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Public transport equity with the concept of time-dependent accessibility using Geostatistics methods, Lorenz curves, and Gini coefficients

Asif Raza [a], Ming Zhong [c,d,e,*], Raymond Akuh [b,e,*], Muhammad Safdar [c,d,e]

[a] College of Civil Aviation, Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, PR China
[b] Mechanical Engineering Department, Dr. Hilla Limann Technical University, P.O Box 553 Wa, Upper West Region, Ghana
[c] National Engineering Research Center for Water Transport Safety, PR China
[d] Engineering Research Center for Transportation Safety, Ministry of Education of P.R. China, PR China
[e] Intelligent Transportation Systems Research Center, Wuhan University of Technology, Wuhan 430063, Hubei, PR China

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ABSTRACT

The primary objective of transport policies is to improve accessibility and mitigate the adverse consequences of private vehicles. Improved accessibility can considerably contribute to urban sustainability and quality of life. To improve accessibility, measuring it as precisely as possible is very important. A greater knowledge of the accessibility levels of public transport systems would not only help in enhancing the level of service but will also aid in resource planning and budgeting (capital costs, operations & maintenance costs, etc.). The research on various accessibility methods used to investigate transportation equity, particularly public transport, revealed that most of these approaches used time-based approaches to analyze public transport accessibility under theoretical traffic conditions and accessibility to public transport corridors, but ignored the overall performance of the transportation network. In this study, we developed an accessibility measurement framework for public transport to capture the performance of the entire transport network in a multimodal fashion and applied the methodology to the City of Wuhan as a case study. The key elements are: (i) develop a multimodal transport network that captures the performance of the entire transport network at a different time of the day. (ii) adopt the utility-based accessibility method to analyze public transport accessibility to opportunities based on the attractiveness of the destination, and (iii) determine the level of the disparity of accessing job opportunities by public transport between the urban and rural areas of the city using Geostatistics methods such as Lorenz curve and Gini Coefficients. The framework adopted in this study allowed us to examine the public transport equity in the study area, and help identify the influencing factors towards enhancing transport policies that consider the fair distribution of public transport infrastructure.

1. Introduction

The Sustainable Development Goals (SDGs), often known as the global goals, seek to reconcile economic growth, environmental stability, sustainable cities, and social equity, ensuring that every-one has the same opportunities and may live a better life without harming the environment (UN General Assembly, 2015). The urban SDG includes the target 11.2 to ensure that all citizens have access to safe, budget-friendly, inclusive, and sustainable transportation systems by 2030, devoting particular attention to the needs of pregnant women, disabled persons, children, and the elderly (Raza et al., 2022a). In order to achieve this target, public transportation plays a crucial role and, therefore it is essential for the development of a viable and equitable city. Public transportation is recognized as a greener, safer, more equitable, and more affordable modes of transportation that significantly contributes to the city's sustainability, quality of life, and public health and safety (Tamim Kashifi et al., 2022, Wang et al., 2021). Due to several economic, social, and cultural factors, the transportation sector is still characterized by an uneven distribution of transport modes. It has been observed in the literature that developing nations face a greater challenge with unequal distribution in public transportation than developed nations.

Accessibility and equity considerations have gained considerable attention in transportation and urban planning literature in the last few decades (Vecchio et al., 2020, Palm et al., 2021, Pereira and Karner, 2021). Transportation infrastructure and services primarily promote

* Corresponding authors.
E-mail addresses: mzhong@whut.edu.cn (M. Zhong), raymondakuh@whut.edu.cn (R. Akuh).

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accessibility or the ease with which individuals can reach essential destinations such as work, healthcare, and educational opportunities by using a particular mode of transportation (Safdar et al., 2022). Increases the accessibility of public facilities and key locations, with significant impacts on social equality and economic growth, and pulls them away from private mobility in order to promote sustainable mobility (Gallo, 2020). The majority of the previous studies have focused on public transit equity issues (Foth et al., 2013, Delbosc and Currie, 2011, Gallo, 2020, Tiznado-Aitken et al., 2018). For instance, Lee et al. (2012) confirmed traffic infrastructure factors in various regions utilizing income categories to quantify equity in regional public transportation. The findings show that regions with low average household incomes have limited access to public transit infrastructure. A previous study conducted in South Korea by Kim and Jun (2012) evaluated the features inside and outside of public transit station areas and analyzed the equity of public transportation in those areas. The results indicated that the accessibility of public transportation services in regions inhabited by socially vulnerable groups is quite poor. Transportation and land use are not integrated in developing countries, particularly Latin America (Wang et al., 2021, Vecchio et al., 2020). In cities of this region, it is typical to see the majority of low-income families located distant from regions where social and economic opportunities i.e., education and employment (Ali Aden et al., 2022). In these settings, non-motorized transportation is frequently unavailable, and, due to low automobile ownership, many households are forced to rely on public transportation. In several situations, the system provides a spatially varied level of service which is frequently inadequate in low-income metropolitan areas. Consequently, public transportation is crucial to the development of a sustainable, accessible, and equitable city (Tiznado-Aitken et al., 2021).

In transportation planning, various factors are involved, and it is very difficult to evaluate equity based on individual categories. However, it is deemed important to consider the basic rights of every-one during transportation planning especially public transport planning as a majority of low-income who are economically not strong enough primarily depend on public transport to reach their daily activities. Hence, individuals with low-income are disadvantaged in competing for jobs located a few miles away from their homes. The equity study of public transport is frequently focused on giving equitable access to all individuals, especially those individuals who are economically or physically or socially underprivileged (Boschmann and Kwan, 2008). Non-motorized modes also relieve governments of the need to invest in new highway infrastructure to some extent. The world's most developed regions are increasingly reliant on private cars. Reasons for this increase have been attributed to a lack of investment in public transport, inability to design for integrated land use and transportation, cycling, and walkability (Raza et al., 2022b). In the City of Wuhan, high-income individuals desire to live in the downtown area, making it even harder for low-income people to afford housing within city centers, even though jobs matching their skills may be available in this area. Hence, households with low-income are pushed to live on the outskirts of the city (Sanchez and Brenman (2008). To achieve social equality, there must be equitable distribution of travel as a fundamental good. In the ideological dimension, mobility for participation in life-sustaining social activities and personal development. Accessibility based on the individual, in terms of its application: Increase accessibility for those who are least disadvantaged. Enhance the threshold's accessibility for those with the fewest disadvantages. Considering this, transportation planning decisions frequently have major equity implications, and it is critical that transportation infrastructure allocations used to offer access to opportunities for all citizens be deemed fair and suitable (Litman, 2017).

Most studies in the literature have employed a traditional static or partially dynamic method to estimate accessibility using a single mode, such as a private car or bus, and have not taken multi-public transportation modes into account. These "static" models assume that home locations and transport availability and options for social exercises are constant in both time and place, which can create biased or even erroneous accessibility model assumptions. Fixed travel time measures tend to exaggerate accessibility, thus weakening the reliability of accessibility research. This exaggeration could cause travelers to underrate their travel time, preventing them from reaching opportunities on time (Yan-yan et al., 2015). In addition, few research has employed a multimodal spatial integrated land use and transport model to measure accessibility to home-based work (HBW) and home-based other (HBO) activities in both urban and rural areas (Raza et al., 2022a). Therefore, additional consideration must be given to spatial accessibility and equity. Vertical equity has also received scant consideration. The spatial distribution of urban services may be unequal due to the allocation priority given to underprivileged or high-demand groups. According to, (Rawls, 2001) the distribution of public facilities should prioritize the most marginalized individuals. Without considering non-spatial variables, it is difficult to assess vertical equity based on the limitations and needs of residents (Li et al., 2021).

The purpose of this study is to analyze the dynamic multimodal spatial accessibility of HBW and HBO activities in urban and rural areas by considering public transit such as metro and bus in the City of Wuhan, China. In addition, this study employs a utility-based accessibility method to examine public transport accessibility to HBW and HBO activities in urban and rural areas based on the attractiveness of the destination. Then, the located urban and rural activities are further examined by employing two geostatic measures such as the Lorenz curve and Gini coefficient to identify the level of accessibility and disparity of various urban and rural activities. The findings of this study would be helpful for policymakers and stakeholders to evaluate the fair distribution of public transport infrastructure to minimize the disparity among citizens.

The rest of the paper has been organized as follows: Section 2 presents the literature review, which includes measures of accessibility and transport fairness. Section 3 contains the study's data and methodology, which includes transport model development, measurement of public transportation accessibility, and equity metrics. Section 4 demonstrates the results and discussion of the study. Finally, Section 5 delineates the key findings of the study, recommendations, and limitations of forthcoming studies.

2. Literature review

2.1. Overview of accessibility

Accessibility has been an integral component of transportation and land-use system since the 1950 s. Hansen (1959) presented the first idea and defined accessibility as the potential for interaction opportunities. Ben-Akiva and Lerman (2021) defined as "the advantages provided by a land use and transportation system". Numerous authors have argued, for a variety of reasons, that the concept of accessibility should be at the core of understanding transportation benefits and equity (Pereira and Karner, 2021, Li et al., 2021, Martens et al., 2019). Accessibility is considered an important planning tool that integrates land use and transportation (Almansoub et al., 2022). Good accessibility enables citizens to access public amenities such as schools and hospitals and engage in activities and social interaction. In contrast, poor accessibility prevents individuals from engaging in these activities and creates obstacles that exacerbate negative socioeconomic effects and inequality (Raza et al., 2022a). Numerous studies have emphasized the integrated accessibility of public transportation in urban and rural activities (Wang et al., 2022, Foth et al., 2013). People depend on transport to access public services; yet, the ease of accessing public services within the same threshold distance or time will differ based on the transport alternative (Raza et al., 2022b). Thus, the accessibility of public amenities and services must take into account various modes of transportation. According to Sanchez and Brenman (2008), individuals who rely on public transport have lower incomes and consequently experience economic inequalities as a result of transportation regulations that favor vehicle use. To provide transport equity, some developed countries are expanding their public transport networks to low-income households with no access to private vehicles. This is evident in the work of Yeganeh et al. (2018) who found access to public transport among low-income households high as compared to middle and high-income households in the U.S. Low-income households are living in the periphery of the study area, and if public transport service is not extended to these areas where individual dwells, they could be facing economic inequalities due to lack of access to public transport.

China's rapid urbanization has exacerbated the disparity between supply and demand, particularly in large and medium-sized cities. Enhancing transportation equity can help to reduce the social inequality of lower-income and socially disadvantaged groups in relation to the urban transport system and ensuring that transportation systems are given development priority (Wang et al., 2022). Due to economic growth, iconic status, and cultural values, the number of private vehicles in China has increased in recent decades, while public transportation remains the dominant motorized mode in mega and medium-sized cities (Li et al., 2021, Wang et al., 2021). Driving is often inexpensive, pleasant, and typically safe (although in some urban areas, due to congestion, certain driving speeds are forbidden at certain times of the day), and land use patterns are dispersed, making it accessible only by automobile mode and difficult to reach by other transportation modes (Safdar et al., 2022). In most places, individuals who can afford personal/private vehicles have relatively high access to medical facilities, grocery stores, education, work, and other social/recreational activities. Consequently, individuals with private/personal vehicle ownership are usually able to fulfill their basic transportation needs. However, the negative externalities of private cars, such as air pollution, traffic congestion, and traffic safety concerns, ultimately impact public health and the viability of a city (Ali Aden et al., 2022; Palm et al., 2022). Commuters often consider transport to be unpleasant and inconvenient. However, it meets the demands of most commuters who cannot afford to own a personal/private vehicle.

2.2. Accessibility measures

Over the last few decades, a variety of measures have been developed and presented. According to a recent study, Raza et al. (2022a) articulated the various accessibility metrics as follows:

(i) Infrastructure approach: This metric concentrates on speed, trip time, road length, road network density, and overall congestion level as measured by vehicle hours wasted. This metric analyzes the accessibility of locations on a macro scale.
(ii) Activity approach: This metric considers the efficiency of both the transport network and land-use. The activity-based accessibility measuring method is used to analyze the distribution of activities in space and time and relevant impedance (time, cost) between origins and destinations.
(iii) Individual's personal preferences approach: This metric focuses on the characteristics, behaviors, and preferences of an individual. This metric spans from socioeconomic characteristics (such as gender, car ownership, marital status, education, and age) to a person's attitudes and intentions to use. Individual accessibility is influenced by activity locations, distances between important locations, journey duration and activity involvement, as well as commuting speeds (Burns, 1980).
(iv) Social exclusion and geographic location approach: This metric concentrates an area access/geographic location when aggregating at the community level. Even though the individualized approach may look fragmented and impractical for the planning process, it assists us in determining the fundamental elements of accessibility study.
(v) Utility-based approach: This metric is based on the benefits received by individuals while accessing spatially dispersed activities, opportunities, and challenges, considering individual characteristics, characteristics of various transport modes, spatial–temporal constraints, speed, daily activity schedules, and time budgets.
(vi) Mixed-measures approach: This metric is employed when there are multiple target factors, such as travel costs (monetary, time, risk, and comfort), volume (number of individuals, vehicle units, etc.), and location.

As mentioned above, each accessibility metric has pros and cons. Therefore, policymakers or analysts should choose the appropriate method based on their study's aims, interests, and data collection methods. One of the intricate accessibility metrics is the utility-based accessibility which is used in several studies since it complies to travel behavior theories (Ben-Akiva and Lerman, 1977, Neuburger, 1971). This accessibility measure follows the random utility model's "logsum" expression. This model depicts the likelihood of an individual choosing a higher utility decision among all other options (Ben-Akiva and Lerman, 2018). The current study employs a utility-based approach to measure accessibility to different land-use activities (HBW and HBO) in urban and rural areas. Utility-based accessibility measurements define accessibility as a result of multiple transport alternatives. Utility-based approach investigates the decision to take one specific option among a range of potential options that satisfy essentially the same need, and it could be utilized simulate individual behavior and the (net) advantages for various transport system consumers. Its applicability in economic analyses is a significant benefit. In other words, the metrics are capable of calculating the transport-user benefits of both transport and land-use initiatives, as accessibility improvements may result from either transport or land-use alterations or even both. Consequently, the metric may imply that it is preferable to improve accessibility for individuals in locations with low accessibility levels (e.g., outlying regions) than in locations that are already highly accessible (e.g., metropolitan cores) (Geurs and van Wee, 2004). Obviously, this is significant for economic and social assessments of transportation and land-use projects.

2.3. Transportation equity

Since the Montgomery Bus Boycotts of 1955–1956 by African Americans in the United States, equity has been regarded as the most pressing issue in public transportation (Delbosc and Currie, 2011). Prior to starting with the equity analysis, it is essential to comprehend the fundamental concept of equity. According to Boucher and Kelly (1998) equity is the allocation of societal benefits and costs. It has two primary types: (i) Horizontal equity: Horizontal equity encourages giving people or groups the same weight as if they had the equal capacity and need; transportation should offer the same level of service regardless of ability or need and avoid prioritizing one person or group over another. (ii) Vertical equity: It recognizes that the abilities and demands of individuals and groups vary; transportation should prioritize socially, spatially, and economically underprivileged individuals and groups in order to compensate for overall inequities. The three components of vertical equity are spatial, social, and economic. Spatial equity relates to the provision of equitable transport services and enhancements to transport infrastructure, particularly in remote or rural locations. Economic equity is associated with transportation services aimed for people with lower incomes or without access to affordable transportation. Social equity is associated with the availability of special transportation services for people with mobility disabilities (Zhou et al., 2018).

In philosophy, "equity" refers to the subject of whether the allocation of a good (such as accessibility) may be regarded as "fair" or "just." Equity is not only concerned with inequality but also with a moral assessment of that inequality, as inequality is not inevitably problematic. As numerous scholars have claimed (Lucas et al., 2016, Pereira et al., 2017, Martens, 2012), for a moral evaluation of inequality, a moral paradigm should be employed, and it is crucial that this is made explicit. According to the concept of equality, everybody should be considered equal and receive an equal share of the advantages. According to researchers, the default principle of justice is equality. As an alternative to equality, the philosophical concept of "sufficientarianism" has gained substantial momentum. It means that every-one has the right to a minimum quantity (a "threshold") of a product or service. When a part of the population goes below this threshold value, injustice arises. This concept has also been presented in innovative methods in transportation planning, typically as part of a larger egalitarian concept (van der Veen et al., 2020). Martens et al. (2019) combine accessibility indicators with the moral code of sufficientarianism to develop a transportation planning method that is fundamentally grounded on "principles of justice." He supports describing and evaluating the justice of transportation systems based on the concept of "sufficiency of accessibility." A transportation and land use system is just "if, and only if, it provides a sufficient level of accessibility to all persons in the vast majority of cases." Low levels of accessibility restrict potential options and enhance the likelihood of social exclusion resulting from transportation issues. In the context of transportation, sufficiency refers to an accessible level below which individuals lack options. For those below the threshold, either enhancement is needed (weak sufficientialism) or is necessary (strong sufficientarianism). Weak sufficientarianism can be integrated with egalitarian policies, such as giving priority to persons experiencing accessibility poverty while also working for an overall rise in accessibility. Strong sufficientarianism suggests that transportation policy should prioritize preventing accessibility deficiencies (van der Veen et al., 2020).

Transportation equity is defined by Sanchez and Brenman (2008) as "a set of initiatives and policies aimed at addressing inequities in a country's transportation planning and project delivery system." Transportation equality is critical for improving people's quality of life by meeting their expectations (especially those of disadvantaged users) to readily access the opportunities they want to partake in (Tiboni and Rossetti, 2014). According to Martens (2012), inequality is not necessarily implied by unequal mobility. Both the egalitarianism and capability approaches of Rawls (2001) and (Sen, 1980) are concerned with the fundamental structure of a society. They highlight the underlying disparities in people's ethnicity, gender, intelligence, and family background. These intrinsic disparities determine inequalities in life chances and the capacity to move in order to participate in social activities that are vital to an individual's survival and social mobility (Sen, 2005). Thus, equity is concerned with how social distribution might promote social opportunity equality. Public transportation projects primarily served urban areas and neglected rural areas (Dalkmann et al., 2008). Inclusive development policies primarily emphasize equal access to basic public facilities for all citizens (Raza et al., 2022b). When investing in public transportation systems, stakeholders and policymakers must examine a range of considerations, including financial, economic, social, etc. However, they ignored the importance of public equity in transport policy. Since the resources are public, they must be allocated as equitably as possible among all citizens or members of society (Gallo, 2020). There are different measures used to quantify transport equity such as the Lorenz curve, Gini index, and Theil index. In economic studies, the Gini coefficient represents the level of equality of income distributions; it varies from ($0 \sim 1$); 0 denotes perfect equality and 1 denotes perfect inequality. In transportation equity, the Gini coefficient is employed to analyze the degree of the accessibility concentration level of different regions or populations and to compare the level of equity before and after the implementation of a policy or transport infrastructure (Zhou et al., 2018). The Lorenz curve depicts the pictorial representation of the cumulative distribution function of wealth throughout the population in economics (Delbosc and Currie, 2011).

3. Data and methodology

3.1. Study area

The City of Wuhan is located in central China and had a population of around 11,081,000 permanent residents by 2018. The city of Wuhan covers an area of 8549 km^2 with 13 major districts (including 7 urban and 6 rural districts). Furthermore, for this study, the city is divided into 690 traffic analysis zones (TAZs) and 147 land-use zones (LUZ) as shown in Fig. 1.

Fig. 2a illustrates the bus and metro lines and their respective stations located within the study area during 2015. Fig. 2b presents the urban and rural classification and among 690 TAZs, 399 are located in the urban area of the city while 291 are located in the rural area.

3.2. Study data

Travel survey data is used to extract households' trip patterns between TAZs by various modes and at different times of the day. Meanwhile, employment survey data is used to extract employment by type in each TAZ. We calculated accessibility to these job locations using a multimodal transport network with an emphasis on public transport. The current study obtained household travel survey data for the year 2015 from Wuhan Transportation Planning Institute (WHTPI)(https://www.whtpi.com/Default.html). Travel data collection is the most costly and time-consuming aspect of the transportation modeling process. Previous research has recommended sample sizes for various populations. According to this study, the recommended sample size for more than one million people is 4 %, while the minimum sample size is 1 %. In our case, the population of Wuhan City is greater than one million, so the recommended sample size is 40,000 and the minimum sample size is 10,000. Our household travel survey sample was comprised of 36,000 individuals from urban and rural areas of Wuhan. This demonstrates that our sample size is sufficient and adequately represents the study area. It indicates that these data are reliable because they were administered by WHTPI. Compared to personal data collecting, the reliability of such data is far higher (Kulpa and Szarata, 2016). The job locations due to land use activities were classified into two main categories of trip purposes thus, Home-based work (HBW) and Home-based others (HBO). The HBW trip purpose includes trips to working activities such as; residential, industrial, education and research, and agriculture. Whereas HBO trip purpose includes trips to services like administration, business, finance, transport, and utility operation. The opportunities terms represent the job and population at the destination. In the case of HBW, a number of jobs available at the destination zones are considered, while in the case of HBO, the total number of households at the destination is considered as they are the ones who obtained these services. This study used opportunities for urban and rural because this classification was used by the Wuhan Planning Institute and the data -available in Wuhan's Yearbooks classify the city as only urban and rural.

Table 1 below shows the public transport lines data for the bus and metro system. The geographical data includes the headways from the various time of the day, the service starting and ending times, number of routes and stations. On average, the headways for both bus and metro are between 3 and 10 min during the entire service hours, thus from 6 am to 10 pm for bus and 6 am to 10:30 pm for metro.

Fig. 3a and 3b present the urban and rural populations in the city of Wuhan during 2015. It is observed from the current population that both urban and rural areas have a huge proportion of living which makes this study very important.

3.3. Methodology

Passengers' willingness to use public transport is influenced by its accessibility and it is critical to measure accessibility as precisely as possible in order to enhance it (Raza et al., 2022a). A greater knowledge

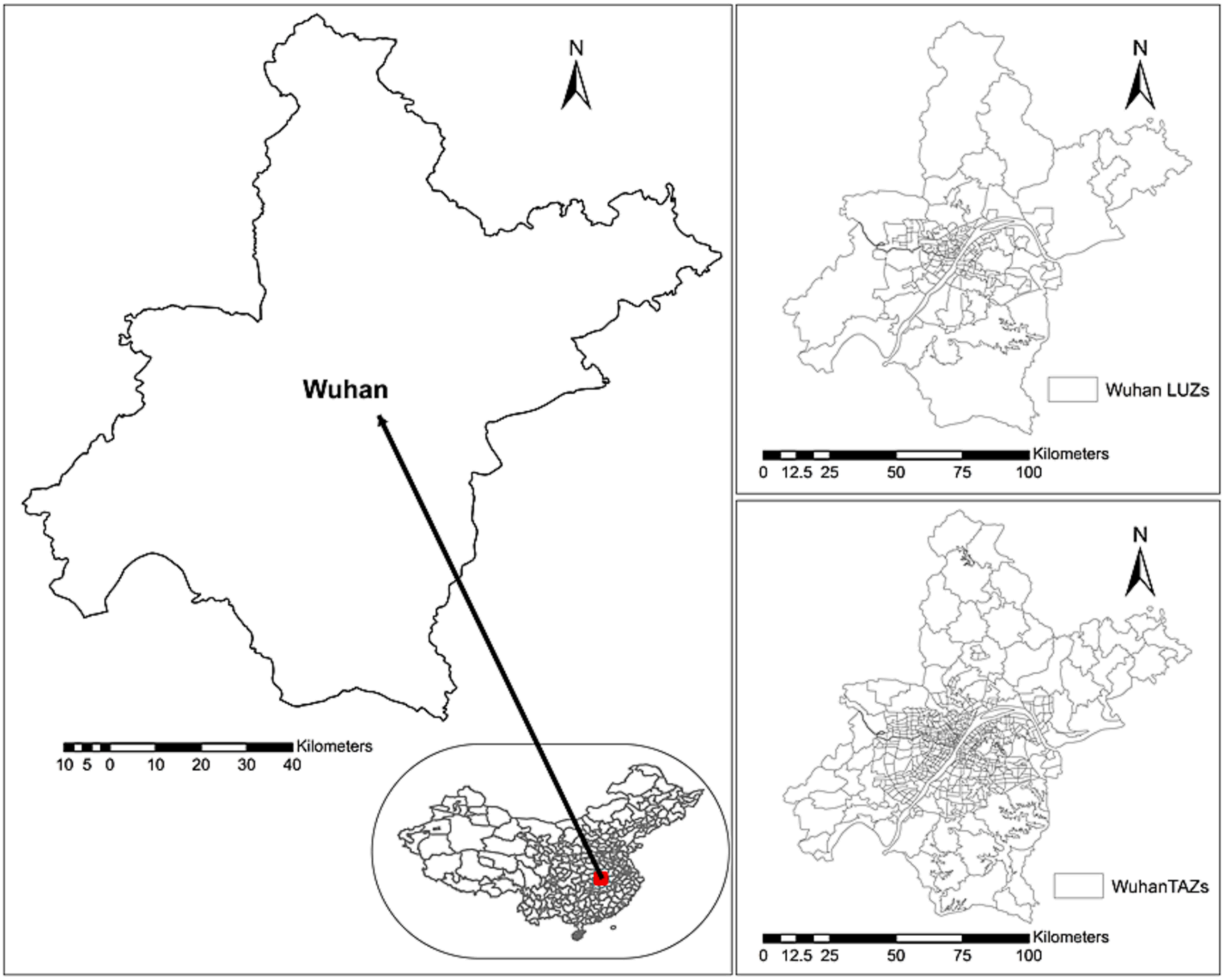


Fig. 1. Study area, Wuhan, China.

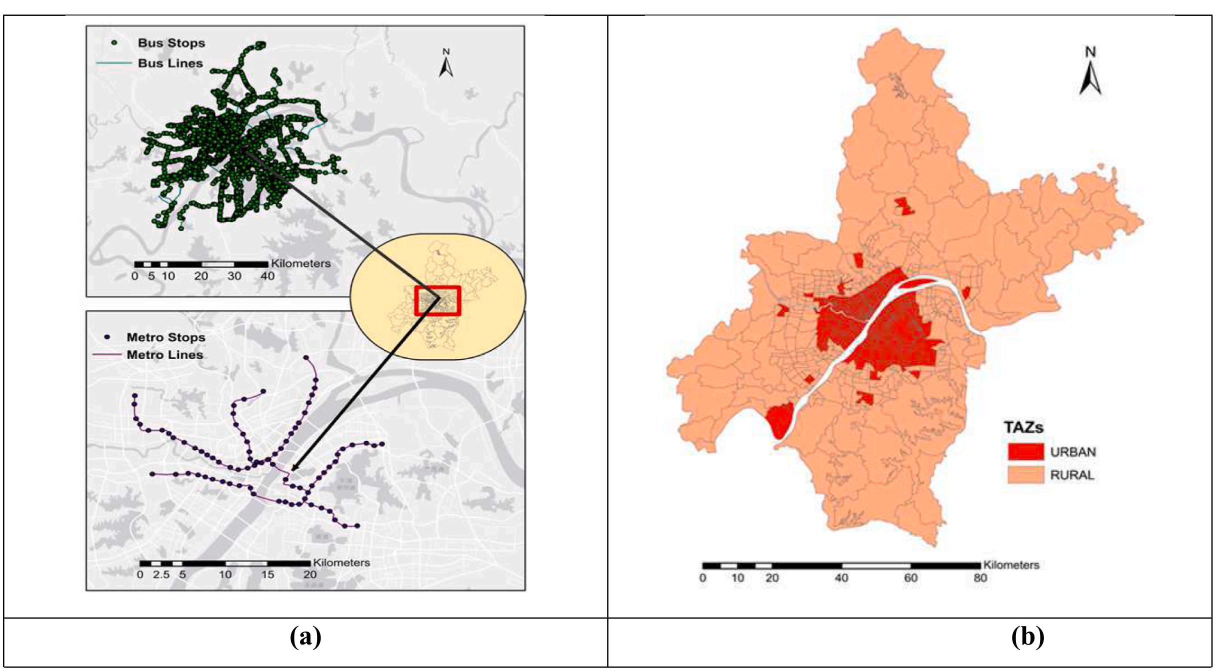


Fig. 2. (a) Bus and Metro lines and their respective stops; (b) Urban and rural classification of the study area.

Table 1
Transit lines data.

Modes	Headway (minutes)			Start time	End time	Routes	Stations
	Morning Peak	off-peak	Evening Peak				
Bus	3	10	5	6:00 AM	10:00 PM	649	5492
Metro	3	7	5	6:00 AM	10:30 PM	3	83

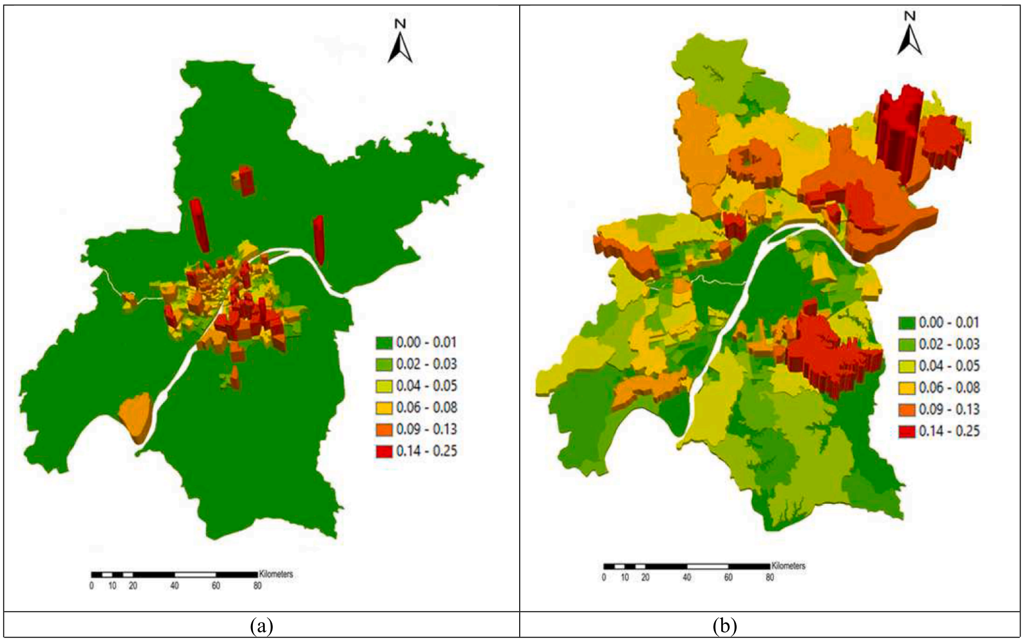


Fig. 3. (a) Urban population; (b) Rural population.

of the accessibility levels of public transport systems would not only enhance the level of service but will also aid in resource planning and budgeting (capital costs, operations & maintenance costs, etc.). A utility-based accessibility measure is used to calculate transit equity in various regions of the city of Wuhan. Lorenz curves, Gini coefficient, and Geo-statistic methods (kinging interpolation) are used to investigate the level of accessibility and distribution of the public transport network in the city. To achieve the aim of the study, a 4-step multimodal Wuhan Transport Model (WTM) was developed, calibrated, and validated for the year 2015 using Cube voyager 6.5. Based on the literature in China, a previous evaluated the 500-meter and 700-meter thresholds for transit stops (Zhou et al., 2018). According to China's "Standard for urban public service facilities planning," the service radius of district-level public amenities (such as libraries, cultural centers, senior citizens' activity centers, and sports centers) in a city with a population of 3 million is between 4,000 and 7,000 m. (Li et al., 2021). In order to determine the stops that were accessible between bus and subway stations, a threshold of 650 m was considered between TAZs and bus stops, 950 m between TAZs and subway stations, and 650 m 650 m for transfer between the modes, in accordance with previous studies conducted in Wuhan, China (Raza et al., 2022a; Raza et al., 2022b). Any public transport stops beyond the specified thresholds are therefore considered inaccessible. Although the utility equation can take care of the non-transit legs generation process, as the non-transit legs distance increases, the utility of using those legs decreases. The assigned thresholds are considered for simplifying the route enumeration process and saving the overall non-transit legs processing time. The public transport equity accessibility framework we adopted in this study is shown in Fig. 4 below. The study considers public transport accessibility to opportunities using two main trip purposes: Home-Based work (HBW) and Home-Based others (HBO) at morning-peak hours, evening-peak hours, and off-peak hours. This enables us to determine the level of public transport accessibility at different times of the day to various activity locations.

3.3.1. *Transport model development*

Initially, the WTM uses economic and demographic data to calculate the trip generation module (production and attraction). A travel survey is used to calculate trip rates by trip purpose (HBW and HBO). The gravity model was adopted to distribute trip and friction factors calculated using mobile phone signal data. The mode choice module consists of 6 modes including car, taxi, metro, bus, bike, and walk among them for this study public transport accessibility is presented and discussed. The transport utilities are calculated based on the sensitivity of each mode and each trip purpose. The person trips are converted to vehicle trips by applying average occupancy, and daily trips are converted to the different times of the day using hourly factors calculated from travel survey data. Traffic counts data is used to optimize and calibrated the time of the day assignment module. The congested skims are feedback in order to rerun the model based on congested time rather than free-flow time. The congested skims, opportunities at destination (jobs), and transport utilities are used to calculate time-dependent public transport accessibility. Each module was fully calibrated and validated with observed data before calculating the time-dependent accessibility. In addition, this study considered the accessibility to HBW and HBO activities in urban and rural areas.

3.3.2. *Measurement of public transport accessibility*

This study employed utility-based accessibility metrics to analyze public transport accessibility to opportunities based on the attractiveness of the destination (Geurs and van Wee, 2004). The utility-based metric considers the travel behavior and sensitivity to other parameters, such as walking, transfer, and relative fare, of the individual (Safdar

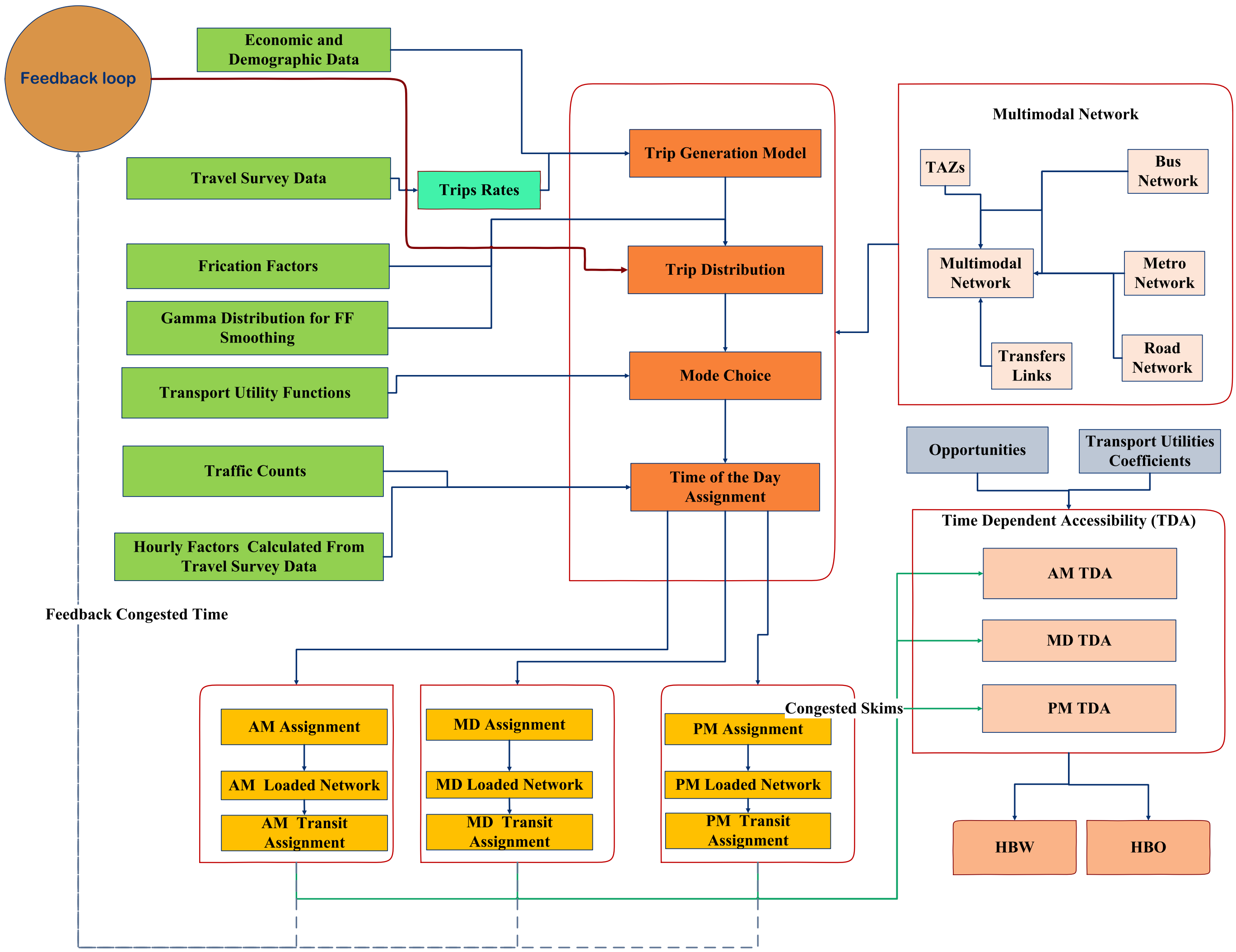


Fig. 4. Accessibility model framework.

et al., 2022). These metrics interpret accessibility as the consequence of a group of transit options. Utility theory examines the decision to acquire one specific option from a group of alternative options that all meet essentially the same need, and it may be employed to simulate individual travel behavior and the (net) advantages of different transport system consumers. It can be regarded as comprehensive and effective accessibility metrics, which can also be applied to social and economic evaluations. In other words, they solve the most significant shortcomings of infrastructure-based measures and can be computed with current land-use and transportation data and models. In addition, utility-based metrics capture the valuation of accessibility by individuals, providing a suitable framework for user-benefit evaluations of both land-use and transport investments (Ben-Akiva and Lerman, 2018). To measure public transport equity, a hierarchical 3-level nested logit structure is used (Fig. 5). Only the findings of public transport are taken into account in this study. The utility constitutes two components of utility: systematic utility and random error component. It is shown in Equation (1).

These utilities comprise two components: systematic utility (V_{ij}) and random error component (ε_{ij}) as shown in equation (1). The probabilities of nested logit upper level choosing an auto, public transport, and non-motorized are presented as (Eqs. (2)–(4)):

$$U_{ij} = V_{ij} + \varepsilon_{ij} \tag{1}$$

$$P_{auto} = \frac{exp(-\lambda C_{auto})}{exp(-\lambda C_{auto}) + exp(-\lambda C_{pt}) + exp(-\lambda C_{nmt})} \tag{2}$$

$$P_{pt} = \frac{exp(-\lambda C_{pt})}{exp(-\lambda C_{pt}) + exp(-\lambda C_{auto}) + exp(-\lambda C_{nmt})} \tag{3}$$

$$P_{nmt} = \frac{exp(-\lambda C_{nmt})}{exp(-\lambda C_{nmt}) + exp(-\lambda C_{auto}) + exp(-\lambda C_{pt})} \tag{4}$$

Using utilities, the probabilities of nested logit lower level choosing a bus,(P_{bus}) and metro (P_{metro}) are presented as (Equations (5) and (6)):

$$P_{bus} = \frac{exp(u_{bus})}{exp(u_{metro}) + exp(u_{bus})} \tag{5}$$

$$P_{metro} = \frac{exp(u_{metro})}{exp(u_{metro}) + exp(u_{bus})} \tag{6}$$

The transport utility coefficient by mode and trip purpose is used to measure the sensitivity of transport commuters. (Equations (7) and (8)):

$$u_{metro} = -a'1*IVT_{ijp} - a'2*WAIT_i - a'3*WALK_i - a'4*FARE_{ij} - a'5*MTMT_{ij} - a'6*MTBT_{ij} \tag{7}$$

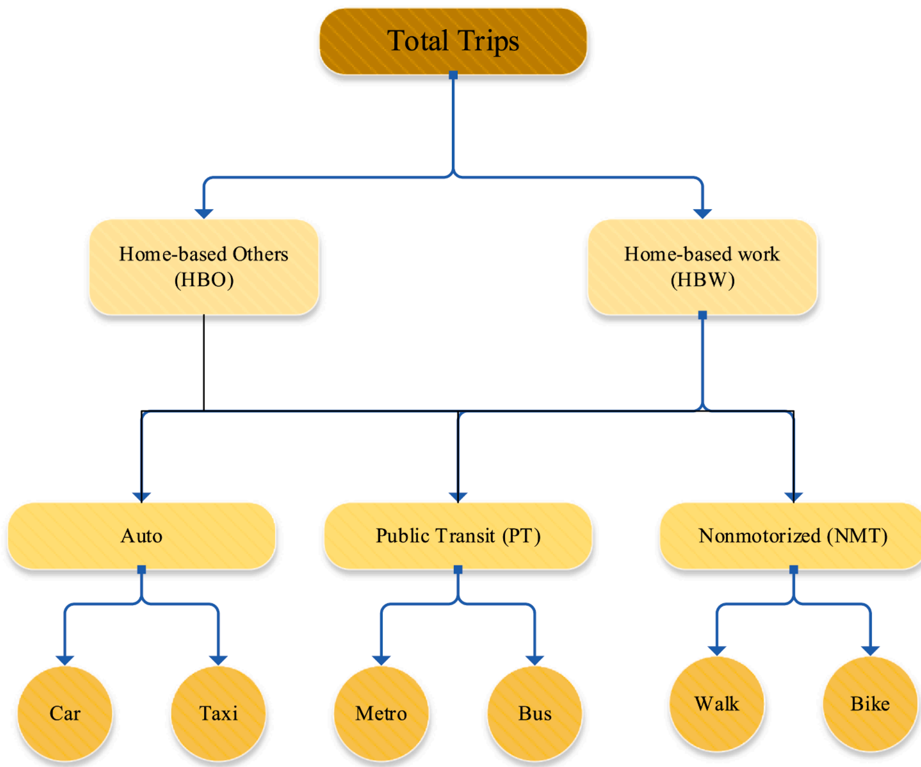


Fig. 5. Three-level nested logit structure.

$$u_{bus} = -a'1*IVT_{ijp} - a'2*WAIT_i - a'3*WALK_i - a'4*FARE_{ij} - a'5*BT_{ij} \quad (8)$$

where:

- IVT_{ijp} = in-vehicle time from origin I to destination J by different mode and by different trip type
- $WAIT_i$ = waiting for the public transport service at origin I
- $WALK_i$ = walk to the public transport station from origin I
- $FARE_{ij}$ = fare from origin I to destination J
- $MTMT_{ij}$ = metro to metro transfer time while traveling from origin I to destination J
- $MTBT_{ij}$ = metro to bus transfer time while traveling from origin I to destination J
- BT_{ij} = bus to bus and bus to metro transfer time while traveling from origin I to destination J
- á1, á2, á3, á4, á5, á6 = Transport coefficients parameters by modes and by trip purpose

Transport coefficients represent the sensitivity of commuters' mode shifting behaviors from one mode to the other in the transport model. Usually, these parameters have to be calibrated for a particular area depending on the travel behavior of commuters. Table 2 below shows the calibrated parameters of all the transport modes used in this study.

Utility-based accessibility metrics are considered feasible and practical when sufficient data for individuals or households are available. Therefore, actual household travel data collection is a pricey endeavor (Ben-Akiva and Lerman, 2021). The coefficients data were obtained from Wuhan Transportation Planning Institute (WHTPI)(https://www.whtpi.com/Default.html). Similar research conducted in Wuhan employed the same method to extract these coefficients from WHTPI (Raza et al., 2022a). Although there are coefficients for other trip purposes, only those used in this study are presented.

The composite utility (or logsum) is given as (Equation (9)):

$$\mathbf{Transport}_U = \ln(\mathbf{exp}(\boldsymbol{u_{bus}}) + \mathbf{exp}(\boldsymbol{u_{metro}})) \quad (9)$$

Utility-based accessibility measure is calculated using Equation (10) as:

$$A_i = \ln\left(\sum_{j=1}^{n} (O_j * \text{Transport}_U)\right) \quad (10)$$

where:

- A_i = utility-based accessibility measure
- Transport_U = composite utility
- O_j = opportunities at destination J
- ln = natural log

Table 2
Transport Coefficients Parameters.

	HBW						HBO					
Mode	á1	á2	á3	á4	á5	á6	á1	á2	á3	á4	á5	á6
Metro	−0.02	−0.04	−0.04	−0.039	−0.1	−0.2	−0.02	−0.04	−0.04	−0.078	−0.1	−0.2
Bus	−0.02	−0.04	−0.04	−0.039	−0.2		−0.02	−0.04	−0.04	−0.078	−0.2	
Taxi	−0.02	−0.04	−0.039				−0.02	−0.04	−0.078			
Auto	−0.02	−0.04	−0.039				−0.02	−0.04	−0.078			
Bike	−0.02	−0.04					−0.02	−0.04				

3.3.3. Lorenz curve and the corresponding Gini coefficient (Index)

Although the Lorenz curve and Gini index are mostly used in the field of economics for analyzing and measuring inequality of income distribution. Recently, it has been widely employed in the field of transportation for the measurement of the spatial distribution of job accessibility. In this study, the Gini coefficient and Lorenz curve are used to present the inequality of public transportation accessibility between urban and rural areas. Previous studies (Delbosc and Currie, 2011, Jang et al., 2017, Tiznado-Aitken et al., 2018) have employed Gini coefficients and the Lorenz curve to quantify equity in public transportation.

(i) **Lorenz Curve:** The Lorenz curve depicts the proportion of demand provided by public transportation as perceived by a proportion of zones. The deflection of the Lorenz curve from the 45-degree line represents the degree of inequity in the utilization of the public transport service. Due to the predominance of the road network in satisfying demand, the Lorenz curve highlights regions with low "quality" public transport service (Gori et al., 2020, Delbosc and Currie, 2011). In fitting the Lorenz curve, the cumulative percentage of job accessibility by public transport is plotted on the y-axis against the cumulative percentage of jobs on the x-axis using Microsoft Excel.

(ii) **Gini Coefficient:** The Gini coefficient or index has been a widely recognized statistical measure of inequality or for evaluating transport equity for more than a century (Lucas et al., 2016), and is also a famous indicator for measuring the spatial distribution of resources (Babuna et al., 2020). In a numerical expression, Gini Coefficient has a maximum value of '1' and a minimum of '0', and the closer the value is to 1, the higher the inequality. The mathematical computation of the Gini coefficient relies on the construction of the Lorenz curve, as represented in Fig. 6. The y-axis of this curve depicts the cumulative proportion of advantages provided by the corresponding cumulative proportion of the population (shown on the x-axis). The 45-degree line illustrates the curve of complete equality (when each person receives the same amount of benefit). Implying with X the region between the Lorenz curve and the line of perfect equality and with Y the integral of the Lorenz curve yields the Gini coefficient as X/(X + Y). The closer the Lorenz curve approaches the line of perfect equality, the closer this ratio approaches 0. The Gini coefficient is also equivalent to 2X or 1-2Y, given that X + Y always equals 0.50. In real-world applications, the area Y of the Lorenz curve is computed as an integral (or, more frequently, as a sum over finite intervals).

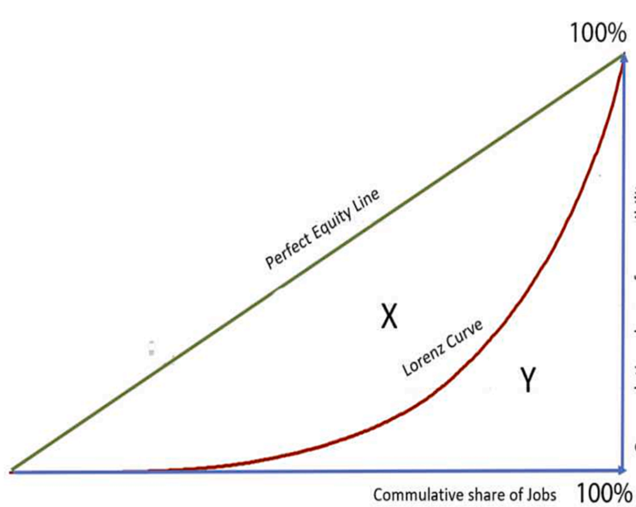


Fig. 6. Gini Index and Lorenz Curve (Lucas et al., 2016).

The general Gini formula (Equation (11)) applied after plotting the Lorenz curve is given as:

$$Gini = \frac{1}{\mu N(N-1)} \sum_{i>j} \sum_{j} |y_i - y_j| \tag{11}$$

where:

Gini is the Gini coefficient, μ is the mean of the variable (accessibility), N is the total number of observations, $y_i andy_j$ are job accessibility values.

4. Results and discussions

Following the above-enumerated public transport accessibility measuring approach adopted in this study, we present the findings and discussions of the results. Figs. 7(a-c) and 8(a-c) below show the results of accessibility to work and services opportunities located in the City of Wuhan displayed using Esri's ArcMap Geostatistics methods (kringing interpolation). Furthermore, we also show the results of accessibility to various activities (HBW and HBO) during different times of the day. Using Lorenz curves and Gini Coefficients, we present the results of how accessibility differs between urban (high income) and rural areas (low income). The color scheme (blue to red) represents the level of accessibility with blue at the highest level and red at the lowest.

Figs. 7a, 7b, and 7c represent the level of accessibility to HBW during the morning peak, off-peak, and evening peak hours respectively. The morning peak ranges between 6 am-9 am, mid-day off-peak hours range between 10 am-1 pm, and evening peak hours range between 5 pm and 8 pm respectively. The accessibility value ranges indicate the level of accessibility in each TAZ. The value ranges are No accessibility (0.0), Low accessibility (0.1 ~ 4.3), medium accessibility (4.4 ~ 5.4), and high accessibility (5.5 ~ 6.5). Starting with public transport accessibility to HBW activities, the result revealed that during off-peak time public transport accessibility is high and covers a wide range of the zones in the study area due to less traffic congestion. This result is consistent with a previous study conducted in Wuhan, China, which indicated that the downtown area is highly accessible during off-peak hours. This could be attributed to the fact that the majority of retail services activities are located in downtown areas (Raza et al., 2022b). On the contrary, morning and evening peak hours show low public transport accessibility in most parts of the city and tend to be high in the central business district (CBD). These findings are in line with previous studies which show that during the morning rush hour, suburban residential zones had the lowest accessibility, as the most of incoming traffic caused serious congestion difficulties and the majority of the population tended to be concentrated in the downtown area (Moya-Gómez et al., 2018). Mostly, the majority of HBW trips are performed during the morning (when people go to work) and evening when people finish work and make the return trip home. It seems from Fig. 7c that during the evening peak the level of congestion is high and eventually the accessibility drops because of the increased time duration of the public transport network. Obviously, traffic congestion is one of the factors that affect accessibility due to delays in the transport network. However, the metro system is not influenced by road congestion but people who transferred from a bus to metro, and metro to a bus, spend more time on public transport affecting the aggregate public transport accessibility during the morning and evening peak hours. The overall results indicate that zones close to or within the CBD have better access to activities hence residents dwelling in these zones are better served by public transport.

Figs. 8a, 8b, and 8c represent the level of accessibility to HBO (commercial services and government services) during the morning peak, off-peak, and evening peak hours respectively. The accessibility value ranges are No accessibility (0.0), Low accessibility (0.1 ~ 4.3), medium accessibility (4.4 ~ 5.4), and high accessibility (5.5 ~ 6.5). As compared to HBW activities during the evening peak hours, HBO

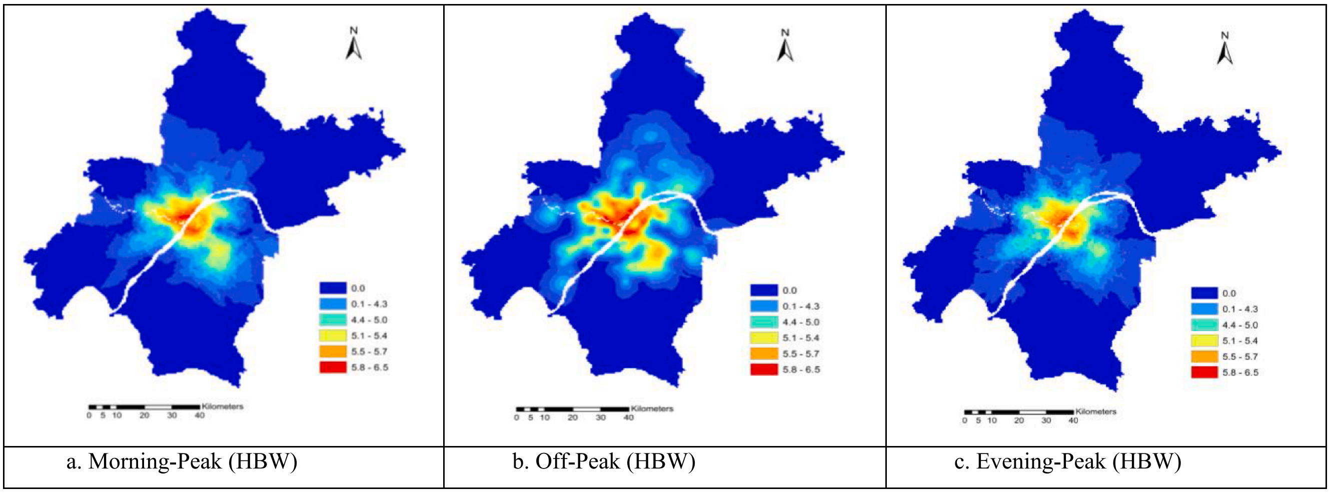


Fig. 7. (a) Morning-Peak (HBW). (b) Off-Peak (HBW). (c) Evening-Peak (HBW).

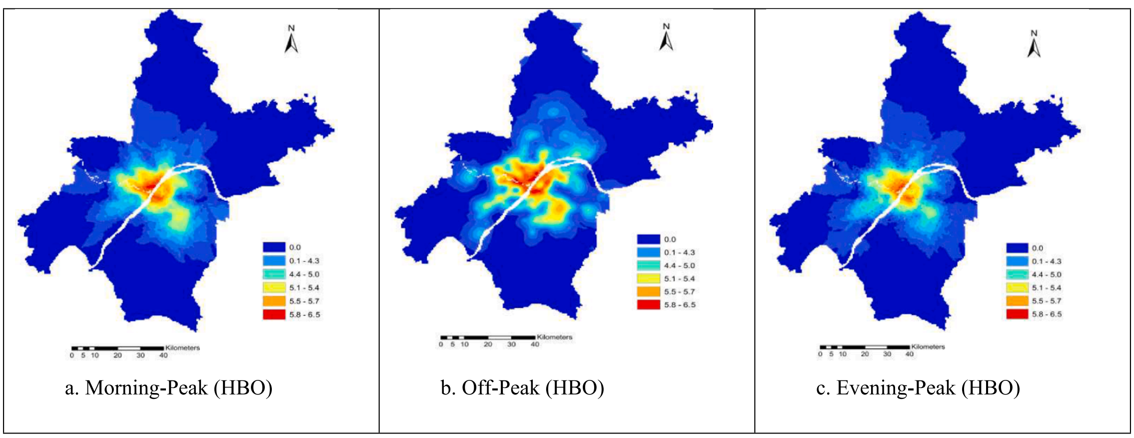
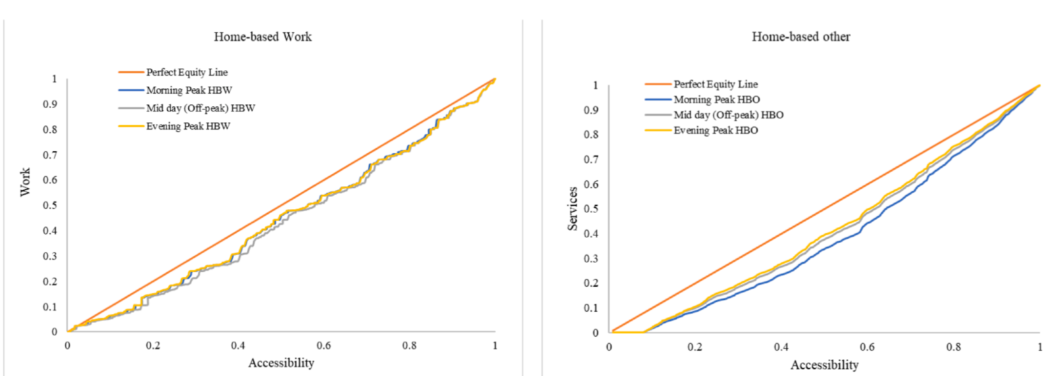


Fig. 8. (a) Morning-Peak (HBO). (b) Off-Peak (HBO). (c) Evening-Peak (HBO).

activities show a low accessibility level. The reason is people usually don't go to other activities such as shopping and leisure activities during the evening hours. The above results showed that during a different time of the day and for different trip purpose, only the downtown (CBD) areas of the city of Wuhan has a high level of accessibility by public transport. Again, the off-peak hours showed a high level of public transport accessibility as compared to the morning and evening peak hours.

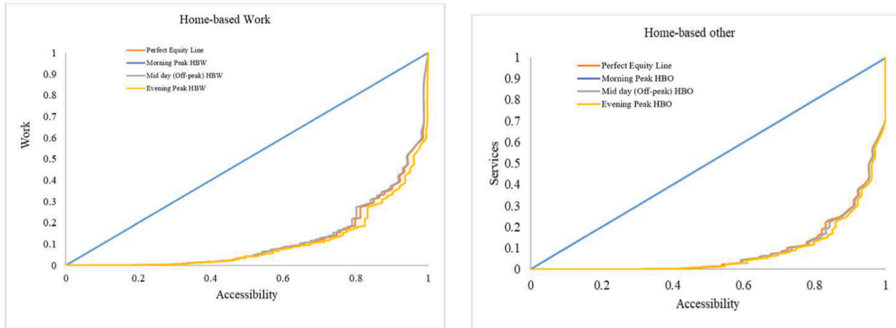
4.1. Public transport accessibility (Urban and rural Area)

Urban areas interchangeably can be referred to as downtown areas or in other words, zones at the CBD of cities whilst rural areas are sometimes known as the periphery of cities. Unlike rural areas, most of the zones in urban areas have a fair share of the distribution of public transport infrastructure hence accessibility to employment opportunities by public transport is usually high in these areas in most cities. Using the Lorenz curve, we show the level of public transport



a. Home-based work b. Home-based others

Fig. 9. (a) Home-based work. (b) Home-based others.



a. Home-based work b. Home-based others

Fig. 10. (a) Home-based work. (b) Home-based others.

accessibility in urban (Figs. 9) and rural (Figs. 10) areas.

Figs. 9a and 9b show the level of public transport accessibility to HBW and HBO activities in an urban area in Wuhan during morning-peak, off-peak, and evening-peak hours respectively. Public transport infrastructure seems to be fairly distributed, indicating a high level of public transport accessibility to various activities located within the study area. The overall result revealed that residents within urban areas have access to better public transport services. It is the goal of urban planners and transport policymakers to provide better public transport access to opportunities located in highly dense areas. This result has revealed that a great effort has been made to improve public transport accessibility in urban areas based on the previous study conducted by Raza et al. (2018). Public transport accessibility in the rural areas is presented in Figs. 10a and 10b. The results indicate that a huge disparity exists between the equality line and all the HBW and HWO activities investigated in the rural zones of the study area. There are no significant differences in public transport accessibility between morning-peak, off-peak, and evening-peak hours as compared to the urban areas. This is because, unlike the urban areas which suffer from traffic jams that affect public transport accessibility at a certain time of the day as explained earlier, rural areas suffer less or no traffic congestion that would impact mode transfer times. Of course, this result, to some extent is in line with what we expected having in mind the socioeconomic status of individuals dwelling in rural areas (vehicle ownership is less to cause traffic congestion), however, the level of equity gap is beyond the expected.

In the next section, we compare the public transport accessibility results between the urban and rural areas using the Gini index to determine the disparity in public transport accessibility and later discussed the results.

4.2. Urban and rural disparity (Gini index Results)

The Gini index(coefficient) has been accepted as one of the tools for measuring the disparity and adopted in the transportation field. In this study, we investigate the level of public transport accessibility between the urban and rural areas in the City of Wuhan using the Gini index. The index, ranging from 0 to 1 (with 1, the high level and 0, the low level), shows the level of disparity in using public transport to access opportunities between urban and rural areas. This indicates that inequality among individuals with a Gini coefficient of 0.3 or less is better to those with a Gini coefficient of 0.4 or higher. Thus, the smaller the Gini coefficient, the smaller inequality among individuals (Giannotti et al. 2022). Accessibility to basic activities is very essential and mostly includes all socioeconomic groups (high, medium, and low-level income). Previous transportation accessibility studies that considered public transport equity used the Gini coefficient range between 0 and 1 and a comparison is often made between the stratified groups investigated. When a Gini index is bigger for a particular group, it indicates that the group has a lower level of accessibility (Stępniak and Goliszek, 2017).

The results, as shown in Fig. 11 revealed that for all the employment opportunities, urban areas have high access to these activities at all peak hours. However, a high level of disparity was found between the urban and rural areas. From these results, it is apparent people living in rural areas are lacking access to various opportunities and cannot compete with others living in urban areas if they are qualified for the same jobs. Low income and the poor reside in rural areas in the city of Wuhan and a lack of public transport to job opportunities such as service jobs could increase their level of poverty (Sanchez and Brenman, 2008). This means that households in urban areas will enjoy better public transport accessibility and those who cannot afford a personal vehicle will be

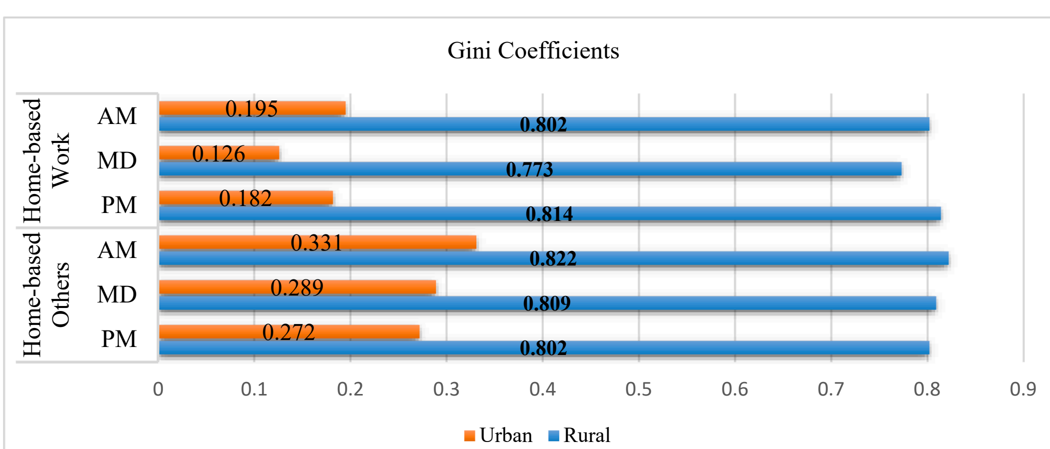


Fig. 11. Gini coefficients for urban and rural areas.

better off if they move from the rural areas.

5. Conclusions

Public transportation is the core element of sustainable development goals and pertains to goal 11.2 of sustainable mobility. This goal urges to provide a transport system for everybody that is safe, inexpensive, accessible, and sustainable by 2030. This study presented the analysis of dynamic multimodal spatial accessibility of HBW and HBO activities in urban and rural areas by considering public transit such as metro and bus in the City of Wuhan, China. This study used four-step multimodal models to comprehensively assess the performance of the complete public transportation system. In order to accomplish this, we developed a four-step multimodal transport model in which we considered nearly all the factors that affect public transport accessibility and used the utility-based accessibility approach to calculate public transport accessibility to different land-use activities at different times of the day. Then, the located urban and rural activities are further examined by employing two geostatic measures such as the Lorenz curve and the Gini coefficient to identify the level of accessibility and disparity of various urban and rural activities. The framework developed in this study has yielded a good result that we believe reflects the real scenario of public transport accessibility in the City of Wuhan. Unlike other studies that consider only free-flow speed in measuring accessibility in China (Liu and Zhou (2015), our study takes into consideration not only congested times on the entire transport network (based on congested speed) but all the transport utilities that affect public transport accessibility. In this case, we presented public transport accessibility in a real-world scenario.

The study findings revealed that public transport accessibility to HBW activities is high during the off-peak time and covers a wide range of the zones in the study area due to less traffic congestion. This could be attributed to the fact that the majority of retail services activities are located in downtown areas. On the contrary, morning and evening peak hours show low public transport accessibility in most parts of the city and tend to be high in the central business district (CBD). As compared to HBW activities during the evening peak hours, HBO activities show a low accessibility level. The reason is people usually don't go to other activities such as shopping and leisure activities during the evening hours. Regarding public transport equity, the results revealed that for all the employment opportunities, urban areas have high access to these activities at all peak hours. However, a high level of disparity was found between the urban and rural areas. From these results, it is apparent people living in rural areas are lacking access to various opportunities and cannot compete with others living in urban areas if they are qualified for the same jobs. Based on the findings, we found that public transport is currently servicing the larger population in the city of Wuhan due to the investment in public transport infrastructure. The results follow a spatial pattern that indicates that public transport accessibility successively diminishes from the urban towards the rural areas which is the reality of most cities. The residents living in urban areas have better access to public transport, implying that households without private vehicles are better off if they dwell in the urban areas. However, there exists a public transport accessibility gap between the urban and rural areas of the city due to the unfair distribution of public transport infrastructure within the entire geographical area of the city.

5.1. Policy implications and recommendations

To achieve this goal, cities should encourage planning strategies that seek to meet the accessibility needs of people by hindering long trips and promoting sustainable modes: walking, cycling, and public transport. According to the findings of the study, the majority of rural areas have inadequate or no transit accessibility to key employment centers. To improve economic development and social prosperity and accomplish the global SDGs, policymakers and stakeholders must equitably incorporate rural areas. Due to the fact that 2.53 million people in Wuhan live in low-income rural areas, government organizations must pay special attention to transit accessibility difficulties in these areas. These challenges should be addressed at both the regional and national levels in order to reduce the growing disparity between urban and rural areas. The Agenda 2030 of the United Nations outlines the goals for supporting the sustainable development of our planet. The majority of these objectives can be attained through the implementation of transportation regulations that consider the influence on the environment, the quality of life in future cities, and social inclusion.

According to the study's findings, public transportation plays an important role to provide accessibility to various activities located in the city centers of Wuhan. To promote the use of public transportation in Wuhan, the following strategies could be implemented: (i) First and foremost, improving public transit frequency could help commuters to reach their desire destination on time, which is also the top priority of every commuter. (ii) Improve bus-to-subway transfers, which are significant for transport efficiency. (iii) Improve passenger comfort and safety. These targets could be attained with a more efficient policy. Promoting the usage of public transportation can significantly reduce vehicle miles traveled and CO_2 emissions. In addition, this study captured almost all the influencing factors of public transport accessibility as far as multimodal transportation networks are concerned which allowed us to obtain profiles that highlight public transport equity in the study area towards enhancing transport policies that consider the fair distribution of public transport infrastructure and land use activities (opportunities). To have public transport equity, better transport solutions are critically needed at both regional and local levels. Accessibility for people within the rural and remote areas must be enhanced, and the inter-relationship between land-use planning strategies and transportation policies should be taken into consideration.

The disparity in public transport accessibility whether between locations or transport modes could have a great impact on the decision of individual mode choices. This will mean that city planners and city authorities would have to make an effort in reducing the public transport accessibility gap between the urban and the rural zones. The poor and low-income groups dwell in the rural areas of the city of Wuhan and cannot afford personal vehicles. This implies that for these individuals to get access to jobs and to engage in other social activities in urban areas, the availability of public transport is the only option. However, this is lacking in most of these areas due to the unfair distribution of public transport infrastructure. There is no doubt that building public transport infrastructure requires a large amount of financial investment and most city authorities would like to recoup their investment within a certain period hence may see rural areas as not curative enough. However, investing in public transport in rural areas to some extent could influence the relocation decision of many people in highly populated areas of the city especially those without private vehicles. As indicated by Liu and Zhou (2015) due to the high level of accessibility in urban areas, most Chinese people prefer to live in urban but not in rural areas. It would also be of great benefit to individuals in rural areas if public transport accessibility is seen as a right of every citizen rather than solely as a business. It is only, in this regard, can public transport infrastructure be equitably distributed in the entire city.

It is worth mentioning that the methodology adopted in this study can only be applied if the appropriate data is available to calibrate and validate the transport model. Although in this study, we argued that public transport accessibility is well represented when the performance of the entire transport network is considered, it does not mean that other methods of public transport accessibility measurement approaches are not appropriate. In the absence of transport models, such methods are still viable for measuring public transport accessibility and transport policy decision-making to some extent towards the enhancement of public transport infrastructure distributions. The findings of this study would be helpful for policymakers and stakeholders to evaluate the fair distribution of public transport infrastructure to minimize the disparity among citizens.

CRediT authorship contribution statement

Asif Raza: Conceptualization, Methodology, Writing – original draft, Software. **Ming Zhong:** Writing – original draft, Supervision, Investigation, Validation. **Raymond Akuh:** Data curation, Writing – original draft. **Muhammad Safdar:** Visualization, Writing – review & editing.

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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