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Article

Spatial Equity Disparities of Work Commuting Based on Job Accessibility in Chengdu, China

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Abstract: Recently, urban spatial equity has become a research hotspot, but research focuses on the equity of work commuting from different dimensions. This paper aims to determine the fairness difference of work commuting in Chengdu from three different dimensions by analyzing job accessibility in Chengdu. Firstly, population residence and employment data are obtained by using mobile phone signaling data, real-time travel data are obtained by using Amap API, and regional housing information is obtained from a real estate website. Secondly, the differences in time and cost of job accessibility in different regions are calculated under different time thresholds. Finally, the equity of job accessibility is evaluated by using the Theil index and the Gini coefficient from three new perspectives: transport mode, house price economy, and spatial region. The experimental results show that (1) when time threshold increases, public transport in Chengdu is more equitable, while car traffic is opposite; (2) regions with higher prices are generally fairer; and (3) Chengdu's equality disparities are more between areas than within areas. In addition to proposing a new accessibility formula based on travel impedance, this study suggests a new method for analyzing equity differences in Chinese cities that can serve as a reference for future researchers. At the same time, the results provide a scientific basis for optimizing the social spatial distribution of public transport services in Chengdu.

Keywords: job accessibility; spatial equity; time thresholds; the Gini coefficient; the Theil index

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1. Introduction

1.1. Background

The concept of accessibility was first introduced by Hansen in 1959 [1], who defined accessibility as the potential for interaction between dispersed locations. Since then, accessibility has drawn a lot of attention. While there is no consensus on the definition of accessibility, it is increasingly seen as a crucial metric in the fields of transport [2] and land planning [3].

Since various regions have different transport bases, Welch et al. proposed the idea of transport equity in 1964 to assess the transport environments of many areas [4]. Transport equity refers to how infrastructure is distributed socially while accounting for the varying requirements and preferences of various population groups [5]. Transport equity can help explain some accessibility phenomena, such as why residents in certain places spend more time to travel less far. Therefore, researching transport equity can aid in resolving a number of urban social issues [6].

Of all the purposes of transport trips, the bulk of personal transport journeys are made for work-related objectives [7]. In Beijing, China, the average commuter count within the sixth ring road was 25 million in 2019, which accounted for more than 52% of all trips, according to the Beijing Transport Research Institute [8]. This led to the creation of the idea of job accessibility, which refers to the convenience of reaching different workplaces [9].

In addition, job accessibility is regarded as a crucial social equality metric as the working environment in a region can reflect its socioeconomic status [10]. For example, Eom found that job accessibility has higher marginal effects on Black employment in Chicago, especially in predominantly Black neighborhoods [11].

1.2. Research Aim and Contents

Job accessibility is an essential metric to measure the efficiency and socioeconomic status of urban transport system. Efficient job accessibility means that residents can get to work more quickly and affordably, which improves quality of life and productivity [12]. It encourages industrial clustering and economic growth by drawing in talent and enterprises [13]. Urban transport equity is also an important cornerstone of the development of society with respect to travel rights. It makes it possible for residents to make use of convenient and secure transport services regardless of their financial situation, age, gender, or physical condition. This helps to alleviate urban traffic congestion, reduce commuting costs, and enhance the overall cohesion and competitiveness of the city.

At the same time, job accessibility and urban equity have a profound impact on human mobility. These might encourage locals to adopt more adaptable and economical commuting strategies, cutting down on travel expenses and time. They can motivate residents to choose more flexible and efficient commuting methods, reducing commuting time and costs. Furthermore, they affect residents' choice of residence and employment, and promote the rational layout and optimization of urban space. In addition, transport equity helps to break geographical and social barriers, promote mobility and integration between different social groups, and enhance the vitality and diversity of society.

Previous studies mostly evaluate transport equity in cities from a single perspective, such as contrasting various transport options [14] or social groups [15]. However, few studies have combined perspectives to target urban transport equity from multiple angles. Urban transport equity involves many aspects, and different perspectives can lead to varying interpretations of equity differences. The more views included, the more comprehensive the explanation of disparities in urban equality. Currently, the study of traffic equity in China is mainly based on the study of specific metropolises, such as Beijing [16] and Shanghai [17]. However, with the development of the economy, the gap between different cities has gradually increased [18], so it is urgent to study inland cities with weak economic strength. For example, Jin focused on the mountainous Chongqing region and established a comprehensive research framework examining the spatial pattern of accessibility of urban green spaces and equity correlation with physical geographical elements and socioeconomic factors [19].

The aim of this study is to use a new calculation method to calculate job accessibility, and then evaluate equity differences in urban transport in a particular Chinese inland city through a variety of different dimensions. This article calculates job accessibility simultaneously from time and cost aspects, and then evaluates the equity of urban transport from three perspectives: varying transport modes, varying housing prices, and varying spatial geographic locations.

The main contributions of this paper are as follows:

(1) A new time accessibility calculation model is used to optimize the traditional cumulative accessibility model and improved based on the idea of travel impedance to make it more consistent with actual journeys;
(2) The addition of a calculation model of cost accessibility, quantification of the travelling cost index, and analysis of job accessibility from different perspectives to make the model more comprehensive;
(3) Through the division of time thresholds, we evaluated job accessibility and equity in different time periods by dividing time thresholds. This is because time is the most concerning parts of residents' daily transport trips [20], directly affecting travel behavior.

(4) We evaluated the equity of job accessibility from the three dimensions of traffic equity, housing price economic equity, and area equity in order to analyze the disparity of traffic equity in Chengdu more comprehensively.

Our methodology involves three key elements. Firstly, many accessibility studies depend on traditional traffic data sources. To better determine job accessibility, this study used mobile phone signaling data to obtain the number of residents and employment, as well as an online map application programming interface (API) to estimate travel data so as to get more accurate travel time data and travel cost data.

Secondly, disparities in housing costs have been discovered in China between various income levels according to earlier research [21]. Therefore, it is necessary to choose appropriate indicators to measure these inequality differences in accessibility. Using an online real-time transacted second-hand house price website, we obtained regional housing price data to assess the equality of job accessibility in three dimensions: transport equity, economic equity, and spatial equity.

Lastly, we used not only the Gini coefficient for measuring equity, but also the Theil coefficient on spatial regions. The Gini coefficient is used to measure the inequality of distribution and is widely used in the economic and transport fields [22]. For instance, Chen et al. studied China's roadway imbalance using the Gini coefficient [23]. On the other hand, due to its strong decomposability, the Theil index is frequently used to analyze differences between regions and differences within a region that are independent of one another [24].

The article is structured as follows. In Section 2, we provide a systematic literature review on job accessibility and transport equity. In Section 3, the experimental steps, system indexes, and methods of calculating accessibility and fairness are presented. In Section 4, we choose Chengdu, China, as a case study for the analysis of job accessibility and urban equity. In Section 5, we draw conclusions and propose further research directions.

2. Literature Review

2.1. Job Accessibility

2.1.1. The Concept of Job Accessibility

There is no clear definition of accessibility but the majority of individuals now agree on the concept of accessibility, which was proposed by Handy and Niemeier in 1997 and is the degree of convenience from the origin to the destination [25]. As a result, accessibility can also be defined as the ease of access to different opportunities, which is usually measured by academicians in terms of distance or time impedance [26]. Due to different research perspectives, academics from different disciplines understand the concept of accessibility differently. Schulke et al.'s study on the accessibility of school play spaces revealed that there is a gap in access to school play spaces for students with disabilities [27], and Wei's study on the accessibility of healthcare facilities discovered that the spatial accessibility of healthcare organizations in China shows a decreasing trend from east to west [28].

Most of the activities in the transport system are related to the travel that individuals do on a daily basis for work; thus, job and reachability have been linked in a number of prior studies [29]. In this study, job accessibility is defined as the proportion of the number of job opportunities that people can reach using different transport modes within different time thresholds. In other words, job accessibility measures how simple or challenging it is to get employment in a certain area.

2.1.2. Measurement of Job Accessibility

Diverse techniques exist for accessibility analysis, and they vary depending on the type of item, so different calculation methods have different characteristics (Table 1). For instance, Zhang et al. assessed the spatial accessibility of transit, education, healthcare, shopping, and recreation facilities for affordable housing neighborhoods, using the Gaussian-based two-step floating catchment area method (2SFCA) [30]. Zhang et al. used the two-step floating catchment area method and potential model to calculate facility accessibility and the potential service scope of public health infrastructure distribution [31]. Yang et al. applied an improved 2SFCA and *k*-means cluster analysis to study park accessibility in the central urban area of Zhengzhou [32]. Cao et al. calculated the equity of the RGS in walking modes of 5, 10, and 15 min using an improved three-step floating catchment area method (3SFCA) [33]. The service capacity of public transport stations can also be measured by the number of public transport service supply points [34]. Alternatively, GIS may be used to build a representation of the public transport network and assess how accessible each location is by public transport. Wang et al. proposed three GIS-based methods to measure park accessibility and discovered that distance thresholds and choice of transport modes have a greater impact on accessibility than choice of destination [35]. Huang et al. integrated the theories and methods of landscape ecology and spatial syntax with GIS technology to construct a comprehensive model for examining the spatial accessibility of green spaces based on remote images and landscape pattern indices [36].

Table 1. Characteristics of different measurement methods for accessibility and equity.

Category	Evaluation Methodology		Features
Accessibility	Distance Metric Measure	merit	Simple calculation and readily comprehensible.
		defect	Considers only the relationship between nodes and centers. Not suitable for multi-center and large-scale regions.
	Space Separation Measure	merit	Simple and intuitive. Considers the effect of spatial distance.
		defect	Only reflects the influence of traffic conditions on accessibility.
	Gravity Model	merit	Considers the attributes of each area, close to the actual situation.
		defect	The region is simplified into the point influence calculation result. The choice of attenuation function is too subjective.
	Cumulative Opportunity Measure	merit	Easy access to data. Takes into account land use factors.
		defect	Does not take into account that spatial utility decays with distance.
	Utility Measure	merit	Considers the influence of transport systems and individual factors.
		defect	Requires a lot of data and complex calculations.
	Two-Step Floating Catchment Area	merit	Considers the impact from both the supply side and the demand side.
		defect	Complex calculation. Difficult to determine space distance and time threshold.
Equity	Gini coefficient	merit	Simple calculation. Can reflect the overall income gap.
		defect	Does not reflect the income distribution of individual classes.
	Lorenz curve	merit	Visual and intuitive.
		defect	It cannot be quantified, nor can it accurately calculate income gaps.
	Theil index	merit	Decomposability and hierarchy.
		defect	Complex calculation and needs a lot of data.

Since the scope of job accessibility is a given region or area, location-based accessibility measures are more applicable for this study. The gravimetric and cumulative opportunity approaches are two widely used methods of measuring. In the gravimetric technique, the quantity of work opportunities inside the limit is employed as a measure of reachability, which limits job opportunities using a distance decay function [37]. The cumulative opportunity method restricts job opportunities by a given range of distances and time thresholds, and the number of job opportunities within the limit is counted as an indicator of reachability [38]. The computational framework of both approaches is similar, and the only difference is in the number of jobs that each approach may count as available. Both methods have their own advantages, the gravimetric method's attenuation curve is thought to be more representative of people's travel habits, whereas the cumulative opportunity method makes it easier to obtain and process traffic data [39], so both approaches are frequently used in practical research.

2.2. Transport Equity

2.2.1. The Concept of Transport Equity

Similar to accessibility, the definition of fairness is not uniform due to the social standards of different groups. In 1984, Litman analyzed the significance of transport equity and classified it into two categories: horizontal equity and vertical equity [40]. Horizontal equity refers to the fact that each study subject has an equal chance of covering the cost of their travels, irrespective of shifts in demand and their ability to travel [41]. Hay studied the transport equity from a horizontal equity perspective and believed that the primary goal is to provide services for the maximum number of users and reduce congestion [42]. Vertical equity means that society should have different distribution systems when facing research subjects who have varying requirements and capacities, and transport resources should be tilted towards disadvantaged groups to compensate for overall social inequality [43]. Based on vertical equity, Currie analyzed the gap in public transport in supporting the needs of transport-disadvantaged groups [44]. From a spatial vertical equity perspective, Yu et al. found the spatial distribution of most public general hospitals does not take into account communities with a high proportion of minors and seniors [45].

Since this study is concerned with the equity of different transport modes, house price economies, and geographic areas, we need to analyze their variations independently based on the many study subjects. In order to ensure the accuracy of the other variables in the analysis, transport equity in this study refers to horizontal equity, where transport costs and benefits are distributed according to the same criteria within a given city, regardless of changes in people's transport modes, house price economies, and geographic areas. This is similar to how Yeganeh's analysis of job accessibility in the US applied the same operational standards to various socioeconomic and ethnic groups [46].

2.2.2. Measurement of Transport Equity

The Gini coefficient, the Lorenz curve, and the Theil index are all indicators of income inequality in economics, while measurements of fairness in economics are more mature [47]. Simultaneously, they have progressively evolved into the three primary statistical methods for evaluating transport equity [48], each of which has its own characteristics (Table 1). Ceriani and Verme defined the Gini coefficient as an evaluation of the uniform distribution of a certain indicator (such as economic income or distribution of harmful substances) for a given object [49]. The range of the Gini coefficient is 0 to 1. The closer the Gini coefficient is to 0, the more equal the distribution of that indicator is. Ricciardi explored the equitable distribution of public transport for three independently disadvantaged groups and found that the population of the city of Perth exhibited a Gini coefficient of 0.52, which is more equitable compared to Melbourne (0.68) [50]. The Lorenz curve is a curve proposed by Lorenz in 1905 that reflects the distribution of income or wealth, in which a point closer to the diagonal line indicates a fairer distribution [51]. The Gini coefficient and the Lorenz curve are closely related. In fact, the Gini coefficient equals the area under the Lorenz curve divided by the area under the diagonal. For example, Asif Raza used statistical methods such as the Lorenz curve and the Gini coefficient to determine the extent of differences in access to employment opportunities through public transport between urban and rural areas [52].

The Theil index is frequently used to assess economic inequality both between and within areas because of its excellent decomposition, which is based on the information theory notion of entropy [53]. The larger the value of the Theil index, the larger the income gap or inequality, and on the contrary, the smaller the value, the smaller the income gap or inequality. For example, Oki Wijaya discovered Bantul town (0.737) had the greatest degree of disparity within Yogyakarta city when he studied the regional economy [54].

3. Data and Methodology

The three primary parts of this experiment are as follows (Figure 1). The first is data acquisition and cleaning, which involves filtering raw data and obtaining online data. Secondly, job accessibility is calculated for different time thresholds and cost thresholds. Lastly, there are three ways to gauge work fairness.

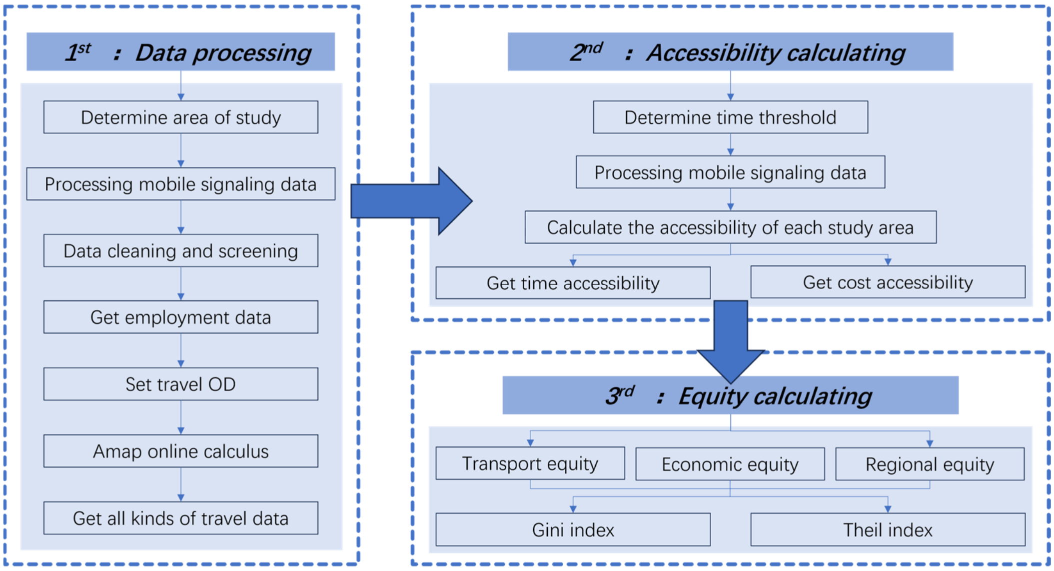
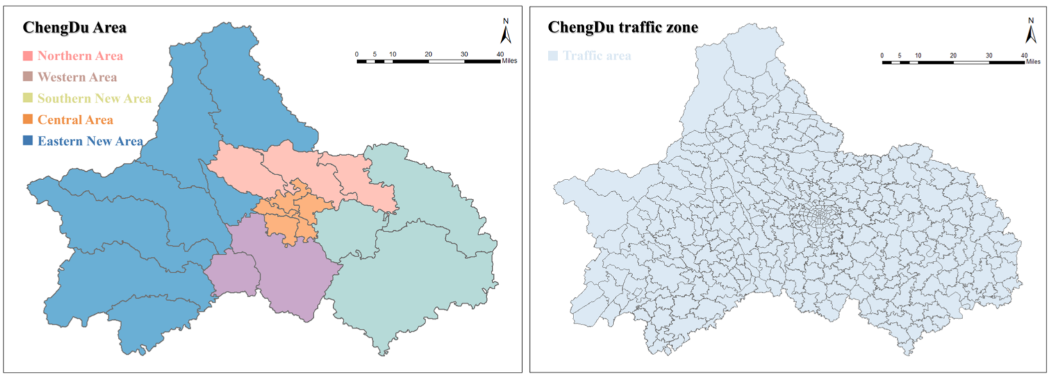


Figure 1. The framework of accessibility calculating and equality calculating.

3.1. Study Area

According to the Chengdu City Master Plan (2016–2035) [55], the city area is divided into five areas: the Central Area, the Northern Area, the Western Area, the Southern New Area, and the Eastern New Area. Next, the districts are divided by administrative sub-districts, with a total of 20 administrative sub-districts (Figure 2a). Ultimately, there were 375 traffic units within the transport community, which was the smallest study unit (Figure 2b).



(**a**) (**b**)

Figure 2. Regional division of Chengdu: (**a**) 5 areas contain 20 administrative districts; (**b**) 375 traffic units.

3.2. Data Acquisition

Three main types of data were used in this study: residential commuting data based on mobile phone signaling, travel-related traffic data, and house price data based on real-time website listings. Mobile phone signaling data were obtained by recording information from mobile company base stations. Owing to China's large population, traditional data sources are less precise and more expensive to survey. Thus, in order to characterize the residential population and employment data needed for the study, we chose mobile phone signaling data, which offer a larger sample size and are more accurate. We processed the collected signaling data of Chengdu city in April 2021, and a total of 1,067,523 OD pairs were obtained.

Traffic data was obtained through programming the Amap API. As one of the leading online map providers in China, Amap's API has the following advantages: (1) it updates the road conditions according to the actual situation, and provides accurate travel time and distance planning; (2) it allows calculation of the estimated travel cost in conjunction with the local traffic bureau; and (3) it provides various travel scenarios and conducts comparative analysis for the same departure and arrival points. We estimated the real traffic time in Chengdu city during the morning peak hour (7:00–9:00) using the Amap API. To obtain the travel data for different transport modes, the Amap API was called using the longitude and latitude of all OD pairs.

The house price data were extracted from the Chain Home website. As one of the top real estate trading websites in China, Chain Home has comprehensive and detailed information on property listings. We could extract the house price, house size, transaction status, and so on in different geographical locations via programming. We used Python to extract the listings data under second-hand transactions in the Chain Home website to get all the information of second-hand rentals listed in Chengdu city. In order to classify the price level community, for multiple listings in the same area, we used the average value of the housing unit price to represent the housing unit price at that point, accumulating a total of 201,960 housing unit prices in latitude and longitude.

3.3. Computational Model

3.3.1. Accessibility Model

There is a wide variety of ways to calculate accessibility, and the conventional cumulative accessibility model counts the number of opportunities to reach a given time or distance threshold from a place [56]. The opportunity is deemed unreachable if it is beyond the time or distance criteria. The traditional formula is as follows:

$$A_\alpha = \sum_{i=1}^{m} \sum_{j=1}^{n} \left[S_{ij} \times f\left(t_{ij}\right) \right], i \in \alpha, j \in ALL, \quad (1)$$

$$f\left(t_{ij}\right) = \begin{cases} 0,\ if\ t_{ij} > t_{threshold} \\ 1, if\ t_{ij}\ \le\ t_{threshold} \end{cases}, \quad (2)$$

where α is any traffic unit; $t_{threshold}$ is a given time threshold; A_α is the traditional cumulative accessibility model that represents the accessibility to traffic unit α via various transport modes within the $t_{threshold}$; S_{ij} denotes the number of jobs from point j to point i; f is a constraint function indicating whether the point is counted according to the constraints; t_{ij} is the travel time between point j to point i; i is the longitude and latitude point where all OD pairs end in the traffic unit α; j is the longitude and latitude points where all OD pairs start in all traffic units (i.e., across Chengdu); m represents the number of points i in traffic unit α; and n represents the number of points j in all areas (i.e., across Chengdu).

Nevertheless, the influence of the overall travel demand is not included in this strategy. In this study, based on the concept of travel impedance put forward by Karen Lucas in

2015 [57], the number of jobs is a weighted average to reflect the actual condition of urban residents traveling. The improved accessibility weighted average formula is as follows:

$$T_\alpha = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left[S_{ij} \times f\left(t_{ij}\right)\right]}{\sum_{i=1}^{m}\sum_{j=1}^{n} S_{ij}}, i \in \alpha, j \in ALL, \tag{3}$$

$$f\left(t_{ij}\right) = \begin{cases} 0,\ if\ t_{ij} > t_{threshold} \\ 1, if\ t_{ij}\ \leq\ t_{threshold} \end{cases}, \tag{4}$$

where T_α is the improved time accessibility to reach traffic unit α by various transport modes within $t_{threshold}$; other parameters are the same as above.

To better reflect the psychology of real travel, we introduce the variable of "travelling cost" based on the cumulative accessibility model. The improved cost accessibility weighted average formula is as follows:

$$C_\alpha = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left[S_{ij} \times f\left(t_{ij}\right) \times G_{ij}\right]}{\sum_{i=1}^{m}\sum_{j=1}^{n}\left[S_{ij} \times f\left(t_{ij}\right)\right]}, i \in \alpha, j \in ALL, \tag{5}$$

$$f\left(t_{ij}\right) = \begin{cases} 0,\ if\ t_{ij} > t_{threshold} \\ 1, if\ t_{ij}\ \leq\ t_{threshold} \end{cases}, \tag{6}$$

$$G_{ij} = \begin{cases} G_{ij}^1,\ if\ Public\ transport \\ G_{ij}^2, if\ Car\ trasport \end{cases}, \tag{7}$$

$$G_{ij}^1 = g_{i-1} + g_{1-2} + \ldots + g_{k-l} + \ldots + g_{(l-1)-l} + g_{l-j} = g_{i-1} + \sum_{k=1}^{l} g_{k-l} + g_{l-j}, \tag{8}$$

$$G_{ij}^2 = d_{ij} \times u \times v \times w, \tag{9}$$

where C_α is the improved cost accessibility to traffic unit α via various transport modes within $t_{threshold}$; G_{ij} is the cost of travelling between point j and point i for different transport modes; G_{ij}^1 denotes the cost of travelling from point j to point i by public transport; g_{k-l} refers to the cost of public transport for the segment $k-l$ from point j to point i, which is calculated in real time by the Amap Online platform; G_{ij}^2 denotes the cost of travelling from point j to point i by car transport; d_{ij} is the actual number of kilometers driven by the vehicle from point j to point i; u is fuel consumption (or electric consumption) used by the vehicle per kilometer; v is the cost of fuel consumption (or electric consumption) per unit of the vehicle; w is the vehicle depreciation cost per kilometer; and other parameters are the same as above.

Due to the combination of the weighted average treatment of travel impedance and the number of jobs, the new calculation formula has higher complexity. We found that it not only improves the accuracy of accessibility, but also makes it more practical in real life due to consideration of time and cost. It more accurately reflects the impact of transport systems on residents' travel choices, as well as the differences in job accessibility in different locations.

In the actual calculation process, we defined four distinct travelling time thresholds, "0–20 min", "20–40 min", "40–60 min", and "60 min<", to count the number of jobs in the area under various travelling time thresholds.

When determining accessibility in terms of travel costs, if the transport mode is public, the travel cost is estimated by Amaps. If the transport mode is a car, the travel cost is calculated by multiplying the actual mileage driven by fuel consumption (or electricity consumption) per 100 km. The depreciation cost of the car must be included to the travel expenses as those who choose car transport must purchase their own car tools.

According to Chinese data [58], fuel vehicles account for 97.46% and electric vehicles account for 2.54% of the market share. The fuel consumption of fuel vehicles is 5.5 to

11.9 L per 100 km, with an average of 8.7 L per 100 km. The mainstream lithium electric vehicles consume 15 kWh per 100 km [59]. The price of gasoline in Chengdu in 2021 is 9070¥ per tonne [60], and the average density of gasoline is 0.72 g/mL, so the price of gasoline is 6.54¥ per L. The price of electricity in Chengdu is 0.8¥ per kWh. According to the above data, the driving cost of fuel vehicles is 0.57¥ per km, and the driving cost of electric vehicles is 0.12¥ per km.

The average selling price of a fuel car in China in 2021 is 154,000¥, whereas the average selling price of an electric car is 226,000¥ [61]. In China, non-operating passenger vehicles reach the end-of-life standard after 600,000 km [62]. According to the mileage depreciation calculation method [63], the depreciation cost of fuel vehicles is 0.25¥ per km, and the depreciation cost of electric vehicles is 0.38¥ per km.

3.3.2. Equity Model

We analyze the accessibility statistics for various transport modes, housing price neighborhoods, and geographic areas to determine whether Chengdu's transport system provides equitable services to different social groups. Firstly, we examine accessibility under various transit scenarios and investigate the disparity in duration and expense between the two transport forms. Secondly, the equity of the distribution of job accessibility in various neighborhoods with varying property prices is characterized by the Gini coefficient. Finally, the Theil index is used to analyze the differences between and within different areas.

The mathematical calculation of the Gini coefficient relies on the construction of the Lorenz curve (Figure 3). The Gini coefficient is the proportion of the total that is unevenly distributed. The value ranges from 0 to 1, with the higher the value, the greater the proportion of the total that is unevenly distributed. According to Lucas's methodology, the blue horizontal axis in Figure 3 can represent the cumulative share of work, and the blue vertical axis can represent the cumulative share of accessibility, when the Gini coefficient evaluates transport equity. Based on a model proposed by Rasche [64], the intersection of the function y = −x + 1 with the Lorenz curve yields the intersection point, which has a coordinate value that can reflect the practical significance of the two occupancy ratios. In this article, the Gini coefficient is a measure of the fairness of time accessibility in different regions, different modes of transportation, and different time thresholds. In other words, the fairer a state is, the lower the Gini coefficient, which indicates the amount of uneven distribution in time accessibility. The Gini coefficient is calculated as follows:

$$X_\alpha = X_{\alpha-1} + P_\alpha, \tag{10}$$

$$Y_\alpha = Y_{\alpha-1} + W_\alpha, \tag{11}$$

$$G = 1 - 2\sum_{\alpha=1}^{375} (X_\alpha - X_{\alpha-1})(Y_\alpha + Y_{\alpha-1}), \tag{12}$$

where G is the Gini coefficient of the whole (i.e., Chengdu); P_α is the proportion of the number of jobs in traffic unit α to the number of jobs in the whole (i.e., Chengdu); W_α is the percentage of the requested indicators in traffic unit α to the requested indicators in the whole (i.e., Chengdu) (such as different transport modes, different housing price communities); X_α is the cumulative percentage of the number of jobs in traffic unit α (ranking all traffic units in order of "W/P" from smallest to largest); and Y_α is the cumulative percentage of requested indicators in traffic unit α (ranking all traffic units in order of "W/P" from smallest to largest). The number of traffic units α in Chengdu is 375.

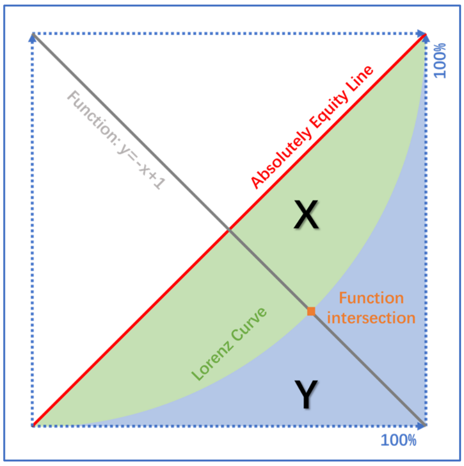


Figure 3. Relationship between Gini coefficient and Lorenz curve.

Plotting the Lorenz curve involves creating an uninterrupted, continuous curve with X_α and Y_α points. The closer the Lorenz curve is to the red line, which symbolizes absolute equity, the closer the ratio is to zero.

The Theil index has good decomposability, which can decompose the overall inequality. It can break down overall differences into between differences and internal differences, and reflect the degree to which the equity of between-resource and internal-resource allocation affects overall equity by calculating the contribution rate. The smaller the value of the Theil index, the better the equity [65]. The Theil Index for each region in this paper reflects the level of inequality in each region, and the Theil Index for each region is further divided into the internal-regional and between-regional Theil Index. The internal-regional Thiel Index indicates the degree of inequality in job accessibility among subdivisions within a region, and the between-regional Thiel Index indicates the degree of inequality in job accessibility between regions. The formula for calculating the Theil index is as follows:

$$T_{total} = T_{between} + T_{internal}, \tag{13}$$

$$T_{between} = \sum_{\beta=1}^{M}\left(A_\beta log\frac{A_\beta}{P_\beta}\right), \tag{14}$$

$$T_{internal} = \sum_{\beta=1}^{M} A_\beta\left(\sum_{\alpha=1}^{N} A_{\beta\alpha} log\frac{A_{\beta\alpha}}{P_{\beta\alpha}}\right), \tag{15}$$

$$D_{between} = \frac{T_{between}}{T_{total}}, \tag{16}$$

$$D_{internal} = \frac{T_{internal}}{T_{total}}, \tag{17}$$

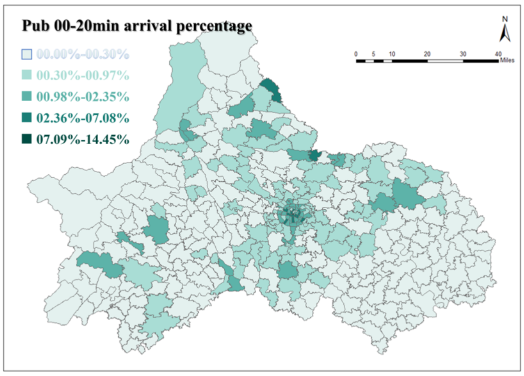
where γ is any area of Chengdu; T_{total} is the overall difference in accessibility of area γ; $T_{between}$ is the difference in accessibility between area γ and other areas; $T_{internal}$ is the differences in accessibility within area γ; β is any administrative district in area γ; A_β is the accessibility of district β as a proportion of the accessibility of area γ; P_β is the number of jobs in district β as a proportion of the number of jobs in area γ; α is any traffic unit in district β; $A_{\beta\alpha}$ is the accessibility of traffic unit α as a proportion of the accessibility of district β; $P_{\beta\alpha}$ is the number of jobs in traffic unit α as a proportion of the number of jobs in district β; M represents the number of districts β in area γ; N represents the number of traffic units α in district β; $D_{between}$ is the contribution rate of difference between area; and $D_{internal}$ is the contribution rate of differences within area.

4. Results and Analysis

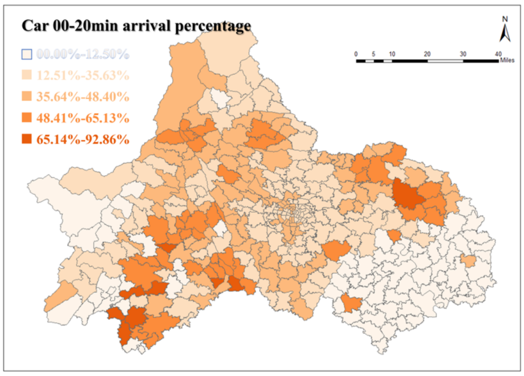
4.1. Job Accessibility Evaluation Results

4.1.1. Time Accessibility Analysis

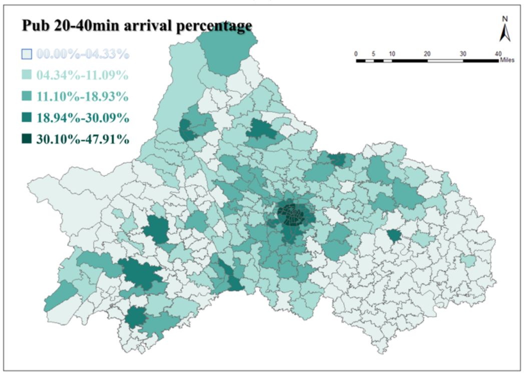
In terms of spatial distribution, there are obvious differences in the job accessibility of each traffic unit within different time thresholds. The time accessibility of public transport in Chengdu shows a clear radioactive structure (Figure 4a–d), meaning that as the time threshold increases, the time accessible public transport area expands outward from the center region along the bypass ring road. For the central region of Chengdu, 33.86–51.79% of jobs can be reached within 40–60 min by public transport. This implies that the central region and its surrounding areas have strong time accessibility by public transport, not only related to the good level of public transport facilities, but also because the central region is a relatively concentrated and large employment center. The jobs on the metropolitan periphery that take more than 60 min to get to by public transport make up at least 87.04 percent of all jobs in the area. The time accessibility of public transport is significantly lower in the Chengdu periphery due to worse public transport infrastructure and fewer job options.



(**a**)



(**e**)



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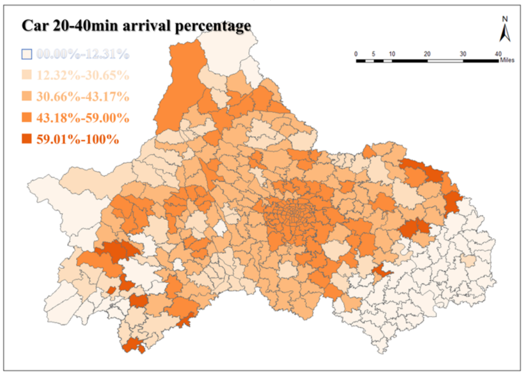

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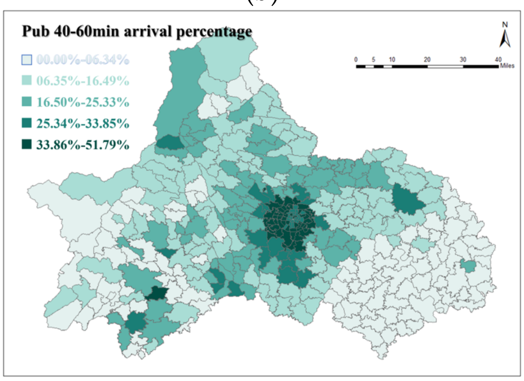
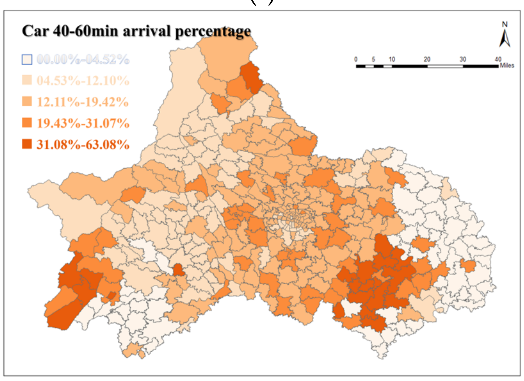
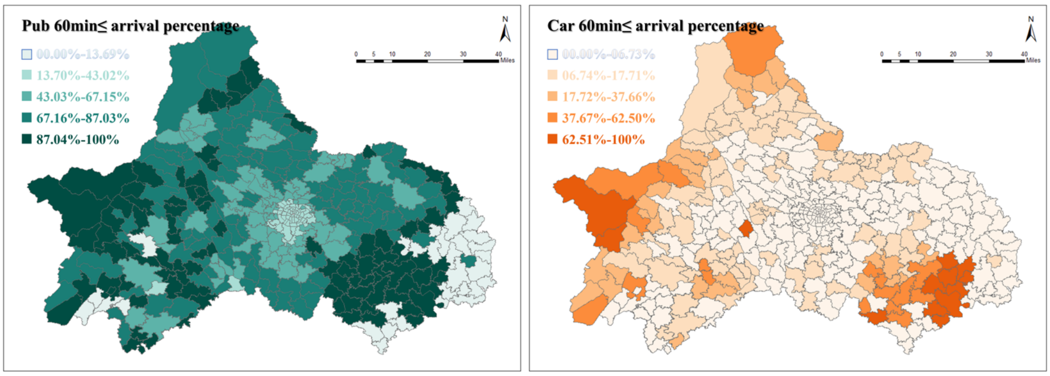


(**c**)



(**g**)

Figure 4. *Cont.*



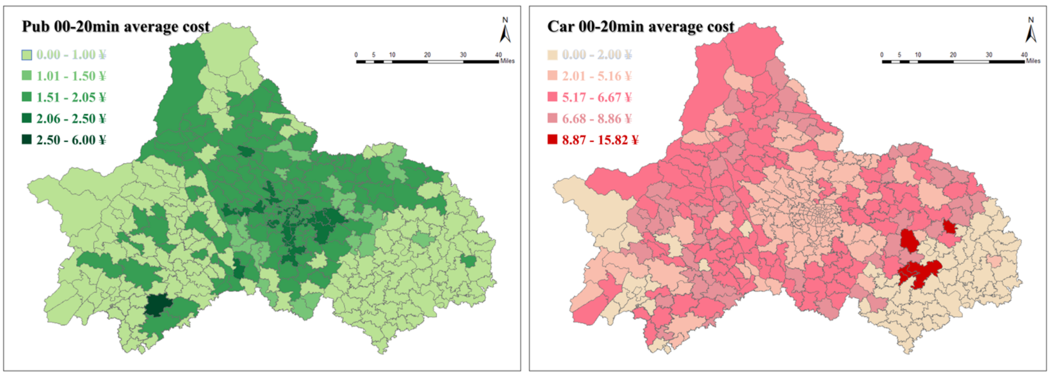
(**d**) (**h**)

Figure 4. Time accessibility under different transport modes and time thresholds: (**a**) Pub 00–20 min arrival percentage; (**b**) Pub 20–40 min arrival percentage; (**c**) Pub 40–60 min arrival percentage; (**d**) Pub 60 min < arrival percentage; (**e**) Car 00–20 min arrival percentage; (**f**) Car 20–40 min arrival percentage; (**g**) Car 40–60 min arrival percentage; (**h**) Car 60 min< arrival percentage.

Within the 20–40 min threshold, the good time accessibility area of car transport is mainly in the central area. As the time threshold increases, the time accessibility of car transport becomes higher at the edge of the town, meaning cars gradually move from the central region to congregate at the edge (Figure 4e,f). It is inferred that this is due to the fact that traffic congestion is worse in the central area during the morning peak period, and car is not an optimal choice relative to public transport. Therefore, if residents in the core urban region decide to drive, the trip takes longer, which leads to poor time accessibility. Meanwhile, residents of the periphery need to commute across the city for work, which increases the likelihood of using cars, improving the area's time accessibility of car transport.

4.1.2. Cost Accessibility Analysis

We analyzed the average cost of travelling by different transport modes (Figure 5a–d). The cost of travelling in the central urban area is higher than the peripheral urban area for public transport with a time threshold of 0–60 min (excluding a very few traffic units where the average cost shows anomalies, which are suspected to be differences in the public transport routes of the traffic unit). Only for time thresholds greater than 60 min are public transport costs higher in the fringe urban areas of Chengdu than in the central urban areas. It is assumed that there are fewer public transport routes in the marginal urban areas, and people can only choose further public transport routes, resulting in higher transport costs.



(**a**) (**e**)

Figure 5. *Cont.*

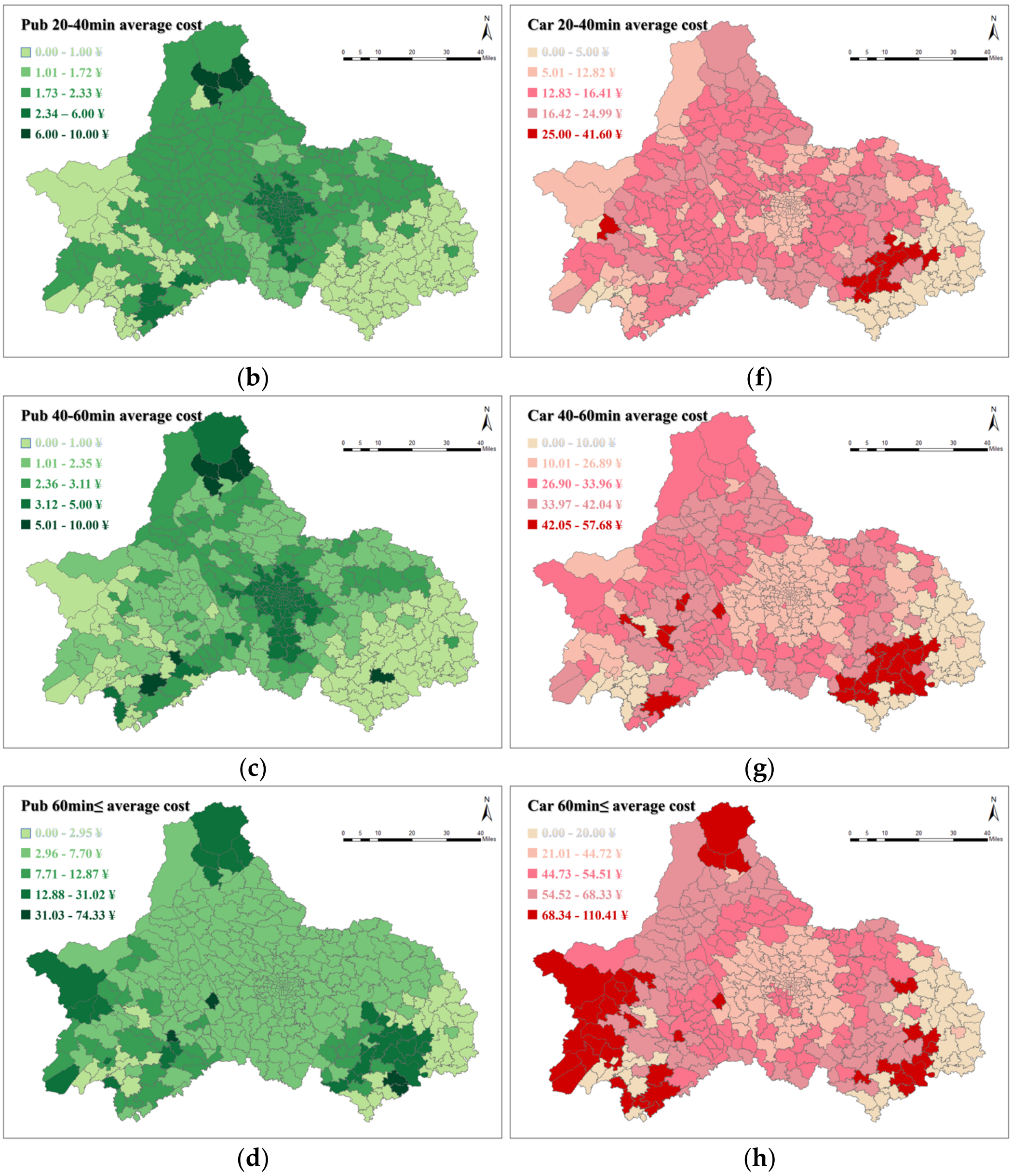


Figure 5. Cost accessibility under different transport modes and time thresholds: (**a**) Pub 00–20 min average cost; (**b**) Pub 20–40 min average cost; (**c**) Pub 40–60 min average cost; (**d**) Pub 60 min< average cost; (**e**) Car 00–20 min average cost; (**f**) Car 20–40 min average cost; (**g**) Car 40–60 min average cost; (**h**) Car 60 min < average cost.

However, the spatial distribution of travel cost of car transport is opposite to that of travel cost of public transport, meaning that the travel cost of car transport is higher in the outer urban areas than in the central urban areas at any given time threshold. Presumably, this is due to the fact that people live in peripheral residential areas and need to commute to work that is relatively close to the interior. It is clear from Figure 5e that the more work is geographically located in the peripheral area, the higher the proportion of car traffic traveling more than 60 min, and therefore the higher the average cost. This is also consistent with the circular radial Chengdu road network layout.

4.2. Job Equity Evaluation Results

4.2.1. Transport Equity Analysis

We compared the average time and average cost under the two modes of transport (Figure 6). The time disparity between public transport and car transport gets larger as the town center expands in all directions (except for a few areas on the eastern edge of the town where jobs could not be counted). The ratio of public transport costs to car transport costs in the central region ranges from 0.14–0.19, falling to 0.06–0.13 as the central region spreads outwards, but varies more on the fringes of the town. It is assumed that this is due to faster growth in car transport costs relative to public transport costs in the central region, where car use is relatively more frequent.

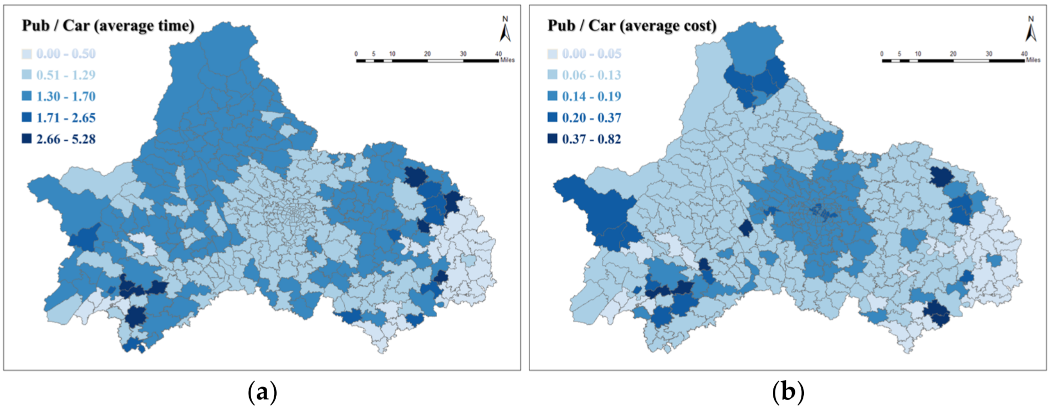


Figure 6. Different transport mode ratios of average time and average cost: (**a**) ratio of Pub average time to Car average time; (**b**) ratio of Pub average cost to Car average cost.

When we relate the average time to the average cost in each traffic unit (Figure 7), we can see that the time cost enrichment areas are significantly different for different transport modes. In the case of public transport, the traffic unit's distribution of the average time and average cost is relatively concentrated, with scatters clustered in a circle with a core of 3¥ and 55 min. On the other hand, in the case of car transport, the overall distribution is similar to a linear distribution, with scatters clustered in long strips in the region of 18–36¥ average cost and 40 min average time.

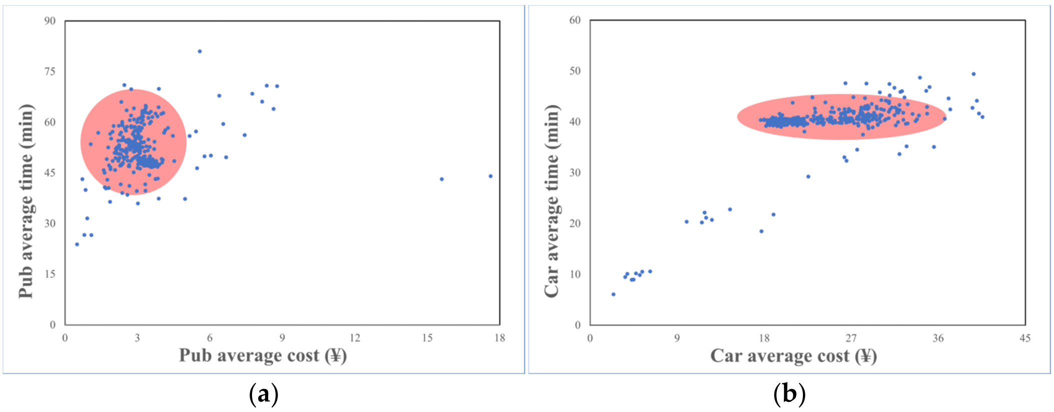


Figure 7. The relationship between time and cost under different transport modes: (**a**) scatter plots of Pub average time and Pub average cost; (**b**) scatter plots of Car average time and Car average cost.

We computed the Gini coefficient of time accessibility for public transport and car transport under different time thresholds. According to the calculation results (Table 2), the Gini coefficient of time accessibility for public transport under the 0–20 min time threshold is the largest (0.467). The Gini coefficient of car transport is generally lower than that of public transport, which means that the time accessibility of car transport is more equitably distributed than that of public transport. For instance, the junction point of car transport is (0.615, 0.385) while that of public transport is (0.558, 0.442) when the time threshold is more than 60 min. This indicates that 61.53% of people who drive can access 38.31% of jobs and 55.79% of those who use public transport can access 44.16% of jobs.

Table 2. Gini coefficients for different transport equity.

	Transport Modes	00–20 min	20–40 min	40–60 min	60 min≤
Gini coefficient	Pub	0.467	0.296	0.189	0.167
	Car	0.123	0.113	0.165	0.324
Intersection point	Pub	(0.674, 0.326)	(0.606, 0.394)	(0.564, 0.436)	(0.558, 0.442)
	Car	(0.541, 0.459)	(0.537, 0.463)	(0.557, 0.443)	(0.615, 0.385)

As shown in Figure 8, the time accessibility of car transport is more equitable than that of public transport in most cases, except for cases where the time threshold exceeds 60 min. With increase of time threshold, the Gini coefficient of public transport gradually decreases, meaning that the time accessibility of public transport becomes more equitable. In contrast, the equity of car transport changes with different trends at different time thresholds. For instance, the Gini coefficient of car transport decreases from 0.123 to 0.113 when the time threshold increases from 00–20 min to 20–40 min. On the other hand, the Gini coefficient of car transport increases from 0.113 to 0.165 when the time threshold increases from 20–40 min to 40–60 min.

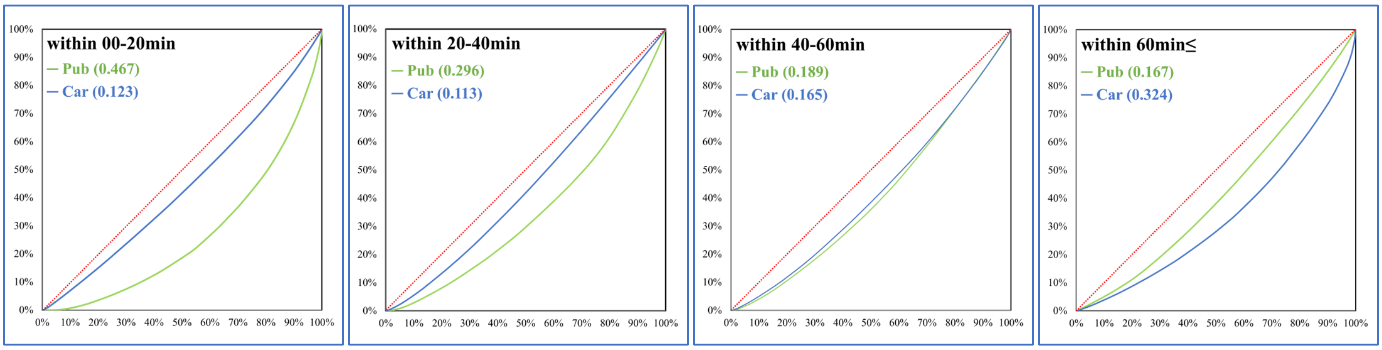
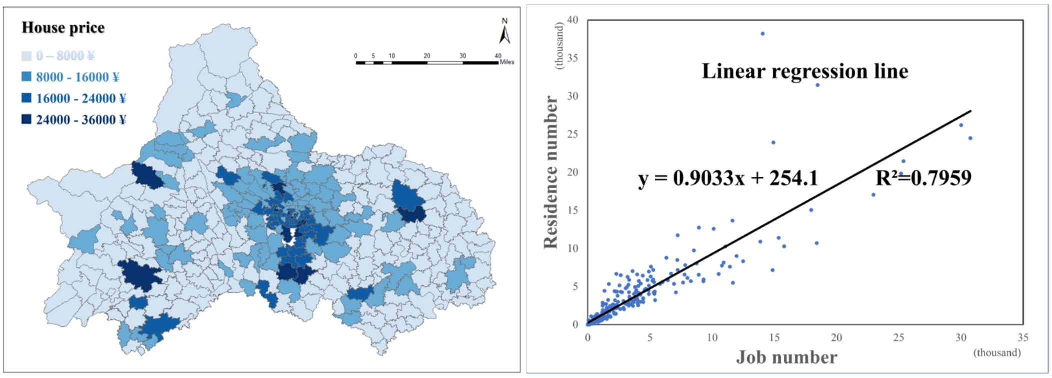


Figure 8. Lorenz curve of transport equity in different conditions: (**a**) 00–20 min threshold by Pub and Car; (**b**) 20–40 min threshold by Pub and Car; (**c**) 40–60 min threshold by Pub and Car; (**d**) 60 min< threshold by Pub and Car.

4.2.2. Economic Fairness Analysis

From the Chain Home website, one of the most popular real estate selling platforms in China, we retrieved the houses prices in various areas of Chengdu, and then obtained the latitude and longitude coordinates corresponding to each point through the Amap API. Due to the limitation of online house buying and selling on the website, we used the average house price within the traffic unit to reflect the house price level of the traffic unit (Figure 9a). Based on the range of housing prices in Chengdu, four categories of neighborhoods were identified: low-price (0–8000¥), middle-price (8000–16,000¥), high-price (16,000–24,000¥), and expensive-price (>24,000¥).



(**a**) (**b**)

Figure 9. The relationship between number of jobs, number of residences, and house prices: (**a**) house prices in different traffic units; (**b**) scatter plots of number of jobs and number of residences.

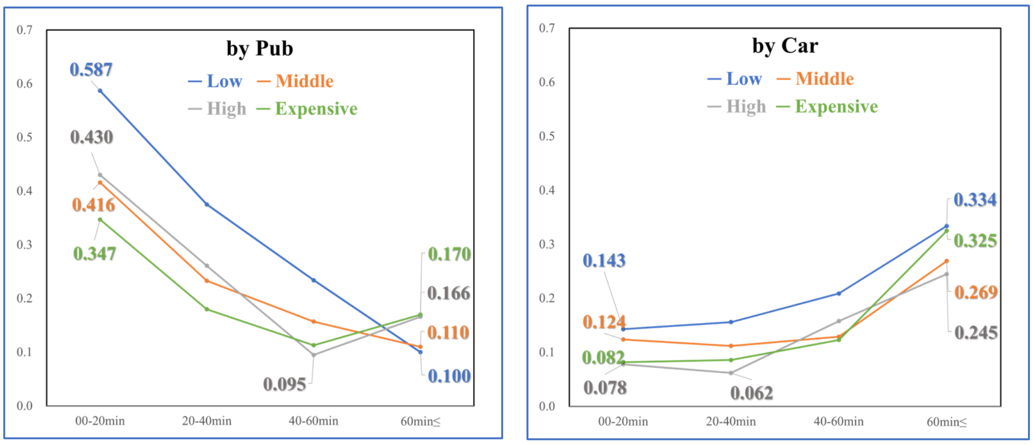
A general linear increasing tendency can be seen in the distribution of the connection between the number of jobs and the number of settlements (Figure 9b). Considering that some areas are undeveloped land, such as forests, snow-capped mountains, and other natural scenic areas, it is difficult to count jobs or residential numbers, so that the data produce strange values.

Comparing the Gini coefficient for neighborhoods with different house prices (Table 3), we find that as house prices rise, the higher priced areas are more equitable overall. For instance, when comparing longitudinally within the time threshold of 00–20 min, the Gini coefficient of time accessibility decreases as house prices increase, whether by public transport or car. Simultaneously, when the time threshold rises, there is an opposite shift in equity across neighborhoods with varying housing prices for various transport modes. Asis visualized in Figure 10, the Gini coefficients of different house price communities by public transport show an overall decreasing trend with increasing time thresholds, while the Gini coefficients of different house price communities by car transport show an overall increasing trend. We speculate that this is because as the house price rises, high-price areas have stronger economies and better distribution of public transport facilities, so the time accessibility of public transport is more equitable. And high-price neighborhoods are located either in the heart of the city or far away from the city center (suburban villas), both of which make car transport more time consuming. For example, the city center is challenging to park in and the roads are often congested, while suburban areas are so far away as to increase the time spent traveling. Consequently, as the time threshold is gradually increased, the equity of time accessibility of car transport becomes worse, with particularly significant changes in expensive-price areas.

As the time threshold increases, the equity gap between different house price areas of public transport gradually narrows, and the equity of car transport gradually becomes worse (Figure 11). We speculate that the shorter the time threshold, the more obvious the advantages and disadvantages of public transport facilities distribution. This is because a long time threshold allows residents to reach their destinations by switching public transport routes even if there is no direct public transport to the destination. The short time threshold has higher requirements on the density of public transport facilities and operating routes, so it better reflects the equity of public transport facilities in the area. On the other hand, car transport has a progressively larger difference because of the longer time and longer distance.

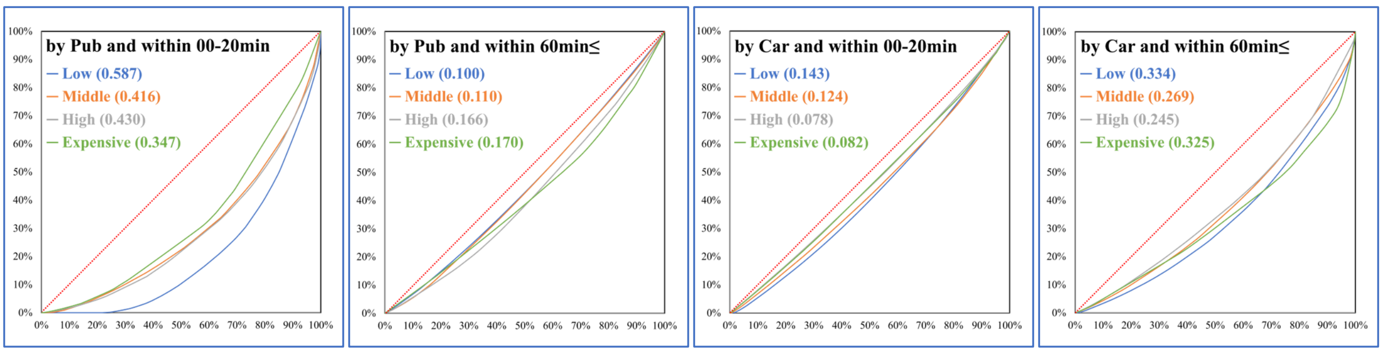
Table 3. Gini coefficients for different housing price communities.

	Transport Modes	Housing Prices	00–20 min	20–40 min	40–60 min	60 min≤
Gini coefficient	Pub	Low	0.587	0.375	0.234	0.100
		Middle	0.416	0.233	0.157	0.110
		High	0.430	0.261	0.095	0.166
		Expensive	0.347	0.180	0.113	0.170
	Car	Low	0.143	0.156	0.209	0.334
		Middle	0.124	0.112	0.129	0.269
		High	0.078	0.062	0.158	0.245
		Expensive	0.082	0.086	0.123	0.325
Intersection point	Pub	Low	(0.714, 0.286)	(0.630, 0.370)	(0.574, 0.426)	(0.535, 0.465)
		Middle	(0.651, 0.349)	(0.577, 0.423)	(0.546, 0.454)	(0.539, 0.461)
		High	(0.661, 0.339)	(0.597, 0.403)	(0.536, 0.464)	(0.558, 0.442)
		Expensive	(0.634, 0.366)	(0.557, 0.443)	(0.537, 0.463)	(0.562, 0.438)
	Car	Low	(0.550, 0.450)	(0.554, 0.446)	(0.571, 0.429)	(0.624, 0.376)
		Middle	(0.543, 0.457)	(0.541, 0.459)	(0.550, 0.460)	(0.590, 0.410)
		High	(0.527, 0.473)	(0.527, 0.473)	(0.553, 0.447)	(0.591, 0.419)
		Expensive	(0.526, 0.474)	(0.528, 0.472)	(0.539, 0.461)	(0.612, 0.388)



(**a**) (**b**)

Figure 10. The relationship of Gini coefficients for different housing price communities: (**a**) line chart of Gini coefficients for different housing price communities by Pub; (**b**) line chart of Gini coefficients for different housing price communities by Car.



(**a**) (**b**) (**c**) (**d**)

Figure 11. Lorenz curve of housing price communities in different conditions: (**a**) 00–20 min threshold by Pub; (**b**) 60 min< threshold by Pub; (**c**) 00–20 min threshold by Car; (**d**) 60 min< threshold by Car.

4.2.3. Area Equity Analysis

According to the Chengdu City Master Plan (2016–2035) (Figure 2), the five areas to be discussed are the Central Area, the Northern Area, the Western Area, the Southern New Area, and the Eastern New Area. The Theil index of different regions was calculated separately, and the results are shown in Table 4. We discovered that for both public and car transport, the order of the Theil index values for each planning area in Chengdu is Central Area < Northern Area < Southern New Area < Western Area < Eastern New Area, in descending order.

Table 4. Theil index values for different areas.

Area	Pub			Car		
	$T_{between}$	$T_{internal}$	T_{total}	$T_{between}$	$T_{internal}$	T_{total}
Central Area	0.006	0.130	0.136	0.006	0.112	0.118
Northern Area	0.002	0.162	0.164	0.002	0.182	0.184
Southern New Area	0.024	0.360	0.384	0.018	0.290	0.308
Western Area	0.129	0.330	0.459	0.139	0.222	0.361
Eastern New Area	0.167	0.500	0.667	0.187	0.349	0.536

We discovered that the more a location geographically borders neighboring cities, the larger the Thiel index value is (Figure 12). The Central Area, which is located in the center of Chengdu and surrounded by other areas of Chengdu, has the smallest Theil index value. The Western Area and the Eastern New Area have the longest borders with other cities and have the largest Theil index values. Conversely, the Northern Area and Southern New Area share fewer boundaries and have lower Thiel index values. We speculate that this is due to the fact that Chengdu's commuters tend to congregate in the center, so the central region already has a more developed transport infrastructure and better equity. The suburban border regions may be too closely connected to external cities to determine the destination of a trip in the statistics within Chengdu city, leading to errors in the calculation of accessibility, which in turn affects equity.

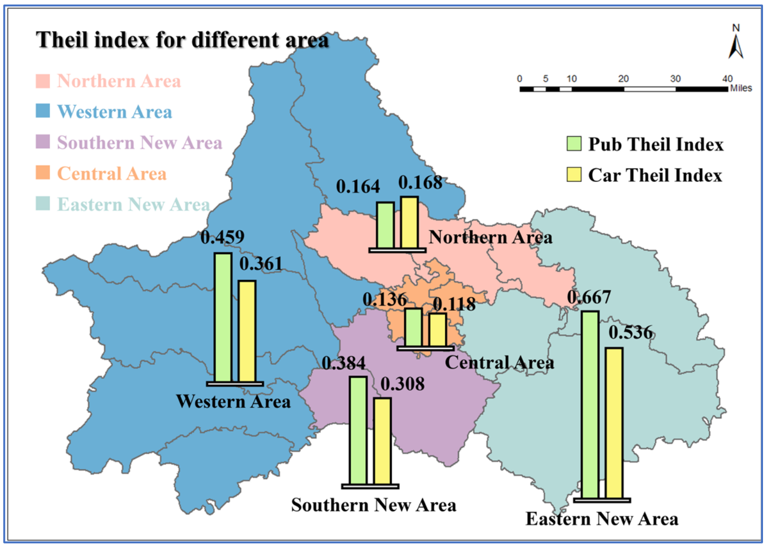


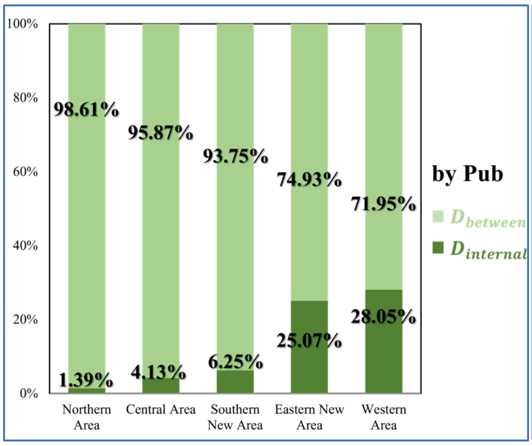
Figure 12. Theil index for different areas by different transport modes.

Table 5 shows our calculations of the contribution of the Theil index to job accessibility by different transport modes. All of the between-area Theil index values are greater than the internal-area Theil index values, suggesting that the imbalance in transport development is mainly within each area.

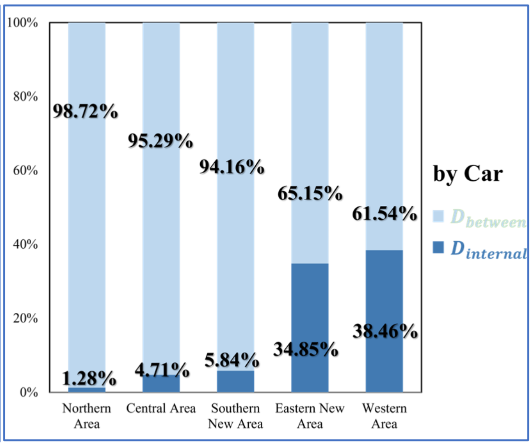
Table 5. Difference contribution rate of Theil index for different areas.

Area	Pub		Car	
	$D_{between}$	$D_{internal}$	$D_{between}$	$D_{internal}$
Northern Area	1.39%	98.61%	1.28%	98.72%
Central Area	4.13%	95.87%	4.71%	95.29%
Southern New Area	6.25%	93.75%	5.84%	94.16%
Eastern New Area	25.07%	74.93%	34.85%	65.15%
Western Area	28.05%	71.95%	38.46%	61.54%

Both public and car transport show an internal-area contribution rate of more than 60% to the overall Theil index (Figure 13). This suggests that accessibility varies significantly within each area. The northern area has a high internal-area contribution rate (98%), indicating that there is very little equality and much unevenness in the distribution of job accessibility among the three administrative districts in the area. We speculate that this is due to the large differences in regional economic development within the Northern Area, with some administrative districts already having relatively well-developed public transport networks, such as metro and light rail. However, other administrative districts in the Northern Region do not even have a metro, resulting in large differences in their time accessibility.



(**a**)



(**b**)

Figure 13. Stacked percentage column chart of Gini contribution rate of Theil index for areas in different conditions: (**a**) Pub; (**b**) Car.

5. Conclusions and Suggestions

This study has analyzed the equity disparities in job accessibility in Chengdu across various transport options, housing prices communities, and geographic areas. Firstly, we determined job accessibility using a new calculating method, separately from the time dimensions and the cost dimensions. We have discussed the percentage of jobs reached by different transport modes, the average cost, and other relevant indicators based on different time thresholds. Secondly, the equity of job accessibility was evaluated in terms of transport, economic, and area dimensions. The average journey time and house price levels under various time thresholds were compared and analyzed using the Gini coefficient and Lorenz curve for various transport modes and property prices. Finally, we calculated the Theil index of the spatial distribution of each area to evaluate the equity of the area. The findings are summarized as follows:

(1) Job accessibility by car transport is superior to public transport in the 00–60 min period. According to the calculation results of the Gini coefficient, only under the time threshold of 60 min is the Gini coefficient of the car larger than that of public transport. This may be because cars can reach most areas within 00–60 min, while public

transport can reach fewer areas within this time threshold, so the job accessibility of car transport is fairer at this time. However, public transport can reach most areas if the time barrier is less than 60 min. At this time, public transport is more equitable in terms of cost, so the job accessibility of public transport is more equitable. The time accessibility and cost accessibility of public transport show a clear central radioactive structure. This indicates that there are clear regional disparities in the development of public transport infrastructure, with urban public transport resources being better in the center. The cost accessibility of car transport, on the other hand, is opposite to the degree of spatial distribution of public transport, showing spatial characteristics of marginal aggregation.

(2) Public transport is more equitable for commuters than car transport. As the time threshold rises, the Gini coefficient for car transport increases while the Gini coefficient for public transport decreases, indicating that the layout of public transport lines in Chengdu is reasonable. In terms of different housing prices, the higher the house price, the smaller the Gini coefficient and the fairer the two modes of travelling. In other words, a higher housing price corresponds to a stronger economic standing and better road and public transport systems.

(3) Comparing the Theil index values of different planning areas in Chengdu, the Theil index values of the peripheral urban areas are higher than those of the central urban areas. For instance, the Theil index for public transport in the Central Area is 0.136, while the corresponding Theil index in the Eastern New Area is 0.667. The Theil index of areas with longer borders with neighboring cities is higher, indicating that area equity may be affected by surrounding cities, such as the influence of transport infrastructure jointly built with neighboring cities. The sources of variation in the Theil index values show that the contribution of both transport modes to internal-area variance is significantly greater than that of between-area variation, and that the Theil index for public transport is higher than that of car transport. This implies that inequalities exist mainly within planning areas and that public transport services are more variable in different areas than road infrastructure.

According to the above conclusions, some specific suggestions are put forward. Firstly, the distribution of public resources must better reflect the real requirements of the populace. For instance, even if the total amount of public transport resources is sufficient, if the distribution is uneven or far away from residential areas, some residents will not be able to make use of convenient services. Secondly, according to the results, the Gini coefficient of public transport in areas with lower housing prices is higher. Therefore, for regions inhabited by low-income groups (that is, areas with low housing prices), the fare system of public transport should take into account the affordability of low-income groups and reduce their travel costs by providing fare discounts and other means. Lastly, in order to achieve sustainable development based on the principle of guaranteeing equity, the government and businesses should collaborate to lower operating expenses by optimizing operational models and enhancing operational efficiency.

The authors acknowledge some limitations of this study. For example, the job numbers derived from mobile phone signaling data are not comprehensive enough. We included OD points where both the workplace and residence were within Chengdu, meaning cross-border commuters in the fringe urban areas were not taken into account. Meanwhile, the data treatment of housing prices is not comprehensive enough, in part because only second-hand rental houses were counted, meaning new houses were not counted; on the other hand, there is no information on the listings of self-built houses in many rural areas because they are not listed on the website for sale, and thus could not be counted. In addition, according to Wan's [66] analysis of differences in fairness between Chinese and Western cultural backgrounds, the case of Chengdu, as a typical inland city in China, may not apply to countries or regions with significantly different characteristics.

For possible future work and new challenges, we propose the following three possibilities. Firstly, the theoretical research on public transport fairness should be deepened.

According to the improved structural equation model (SEM) proposed by Zhu [67], the elements that influence accessibility and transport equity may be examined. Combined with the research results of this paper, we can further analyze the needs, satisfaction, and obstacles of different social groups (such as low-income groups, the elderly, the disabled, etc.) in terms of public transport services, and how these groups are affected by changes in public transport policies and services. Secondly, the quality of public transport services should be evaluated and improved. Although it is difficult with current technology, it is necessary to establish a set of scientific, comprehensive, and operational public transport service quality evaluation systems that can reflect the needs and satisfaction of different social groups. Thirdly, based on the actual situation of Chengdu, sustainable development should be emphasized in public transport research. Researchers should discuss how to reduce the impact of public transport on the environment by promoting new energy-efficient buses, optimizing the layout of public transport networks, reducing traffic congestion and emissions, etc.

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Conflicts of Interest: None of the authors have a conflict of interest to declare.

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