Research paper

Collective and individual spatial equity measure in public transit accessibility based on generalized travel cost

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ABSTRACT

This study devises a novel two-dimensional analysis framework for spatial equity in public transit accessibility. We incorporated door-to-door travel time and ticket price by public transit into a generalized travel cost function to measure utility-based accessibility following a log-sum formulation. Then, this study designed a Palma ratio of accessibility and a neighboring accessibility gap index to respectively examine the collective spatial equity and individual spatial equity of public transit. Finally, we took an empirical case of Kunming city, China to analyze the unity-based accessibility distribution and checked collective and individual spatial equity levels reaching business centers, transport hubs, and 3-A hospitals. The results show that the utility-based accessibility reaching transport hubs by public transit is less than 50% to business centers and 32% to 3-A hospitals. Collectively, the expected minimum generalized travel cost by public transit in the poorest 40% of traffic analysis zones is almost 2.5 times as much as in the richest 10% of traffic analysis zones, and the collective spatial equity in old blocks is superior to new blocks. Individually, the number of traffic analysis zones with no spatial inequity, slight inequity, and medium inequity in public transit accessibility respectively occupied almost 57%, 38%, and 5%. We also found individual spatial equity may be associated with the walking distance during taking public transit and the number of neighboring traffic analysis zones.

1. Introduction

Promoting equitable development of public transport system in the aspect of social equity (Behbahani et al., 2018; Grengs, 2013) and spatial equity (Delmelle & Casas, 2012; Kelobonye et al., 2019) has become a primary agenda for traffic planners and city engineers. Especially, public transit has been an essential role to provide necessary access to social activities for low-income people without cars for a long time (Ignaccolo et al., 2016; Nahmias-Biran et al., 2013; Stanley & Lucas, 2008). Many cities have been aware of the impact of transportation projects (Nahmias-Biran et al., 2013; Niehaus et al., 2016) and transportation plans (Behbahani et al., 2018; Camporeale et al., 2016) on equity in different aspects, and they attempt to advocate the equity-oriented transport development for enhancing public transport services (R. J. Lee et al., 2016; Oswald Beiler & Mohammed, 2016). Therefore, planning an equitable public transport system has potential benefits for the sustainable and inclusive development of urban mobility (Wang et al.,

2019).

In the last decade, researchers have devoted significant attention to exploring the concepts and measurements of equity in public transit. However, it is more difficult to measure transit equity than to understand one since the principle of equity remains sophisticated and diverse. There are three basic categories of transit equity: horizontal equity, vertical equity, and spatial equity in the existing literature. Litman (2012) developed horizontal equity and vertical equity with income and social class, and Ricciardi et al. (2015) discussed vertical equity with mobility demand and ability. Meanwhile, several studies attempted to apply the gap of accessibility to identify the difference in transportation benefits distributed in spatial units, which was usually called spatial equity (Kelobonye et al., 2019; Martens et al., 2012). As far as assessment methods of transportation equity are concerned, their principles and measures both remain unclear. There is no doubt that these proposed methods based on different equitable principles may exert some bias when evaluating horizontal equity, vertical equity, and

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others (Golub & Martens, 2014; Martens et al., 2012).

In previous works, accessibility has been a prevalent tool to examine the spatial equity level in public transit accessibility. The most common research paradigm concerning accessibility-based equity measures is as follows. To begin with, the travel time by public transit will be estimated as accurately as possible based on a Geographic Information System (Tahmasbi & Haghshenas, 2019; Yang et al., 2017). Then, a mathematical model (such as the gravity model, utility model, space-time model, and opportunity model) is developed to compute public transit accessibility considering main trip purposes (Ben-Elia & Benenson, 2019; Hansen, 2007; Kelobonye et al., 2019; L. Li et al., 2017; Zhou et al., 2018). Finally, the Lorenz curve and Gini coefficient are used to measure equity level (Lucas et al., 2015; Ricciardi et al., 2015; Welch, 2013). Table 1 summarizes related studies on public transit accessibility-based equity measures in the last four years. In these studies, transit modes involved common bus and metro modes.

Recent developments in public transit accessibility-based equity measures concentrated on the following four aspects. First, in the aspect of public transit accessibility measures, travel time has become the most prevalent indicator for accessibility formulation. Most researchers are used to developing a direct function or composite function of travel time to measure public transit accessibility. Second, main three types of concerning equity measure indicators have been widely used, including several economical indexes (such as the Theil index, Paloma ratio, Lorenz curves, Gini index, and average consumer surplus), statistical indicators (such as Getis-Ord statistic and local indicators of spatial association) and self-proposed indicators (such as accessibility sufficiency index, travel time gap/ratio). Third, in terms of equity types, most existing studies have been mainly focused on the collective equity level. This is, these studies are devoted to taking the above equity measure indicators to examine whether public transit accessibility is equitable for a population group or a region. Fourth, about citizens' trip purposes,

Table 1
Review on public traffic accessibility-based equity measure.

References	PTA measure	Equ. indicator	Equ. type	Activity
Bills et al. (2022)	Travel time	ACS	C&I	Job
Tao et al. (2022)	Travel time	SDC	C	Job
Martens et al. (2022)	Travel time	ASI	C&I	Job
Jin et al. (2022)	Travel time	Theil index	C	Healthcare
Singer et al. (2022)	Distance	ASI	I	Job
Costa et al. (2021)	Travel time	TTG/TTR	C&I	CBD
Zuo et al. (2020)	Travel time	GE, Atkinson indexes	C	Job
Jomehpour Chahar Aman & Smith-Colin (2020)	Travel time and distance	/	C	Job, Healthcare
Li and Fan (2020)	Distance	TGI	C	/
Ermagun and Tilahun (2020)	Travel time	/	C	Job, Park;
Allen and Farber (2020)	Cumulative opportunity	Getis-Ord statistic	C	Job
Chen and Wang (2020)	Cumulative-opportunity	/	C	Job, Dining
Boisjoly et al. (2020)	Travel time	/	C	Job
Ben-Elia and Benenson (2019)	Travel time	Gini index	C	Job
Chen et al. (2019)	Cumulative-opportunity	Lorenz curves and Gini index	C	/
Lee and Miller (2019)	Space-time prism	Elliptic shape	C	Healthcare
Slovic et al. (2019)	Travel time	LISA	C	Job

Note: PTA – public transit accessibility; Equ. – equity; C – Collective; I – individual; ACS - Average consumer surplus; SDC – standard distance circle; ASI – accessibility sufficiency index; TTG &TTR – travel time gap and ratio; GE – general entropy; TGI – transit gap index; LISA – local indicators of spatial association.

accessibility-based equity related to workplaces, dining, and healthcare has been usually checked.

Although extensive research has been carried out on public transit accessibility-based equity formulations, to the best of our knowledge, there is limited research that investigates spatial equity levels in public transit accessibility both collectively and individually in a multimodal transit network. Therefore, this study is motivated to address the identified research niche, and the following contributions are made.

(1) We introduce the generalized travel cost into a utility-based accessibility measure that integrates door-to-door travel time (including walking time, waiting time, transfer time, and travel time) and ticket price by public transit. Recalling Table 1 has pointed out that accurate travel time plays a key role in public transit accessibility measures. The difference and novelties of this study compared with existing literature related to travel time estimation by public transit are summarised in Table 2. On the one hand, a part of previous studies adopted the self-built transit network to estimate travel time by public transit. Under this workflow, passengers' walking time and waiting time usually are assumed to be constant or directly overlooked. Meanwhile, congestion effects of background traffic in the road network do not consider in their formulations. On the other hand, previous studies firsthand took travel time rather than generalized travel costs to model public transit accessibility, which led to the impact of the ticket price on public transit accessibility is not considered.

(2) We devise a two-dimensional measure framework of spatial equity in public transit accessibility, including collective spatial equity and individual spatial equity. Concerning collective spatial equity, we proposed a Palma ratio to examine whether public transit accessibility is equitable distributed in the study area. Regarding individual spatial equity, we developed a neighboring accessibility gap index to check which spatial units are more advantaged or disadvantaged in the study area.

(3) We conduct an empirical case in Kunming city, China to comprehensively examine the utility-based accessibility distribution reaching business centers, transport hubs, and 3-A hospitals, collective and individual spatial equity levels in public transit accessibility, and the association between individual spatial equity levels and some key factors including transfer times and walking distance during using public transit and the number of neighboring traffic analysis zones.

The remaining of this paper is organized as follows. Section 2 provides a detailed introduction to the proposed model, including generalized travel cost function, utility-based accessibility measure, individual spatial equity measure, and collective spatial equity level. Section 3 conducts an empirical case in Kunming city to examine the spatial equity level of public transit accessibility and its associated factors. Finally, Section 4 concludes this study, offers managerial insights, and sheds light on future research directions.

2. Methodology

2.1. Problem description and notations

In this section, we first formulate the generalized travel cost formulation by public transit for each traffic analysis zone. Then based-utility accessibility measure is devised. Finally, we proposed a straightforward framework for spatially collective equity measures and individual equity measures. Furthermore, to compare the public transit accessibility disparity among different locations within the study area, we distinguish the old blocks and new blocks from all traffic analysis zones. The workflow for the two-dimensional spatial equity measure of public transit accessibility is shown in Fig. 1.

The related notations used in the main formulations are listed below.

Table 2
Difference between previous studies related to accessibility measures and this study.

References	PTA model	TTE	Price	Walking	Waiting	Transfer	Congestion
Bills et al. (2022)	Utility-based	SBN	yes	no	yes	yes	no
Tao et al. (2022)	Population-weighted	SBN	no	yes	no	yes	no
Martens et al. (2022)	Utility-based	SBN	no	yes	no	yes	no
Jin et al. (2022)	G2SFCA	API	no	yes	yes	yes	yes
Costa et al. (2021)	Income-weighted	API	no	yes	yes	yes	yes
Zuo et al. (2020)	Isochronic index	SBN	no	yes	yes	no	no
Ermagun and Tilahun (2020)	Utility-based	SBN	no	yes	yes	yes	no
Boisjoly et al. (2020)	Utility-based	API	no	yes	yes	yes	yes
Ben-Elia and Benenson (2019)	Gravity-based	SBN	no	yes	yes	yes	no
Slovic et al. (2019)	Utility-based	SBN	no	no	no	no	no
This study	Utility-based	API	yes	yes	yes	yes	yes

Note: PTA – public transport accessibility; TTE – travel time estimation; API – application of program interface; G2FSCA – gaussian two-step floating catchment area.
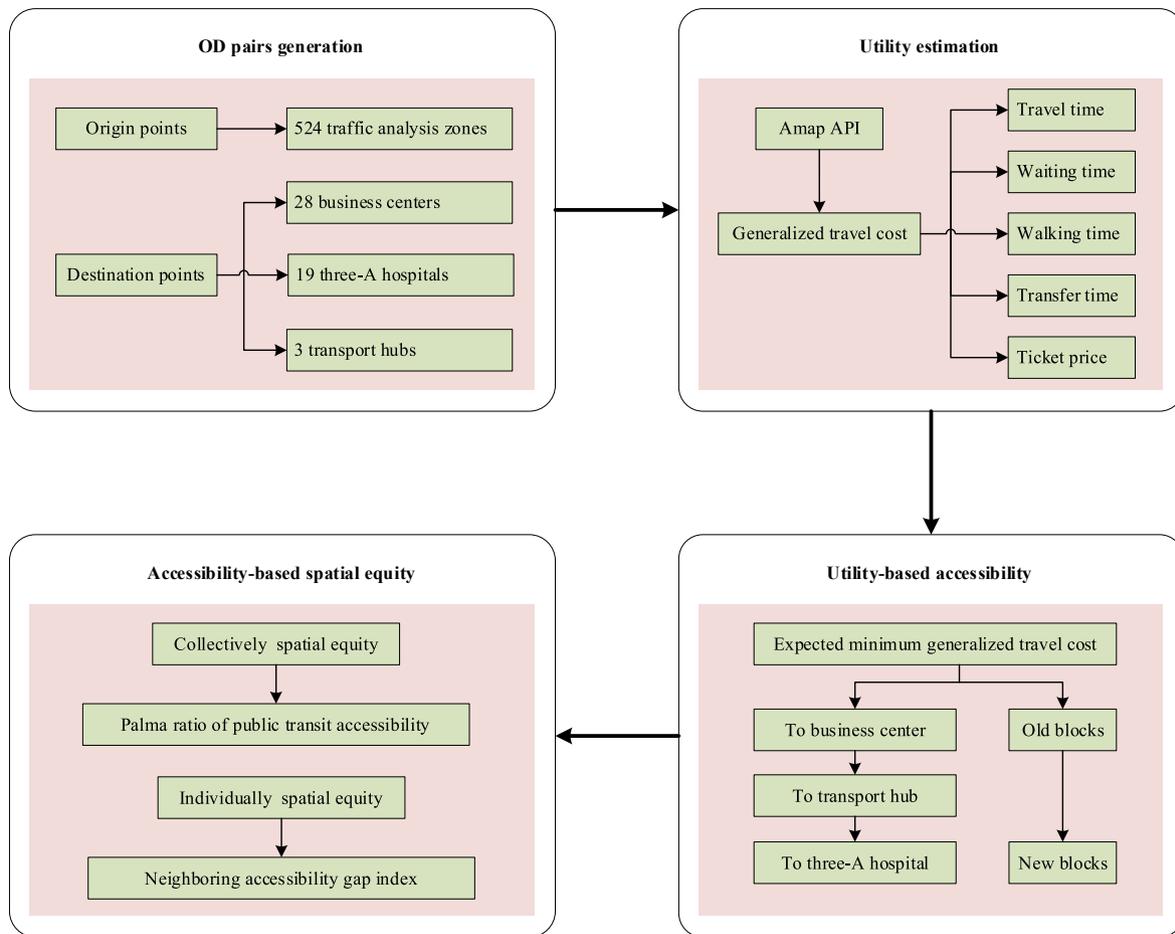

Fig. 1. Workflow of public transit accessibility-based equity measure.

The functions of variables are explained when using them.

Sets	
M	Set of destination type, $M = \{BC, TH, HP\}$
R	Set of origin zones
S^m	Set of alternative destinations of the mth type
N^r	Set of neighbors of origin zone r
$T^r_{10\%}$	Set of origin zones with top 10% accessibility
$B^r_{40\%}$	Set of destination zones with bottom 40% accessibility
Indices	
m	Index of destination type
r, s	Index of origin, and alternative destination
n	Index of neighboring TAZ
Parameters	
μ^{in}	Value of in-vehicle time (RMB/h)
μ^{out}	Value of out-vehicle time (RMB/h)

(continued on next column)

(continued)

θ	Perception dispersion parameters used in the utility measure
Decision Variables	
$\pi^{travel}_{rs,m}$	Travel time by transit between OD pair rs, s belonging to the mth type
$\pi^{walk}_{rs,m}$	Walking time by transit between OD pair rs, s belonging to the mth type
$\pi^{waiting}_{rs,m}$	Waiting time by transit between OD pair rs, s belonging to the mth type
$\lambda^{ticket}_{rs,m}$	Fare by transit between OD pair rs, s belonging to the mth type
$j^m_{top\ 10\%}$	Number of origin zones with top 10% accessibility to the mth-type destinations
$j^m_{top\ 10\%}$	Number of origin zones with bottom 40% accessibility to the mth-type destinations
k^N_r	Number of neighbors of origin zone r
Functions of decision variables or parameters	
c_{rs}	Travel cost by transit between OD pair rs, s belonging to the mth type

(continued on next page)

(continued)

A_r^m	Accessibility of origin zone r to the mth-type destinations
$A_r^{m,\text{neighbor}}$	Accessibility of neighbors of origin zone r to the mth-type destinations
$\overline{A}_{\text{top } 10\%}^m$	Average accessibility of the top 10% of the origins to the mth-type destinations
$\overline{A}_{\text{bottom } 40\%}^m$	Average accessibility of the bottom 40% of the origins to the mth-type destinations
NAG_r^m	Neighboring accessibility gap of origin zone r to the mth-type destinations
P_{ratio}^m	Palma ratio of public transit accessibility related to the mth-type destinations

2.2. Generalized travel cost

We assume all passengers will choose a path with the lowerest travel cost from a given TAZ to a potential destination by public transit (El-Geneidy et al., 2016). Their generalized travel cost by public transit can be formulated as Eq. (1). Eq. (1) means a door-to-door public transit trip. The first term on the right is walking cost, $\pi_{rs,m}^{\text{walk}} \cdot \mu^{\text{out}}$, where we consider the walking time from the origin to the access of public transit, from the egress of public transit to the destination, and the transfer time between bus and metro. The second term on the right represents the waiting cost of passengers for the first vehicle arriving at a bus stop or metro station ($\pi_{rs,m}^{\text{waiting}} \cdot \mu^{\text{out}}$). The third term means the in-vehicle travel cost. The final term, $\lambda_{rs,m}^{\text{ticket}}$, is the ticket price by public transit.

$$c_{rs}^m = \pi_{rs,m}^{\text{walk}} \cdot \mu^{\text{out}} + \pi_{rs,m}^{\text{waiting}} \cdot \mu^{\text{out}} + \pi_{rs,m}^{\text{travel}} \cdot \mu^{\text{in}} + \lambda_{rs,m}^{\text{ticket}}, \forall r \in R, s \in S^m, m \in M \quad (1)$$

2.3. Utility-based accessibility

Utility-based accessibility measure derives from the random utility theory and destination-mode choice model (Ben-Akiva & Lerman, 1979; Domencich & McFadden, 1975). Passengers living in a given traffic analysis zone, usually, will be attracted by a few alternative destinations to achieve their activities in a city. It is fashionable to use systematic utility to measure the attractiveness of these alternative destinations, which can consist of attributes related to alternatives, characteristics related to travelers, and other unobservable portions. As far as the systematic utility of public transit is concerned, door-to-door travel time and ticket price from the origin to destination are the most important determines impacted its usage. Therefore, we take a generalized travel cost function that incorporates door-to-door travel time and ticket price based on travelers' value of time as the systematic utility of public transit. Under this context, for each TAZ, its accessibility can be regarded as the expected minimum generalized travel cost from itself to a set of alternative destinations. Following a log-sum formulation (Chorus, 2012; Handy & Niemeier, 2006), the public transit accessibility of a TAZ reaching a certain type of destination can be expressed as:

$$A_r^m = E\left|\min_{s \in S^m}\{c_{rs}^m\}\right| = -\frac{1}{\theta}\ln\sum_{s \in S^m}\exp(-\theta \cdot c_{rs}^m), \forall r \in R, m \in M \quad (2)$$

where θ is a scale parameter that reflects the perceptional variation in the generalized travel cost among alternative destinations. Compared to other measures for public transit like isochrone and gravity-based approach, an advantage of the utility-based approach is that it can capture the impact of the travel mode on accessibility and equity by using the generalized travel cost function. Another advantage is that the introduction of the expected minimum generalized travel cost makes the results of the accessibility measure easier to interpret in intuition. Due to that travelers usually expect as less travel cost as possible, therefore, the higher value of utility-based accessibility means poorer public transit accessibility.

2.4. Public transit accessibility-based equity

Following horizontal equity principles, this study defines public transit accessibility-based equity as the accessibility levels between a given TAZ and its neighboring TAZs should be spatially equal. We design a two-dimensional measure framework for spatial equity in public transit accessibility, which consists of collective equity and individual equity. Collective spatial equity in public transit accessibility mainly focuses on the accessibility gap between the richest spatial units and the poorest spatial units, which shows whether the public transit system provides equitable services across a geographic area. In converse, individual spatial equity in public transit accessibility pays attention to the accessibility gap between itself and its neighbors for each spatial unit belonging to a geographic area, which can help find which spatial units are inequity in public transit accessibility, and their accessibility should be improved in future public transit planning and operation.

2.4.1. Individual spatial equity

For individual spatial equity, measuring the disparity of public transit accessibility between a given traffic analysis zone and its neighbors is the most straightforward approach. This approach will give a specific value in spatial equity for each traffic analysis zone. It can make traffic analysis zones with inequitable accessibility easy to be found. Following the thought to measure the modal accessibility gap (Kwok & Yeh, 2004; Yang et al., 2017), this study proposes a similar neighboring accessibility gap (NAG_r^m) formula to measure individual equity for a specific traffic analysis zone, expressed as the following equation:

$$NAG_r^m = \frac{A_r^m - A_r^{m,\text{neighbor}}}{A_r^m + A_r^{m,\text{neighbor}}}, \forall r \in R, m \in M \quad (3)$$

$$A_r^{m,\text{neighbor}} = \frac{1}{k_r^N}\sum_{r \in N^r}A_r^m, \forall r \in R, m \in M \quad (4)$$

It should be indicated that there are two indicators of public transit accessibility within each traffic analysis zone, including its own accessibility (A_r^m) and neighboring accessibility ($A_r^{m,\text{neighbor}}$). The neighboring accessibility is expressed in the average minimum expected generalized cost from the neighboring traffic analysis zones to the same destination. We define two traffic analysis zones are neighbors if their boundaries have an edge in common at least according to the adjacency principle, as shown in Fig. 2 (a). Eq. (3) measures the accessibility gap between the given traffic analysis zone and its neighbors, and its value has been standardized from −1 to 1. If the NAG_r^m is between −1 and 0, the expected minimum generalized travel cost from the given traffic analysis zone to the given destination is less than from its neighboring traffic analysis zones to the same destination. If the NAG_r^m ranges from 0 to 1, the expected minimum generalized travel cost from the given traffic analysis zone to the given destination is more than that from its neighboring traffic analysis zones. If the NAG_r^m is equal to 0, the expected minimum generalized travel cost has no difference whether departing from the given traffic analysis zone or departing from its neighbors. Fig. 2 (b) depicts the changes in the neighboring accessibility gap with generalized travel costs. In summary, the more the neighboring accessibility gap approaches zero, the more equitable the services provided by the public transit system are. Without loss of generality, we define the following mapping relationships between the neighboring accessibility gap and inequity level, as shown in Table 3.

2.4.2. Collective spatial equity

Inspired by Palma (2011) who applied an index to investigate income inequity between the income share of the top group and the bottom group, this study also adopts a similar ratio index to formulate collective equity in public transit accessibility based on Eq. (5):
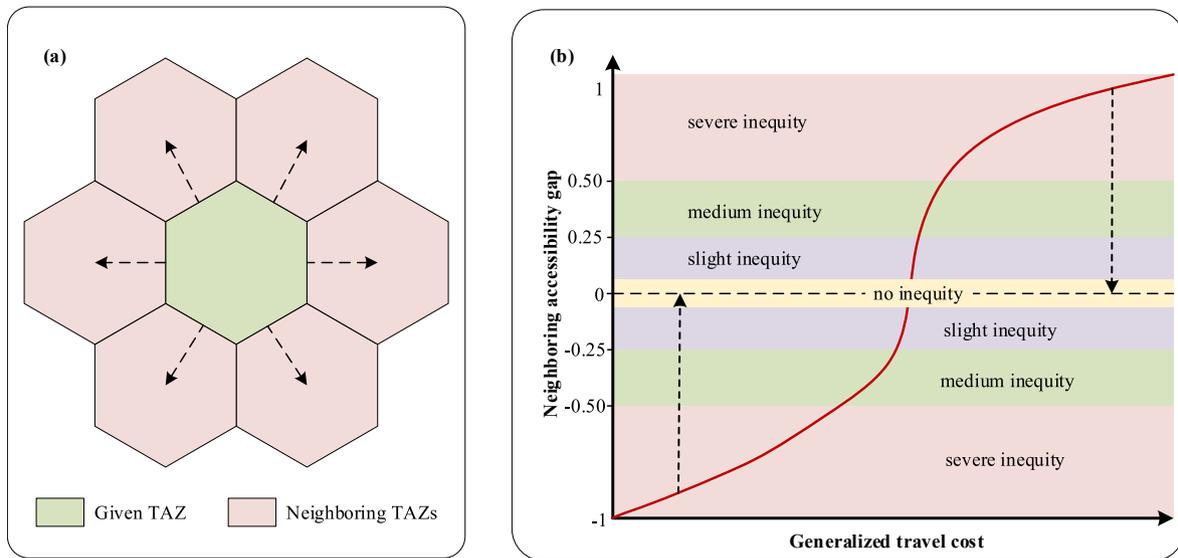
Fig. 2. Neighboring traffic analysis zones and neighboring accessibility gap.

Table 3
Mapping relationships between the neighboring accessibility gap and inequity level.

NAG	$[-0.05, 0.05]$	$[-0.25, -0.05) \cup (0.05, 0.25]$	$[-0.5, -0.25) \cup (0.25, 0.5]$	$[-1, -0.5) \cup (0.5, 1]$
Level	no inequity	slight inequity	medium inequity	severe inequity

Note: NAG – neighboring accessibility gap.

$$P_{\text{ratio}}^m = \frac{\overline{A}_{\text{top }10\%}^m}{\overline{A}_{\text{bottom }40\%}^m} = \frac{\frac{1}{j_{\text{top }10\%}^m} \sum_{r \in T_{10\%}^r} A_r^m}{\frac{1}{j_{\text{bottom }40\%}^m} \sum_{r \in B_{40\%}^r} A_r^m}, \forall m \in M \quad (5)$$

In this Paloma ratio model of public transit accessibility, the numerator denotes the top 10%'s average accessibility over the whole area, and the denominator is the lowest 40%'s average accessibility across the area. Unlike the frequently used Gini index that includes the distribution over all groups, for example, all populations in a country, or all spatial units (traffic analysis zones) in a city, the Paloma ratio index is more concerned about extreme groups (the richest and the poorest) excluding the groups with middle accessibility. In the context of spatial accessibility, using the Paloma ratio rather than other measures is because of the ease of interpretability and communication, which directly shows how much the richest accessibility is higher than the poorest. This just fills a drawback that the Gini index is not very sensitive to measure differences in the bottom portion of the distribution. Therefore, the Paloma ratio has been gradually adopted in existing studies related to assessing accessibility-based equity (Guzman & Oviedo, 2018; Liu et al., 2021; Rosas-Satizábal et al., 2020).

3. Case study

3.1. Study area

The main urban area of Kunming city is used as an empirical area in this study. As the capital of Yunnan Province located in southwestern China, Kunming city has a population of 3.58 million inhabitants and covered an area of 3,243 km². It owns a convenient, dense, and efficient public transit system that serves citizens' daily trips by 280 lines and 10,136 bus stops. Thus, it is also one of the outstanding transit metropolises in China. By 2020, the bus ridership and metro ridership in

Kunming had respectively reached 1.37 and 0.61 million passengers per day. Fig. 3 (a) plots the location of Kunming and the spatial distribution of public transit.

We use the traffic analysis zone as a spatial unit to measure public transit accessibility and its equity. Based on the urban road network of Kunming, the study area has been divided into 524 traffic analysis zone. For each zone, we assume that all public transit users will depart from its centroid, then ride the transit system to reach their destinations. Fig. 3 (b) shows the spatial distribution of traffic analysis zones used in this study.

Regarding possible destinations related to transit-based trips, we only consider cities' three daily activities, including leisure activities, seeking medical care, and transfer of intercity travel. Correspondingly, we select three types of POIs (points of interest) as destinations: the business center POI (comprehensive commercial buildings where citizens can shop, repast, visit, and recreate), the medical POI (3-A hospitals where citizens can seek medical care), the transport hub POI (airport or railway station where citizens can transfer for intercity travel). There are 21 business centers, 19 3-A hospitals, and 3 transport hubs within the study area by searching for the Gaode map (also named the Amap[1]), as shown in Fig. 3 (c)–(e).

3.2. OD pairs generation

Based on the identified traffic analysis zones and possible destinations, the origin and destination (OD) pairs between them are extracted to estimate the OD travel time and trip fare for public transit accessibility-based equity research in this paper. It should be indicated we only consider the most possible public transit trips rather than all trips. For example, for leisure activities, we only examine the public transit trips from each traffic analysis zone to business centers with the top 5 shortest travel times. The process of seeking medical care is the same. Due to only three transport hubs in the study area, for public transit-based intercity travel, we check all public transit trips from each traffic analysis zone to each transport hub. Table 4 describes the number of OD pairs used for public transit accessibility-based equity modeling.

Then, the Application Programming Interface (API) of the Gaode map LBS (Location Based Service) open platform[2] has been adopted to automatically query trip information including travel distance,

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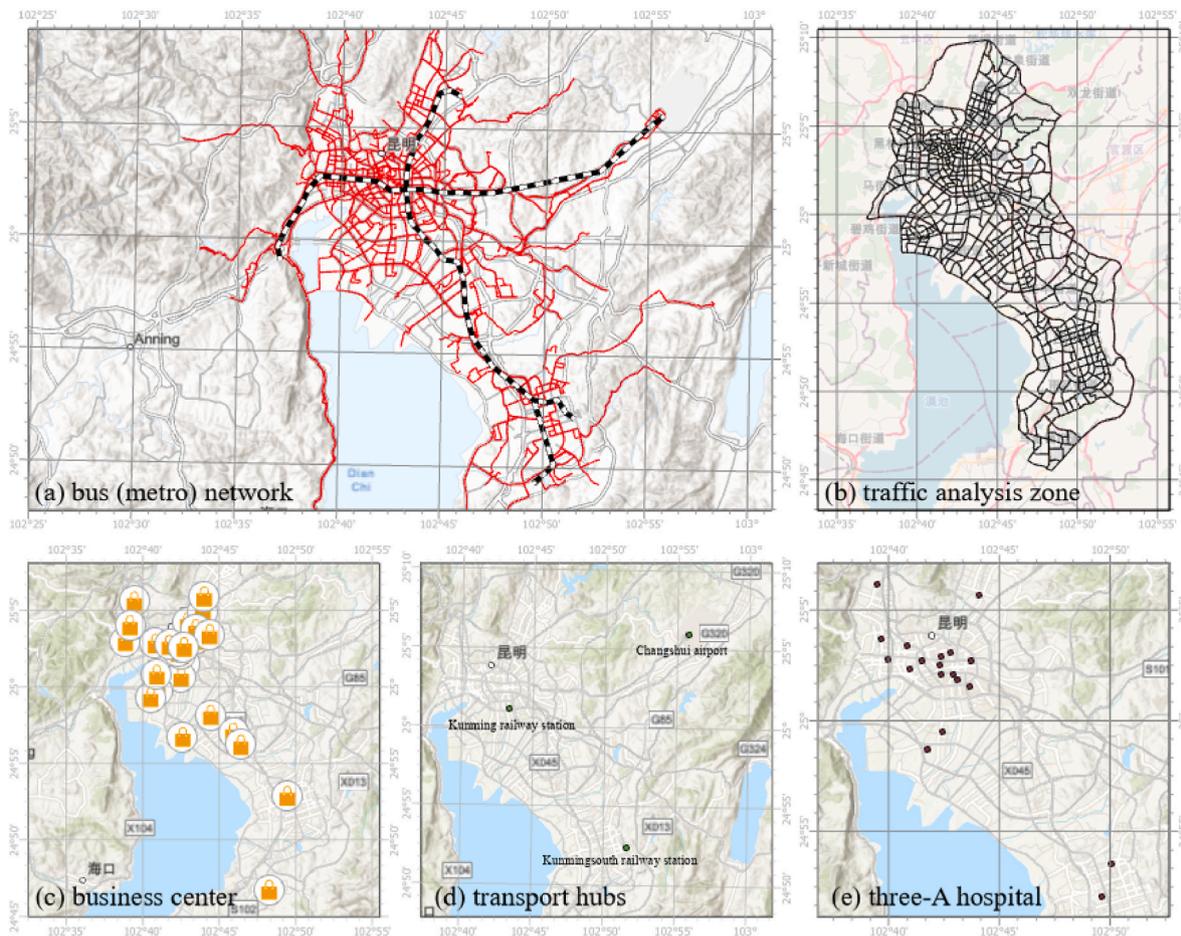[1] https://www.amap.com/.
[2] https://lbs.amap.com/.

Fig. 3. Study area: Kunming city, China.

Table 4
OD pairs information.

Trip scenarios	Leisure activities	Seeking medical care	Transfer of intercity travel
Origin points	524 TAZs	524 TAZs	524 TAZs
Destinations points	28 business centers	19 3-A hospitals	3 transport hubs
Effective destinations	Top 5	Top 5	Top 3
All OD pairs	14,672	9956	1572
Effective OD pairs	2620	2620	1572

Note: O – origin; D – destination; TAZ – traffic analysis zone.

Table 5
Three samples of trip information of all OD pairs.

OD id	TAZ_154 – BC_21	TAZ_132 – 3AH_18	TAZ_175 – TH_3
Price (RMB)	1.0	4.0	7.0
Distance (km)	5.72	17.29	42.68
Duration (minutes)	38.97	78.75	91.53
In-bus time (minutes)	28.77	50.76	64.85
Out-bus time (minutes)	10.20	27.97	26.64
Walking distance (km)	0.71	1.96	1.87
Transfer times	0	1	2

Note: OD – origin and destination; TAZ – traffic analysis zone; BC – business center; 3AH – 3-A hospital; TH – transport hub.

duration, and fare for each traffic analysis zone in Python script. The API inputs location coordinates (latitude and longitude) of each traffic analysis zone and planned departure time, and outputs corresponding trip data based on the road network, transit operation schedule, and real-time traffic of the Gaode map. In our study, the location information of traffic analysis zones has been prepared in advance based on ArcGIS software, and the planned departure time is set at 10 a.m. on August 1st. Compared with other methods, for example, using the Network Analysis tool in ArcGIS or distance and speed-based measures, the Gaode map's API has three obvious advantages: (1) the road network used for travel time estimation is more complete than the self-built road network. (2) the Gaode map's API introduced the transit schedule which might make the estimation of waiting time more precise. (3) The real-time speed and congestion have also been considered. Sample trip information is shown in Table 5.

3.3. Unity-based accessibility distribution

Before discussing public transit accessibility-based equity, we first need to preset a few exogenous parameters to assist examine different travel scenarios, including the perceptional variation parameter (θ), the value of in-vehicle time (μ^{in}), and the value of out-vehicle time (μ^{out}). First, the perceptional variation parameter is set as 0.5. Referring to Liu et al. (2022), the following formula is used to determine the value of in-vehicle time:

$$\mu^{in} = W/12/4.2/5/8 \tag{6}$$

where W denotes the Gross Domestic Product (GDP) per capita in the study area, 12, 4.2, 5, and 8 respectively are the number of months per

year, the number of weeks per month, the number of working days per week, and the number of working hours per day. In our study, the value of time is assumed to be homogeneous for all users. The effect of heterogeneous users is left for future study. According to the GDP per capita level in Kunming city in 2021, the value of in-vehicle time is set as 40 RMB per, and the out-vehicle VOT is set as 1.5 times the value of in-vehicle time.

Fig. 4 presents the spatial distribution of public transit accessibility in all traffic analysis zones. Considering the expected minimum generalized travel cost in routes, citizens in a part of traffic analysis zones that are either close to the business centers, transport hubs, or 3-A hospitals or directly linked by transit lines (inappreciable walking) can arrive at them within 30-RMB travel cost by public transit. Citizens living in the majority of traffic analysis zones can reach business centers, transport hubs, and 3-A hospitals within 30-RMB to 90-RMB generalized travel costs. For some traffic analysis zones, however, citizens' generalized travel costs are more than 90 RMB away from them. Most of these traffic analysis zones are the furthest from business centers, transport hubs, and 3-A hospitals or are located in suburban and semi-rural areas where there is inadequate coverage of public transit services.

Fig. 5 (a) shows a significant disparity in public transit accessibility of all traffic analysis zones. As far as all traffic analysis zones are concerned, citizens to transport hubs usually bear the highest travel cost. Specifically, the mean public transit accessibility to business centers, transport hubs, and 3-A hospitals are respectively 30 RMB, 45 RMB, and 34 RMB. The expected minimum generalized travel cost to transport hubs is more than 50% to business centers, and 32% to 3-A hospitals. The public transit accessibility to business centers and 3-A hospitals are very close. A possible reason is that the number of transport hubs in Kunming city is relatively less than the number of business centers and 3-A hospitals. In our study, we only considered three key transport hubs in the study area, e.g., the Kunming Changshui International Airport, Kunming Railway Station, and Kunmingnan Railway Station.

As shown in Fig. 5 (b), the statistical distribution of public transit accessibility for three types of locations, including old blocks, new blocks, and other locations, is significantly different. Recalling that the old blocks are located in the city center, and the new blocks are located in the south of Kunming city. In terms of public transit accessibility to business centers and 3-A hospital, their accessibility distributions are consistent that both follow such a pattern: old blocks > new blocks > other locations. Interestingly, the public transit accessibility to transport hubs is the opposite. It can be found the accessibility to transport hubs from new blocks is superior to old blocks and other locations. This is attributed to the Kunmingnan railway station located in new blocks,

which makes convenient public transit accessibility to transport hubs available in these areas, providing affordable and also efficient services.

3.4. Collective spatial equity

To calculate the public transit accessibility-based Palma ratio, we classified each traffic analysis zone by accessibility decile considering the expected minimum generalized travel cost. Each decile is composed of a different number of traffic analysis zones. The top 10% of public transit accessibility is concentrated in 53 traffic analysis zones, and the poorest 40% of public transit accessibility is distributed among 210 traffic analysis zones across the whole study area. Fig. 6 presents the statistical distribution of the accessibility-based Palma ratio in Kunming city when taking into account distinct destinations and locations.

Fig. 6 (a) shows how the magnitude of public transit accessibility inequity among traffic analysis zones with rich accessibility and poor accessibility in Kunming city when considering different destinations. The public transit accessibility-based Palma ratios for business centers, transport hubs, and 3-A hospitals are respectively 0.40, 0.41, and 0.38. They look very close, the value of which means that the expected minimum generalized travel cost from the poorest 40% of traffic analysis zones to these destinations is almost 2.5 times (1/0.4) as much as from the richest 10% of traffic analysis zones. This should be noticed by public transit planners and managers because the disadvantages in utility-based accessibility for the poorest 40% can lead to deterioration in socioeconomic status. It is also worth noting that there are no significant public transit accessibility gaps among reaching business centers, transport hubs, and 3-A hospitals when considering the collective Palma ratio.

Moreover, the disparity of collective accessibility-based equity among different locations in the study area is compared, as shown in Fig. 6 (b)–(d). As expected, collective spatial equity levels of public transit accessibility for reaching each kind of destination seem to be changed among different urban locations. A consistent finding can be seen for three types of destinations, public transit accessibility-based Palma ratio in old blocks are both higher than in new blocks. For example, for reaching business centers by public transit, the accessibility-based Palma ratio in old blocks and new blocks are respectively 0.62 and 0.46. This result indicates that for citizens in old blocks, it will take 1.61 times (1/0.62) the expected minimum generalized travel cost departing from the poorest 40% of traffic analysis zones to reach business centers than departing from the richest 10% of ones. However, for citizens in old blocks, the gap in expected minimum generalized travel cost between the top 10% of traffic analysis zones and
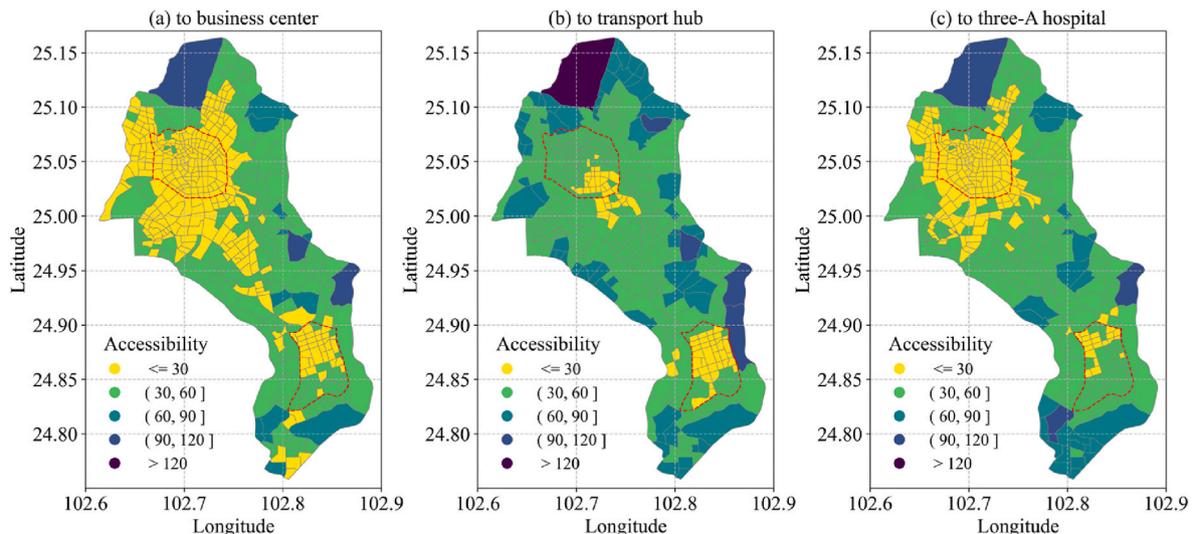

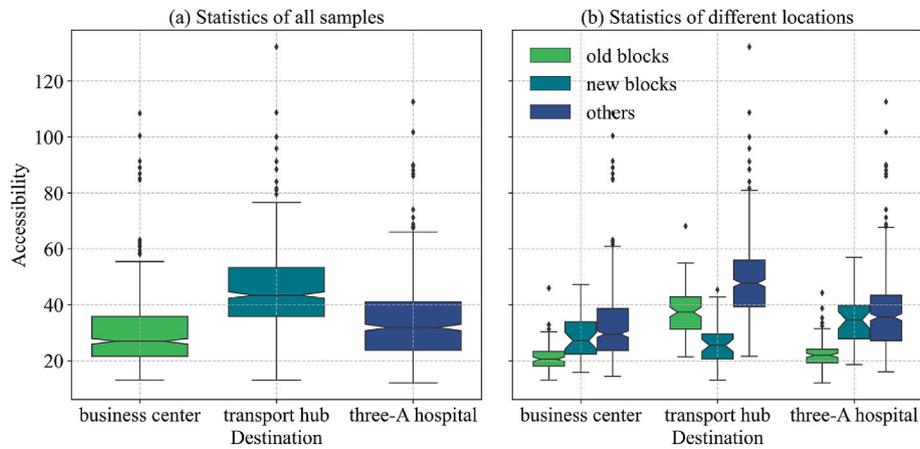**Fig. 4.** Spatial distribution of public transit accessibility in TAZs.

Fig. 5. Disparity of public transit accessibility among different locations.
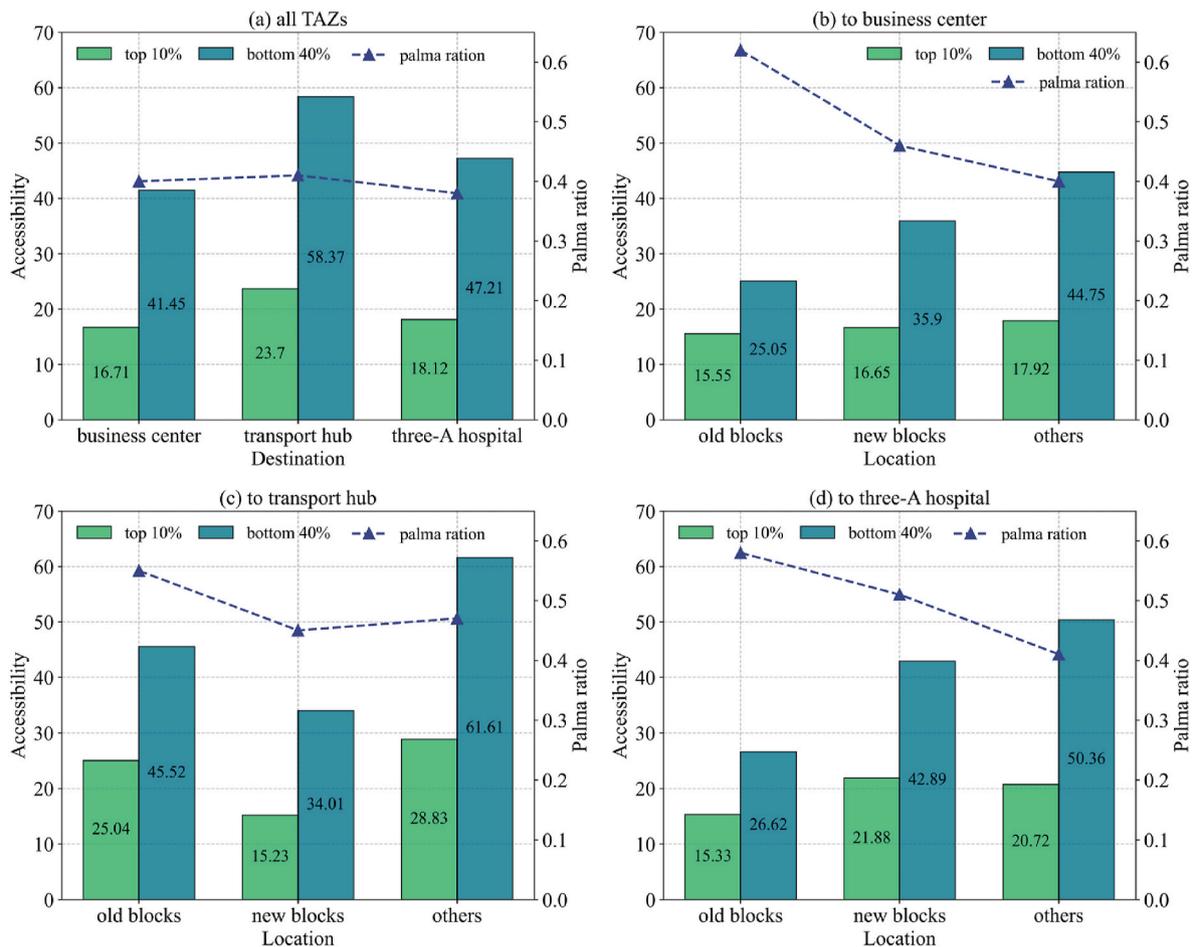

Fig. 6. Statistic distribution of the public transit accessibility-based Palma ratio.

the bottom 40% of traffic analysis zones can reach 2.17 (1/0.46) times. A similar situation exists in the public transit accessibility-based Palma ratio reaching transport hubs and 3-A hospitals. That is to say, traffic analysis zones in new blocks may face inequity in public transit accessibility relative to old blocks. A possible explanation is that there is complete coverage in public transit networks and stops in the old blocks. However, in new blocks, some feeding transit networks need further improvement.

3.5. Individual spatial equity

The collective Palma ratio in section 4.3 uncovers that public transit accessibility may be inequitable distributed in the study area. However, it does not indicate which traffic analysis zones maybe face poorer public transit accessibility. Therefore, following the neighboring accessibility gap index model (see Eqs. (3) and (4)), this section shows the individual equitable level for each traffic analysis zone. We first drew the scatter diagram and histogram of its public transit accessibility and its neighboring public transit accessibility for each traffic analysis zone

(see Fig. 7). Fig. 7 shows that the traffic analysis zones' public transit accessibility is not far greater than that of their neighbors. The vast majority of scattered points are distributed on both sides of the gray dotted line ($y = x$), meaning that the expected minimum generalized travel cost by public transport for each traffic analysis zone is likely to its neighboring zones. This is, the public transit accessibility is equitable for these traffic analysis zones. However, a few scattered points are falling on the lower part of the gray dotted line ($y = x$), indicating that the gap in citizens' expected minimum generalized travel cost between given traffic analysis zones and their neighbors becomes large.

Furthermore, based on the mapping relationships between the neighboring accessibility gap and the inequity level of public transit accessibility (see Table 1), the histogram distribution and spatial distribution of the neighboring accessibility gap values for each traffic analysis zone are shown in the following (see Fig. 8). The value of the neighboring accessibility gap ranges from −0.4 to 0.4 under scenarios reaching business centers, transport hubs, and 3-A hospitals. Overall, public transit accessibility for given traffic zones and their neighbors does not present a huge gap because of around 300 traffic analysis zones (almost 57%) with a neighboring accessibility gap index between −0.05 and 0.05. These traffic analysis zones are almost located in new blocks and old blocks of Kunming city. The number of traffic analysis zones with values of neighboring accessibility gaps within an interval of −0.25 and −0.05 and an interval of 0.05 and 0.25 was relatively medium, accounting for around 38%. These traffic analysis zones with slight inequity are mainly concentrated in the peripheral urban areas and urban-rural fringe areas, which indicates that the layout of transit networks and stops in these areas should be paid attention to improve spatial inequity in public transit accessibility. In addition, a few traffic analysis zones are with medium inequity in public transit accessibility, the number of which only occupied less than 5% of all traffic analysis zones in the study area. These zones are distributed in the urban fringe area where the public transit networks have little service catchment.

3.6. Analysis of associated factors

After showing the spatial pattern of individual spatial equity in public transit accessibility, we further examine whether the transfer times and walking distance during riding public transit and the number of neighboring traffic analysis zones are associated with the individual spatial equity level. Fig. 9 depicts the scatter diagram and regression plot of the above factors and the neighboring accessibility gap for each traffic analysis zone. Correspondingly, it can be first observed that the neighboring accessibility gap seems to be not directly associated with transfer times during the whole trip as the regression plots almost overlap with the red dotted baseline ($y = 0$). Interestingly, it can be found that the neighboring accessibility gap can gradually increase with the growth of walking distance during taking public transit. When the walking distance is within 2 km, the neighboring accessibility gap is very small. That is to say, the traffic analysis zones are spatially equitable in public transit accessibility under this scenario. However, a long walking distance out of travelers' acceptable walkability can lead to some spatial inequities in public transit accessibility. The number of neighboring traffic analysis zones also presents a similar association with individual spatial equity in public transit accessibility. But the growth affected by the number of neighboring traffic analysis zones is obviously less than the ones affected by walking distance. The traffic analysis zones with 5–8 neighbors usually have more equitable public transit accessibility.

4. Conclusions

Due to lacking related studies in both examining individual spatial equity and collective spatial equity in public transit accessibility, we hope to obtain some referred insights for developing helpful policies on equitable public transit planning and operation. This research develops a novel measure framework for public transit accessibility that integrates individual equity and collective equity to cope with such two meaningful questions: how is the spatial equity in public transit accessibility for the whole region and which zones' public transit accessibility
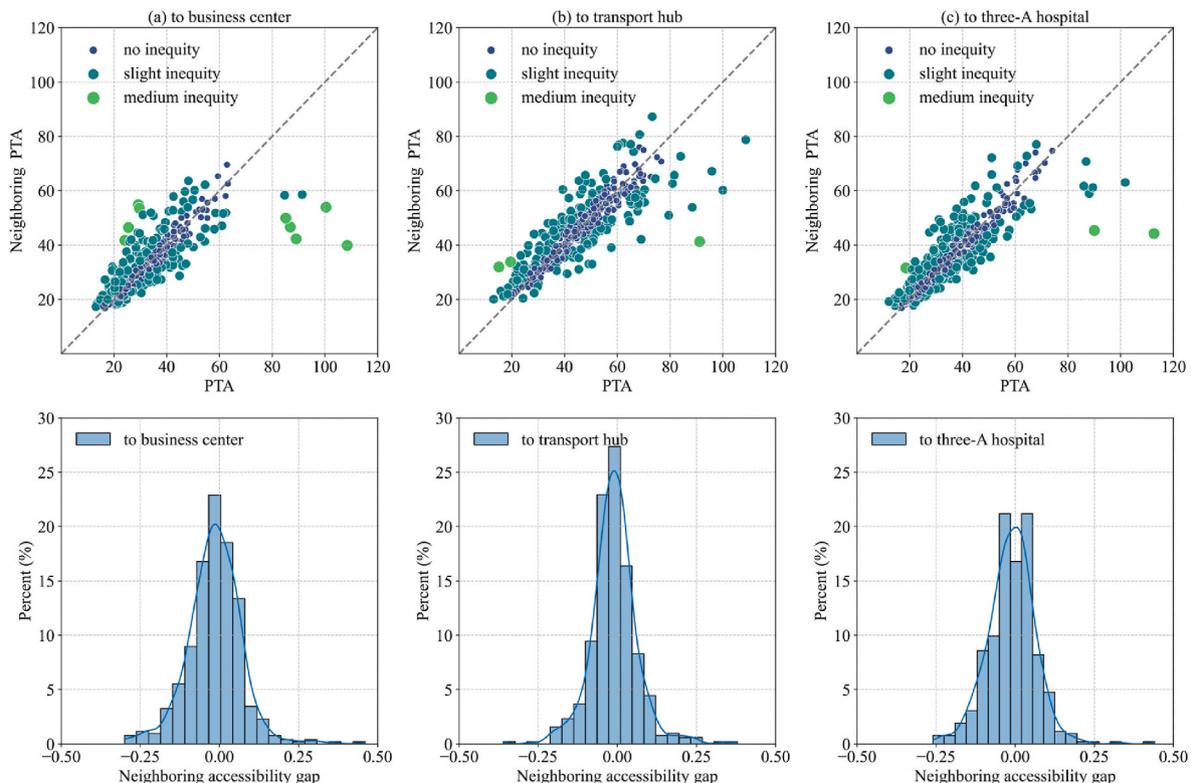

Fig. 7. The scatter diagram and histogram of neighboring accessibility gaps.
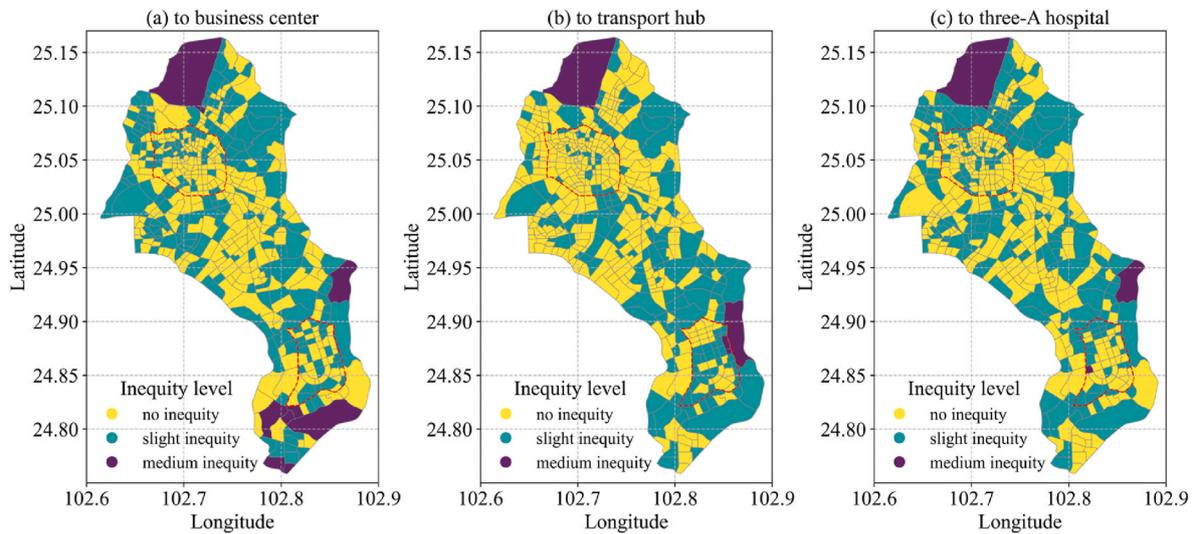
Fig. 8. The spatial distribution of inequity levels.

is more disadvantaged in the region?

Considering a multimodal transport network covering walking, bus, and metro, a utility-based accessibility measure model embedded with the log-sum formula is proposed to quantitatively evaluate spatial accessibility from each traffic analysis zone to possible activity destinations. The utility function of accessibility measure encompasses the generalized travel cost by public transit considering travelers' travel time, waiting time, transfer time, and ticket price. They are connected by travelers' value of time. We then apply a Palma ratio of public transit accessibility to examine the accessibility gap between the top 10% of traffic analysis zones and the bottom 40% of traffic analysis zones, which is defined as the collective spatial equity in our study. Closely followed by this, we design a neighboring accessibility gap index to measure individual equity levels in public transit accessibility. Finally, an empirical study of Kunming city is conducted to analyze the present equity situation in public transit accessibility individually and collectively, including accessibility reaching business centers, transport hubs, and 3-A hospitals. Additionally, the relationships between individual spatial equity and transfer times, walking distance, and the number of traffic analysis zones are also checked. By considering our results, several conclusions can be drawn as follows.

(1) First, in the aspect of utility-based accessibility measures, there is a significant disparity in public transit accessibility of all traffic analysis zones. The expected minimum generalized travel cost of reaching transport hubs by public transit is more than 50% to business centers, and 32% to 3-A hospitals in Kunming city. The public transit accessibility reaching business centers and 3-A hospitals in old blocks are superior to the new blocks. Conversely, the accessibility to transport hubs is more advantaged in new blocks.

(2) Second, in terms of collective spatial equity in public transit accessibility, accessibility-based Palma ratios reaching business centers, transport hubs, and 3-A hospitals are both very close to 0.4, which means that in Kunming city, the expected minimum generalized travel cost by public transit from the poorest 40% of traffic analysis zones to these destinations is almost 2.5 times as much as from the richest 10% of traffic analysis zones. For three types of destinations, the public transit accessibility-based Palma ratio suggested that the collective spatial equity in old blocks is superior to new blocks.

(3) Third, concerning individual spatial equity in public transit accessibility, almost 57% of traffic analysis zones have no obvious spatial inequity because the expected minimum

generalized travel cost by public transit in these zones is nearly equal to the ones in their neighboring traffic analysis zones. The number of traffic analysis zones with slight inequity in public transit accessibility accounts for around 38%, which are mainly located in the peripheral urban areas and urban-rural fringe areas. Only less than 5% of traffic analysis zones are with medium inequity in public transit accessibility.

(4) Fourth, we also found that the individual spatial inequity level in public transit accessibility can be associated with the walking distance during taking public transit and the number of neighboring traffic analysis zones. However, a direct connection between the individual spatial inequity level and the transfer times during using transit is not been obviously observed.

For policymakers working to improve spatial inequity in public transit networks and increase public transit users, this research provides some referable insights. While encouraging public transit use, seamless connection for bus and metro and excellent walkability between origin/destination points and nearest bus stops may be efficient measures to increase public transit ridership, as they may be associated with the expected minimum travel cost by transit. The high levels of neighboring accessibility gaps in some traffic analysis zones indicate that many citizens lack convenient alternatives to public transit use. Our results suggested that this risk can be somewhat easily found in urban peripheries and transport poverty areas. These findings can be useful for policymakers to design equitable transit networks and attract more users to shift the car mode to transit mode. On the one hand, authorities and agencies can take ride-hailing or taxi services as a feeder to connect with the transit network (Singer et al., 2022; Yan et al., 2019; Zhang & Khani, 2021; Zuniga-Garcia et al., 2022). Incorporating ride-hailing and transit services is conducive to decreasing passengers' waiting time costs in these disadvantaged traffic analysis zones. On the other hand, this result can motivate operators and managers to optimize transit networks with the schedule- and frequency-based services in accessibility-equitable and accessibility-inequitable traffic analysis zones respectively (Jiang et al., 2022).

Several extensions under this study need to be carried out in the future. For example, (1) this study mainly involved three daily activities: leisure activities, seeking medical care, and intercity travel correlated with public transit. The public transit accessibility-based equity of other activities, such as commute activities and city tourism activities also is worth noticing and comparing. (2) In utility-based accessibility measures, the value of time (VOT) is assumed to be homogeneous for all traffic analysis zones. One way to improve this would be to incorporate
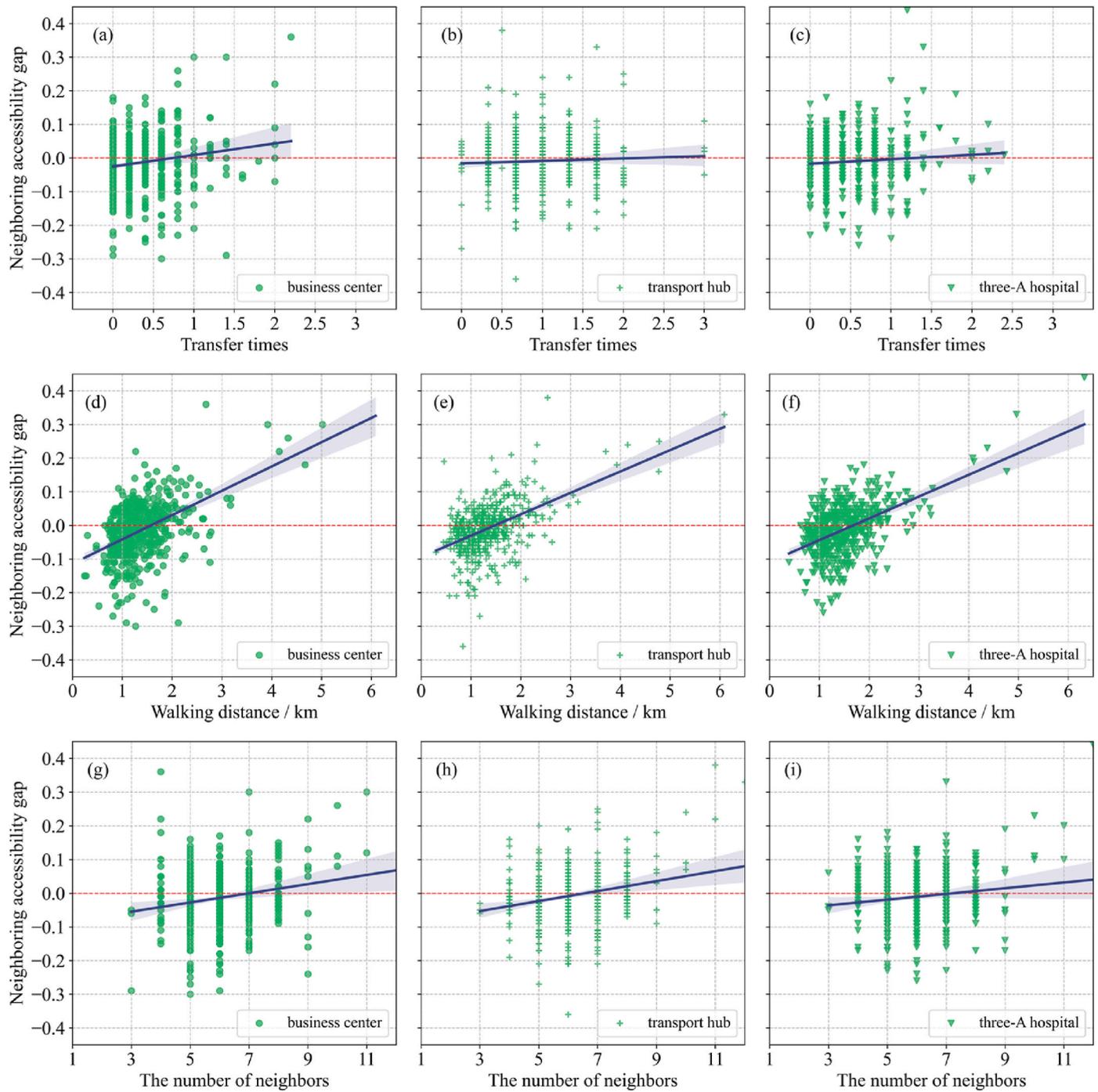
Fig. 9. The scatter diagram and regression plot of some factors and neighboring accessibility gaps.

spatially heterogeneous VOT into the accessibility measure. (3) In spatial equity measure, we do not consider the effects of zonal population and economics. The following studies can involve these factors to develop a population/economics-weighted Palma ratio and neighboring accessibility gap index in spatial equity measure. (4) With a zonal-level unit of analysis, the results of the accessibility measure and spatial equity measure in traffic analysis zones may be inevitably sensitive to the modifiable areal unit problem (MAUP). Although the generation of traffic analysis zones in this study is consistent with the layout of the road network in Kunming city, other spatial units like Voronoi diagram cells and hexagonal cells are worth to been introduced in future studies to relieve MAUP bias. (5) Another interesting topic is to examine how the built environment affects individual spatial equity in public transit

accessibility for designing the equitable public transit system.

CRediT authorship contribution statement

Wu Li: Conceptualization, Methodology, Software, Investigation, Validation, Visualization, Writing - original draft, Writing - review & editing. **Haotian Guan:** Validation, Writing - review & editing. **Wenwen Qin:** Methodology, Validation, Writing - review & editing. **Xiaofeng Ji:** Supervision, Funding acquisition, Conceptualization, Project administration, Writing - review & editing.

Declaration of competing interest

No conflict of interest exists in the submission of this manuscript, and that is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and is not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

Data availability

Data will be made available on request.

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