodes, and the Dijkstra algorithm is greater efficient for a large wide of nodes [52,53]. Therefore, for the public transit network, we applied SPFA. Initially, the shortest distance of all nodes is set to infinity, and the distance of the source node is set to zero, then the source node is added to a queue. The queue is then polled continuously, taking out one node at a time and examining all the edges originating from that node. If an edge can shorten the distance to another node, the distance is updated and that node is added to the queue. This process is repeated until the queue is empty or no edge can further shorten the distance to any node. At this point, the shortest path values recorded in the queue represent the final results. In previous studies on the shortest path, the maximum transfer limit of travelers was often overlooked. Based on the "Traffic Analysis Report of Major Cities in China in 2021", 79 % of people in Shanghai have less than or equal to one transfer per day [54]. As a result, the maximum transfer times are set at 2 times in this study.

For private vehicles, the road network data contains 41,841 nodes and 102,722 links. When dealing with a large number of OD pairs, the traditional point-to-point calling method is inefficient and requires a significant amount of computing time. This study projects any start and end points on the map to the nearest road network node, and then searches the network between nodes, assuming that any point on the map is accessible by car. As a result, the Dijkstra algorithm is used. Compared with SPFA, the Dijkstra algorithm selects the closest unprocessed node to the source node for processing each time, and each node is only processed once. The process continues until all nodes have been processed. At this point, the stored distance in each node is the shortest distance from the starting node to it. Furthermore, as the OSM road network is not fully connected, there are still some points where their paths cannot be searched, as well as some abnormal distance values (either too large or too small). Therefore, those with a non-linear coefficient less than 1 or greater than 5 are defined as anomalies, and they are replaced by the Euclidean distance multiplied by 1.3 (average non-linear coefficient).

3.2.2. *Accessibility modeling and calculation*

As used in this paper, accessibility is defined as the potential of an origin to city key points in the city. Based on the "Shanghai Urban Master Plan 2017–2035" [12], the 22 city key points are divided into two grades. The first grade includes main city centers and transportation hubs. The two main city centers are planned to be the core area of linking the global network and serving the whole city. The four selected transportation hubs are planned to be international and national trunk line core stations, which are responsible for the transfer and connection between urban agglomerations and urban internal. The second grade includes city sub-centers, core county centers, and new town centers. These points are planned to serve the citizens as public activity centers for the region. To distinguish the importance of different points, the weight ratio of the two grades is 2:1. In this paper, we define accessibility as the weighted travel time to reach key points in the nearby city, as shown in Equation (2):

$$A_i = \frac{\sum_{j=1}^{n} \lambda_j t_{ij}}{\sum_{j=1}^{n} \lambda_j} \tag{2}$$

A_i is the accessibility of grid i; n is the number of city key points included in the study; λ_j is the weight of city key point j; and t_{ij} is the travel time from grid i to city key point j.

After the accessibility results of each grid are obtained, the results need to be divided into levels. In this study, the geometric interval classification method is used to better match the accessibility results with the actual network in the subsequent analysis.

3.2.3. *The social groups and Gini coefficient*

To study whether Shanghai transportation system meets the need for equity, we categorize Shanghai residents into four groups. Two characteristics of a resident are used to reflect his/her social features, including the income level and location of residence. For the former, the average price per square meter of housing is used. As mentioned before, we collected 3000 on sale second-hand housing data, which is located in 1098 grids and is used to represent income levels of 7,448,546 people (32 % of Shanghai population). For the latter, the outer ring road separates Shanghai into central city and suburbs. The central city accounts for 1507 grids (10 % of the total grids).

The Gini coefficient of accessibility is also calculated, within each group and between groups, to quantify the travel equity for each destination and each mode. The difference within each group can reflect the even degree of traffic resource allocation in the whole city, and the difference between groups can show whether different groups enjoy equitable public transport services.

4. Results

4.1. Results of private vehicles

Fig. 4 (a) and Fig. 4 (b) show the accessibility of Shanghai's transportation hubs and graded city centers by PV respectively. It can be seen that the accessibility of the graded city centers is lower than that of the transportation hubs. The grids that can reach the hubs within 45 min account for 36 %, and the population accounts for 80 %; while the grids that can reach the graded city centers within 45 min account for only 14 %, and the population accounts for 49 %. The average weighted travel time of citizens to the transportation hubs is 39 min, with a standard deviation of 7.1; and to the graded city centers is 46 min, with a standard deviation of 5.6.

For both transportation hubs and graded city centers, the accessibility gradually weakens from the city center within the outer ring to the outside. The weighted travel time of the population in the central city and suburbs to the transportation hubs are 35 min and 43 min respectively, with a difference of 24 %; while the weighted travel time to the graded city centers are 43 min and 49 min respectively, with a difference of 14 %.

Furthermore, Fig. 4 also illustrates that the spatial distribution of accessibility by PV is related to the distribution of highways and expressways. The accessibility of grids adjacent to highways is higher than those farther away. This is because highways and expressways, which are high-grade roads, have higher speeds and therefore contribute more to higher accessibility. The central city has higher accessibility than the suburbs due to the dense high-grade road facilities. The sharp drop in accessibility where the expressway is interrupted within the central city also proves the contribution of high-grade roads.

4.2. Results of public transit

(1) Number of city key points reachable by public transit

Due to the restrictions given in this study that people can only reach the PT station within a radius of 800 m and accepts a maximum of 2 transfers, some of the grids cannot reach certain city key points by PT. On the contrary, this study assumes that private vehicles can go from any grid to all other grids. Fig. 5 (a) and Fig. 5 (b) shows the number of transportation hubs and graded city centers that can be reached by PT for each grid in Shanghai. Since Chongming Island is separated from other areas of Shanghai by the sea and there are few connections through PT, it is not analyzed in this section.

Fig. 5 reflects that 55 % of the grids (52 % of the population) cannot reach any transportation hub by PT. 46 % of the grids (47 % of the population) cannot reach any graded city centers by PT, where PT is completely uncompetitive. 16 % of the grids (11 % of the population) can reach 4 transportation hubs by PT. 10 % of the grids (5 % of the population) can reach more than 13 graded city centers by PT, and most of these grids are located in the central city. The number of reachable city key points by PT gradually decreases from the city center to the outside, and the competitiveness is gradually weakening. There are few public service facilities in the

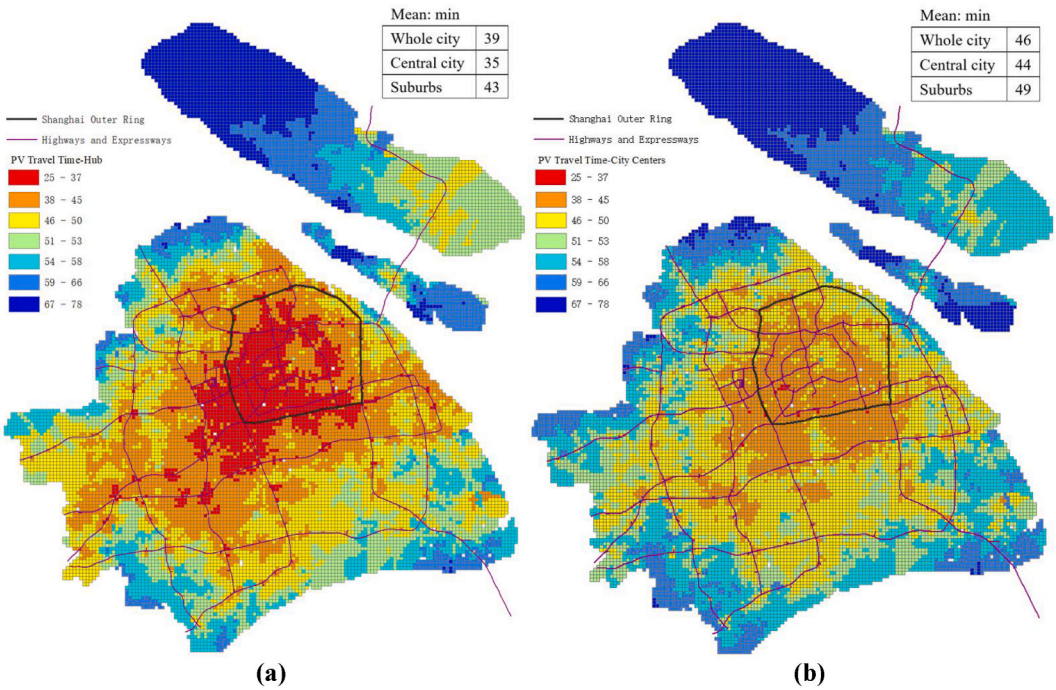


Fig. 4. Accessibility of Shanghai city key points by private vehicles: (a) transportation hubs; (b) graded city centers.

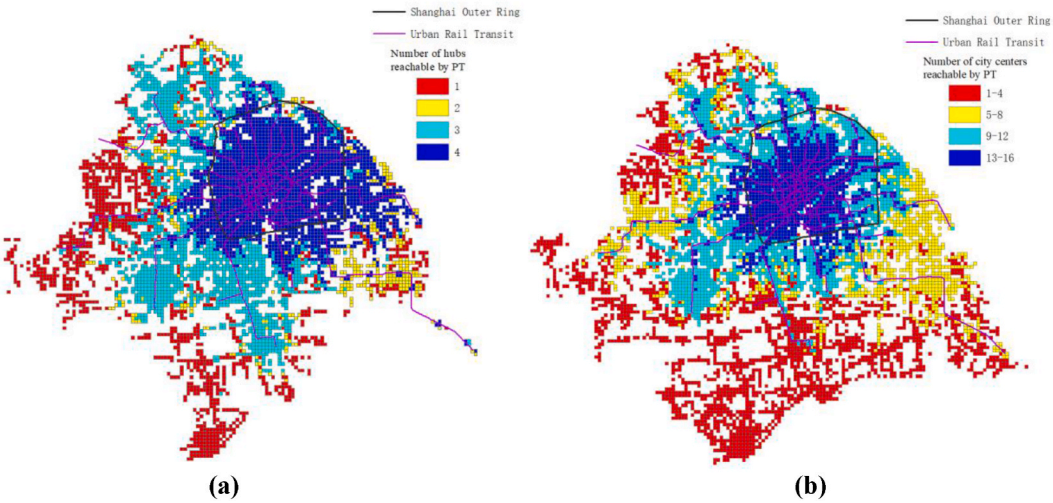


Fig. 5. Number of city key points reachable by public transit: (a) transportation hubs; (b) graded city centers.

suburbs, especially transportation hubs. Government and transportation companies should develop more public service facilities and PT lines in the suburbs.

(2) Accessibility of city key points by public transit

Fig. 6 (a) and Fig. 6 (b) illustrate the accessibility of transportation hubs and graded city centers by PT respectively. Since some suburban grids can only reach the nearest key point, their weighted travel time is unusually small. However, this does not affect our analysis of the overall trend of accessibility.

The average weighted travel time of the transit-accessible citizens to the transportation hubs is 73 min, with a standard deviation of 18.1; and to the graded city centers is 75 min, with a standard deviation of 16.4. People who can reach the hubs and the graded city centers within 60 min account for 27 % and 18 % of the population respectively. Most of them are located in the central city. It can be seen from Fig. 6 that the accessibility of PT from the city center to the outside gradually decreases. The weighted travel time from the central city and suburbs to the transportation hubs are 64 min and 86 min respectively, with a difference of 35 %. The weighted travel time to the graded city centers are 66 min and 87 min respectively, with a difference of 31 %.

Figs. 5 and 6 reveal that the spatial distribution of PT accessibility is also related to the distribution of rail transit, with higher accessibility and more accessible key points for grids near rail transit. Although there are many bus lines in the suburbs, the central city has denser rail transit facilities. PT accessibility in the central city is better compared to the suburbs. It can be seen that rail transit has

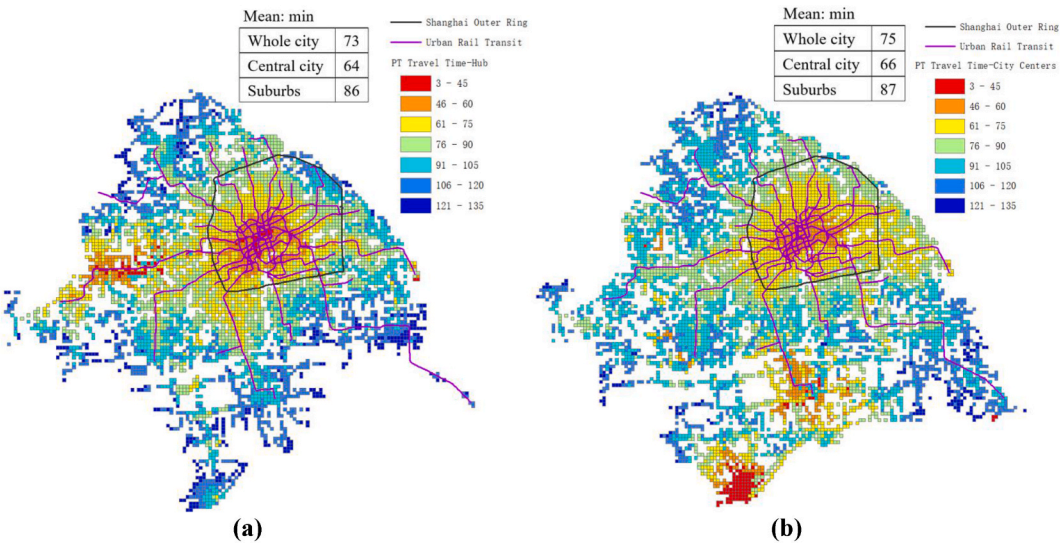


Fig. 6. Accessibility of Shanghai city key points by public transit: (a) transportation hub; (b) graded city centers.

significant speed advantages compared to conventional buses, and plays an important role in connecting various parts of the city.

4.3. Differences in accessibility between public transit and private vehicles

In the calculation of the accessibility differences between PT and PVs, only the grids with city key points accessible by PT are comparable. A total of 5359 grids are accessible to the hubs, and 6523 grids are accessible to the graded city centers. Fig. 7 (a) and Fig. 7 (b) illustrate the accessibility differences between PT and PVs for the transportation hubs and the graded city centers in Shanghai. The smaller the travel time ratio, the smaller the accessibility difference, and the higher the competitiveness of PT compared with PVs.

The average travel time ratio of population in all comparable grids is 2.04 for the transportation hubs, and 2.10 for the graded city centers. The grids with accessibility differences within 1.5 between PT and PV for the hubs account for 5 %, and the population accounts for 14 %, over 85 % of whom live in the central city. The grids with accessibility differences within 1.5 for the graded city center account for 4 %, and the population accounts for 10 %, over 98 % of whom live in the central city. These results indicate that PT has a certain degree of competitiveness relative to PVs in these locations.

The average travel time ratios of traveling from the central city and suburbs to the transportation hubs are 1.84 and 2.31 respectively, with a difference of 26 %. The average travel time ratios to the graded city centers are 1.82 and 2.46 respectively, with a difference of 35 %. The accessibility difference between PT and PVs is significantly lower in the central city, and this attributes to the contribution of rail transit. Fig. 7 shows that the spatial distribution of accessibility differences is closely related to the distribution of rail transit corridors, and the accessibility differences along rail transit lines are even smaller. Results also reflect that in large cities and megacities, only rail transit can compete with PVs. Conventional buses can only provide basic services. At present, the density of rail transit facilities in suburban areas is much lower than that in the central city, and the spatial equity in the distribution of high-level facilities and transportation resources needs to be improved.

Furthermore, we analyzed the influence of travel distance on the differences and competitiveness of PT and PV. The results show that the longer the travel distance, the smaller the travel time ratio between PT and PV. For travel distances ranging from 0 to 20 km, the average travel time of PT and PV are 67 min and 31 min respectively, with a travel time ratio of about 2.28; for travel distances spanning 20–40 km, the average travel time of PT and PV are 99 min and 46 min respectively, with a travel time ratio of about 2.21; for travel distances greater than 40 km, the average travel times of PT and PV are 116 min and 57 min respectively, with a travel time ratio of about 2.08. This implies that the travel time difference between PT and PV gradually decreases as the travel distance increases, emphasizing a greater relative competitiveness of PT.

4.4. The comparisons of accessibility and Gini coefficients between groups

Table 2 shows the weighted travel time of different groups to hubs and centers by PT and PV. In general, the higher the household income, the closer the residence is to the downtown, and the shorter the weighted time to city key points through PT. For the two groups with the most extreme differences, 32 % and 28 % more time is needed for the poor people who live suburbs compared to the rich people who live in city center, respectively. For PV, rich people can always enjoy better PV accessibility, even if they live in the suburbs. In addition, the PT travel time difference between the suburban and urban areas is more significant than that of PV, which

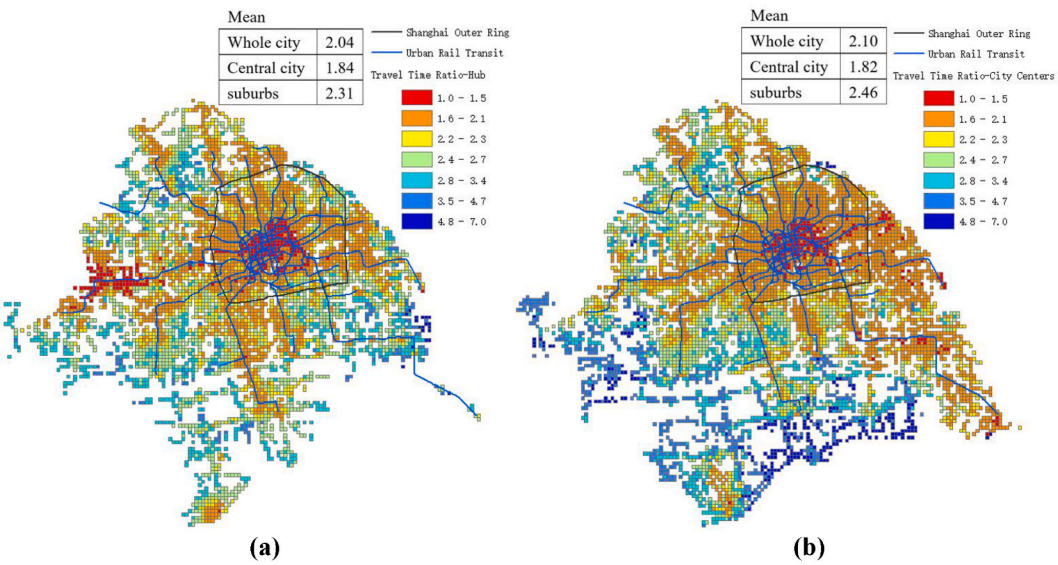


Fig. 7. Accessibility differences between private vehicles and public transport for city key points in Shanghai: (a) transportation hubs; (b) graded city centers.

Table 2
Weighted travel time (minutes) to city key points by public transit and private vehicles.

	Hub PT	Cen PT	Hub PV	Cen PV
Rich in Center	59.56	63.16	33.60	42.16
Poor in Center	66.94	67.97	35.98	43.70
Rich in Suburb	71.84	75.76	35.65	42.90
Poor in Suburb	78.66	80.68	41.23	47.16

leads to the further reduction of the competitiveness of PT in the suburbs. In general, the groups with higher demand for PT do not receive better services.

We also calculated Gini coefficients for accessibility indexes within each group and among groups, as shown in Table 3. It can be seen that all Gini coefficients within each group are less than 0.2, indicating that the ability of people to reach city key points in the same group has little difference under grid based crowd segmentation method. The accessibility is closely related to the change in residential distribution and house price, and within the rich class is more even. However, Gini coefficients among the four groups are all greater than 0.5, indicating that there seemed to be an enormous class difference in weighted travel time among Shanghai residents. More public transportation resources should be distributed to travel vulnerable groups such as the poor living in the suburbs.

5. Discussion and conclusions

This study uses Shanghai's public transit network and operation data, road network data, and city key points data to examine the development status and competitive relationship between public transit and private vehicles. Shortest path algorithms and an improved weighted travel time model are applied to construct virtual networks and visualize results. We identify the accessibility results to city key points to measure the impact of traffic mode and urban location on the travels of citizens. More importantly, this study addressed the gap between PT and PV by travel time ratio on the scale of the whole city, reflecting the planning and development situation of Shanghai's urban comprehensive transportation network. What's more, we separated Shanghai residents into four groups and used Gini coefficient to target the travel vulnerable people.

Our findings underscore the pressing need for an intensified focus on public transit development in future urban planning agendas. In the rapidly evolving landscape of metropolises like Shanghai, it's striking to note that about half the population is either underserved by PT services or cannot reach any city key points within two transfers. Almost all of these residents live in the suburbs, highlighting a concerning disparity in PT accessibility. What's more, only 27 % of the population can reach the hubs within 1 h, and for the graded city centers, the ratio is 18 %. Most of these advantaged people are located in the central city. This trend, echoing the findings of previous studies like those conducted by Chen et al. reveals that despite continuous efforts in urban transit development, PT accessibility always decreases progressively from center to periphery [55]. Given the concentration of underserved populations in the suburbs, and their relative isolation from vital city centers, the focus should shift towards enhancing these connections. In line with the views of Yi et al. we believe that the extension of subway systems in the suburbs is a more effective method to address spatial inequalities [22].

Comparing PT with PV in terms of travel time and convenience, it's unsurprising to find the latter holding an significant advantage in Shanghai. The average travel time ratio in all comparable grids is 2.04 for the transportation hubs, and 2.10 for the graded city centers, which are much higher than the ideal line of 1.5 proposed based on Stockholm case study [32]. Only 10 % of the citizens have access to competitive PT services, and 98 % of them reside in the city center. In addition, the average travel time ratio of the central city to hubs and graded city centers are 1.84 and 1.82, while 2.31 and 2.46 in the suburbs. The disparity in travel time ratio between Shanghai's city centers and its suburbs is markedly more pronounced than that observed in previous studies. Contrastingly, a study from Finland, as described by Salonen and Toivonen, present a disparity value of 0.29 between the city center and the suburbs, showcasing a more balanced transport network [31]. Shanghai's transport disparities largely stem from its vast geography. The city center has a dense public transport route network, whereas suburbs exhibit sparser, irregular transit coverage. In contrast, the road infrastructure for PV is more developed, with average weighted travel times to key city points being less than an hour. While accessibility in the suburbs gradually decreases, the continued construction of expressways and highways offers a promising solution for the future. Similar conclusions have been concluded in previous studies [56].

From an equity perspective, the application of the Gini coefficient unveiled significant inequalities in Shanghai's public transport services concerning spatial distribution and income disparities. In essence, affluent neighborhoods often have access to superior PT services, whereas the more economically disadvantaged areas lag behind. PT should offer everyone basic and efficient travel services, especially for those who can hardly rely on other travel modes but need to travel a long distance. In comparison with other studies that utilize the Gini coefficient to gauge weighted travel times, Shanghai's differential of over 0.5 between various social groups is alarmingly high [57,58]. These inequalities could further exacerbate socio-economic stratification within urban landscapes. Consequently, forthcoming transportation strategies ought to prioritize equity at one of their cores to ensure balanced urban growth.

Several limitations of this study can provide directions for future research. Firstly, while the methodologies employed within this research are applicable to diverse cities, the uniqueness of Shanghai, as a megacity, should be acknowledged. The results derived from this study, thus, might not be readily extrapolated to medium and smaller cities. This indicates the necessity of localized studies for generating more nuanced urban transportation insights. Secondly, our research did not factor in the impact of distance decay, meaning the choice of transportation for residents might be influenced by the trip distance, and this variable was overlooked in our analysis.

Table 3
Gini coefficients of accessibility for public transit and private vehicles.

	Hub PT Gini within Groups	Hub PT Gini among Groups	Cen PT Gini within Groups	Cen PT Gini within Groups	Hub PV Gini within Groups	Hub PV Gini among Groups	Cen PV Gini within Groups	Cen PV Gini among Groups
Rich in Center	0.09	0.53	0.06	0.53	0.06	0.51	0.03	0.51
Poor in Center	0.12		0.09		0.07		0.04	
Rich in Suburb	0.08		0.08		0.06		0.04	
Poor in Suburb	0.12		0.11		0.08		0.05	

Finally, the absence of resident travel survey data constitutes a significant limitation. Without such granular data, it becomes challenging to comprehend the actual public transport service levels enjoyed by marginalized groups, such as low-income households or those without private vehicles. Addressing these shortcomings in subsequent research will yield a more holistic understanding of PT development and equity issues.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author. Due to the inclusion of sensitive information such as regional population data, the data will not be publicly available.

CRediT authorship contribution statement

Naifu Fan: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Xiaohong Chen:** Conceptualization, Funding acquisition, Project administration, Resources, Software, Supervision. **Tiantian Tian:** Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Siyu Zhao:** Conceptualization, Data curation, Investigation, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] X. Guan, H. Wei, S. Lu, Q. Dai, H. Su, Assessment on the urbanization strategy in China: Achievements, challenges and reflections, Habitat Int. 71 (2018) 97–109.
[2] Y. Li, L. Miao, Y. Chen, Y. Hu, Exploration of sustainable urban transportation development in China through the Forecast of private vehicle ownership, Sustainability 11 (16) (2019) 4259.
[3] Q. Shen, Urban transportation in Shanghai, China: problems and planning implications, Int. J. Urban Reg. Res. 21 (4) (1997) 589–606.
[4] E. Pieterse, Urban governance and spatial transformation ambitions in Johannesburg, J. Urban Aff. 41 (1) (2019) 20–38.
[5] F. Tonkiss, City government and urban inequalities, City 24 (1–2) (2020) 286–301.
[6] S. Jang, Y. An, C. Yi, S. Lee, Assessing the spatial equity of Seoul's public transportation using the Gini coefficient based on its accessibility, Int. J. Unity Sci. 21 (1) (2017) 91–107.
[7] R. Akuh, M. Zhong, A. Raza, J. Sun (Eds.), Proposed New City Development and Public Transport Accessibility: A Case Study of Yangtze River New City of the City of Wuhan, 2021 6th International Conference on Transportation Information and Safety (ICTIS), 2021, 2021 22-24 Oct.
[8] N. Wu, S. Zhao, Q. Zhang, A study on the determinants of private car ownership in China: findings from the panel data, Transport. Res. Pol. Pract. 85 (2016) 186–195.
[9] A. Frenkel, E. Israel, Spatial inequality in the context of city-suburb cleavages–Enlarging the framework of well-being and social inequality, Landsc. Urban Plann. 177 (2018) 328–339.
[10] X. Zhang, Y. Chai, Z. Chen, Y. Tan, Analysis of spatial and temporal patterns of daily activities of suburban residents based on GPS data: a case study of the Shangdi-Qinghe area of Beijing, International Review for Spatial Planning and Sustainable Development 4 (1) (2016) 4–16.
[11] S. Celep, Assessment of Sub-center Development, Middle East Technical University, Batikent, Ankara, 2009.
[12] S.M. Government (Ed.), Shanghai. Shanghai Urban Master Plan (2017-2035), 2018.
[13] A.T. Murray, R. Davis, R.J. Stimson, L. Ferreira, Public transportation access, Transport. Res. Transport Environ. 3 (5) (1998) 319–328.
[14] John Pucher, Public Transportation (2004) 199–236.
[15] T. Litman, Measuring Transportation, Traffic, Mobility and Accessibility, 2011.
[16] W.G. Hansen, How accessibility Shapes land Use, J. Am. Inst. Plan. 25 (2) (1959) 73–76.
[17] G.R. Leake, A.S. Huzayyin, Accessibility measures and their suitability for Use in trip generation models, Traffic Eng. Control 2 (1979) 566–572.
[18] D.R. Ingram, The concept of accessibility: a search for an operational form, Reg. Stud. 5 (2) (1971) 101–107.
[19] M. Wachs, K.T. G, Physical accessibility as a social indicator, Soc. Econ. Plann. Sci. 7 (5) (1973) 437–456.
[20] L. Bertolini, F. Le Clercq, L. Kapoen, Sustainable accessibility: a conceptual framework to integrate transport and land use plan-making. Two test-applications in The Netherlands and a reflection on the way forward, Transport Pol. 12 (3) (2008) 207–220.
[21] J. Grengs, Nonwork accessibility as a social equity indicator, International Journal of Sustainable Transportation 9 (1) (2014) 1–14.
[22] S. Jang, Y. An, C. Yi, S. Lee, Assessing the spatial equity of Seoul's public transportation using the Gini coefficient based on its accessibility, Int. J. Urban Sci. 21 (1) (2017) 91–107.
[23] J. Jeon, S. Kim, K. Suh, M. Park, S. Yoon, Accessibility to public service facilities in Rural area by public transportation system, Journal of Korean Society of Rural Planning 22 (4) (2016) 1–11.
[24] W. Seo, H.K. Nam, Trade-off relationship between public transportation accessibility and household economy: analysis of subway access values by housing size, Cities 87 (2019) 247–258.
[25] B. Ilir, N. Soowoong, Z. Gu, R.L. Steiner, S.M. Winter, Analytical method to Determine transportation service gaps for transportation disadvantaged populations, Transportation Research Record Journal of the Transportation Research Board (2018) 036119811879429.

[26] G. Cheng, X. Zeng, L. Duan, X. Lu, H. Sun, T. Jiang, et al., Spatial difference analysis for accessibility to high level hospitals based on travel time in Shenzhen, China, Habitat Int. 53 (2016) 485–494.
[27] S.S. Sakaran, H.M. Noor, The concept of accessibility in public transportation services, Jurnal Kinabalu 26 (2020).
[28] Y. Zhou, Y. Lin, Y. Chen, Q. Zhao, Z. Jin (Eds.), Comprehensive Evaluation Framework of Multi-Mode Public Transportation Service Levels, 16th COTA International Conference of Transportation Professionals, 2016.
[29] R. Woods, J. Masthoff, A comparison of car driving, public transport and cycling experiences in three European cities, Transport. Res. Part A Policy & Practice 103 (2017) 211–222.
[30] L. Tao, A.A. Ceder, R. Bologna, B. Cabantous, Commuting by Customized bus: a Comparative analysis with private car and conventional public transport in two cities, Journal of Public Transportation 19 (2) (2016) 55–74.
[31] M. Salonen, T. Toivonen, Modelling travel time in urban networks: comparable measures for private car and public transport, J. Transport Geogr. 31 (jul) (2013) 143–153.
[32] G. Hitge, M. Vanderschuren, Comparison of travel time between private car and public transport in Cape Town, Civ. Eng. 57 (3) (2015) 35–43.
[33] Authority SsLT, Singapore's Land Transport Master Plan, 2013.
[34] G. Beirão, J.S. Cabral, Understanding attitudes towards public transport and private car: a qualitative study, Transport Pol. 14 (6) (2007) 478–489.
[35] S. Jain, P. Aggarwal, P. Kumar, S. Singhal, P. Sharma, Identifying public preferences using multi-criteria decision making for assessing the shift of urban commuters from private to public transport: a case study of Delhi, Transport. Res. F Traffic Psychol. Behav. 24 (2014) 60–70.
[36] L. Redman, M. Friman, T. Gärling, T. Hartig, Quality attributes of public transport that attract car users: a research review, Transport Pol. 25 (2013) 119–127.
[37] J. Pucher, H. Park, M.H. Kim, J. Song, Public transport reforms in Seoul: Innovations motivated by funding crisis, Journal of Public Transportation 8 (5) (2005) 3.
[38] M.F. Guagliardo, Spatial accessibility of primary care: concepts, methods and challenges, Int. J. Health Geogr. 3 (1) (2004) 3.
[39] Jared Hewko, Smoyer-Tomic, E. Karen, Hodgson, et al., Measuring neighbourhood spatial accessibility to urban amenities: does aggregation error matter, Environ. Plann. 34 (7) (2002) 1185.
[40] L. Rosero-Bixby, Spatial access to health care in Costa Rica and its equity: a GIS-based study, Soc. Sci. Med. 58 (7) (2004) 1271–1284.
[41] L. Wei, Q. Yi, An enhanced two-step floating catchment area (E2SFCA) method for measuring spatial accessibility to primary care physicians, Health Place 15 (4) (2009) 1100–1107.
[42] H.C. Chin, K.W. Foong, Influence of school accessibility on housing values, J. Urban Plann. Dev. 132 (3) (2006) 120–129.
[43] S. Mavoa, K. Witten, T. McCreanor, D. O'sullivan, GIS based destination accessibility via public transit and walking in Auckland, New Zealand, J. Transport Geogr. 20 (1) (2012) 15–22.
[44] M.A. Jin, B. Hk, The Intra-metropolitan Distribution of Airport Accessibility, Employment Density, and Labor Productivity: Spatial Strategy for Economic Development in Tokyo - ScienceDirect, vol. 125, Applied Geography, 2020.
[45] L. Rui, C. Yun, J. Wu, T. Xu, X. Zhao, Mapping spatial accessibility of public transportation network in an urban area – a case study of Shanghai Hongqiao Transportation Hub, Transport. Res. Transport Environ. 59 (2018) 478–495.
[46] Shanghai, 2020 Shanghai Comprehensive Transportation Operation Annual Report, Shanghai Urban & Rural Construction and Transportation Development Research Institute, 2020.
[47] China MoHaU-RDotPsRo, Standard for Urban Comprehensive Transport System Planning, 2019.
[48] J. Feng, A Comparative study on the development level of public transport and rail transit in Shanghai and global cities, Communication Shipping 4 (1) (2017) 44–48.
[49] H. Chen, S. Xu, Y. Wu, M. Zhang, Study on the suitability of urban rail transit transfer distance, Public Utilities 7 (2) (2020) 40–46.
[50] H. Yan, R. Yang, W. Xiong, T. Liu, N. Chen, Critical accessing time and distance for Pedestrian and Cyclists to urban rail transit, Urban Transport of China 2 (2013) 83–90.
[51] M. Gaode. https://lbs.amap.com/.
[52] J.B. Singh, R. Tripathi, Investigation of Bellman-Ford algorithm, Dijkstra's algorithm for suitability of SPP, Int J Eng Dev Res 1 Dean Res. 6 (1) (2018) 2321–9939.
[53] H. Chen, H.-J. Suh, An improved Bellman-Ford algorithm based on SPFA, The Journal of the Korea institute of electronic communication sciences 7 (4) (2012) 721–726.
[54] Map G, Traffic Analysis Report of Major Cities in China in 2021, 2021. https://pdf.dfcfw.com/pdf/H3_AP202111241530849641_1.pdf?1637766880000.pdf;.
[55] C. Yan-Yan, W. Pan-Yi, L. Jian-Hui, F. Guo-Chen, L. Xin, G. Yi, An evaluating method of public transit accessibility for urban areas based on GIS, Procedia Eng. 137 (2016) 132–140.
[56] S-m Li, Y-m Shum, Impacts of the national trunk highway system on accessibility in China, J. Transport Geogr. 9 (1) (2001) 39–48.
[57] B. Tahmasbi, H. Haghshenas, Public transport accessibility measure based on weighted door to door travel time, Comput. Environ. Urban Syst. 76 (2019) 163–177.
[58] J. Chestnut, E.E. Boschmann, Exploring the utility of Gini coefficients as a measure of temporal Variation in public transit travel time, Papers in Applied Geography 8 (1) (2022) 112–123.