

## Article

# How Diversity and Accessibility Affect Street Vitality in Historic Districts?

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**Abstract:** The loss of traditional features and place memory, and ultimately vibrancy in historic districts, has attracted substantial attention in today's urban design. Most conventional theories are of the consensus that diversity and accessibility characteristics play important roles in creating street vitality, whereas how these characteristics influence street vitality in historic districts has not been thoroughly explored. Furthermore, it is less clear as to which characteristics exert greater influence. Taking the Drum Tower Muslim District, a historical neighborhood in Xi'an, China, as a case study, this paper employs geospatial data to examine how diversity and accessibility influence street vitality. This study identifies seven factors of diversity and accessibility, and incorporates them into a spatial multivariate regression model for analysis. The results indicate that accessibility makes a stronger impact on the street vitality than diversity does. Furthermore, the closeness of streets, the functional density, the intersection density, the location of public transportation and the density of public infrastructure are the top five factors influencing street vitality. The outcome of this study will shed light on what constitutes a vibrant historic district and will help to inform us as to where and how we can improve street vitality.

**Keywords:** street vitality; diversity; accessibility; historic districts

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## 1. Introduction

Urban regeneration in historic districts has been undergoing a process of reconsideration in the last few decades [1,2]. In this process, physical environments (e.g., buildings, monuments and landscapes) and socio-cultural environments (e.g., indigenous lifestyles and collective memories) of the historic district are more or less changed, redefined, or destroyed, which ultimately leads to the decaying of street vitality [3]. Given this background, focusing on sustainability, livability and vitality has become a new paradigm with regard to historic districts' regeneration [4]. As the *Green Paper on the Urban Environment* claims, vitality should be a fundamental factor for achieving the high-quality living environment rather than a luxury. In today's studies, effectively enhancing the quality of urban life and developing vibrant urban communities through better street vitality is always a main focus of research [5]. Although there have been some efforts to improve street functionality and forms in historic districts, the spatial quality is still problematic and cannot fully meet the needs of residents and tourists [6]. Therefore, investigating the vitality of streets in urban historic districts during the transitions of urban renovation and redevelopment is crucial for today's urban studies [7].

The discussions on street vitality can be traced back to conventional theories of urban design, which indicate that diversity and accessibility have significant effects on the creation of vibrancy in urban spaces [8]. Jane Jacobs first introduced the concept of vitality into the field of urban design, stating that the vitality of a street depends on the 'diversity' of activities and functions [9]. Montgomery defined street vitality as an active street life, which can be described by the flow of people, the use of facilities, and the number of cultural

activities on the street, emphasizing that the mix and diversity of functions are key elements in determining street vitality [10]. Bentley described vitality as the degree to which the space accommodates diverse functions [11]. Lynch proposed that vibrant space is generated by appropriate diversity and the ability to provide obvious access [12]. Gehl noted that public space vitality is derived from pedestrian oriented streets and a high level of accessibility [13]. Hillier stated that spatial configuration is highly relevant to human activities and urban commercial agglomeration [14,15], and that street vitality can be explained by the accessibility properties of a street [16]. In summary, diversity and accessibility have been highlighted as important physical underpinnings of street vitality [17].

Nevertheless, today's cities have made tremendous changes since the era when those principles were introduced. Technologies are constantly leading to changes in human lifestyles, which directly affects the use of public spaces. New means of transportation are reshaping the physical forms of cities, creating new symbols and landmarks. The measures and restrictions of the COVID-19 global pandemic are redefining the way people interact with each other. Therefore, there is a strong need to examine to what extent those principles are still suitable for today's streets and cities. In recent years, some studies based on those principles have started to examine the impacts of the built environment on street vitality integrated with quantitative analysis. The effect of diversity and accessibility on street vitality remains a major area of urban studies. However, most of the existing research primarily focuses on large-scale urban spaces, while little attention is placed in historical districts within city centers.

This study focuses on two research questions: (1) What are the temporal and spatial characteristics of street vitality in historical districts? and (2) How do diversity and accessibility affect street vitality in a historic district? To answer two questions, we measured the spatio-temporal characteristics of street vitality of the historic district Drum Tower Muslim District in Xi'an, China. We then evaluated and compared the influence of diversity and accessibility on street vitality. Finally, the spatial correlations were analyzed, and some implications for urban policy and design were proposed. This study gave a more in-depth interpretation of conventional theories through empirical research in the historical district and revealing associations between diversity, accessibility and street vitality, eventually providing planning strategies to optimize resource allocation and promote sustainable development.

## 2. Literature Review

### 2.1. Definition of Street Vitality

Streets are significant spatial elements of cities: they are the most important public spaces where people spend more time than they do in any other public space. In addition, streets are the main spatial connectors through which people, goods, and services move within and outside of the city [18]. However, with the development of cities as well as their increased traffic flows, there is a shift of streets and roads from being areas of vibrant human activities to serving as means for the efficient movement of vehicles [19,20]. Today's streets tend to facilitate vehicular traffic while pushing pedestrians away, which consequently undermines the quality of public life and street vitality. This phenomenon leads to debates on street vitality in the fields of sociology and urban planning.

Street vitality is difficult to define because of its intangibility. From the perspective of sociologists, who mainly focus on human activities, street vitality can be regarded as a series of socio-economic activities [9,21], while urban designers generally view street vitality as a spatial quality in terms of visual and experiential dimensions [10,22]. For example, Nia highlighted the essence of aesthetic design in public urban spaces by referring to the five main dimensions involved in the shaping of urban vitality [23]. Early explorations of street vitality, such as those by Jacobs and Gehl, are mostly based on behavioral observations and qualitative discussions. Pioneers have induced waves of quantitative measurement of street vitality with various indicators, focusing on either human activities or the built environment. In recent studies, scholars have tended to combine these two aspects and define street vitality as human activities influenced by the built environment [24,25]. For

instance, Ye and Long et al. pointed out that social activities are strongly tied to the physical entities of urban form [17,26,27], and street vitality can be viewed as the presence of people engaged with diverse of activities and the physical environment that caters to the needs of people. We comparatively reviewed the studies, in terms of their main areas of focus, study area and scale, study method and data sources, the indicators they utilized, and then synthesized them in Table 1.

**Table 1.** Literature on street vitality.

Focus	Authors	Year	Study Area and Scale	Study Method/Data	Indicators
human activities	Jacobs, J. [9]	1961	America urban scale	Behavioral observations	The presence of pedestrians in streets
	Gehl, J. [22]	2006	Copenhagen Street scale	Behavioral observations	Number of people passing by/stop/turn head/go in or out/stay Passed Speed
	Sulis et al. [28]	2018	London Urban scale	Smart card Mobile phone Twitter data	Intensity of people Variability of flows Consistency of flows
Both human activities and built environment	Montgomery, J. [10]	1998	UK Urban scale	Qualitative discussions	Pedestrian flows Uptake of facilities Cultural events Mixtures of activities
	Sung et al. [29]	2013	Seoul Street scale	Survey data	The number of pedestrians
	Ye et al. [17]	2018	Shenzhen Street blocks	Dianping life services reviews data	Small catering business
	Kim [30]	2018	Seoul City center	Cell phone data, Bank card transactions, Wi-Fi access points	Social vitality Economic vitality Virtual vitality
	Huang et al. [31]	2019	Shanghai 1-km <sup>2</sup> grids	Sina Weibo data Dianping life services review data Mobile phone GPS data	Social activity intensity Economic intensity Pedestrian density
	Li et al. [32]	2021	Lanzhou Street scale	Baidu Heatmap Data	Temporal characteristics of vitality Spatial distribution characteristics of vitality

Meanwhile, it is worth noting that the concept of street vitality varies greatly in different cultural contexts. In Western countries, street vitality implies that citizens can share the public space equally and safely. In the eastern countries, street vitality can often be associated with prosperous businesses and high-density crowds. Therefore, the discussion of street vitality in this paper is limited to the Eastern context, and the measurement of street vitality will be based on both perspectives: human activities and corresponding objective indicators of the built environment.

## 2.2. Diversity and Accessibility Effects on Street Vitality

With regard to vitality-related issues, Jacobs' theory of diversity simulating vitality cannot be ignored, and it has been regarded as an urban design and planning principle that can be used to address today's urban issues [33]. In the last decade, an increasing number of scholars have developed empirical studies with different methodologies for different contexts based on Jacobs' principle [29]. Most studies have further developed the concept of diversity into urban morphological features, measuring specific proxies, such as functional diversity, density or mixed land use [29,34]. Sung conducted an empirical study to investigate the association of a diverse physical environment with street life in Seoul, using the land use mix index. The result supports Jacobs' claim that street vitality can be maintained by the diversity of the physical environment [29]. Similar findings

can be observed in China, and results indicate that building density and the diversity of street functions are positively correlated with neighborhood vibrancy [35]. Nonetheless, some studies suggest that Jacobs' principles should be revised for today's street vitality studies. For instance, Gómez-Varo and Xavier verified Jacobs' principles in the case of Barcelona [33,36]. However, their result challenges the widely-held assumption that a high level of street vitality is mostly found in city centers, bonding with high population density and mixed uses. According to their findings, urban vitality follows a polycentric pattern, and is associated with everyday facilities and dense networks of local business. In addition, Chang Xia noted that the land-use mixture presented limited or unintended effects on street vitality by examining the relationships between multidimensional urban form and vitality at the street block level [37], while a small group of scholars regard diversity as the dynamic characteristics of crowd activity. Kang et al. categorize the concept of diversity according to three levels: activity, time, and space, using POI Richness, time Simpson and flow Richness as metrics respectively [38], confirming that the above three diversity dimensions are essential components of vitality.

In summary, as is shown in Table 2, the diversity can be measured by different proxies. Although different research conclusions will be drawn in different research contexts, they provide clear evidence with regard to whether Jacobs' views are still suitable for today's cities.

Hence, the present study attempts to describe diversity as the spatial characteristic of the street, taking the function density and mixed-use into consideration. In addition, the amenity density is adopted in this study because the role of amenities, such as education, health and sports, in providing the convenience and quality of urban life is discernible, particularly at the neighborhood level [39].

From the accessibility perspective, accessibility is a specific street network characteristic which can be defined as the ability to reach desired activities, destinations and services [40,41]. The study of accessibility can be regarded as two perspectives: one referring to the supply of public amenities, and another referring to the spatial configuration of the street. Some indicators, such as intersection density, or the distance to a bus, subway station or parking lot, are used to measure the accessibility to the supply of public amenities [26,33,42]. Many studies clearly indicate that accessibility has a positive impact on street vitality. For instance, Long Yin found that the intersection density is the most important factor positively contributing to vitality, and subsequent factors are the access to transit and amenities [26]. However, some studies came to the opposite conclusion that accessibility does not always improve vitality. In the study of waterfront open space, the bus station coverage index, road network density and non-motorized vehicle lane are used as proxies for accessibility, finding that high levels of traffic accessibility may have a negative effect on vitality [43]. Similarly, some authors highlight that the number of inter-circulation systems and traffic accessibility do not always translate to social interaction [44]. In terms of spatial configuration, one of the most commonly used methods has been space syntax, which was initially proposed by Bill Hillier and has been developed in recent studies [45]. It is used to investigate the relationship between street configuration and group activities, providing quantitative evidence for recognizing the dynamic mechanism of street vitality [46]. Employing spatial design network analysis (sDNA), Fang et al. find that the correlation between street network characteristics and vitality is sensitive to different spatial scales, and the connectivity of streets makes the largest contribution to their vitality [47]. Researchers conclude that better accessibility to public amenities and pedestrian-friendly streets can critically enhance street vitality and street network integration, which consequently reshapes the quality of urban life [32,48].

Accordingly, on basis of the discussion above, this study intends to interpret accessibility from the perspective of the supplements of public transportation and the spatial configuration of the street, employing the sDNA as a basic tool.

**Table 2.** Literature on diversity and accessibility effects on street vitality.

Dimension	Study Area and Scale	Variables	Conclusion
diversity	Fifteen megacities in China [37]	Land-use diversity	Land-use mixture and building density presented limited or unintended effects
	Neighborhood scale in Shanghai [31]	Diversity of urban function Diversity of building height Diversity of building age Diversity of house prices	The mixture of urban functions is the most positive generator of vibrancy. Other indicators have slightly or significant associations
	Main urban zone of Xining city in China [49]	Density Richness Simpson index Main land-use types	Density is positively correlated with vitality intensity; Richness and the Simpson index are positively correlated with vitality stability
accessibility	The central city of Wuhan [47]	Connectivity Closeness Betweenness	Connectivity explains the largest amount of the variance in urban vitality, followed by betweenness and closeness
	Main urban area in Wuhan [50]	Bus station density Distance of nearest subway station Road density	Block accessibility exerts a significant impact on enhancing block vitality
	The open space in the core section of the Huangpu River in Shanghai [43]	Bus station coverage index Road network density Non-motorized vehicle lane accessibility	Traffic accessibility showed a negative effect on vitality

### 2.3. Current Trends, Gaps and Our Study

Street vitality has been continuously studied over the past decades. The emergency of multisource big data brings new opportunities and paradigms for urban research [51]. It is possible to quantitatively measure the intangible street vitality from the perspective of human activities and corresponding objective indicators of the built environment. Focusing on human activities, the multisource big data/open data, such as heat map data, small catering business data, social media data and mobile signaling data have been adopted as proxies for street vitality. Hence, the Baidu Heat Map is most commonly used to show the spatio-temporal distribution of the population [42,52]. Meanwhile, advances in urban analytical tools and ArcGIS have provided new ways of describing, quantifying, and presenting the built environment characteristics of streets. Regression models, such as ordinary least squares (OLS) regression and geographically weighted regression (GWR) are used in many studies to accurately reveal the spatial effect of the built environment on street vitality [50,53,54]. For example, Lu et al. used the linear regression model to compare the correlations between the built environment and neighborhood vitality of two cities [55]. Lotfata et al. employed the multiscale GWR model to examine the spatially varying relationships between the socio-environment and physical activity [56].

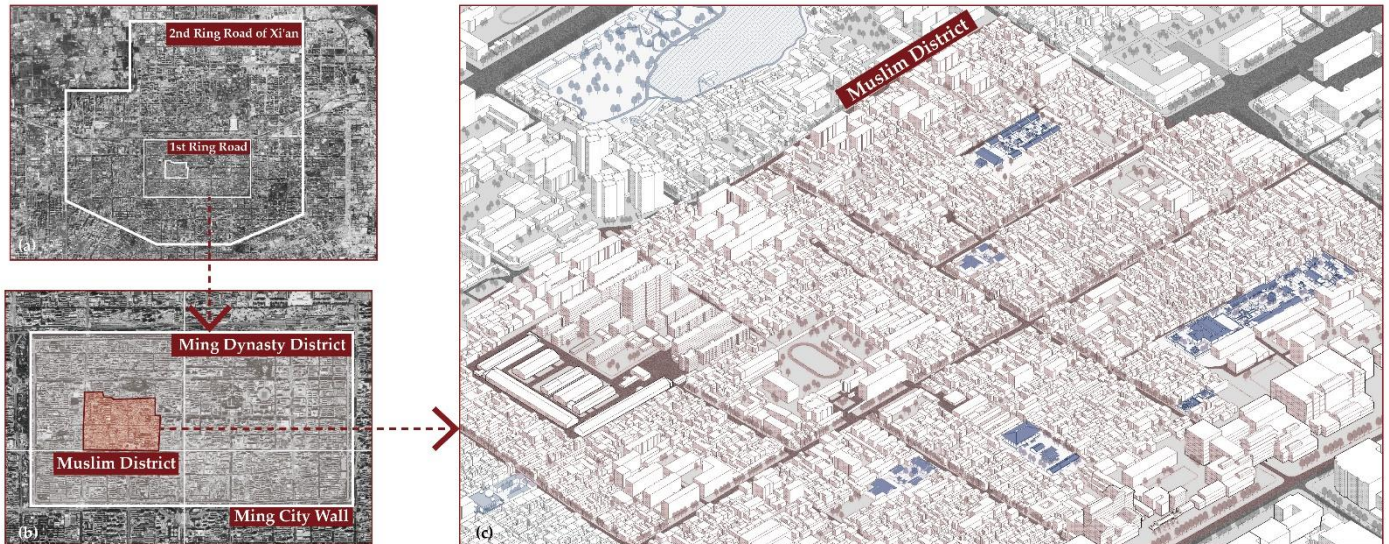
In summary, there is an increasing scholarly interest in applying new data and tools to test urban design theories. Nevertheless, two research gaps exist. First, in spite of the comprehensive and systematic evaluation of built environment features that help with capturing the law of vitality, very few studies have focused on accessibility and diversity dimensions and compared its effect simultaneously. It is still unclear as to what extent diversity and accessibility provide an impetus to street vitality, which is of great significance for urban design practice. Second, we can easily find that existing studies mainly focus on the urban scale from Table 2. Limited investigations have focused on historical districts. Therefore, employing geo-spatial analysis, this paper examines how the diversity and accessibility aspects of urban theories relate to street vitality in a historic district.

## 3. Data and Methods

### 3.1. Study Area

The main site for this study is the Drum Tower Muslim District (DTMD) in Xi'an, China, which has been declared as a historical district since 2002 in “the Conservation Regulations on Xi'an Historic City”. The DTMD is located in the city center of Xi'an (Figure 1a), serving as a commercial and cultural center for both tourists and local residents,

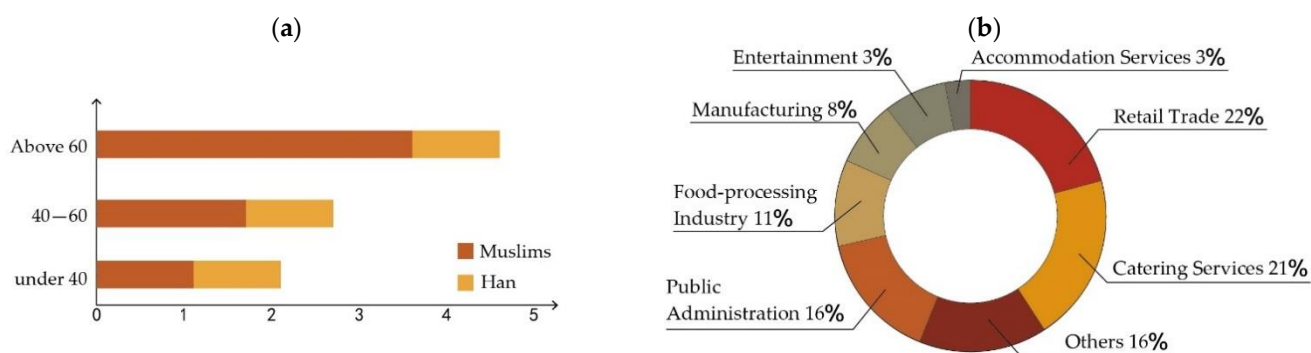
with well-preserved historic urban forms. Located inside the old city wall of Xi'an, this area is also the largest Muslim residential area in Xi'an. Figure 1b illustrates its boundaries in red, with the old city lined in white.



**Figure 1.** Study area (a) the DTMD in Xi'an. (b) the DTMD in the Ming Dynasty District. (c) Perspective of the DTMD.

The size of the DTMD is 1.3 square kilometers, with total population of 69,600 local residents and 20,000 immigrants. Among the local residents, 33,800 are Muslims who used to be the majority of residents until the beginning of the 2000s. With the rise of tourism and commercialization, the local population has become more diverse. The proportion of the Muslim-Han population in different age groups is quite different (Figure 2a). The proportion of the Muslim-Han population over 60 years old is 3.6:1, and the proportion of those between 40–60 years of age and those under 40 years of age is 1.7:1 and 1.1:1, respectively. The portion of the aging population is increasing year by year.

As with most of the Muslim districts in China, the residents in the DTMD follow the typical living pattern known as “spread widely throughout the country, and concentrated in a particular location” [57]. This phenomenon is related to the Muslim religion. Muslims tend to live around mosques, attending worship ceremonies regularly. In addition to religion, the attachment of many Muslims to the DTMD is mainly due to the business opportunities this region can provide. Most local Muslims conduct catering businesses or retailing based on families (Figure 2b). The businesses related to the Muslim religion, such as handicrafts, halal restaurants and ethnic foods, have stimulated the local economy and tourism industry, which boosted the income growth of residents [58].



**Figure 2.** (a) Proportion of Muslims and Han populations in different age groups. (b) Occupation composition of the DTMD residents.

The DTMD is a typical street-oriented community with a high building density. Most buildings are one to three floors tall. The formation of DTMD can be traced back to the Ming and Qing Dynasties. It is characterized by a “small block, dense road network.” As is shown in Figure 1c, the streets and alleys that constitute the Muslim district are densely packed with small businesses, restaurants and residence buildings, laid out with mosques as their public space. The district assembles an abundant collection of cultural heritage, including historical streets, religious temples and traditional dwellings, which are also home to many cultural places, religious temples, and tourist facilities [57].

In the past few decades, Xi’an witnessed massive property-led urban redevelopment practices, while the DTMD has not undergone extensive demolition and renovation, effectively preserving the humanistic ecology and traditional morphology [59]. The DTMD can be regarded as a successful example of how local residents resist top-down regeneration to protect the neighborhood environment from being destroyed, helping it become a vibrant community.

### 3.2. Data

Two sets of spatial data will be used for this study: the first is the point of interest (POI) data from Open Street Map in 2021, including road network and buildings. The second is the Baidu Heat Map from Baidu.com. In the POI dataset, the road network data contains the information of road names, road centerlines, road lengths, road grades, road spatial attributes, and public transportation stations. The building data include the basic information of building outlines, building floor areas and the number of floors. The POI data is “nano-level” urban data, which has high accuracy and comprehensive information [60]. It has three layers of information, including the name, type and location of the format. Multiple field trips to the study area have been made to verify the accuracy of the POI data.

The Baidu Heat Map is a widely-used human-oriented visualization product, presenting real-time population density and distribution with distinguished colors on the map [61]. It is based on the location information obtained by mobile phone users who access Baidu application products, such as search engines, maps, weather information, etc. The access data is calculated by population density and population flow rate, and is eventually reflected on the Baidu Map in different colors. Hence, the value obtained from the Baidu Heat Map only reflects the relative population density according to time and place changes. Thus, this study attempts to adopt the Baidu Heat Map data as a proxy for describing the spatiotemporal characteristics of street vitality in DTMD.

### 3.3. Methodology

The purpose of this study is to examine the association between street vitality and the street spatial features in diversity and accessibility dimensions. This study will identify the quantitative indicators of diversity and accessibility and then will employ the following methods to measure them.

Firstly, the varying characteristics of human activity in both the temporal and spatial characteristics are identified as important indicators of street vitality. The temporal variation of street vitality can be reflected in the time points corresponding to the peaks and troughs of human activity density. The spatial variation of street vitality can be characterized by changes of aggregation scope and intensity of human activities. Secondly, in order to measure the diversity characteristics of street space, we select three indicators (e.g., functional density, mixed-use index and amenity density), which is extracted from the previous work in Section 2.2. In the third step, this study will measure the accessibility characteristics of street space. According to the literature, street vitality is primarily correlated with three indicators: street network configurations, the density of road intersections, and the distance to public transportation. Thus, this study will focus on those three indicators to measure the accessibility characteristics of the street. Finally, a multiple regression model and geographically weighted regression model will be used to explore the comparative analysis to find out their associations with street vitality.

### 3.3.1. Measurement of Street Vitality

The measurement of street vitality is carried out in terms of temporal characteristics (dynamism) and spatial characteristics (aggregation). The dynamics of street vitality describes the continuous change of crowd activities in a day, which includes the peak and trough values of crowd density as well as the rising or falling trend of vitality. The aggregation of street vitality describes the distribution of crowds, reflecting the changes of crowd aggregation in different regions.

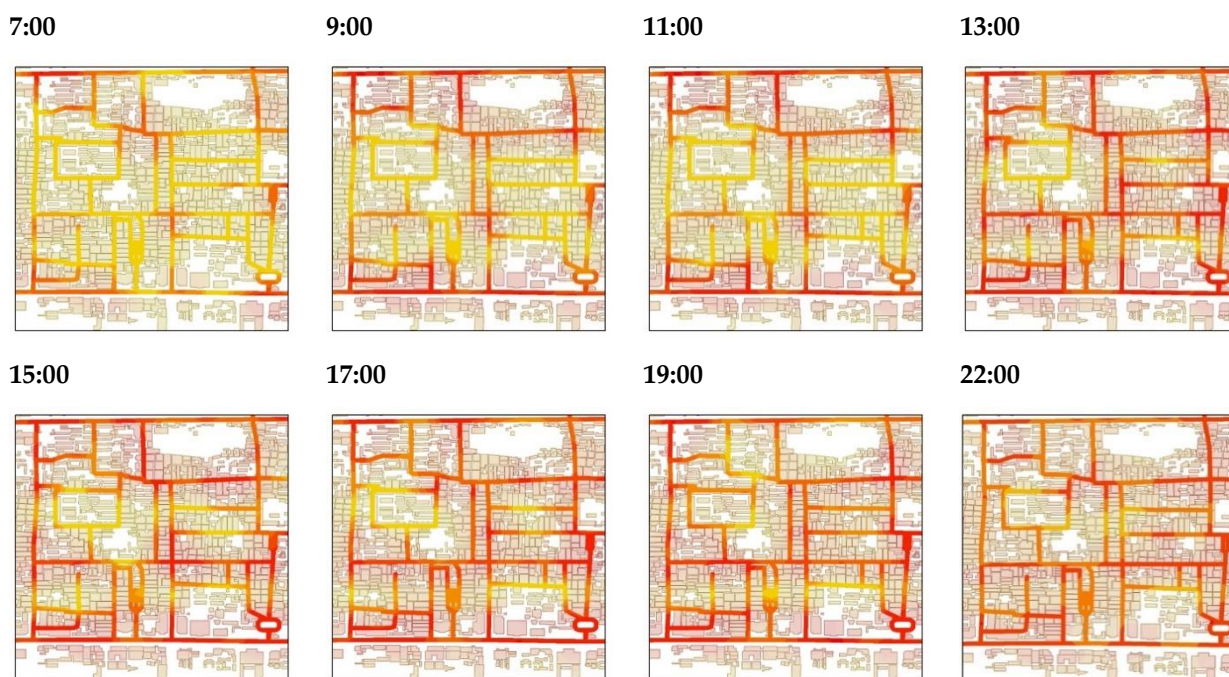
The Baidu Heat Map was employed for measuring street vitality. As crowd activity has a cyclical change pattern, Python is used to obtain the data of study area for one week (9–15 November 2021) from 7 p.m. to 12 a.m., with a time interval of one hour. A total of 126 samples (18 samples per day) have been collected. Since the Baidu Heat Map is produced in the format of raster data and cannot be used directly for quantitative analysis, all of the collected samples have been vectorized and reclassified according to the color range (RGB) in ArcGIS 10.5. The heat values are divided into 1–7 levels as the quantitative values of street vitality for data analysis and visualization.

The dynamics of street vitality are calculated through “Zonal Statistics” in ArcGIS 10.5. The average street vitality value can be quantified as follows: Where  $V_i$  is the average street vitality,  $A_i$  is the vitality of street  $i$  at a given time,  $S_i$  is the area of street  $i$ .  $n = 7:00, 8:00, \dots, 24:00$  (18 time slots).

$$V_i = \frac{\sum_{i=1}^n A_i}{n \times S_i}$$

The aggregation of street vitality can be visualized through the Baidu Heat Map at hourly intervals from 7:00 to 22:00 across the DTMD (Figure 3). The time- and place-based population density change can be tracked by the change of colors, where red represents high density, and yellow represents low density.





**Figure 3.** The sample data of the Baidu Heat Map in the study area.

### 3.3.2. Measurement of Street Diversity and Accessibility

In this study, three indicators of the dimension of street feature diversity are used: functional density, the mixed-use index, and amenity density. The functional density represents the intensity of street development, which directly depends on the number of POIs. The mixed-use index reflects the mixed functions, providing a variety of options for street users. The amenity density refers to the density of POIs in amenities, such as education, health, public services, administration and sports on the street as a reference of meeting the daily needs of users. The detailed quantification variables are listed in Table 3.

**Table 3.** Description of diversity variables.

Dimension	Variables	Variables Descriptions	Formula	Formula Description
diversity	Mixed-use index (MUI)	the degree of the street mixed functions	$MUI = -\sum(P_i \times \ln P_i)$ ( $i = 1, 2, 3 \dots n$ )	$P_i$ refers to the proportion of the particular type to the total number of POIs in the street, $n$ is the number of POI types
	Functional density (FD)	the intensity of the street development	$FD = \frac{poi\_num}{road\_length}$	$poi\_num$ means the total number of POIs within a street buffer area; $road\_length$ is the length of the street
	Amenity density (AD)	the intensity of the street public amenities	$AD = \frac{PS\_num}{road\_length}$	$PS\_num$ (Public Service) refers to the total number of POIs in education, health, public services, administration and sports within the street

In terms of accessibility, we employ the spatial design network analysis (sDNA) tool to assess accessibility. More specifically, this study focuses on two indicators: “betweenness” and “closeness” in sDNA to measure the accessibility of the street network. Closeness refers to the sum of the distance costs to be overcome to reach any other place in the street network within a specified radius from a certain place, i.e., the higher the closeness, the lower the distance costs to be overcome to reach other places from that street and the higher the potential of the street for people to view it as a destination. In sDNA, the

Closeness is commonly defined as Network Quantity Penalized by Distance in Radius Angular (NQPDA) [62]. Betweenness reflects the potentials of “through-movements”, which means that individual street segments are selected by pedestrians or drivers as the path [63]. The higher the Betweenness, the greater the potential of the street to attract people to move through the street. In addition, this study will also use two additional indicators: the density of road intersections is used to measure street connectivity [64], and the distance to public transportation is used to represent the degree of convenience. The detailed quantification variables are listed in Table 4.

**Table 4.** Description of accessibility variables.

Dimension	Variables	Variables Descriptions	Formula	Formula Description
	Closeness	the average reverse distance from a given link or node on the network to all other links or nodes within a local radius	$NQPDA(x) = \sum_{y \in R_X} \frac{W(y)P(y)n^{qpdn}}{d_m(x,y)^{ngpdd}}$	NQPDA (x) respects the closeness of link x; y and z are the geodesic endpoints, NQPDA (x) respects the closeness of link x; y and z are the geodesic endpoints
accessibility	Betweenness	The number of times a street segment is traversed as the shortest path from all origins to all destinations in the network	$Betweenness(X) = \sum_j \sum_i d_{jk}(i) / d_{jk}$	$d_{jk}$ refers to the shortest path between segments $j$ and $k$ and $d_{jk}(i)$ refers to the shortest path containing segment $i$ between segments $j$ and $k$ .
	Intersections density	the degree of street connectivity	$Den\_intersection_i = \frac{intersection_i}{road\_length}$	$intersection_i$ is the number of intersections
	Public transportation accessibility	the degree of street convenience	$Accessibility = Min(D\_pt)$	Min(D_pt) (Public Transport) is the distance to the nearest bus or subway station

### 3.3.3. Regression Models

Following previous studies, this paper implements three sets of multiple linear regression models to investigate how diversity and accessibility are associated with street vitality. Model 1 served as the base model to assess the association of diversity and street vitality, in which three indicators, i.e., functional density, mixed-use index and amenities density serve as the independent variables. For comparison purposes, model 2 contained four indicators of accessibility, i.e., closeness, betweenness, density of road intersections and the distance to public transportation as the independent variables. Model 3 included both diversity indicators and accessibility indicators as the independent variables. These three models enable us to evaluate and compare the contribution of each individual indicator to the combined influence on street vitality.

The above three regression models are conducted by the OLS regression model, which is considered to be a common means and effective statistical model for research concerning street vitality [65]. However, OLS regression analysis fails to represent the geospatial heterogeneity of the correlations [66]. We also employed the geographically weighted regression (GWR) model, which is an extension of the basic OLS regression that allows for the exploration of the spatial effect between dependent and independent variables, considering spatial non-stationarity [50,66]. Thus, the GWR model is used to reveal the spatial effect of the diversity and accessibility on street vitality, generating a set of local parameter estimates that show how a relationship varies across space [57]. The mathematical form of the GWR model is:

$$y_i = \beta_{0(u_i,v_i)} + \sum_{i=1}^m \beta_i(u_i,v_i)x_{ji} + \varepsilon_i$$

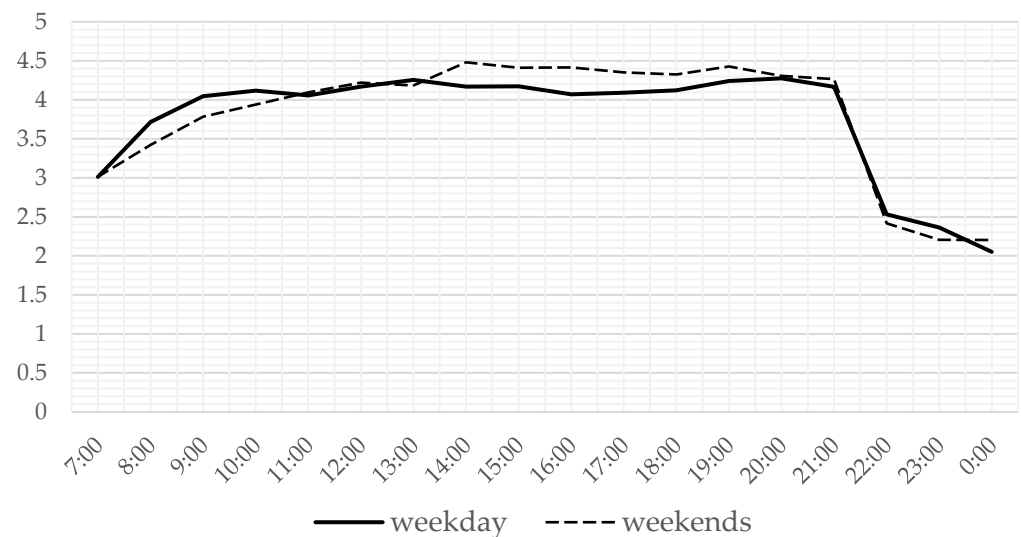
where  $i$  represents the spatial unit  $i$ ,  $y_i$  refers to the value of street vitality of the spatial unit  $i$ ;  $x_{ji}$  denotes the indicators of the spatial unit  $i$ ,  $m$  stands for the total number of spatial units;  $\varepsilon_i$  is the random error term of the spatial unit  $i$ ;  $(u_i,v_i)$  signifies the location of the

spatial unit  $i$ ;  $\beta_{0(u_i, v_i)}$  stands for the intercept at the location  $i$ ; and  $\beta_i(u_i, v_i)$  represents the local estimated coefficient of variable  $x_{ji}$  [61].

## 4. Results

### 4.1. Temporal and Spatial Characteristics of Street Vitality

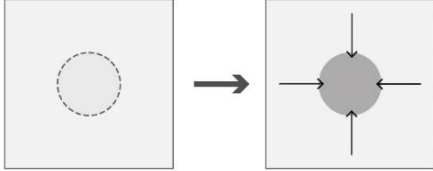

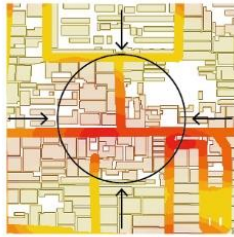
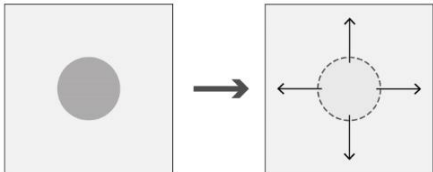
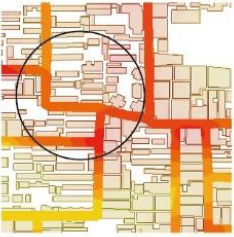
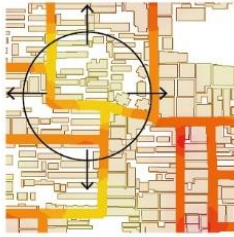

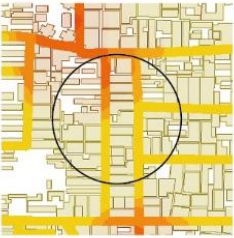
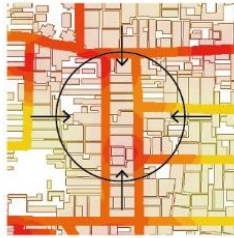
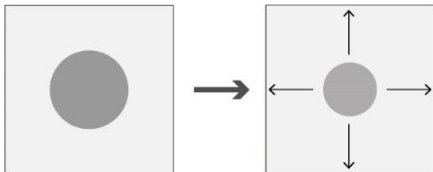
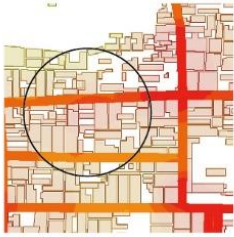
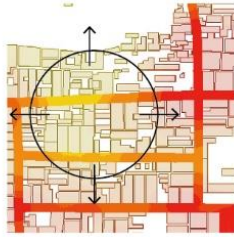
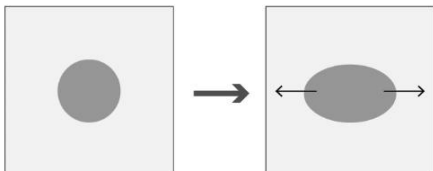
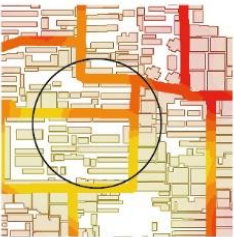
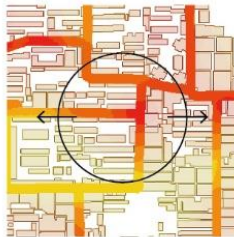
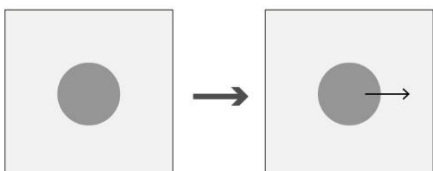
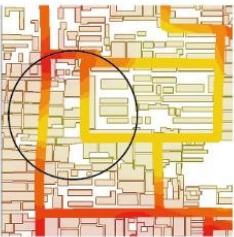

The analysis indicates the temporal and spatial characteristics of the street vitality in the DTMD. Figure 4 shows the temporal fluctuation characteristics of street vitality from 7 p.m. to 12 a.m. (one-hour slices) on weekdays and weekends, respectively. The fluctuating pattern of street vitality is in line with the movements of daily life. Multiple instantaneous vitality peaks occur at different times throughout the day on weekdays. The first peak of street vitality on weekdays appeared at 10 a.m., in line with the rapid gathering of people during the morning rush hours. Subsequently, leisure and commercial activities in the DTMD gradually become active towards early afternoon, which leads to the second peak at around 13:00, staying at a high level during the entire afternoon period. Shaped by the evening rush and nightlife activities, another peak appears around 20:00, followed by a rapid decline after 21:00 in street dynamics as the crowds gather and disperse. The changing trend of vitality on weekdays can be described as the “slow rise—smooth fluctuation—rapid decline” pattern. The fluctuation on weekends is roughly similar to that of weekdays, while, the change of street vitality on weekends is more moderate, and the peak value occurs later on weekends and lasts longer at night. The vitality value on weekends is significantly higher than that on weekdays, and weekends have slightly higher peaks compared with that of weekdays between 14:00 and 18:00.



**Figure 4.** Temporal distribution of Street Vitality during the day.

In order to further understand the spatial distribution patterns of crowd activity in the streets, the spatial aggregation patterns of street vitality are visualized by using the weekday heat map as the base data. The spatial aggregation of street dynamics can be summarized in six patterns, as shown in Table 5. The appearance and disappearance of users depict the intensity change of aggregation. The expansion and shrinkage of human activities depict the spatial scope change of aggregation. The growth and movement of human traffic describes the direction change of aggregation.

**Table 5.** The spatial distribution patterns of street vitality.

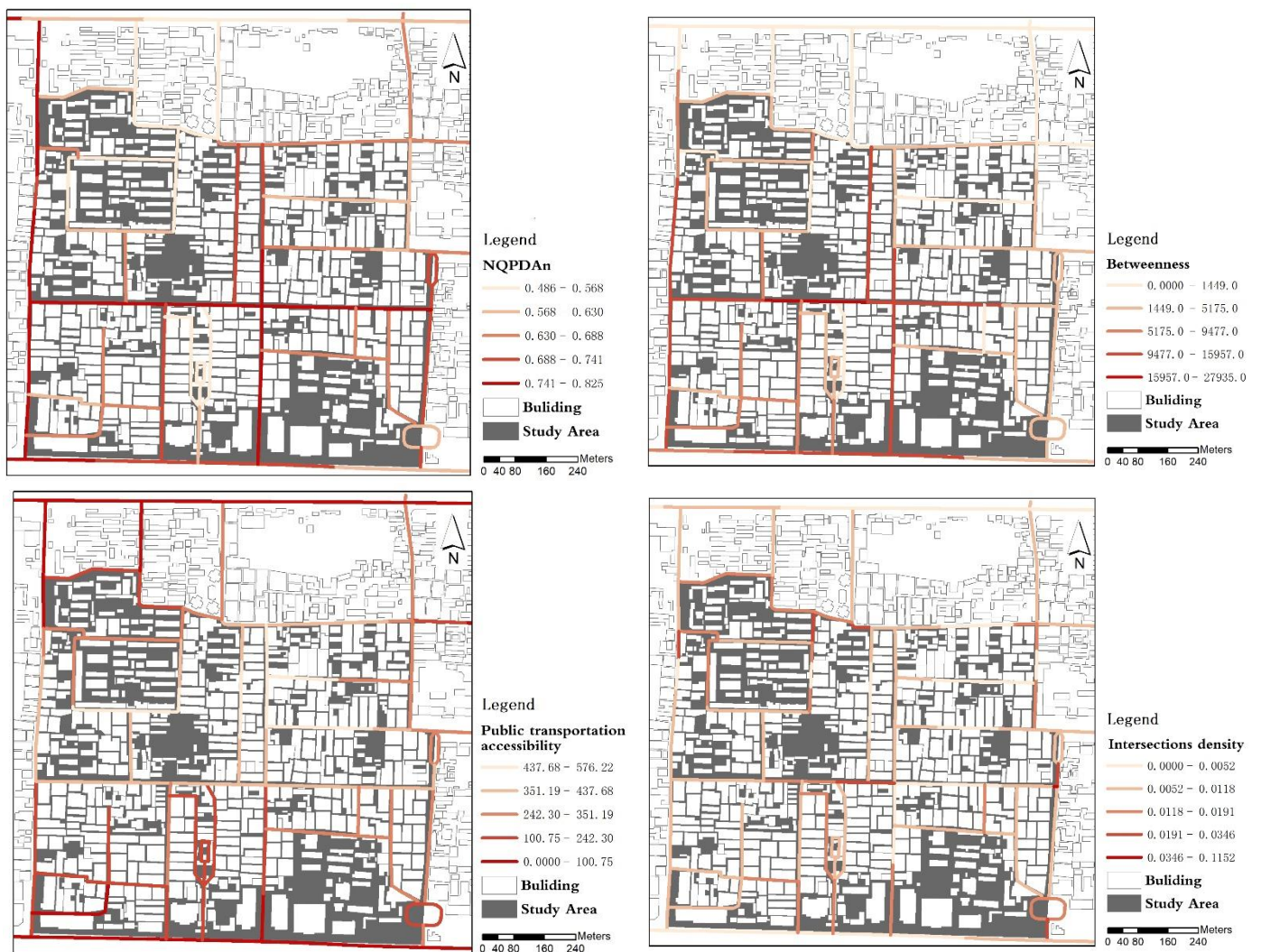
	Diagram	Before	After
Appearance			
		7:00	8:00
Disappearance			
		18:00	19:00
Expansion			
		7:00	10:00
shrink			
		19:00	21:00
Growth			
		15:00	18:00
Movement			
		13:00	14:00

#### 4.2. Quantitative Results of Vitality Impact Indicators

The quantitative results of diversity and accessibility indicators are shown in Figures 5 and 6. The evaluation results are divided into five levels by the natural breaks classification method. The spatial distribution of the functional density of streets in DTMD varies significantly, and the streets with higher functional density mainly concentrated in major streets along the East-West and North-South directions, which are homes with a high density of commercial POIs. The spatial distribution of functional diversity is distinctive to functional density, i.e., streets with high functional density are more likely to have relatively lower diversity. The spatial distribution of public amenities (government institutions, education and culture, healthcare, sports and leisure, and infrastructure) is relatively balanced in the study area.



Figure 5. Visualization of diversity indicators estimate results.



**Figure 6.** Visualization of accessibility indicators estimate results.

The results of closeness and betweenness exhibit the characteristics of spreading from major streets to lower-level streets. The closeness of the major streets is relatively high, reflecting the higher potential of the street to attract people arriving. The results of betweenness exhibit the cross-shaped characteristics. The road in the center presents the highest potentials of “through-movements”, showing the higher potential of the street to be selected by pedestrians or drivers as the path. Public transportation accessibility describes the nearest distance to the bus or the subway station. The periphery of the DTMD presents a higher level of accessibility to public transportation. Intersection density is measured by the number of intersections per unit area of the street network, reflecting its connectivity. The average density of intersections in the DTMD is one intersection/200–300 m, with an overall homogeneous distribution.

### 4.3. Analysis of Regression Model

#### 4.3.1. Linear Regression Models

To compare the effect of diversity and accessibility on street vitality, three sets of multiple linear regression analyses were conducted for the study area, as outlined in Table 6. The seven independent variables of diversity and accessibility are calculated based on the formula in Section 3.3.2. Before conducting a regression analysis, the multicollinearity between independent variables is examined by using the variance inflation factor (VIF). The VIF value of variables in three linear regression models is below the recommended

threshold of 3, indicating that the variables are not redundant; therefore, multicollinearity cannot impact the analysis results.

**Table 6.** Regression models for the effect of diversity and accessibility on street vitality.

Indicator	Model 1		Model 2		Model 3	
	Beta	Sig.	Beta	Sig.	Beta	Sig.
Mixed-use index	0.173	0.143			0.157	0.160
Functional density	0.440	0.000 *			0.329	0.027 *
Amenities density	−0.307	0.011 *			−0.280	0.003 *
Public transportation accessibility			−0.193	0.046 *	−0.223	0.028 *
Intersections density			0.275	0.010 *	0.303	0.004 *
Closeness			0.620	0.000 *	0.386	0.024 *
Betweenness			−0.264	0.090	−0.149	0.312
Adjust R2	0.310		0.401		0.499	
AICc	230.261		223.249		217.460	
Durbin-Watson	1.362		1.596		1.498	

\* Significant at 0.1 level.

In the first set of regression models, the diversity indicators are considered to explain the variances of street vitality. The regression results show that diversity indicators accounts for approximately 31.0% of the street vitality. In particular, there is a strong positive correlation between functional density and street vitality at the confidence level of  $p < 0.001$ , while the amenities density influence is significantly negative ( $p = 0.011$ ). There is a nonsignificant correlation between mixed-use index and vitality, which differs from Jacobs' suggestion that mixed urban functions motivate varied activities [9]. Model 2 serves as the comparison model, conducting the accessibility indicators as the independent variables. The closeness ( $p < 0.001$ ) and intersections density ( $p = 0.01$ ) present a significantly positive association with street vitality. Moreover, the influence of public transportation accessibility ( $p < 0.05$ ) is significantly negative, indicating that the distance to the nearest bus or subway station is inversely proportional to the street vitality. Notably, the influence of betweenness has a nonsignificant negative effect on street vitality ( $p > 0.1$ ). Model 2 (Adjust  $R^2 = 0.401$ ) fits street vitality slightly better than Model 1, demonstrating that the performance of the accessibility has a stronger impact on street vitality than diversity does. Model 3 includes both the diversity and accessibility indicators as the independent variables. These factors are included in the regression analysis, significantly improving model accuracy, with the Adjust  $R^2$  increased to 0.499. For model 3, closeness has the strongest positive associations with street vitality, demonstrating that high-closeness is significantly correlated with sustained vitality. The following influential factors are functional density and intersection density. The results also show that the amenity density has a negative correlation with street vitality. Nonsignificant influences are found in the functional diversity ( $p = 0.160$ ) and the Betweenness ( $p = 0.312$ ).

#### 4.3.2. GWR Models

The GWR models are conducted to further measure the correlations between diversity, accessibility and street vitality with the consideration of geospatial heterogeneity. They use multiple combinations of diversity indicators and accessibility indicators as the independent variables to construct GWR models 4 and 5. The results are detailed in Tables 7 and 8. According to the diagnostic indicators of the modeling results, the Adjusted  $R^2$  values of GWR models (0.498 for Model 4 and 0.551 for Model 5) have increased in contrast to those derived from OLS regression models (0.310 for Model 1 and 0.401 for Model 2). Furthermore, the AICc values of GWR models (220.96 for Model 4 and 218.933 for Model 5)

are remarkably lower than those of OLS regression models (230.261 for Model 1 and 223.249 for Model 2). The increase of Adjusted  $R^2$  values and the significant reduction of AICc values demonstrates that the GWR model can better explain the relationship between diversity, accessibility characteristics, and street vitality. Comparing the results of the GWR model 4 and 5, we can find that accessibility indicators accounted for approximately 55.1% of the street vitality, which is higher than that of diversity. Therefore, the accessibility tends to exert a greater influence on street vitality than diversity.

**Table 7.** GWR modeling results of diversity indicators (model 4).

Variable	Mean	Std.	Min	Median	Max	Model Diagnosis
Mixed-use index	0.048	0.139	−0.234	0.05	0.504	AICc = 220.96 Adjusted $R^2$ = 0.498
Functional density	0.437	0.240	−0.324	0.437	0.714	
Amenities density	−0.196	0.136	−0.725	−0.193	0.078	

**Table 8.** GWR modeling results of accessibility indicators (model 5).

Variable	Mean	Std.	Min	Median	Max	Model Diagnosis
Public transportation accessibility	−0.247	0.077	−0.420	−0.233	−0.082	AICc = 218.933 Adjusted $R^2$ = 0.551
Intersection density	0.189	0.128	0.062	0.189	0.612	
Closeness	0.550	0.095	0.332	0.549	0.707	
Betweenness	−0.176	0.083	−0.345	−0.176	0.097	

To further visualize the effect of each independent variable on street vitality, Figures 7 and 8 illustrate the coefficient of different influencing factors. Among the independent variables of the diversity dimension, the functional density is observed to have great impacts on the liveliness of a place, especially in the central DTMT with the highest coefficient. Its influence dwindled by degrees from the center to the outer area. In contrast, Figure 7b indicates that the mixed-use index does not have an apparent contribution to the street vitality in the central area, but it can be found that in the Northwest corner of the DTMT, where the functional density is low, the driving effect of the mixed-use index is obvious, with the highest coefficient. This suggests that the accumulation of functions can largely promote street vitality, whereas the diversity of function makes a significant contribution to street vitality where the density of function is relatively low. In other words, the impact of the mixed-use index is negligible in areas with comparatively high functional density. Additionally, the amenities density is found to have a negative effect on vitality in most study areas. Its influence can be mainly visualized in the Eastern part of the study area, gradually weakening from East to West.

Among the independent variables of accessibility, the closeness and the public transportation accessibility have a more significant impact on vitality, as shown in Figure 8. To be specific, a remarkable positive effect of closeness is detected in the central and southeast areas of the DTMD (Figure 8c). For public transportation accessibility, the spatial characteristics of the correlation coefficients are higher in the central-southern areas (Figure 8a). The results indicate that the distance to the public transportation in this region make more of a contribution to street vitality. As to intersection density, a strong positive effect can be observed in the Northwest corner of study area (Figure 8b). In terms of betweenness, a slight negative effect can be found in most of the study regions.

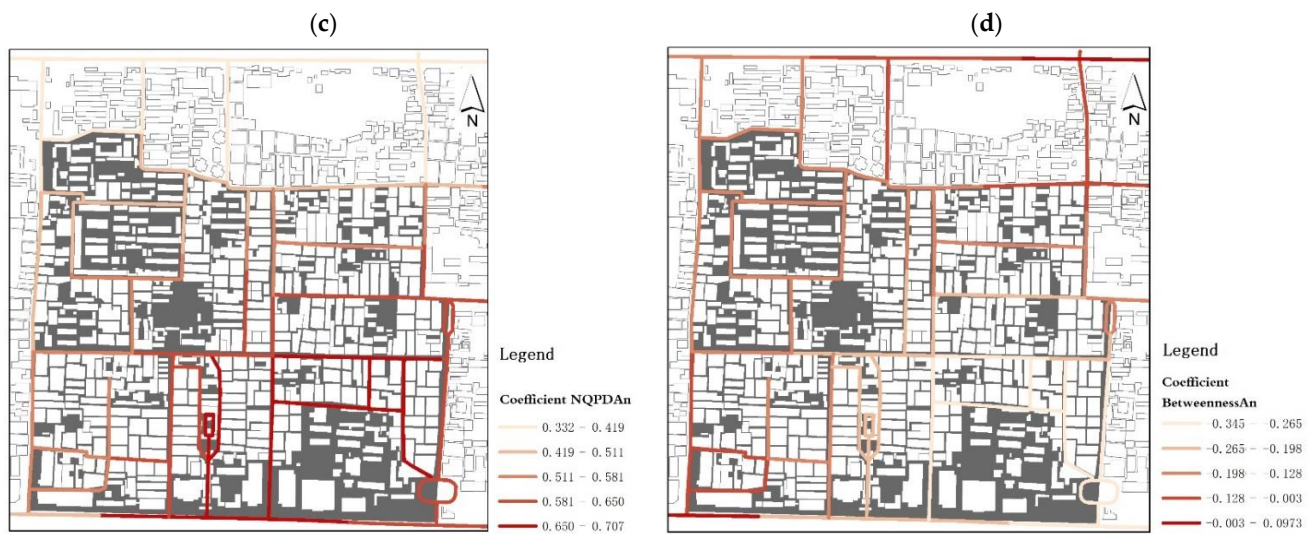




Figure 7. Spatial characteristics of estimated coefficients of diversity indicators with GWR. (a) Functional density; (b) Mixed-use index; (c) Amenities density.



Figure 8. Cont.



**Figure 8.** Spatial characteristics of estimated coefficients of accessibility indicators with GWR. (a) Public transportation accessibility; (b) Intersection density; (c) Closeness; (d) Betweenness.

## 5. Discussion

### 5.1. The Influencing of Diversity and Accessibility Characteristics on Street Vitality

In line with the conventional theories that highlighted the importance of diversity and accessibility in inducing street vitality, this study analyzes and compares the effects of both aspects on street vitality in historic districts, including the DTMD.

With regard to the aspect of diversity, the results indicate that the functional density has a remarkable positive influence on street vitality, while the mixed-use index has no significant driving effect. Moreover, through the GWR model, this study further finds that the functional density has a higher impact on the street vitality within the central area of the DTMD, while the mixed-use index exerts a limited contribution here. The central area has high functional density and most businesses are located in it. On the contrary, the mixed-use index clearly influences the streets in the north-west corner of the study area, which has low functional density. The results demonstrate that street vitality in the historic district is not necessarily related to the mixed-use index, which challenges the widely-held assumption that the mixed-use index is regarded as the primary generator of street vitality. Similar findings can also be seen in studies in Hankou and Italy [50,67]. In the case of the old city in Hankou, which also has high functional density, mixed-use indicators contribute little to the street vitality. In the case of Italy, the mixed land use only matters in urban areas with a single function. This finding provides additional evidence about the spatial density's significant effect on street vitality, as it provides more possibilities and more choices [37,68]. In addition, this study shows that the amenities density has a significant negative association with street vitality. This finding indicates that streets with a concentration of amenities such as education, health, or administration tend to have lower vibrancy, as it mainly serves the local residents and is not attractive enough for visitors.

With regard to the aspect of accessibility, this study's result indicates that closeness is the most obvious factor that has an impact on street vitality. The closeness, as an indicator of street network configuration, implies the potential of the street to be selected as a destination and attract people to it. The results indicate that a well-developed street network with close linkages to main roads is essential to the street vitality level. This coincides with the findings of previous studies that consider a good street network as a key factor to make neighborhoods, especially historical districts, vibrant [69]. In this study, the density of intersections has a significant effect on improving the street vitality. The higher density of intersections suggests smaller building blocks that bring more street fronts and storefronts to engage with people. This finding reflects conclusions from other studies which show that a higher density of intersections slows down the pace of people's movements, giving them

more time and space for random social and consumption activities [26,31]. The coefficient of public transportation accessibility presents higher values in the central-southern regions, where most bus or subway stations are located, reflecting that public transportation stations have a larger contribution to street vitality in this service range.

A comparative analysis between diversity and accessibility is another important task of this research. The results have demonstrated that accessibility exerts stronger effects on street vitality than diversity does, which is verified by the larger adjusted  $R^2$  for accessibility, both in the OLS and GWR models. This finding indicates that the morphology and spatial configuration features of streets make higher contributions to street vitality than streets' function does. The spatial configuration of streets is the core element of spatial features within historic districts, including tangible indicators such as the higher density of buildings and the road network, smaller building block sizes, and intangible indicators, such as the sense of belonging and shared memories. This finding has important implications for guiding the practice of urban regeneration in historic districts.

### *5.2. Implications for Urban Policy and Design Practices*

The results of this study also have a few significant implications in the area of urban regeneration policy and practice. The DTMD is a unique historic district that has maintained much its old urban fabric over the centuries and survived a series of large-scale demolitions and reconstructions over recent history. The revealed spatial configuration features of streets making higher contributions to street vitality is important in solving the urban regeneration issues in China's historic districts. As a result, in order to maintain or enhance the street vitality within historic districts, policymakers should pay more attention on the improvement of spatial configuration. Preserving the original morphology of streets is recommended rather than building magnificent avenues. In addition, the intersection density in this study is the second influential factor for street vitality among accessibility dimensions. As mentioned by Jacobs, intersections provide more possibilities for human interactions on streets. Therefore, future regeneration efforts can consider street intersections as the strategic locations for redevelopment.

The findings of this study can also provide a new direction for urban designers and scholars to rethink strategies to revitalize streets in historical districts. In the diversity dimension, functional density has a significant positive effect on street vitality, while amenity density has a negative effect. Evidence indicates that streets with higher functional density tend to have a higher concentration of diverse businesses and attract more users from both inside and outside of the district, which consequently lead to higher street vitality. However, streets with higher amenity density have lower street vitality because they mainly serve local residents and attract fewer users from the outside.

In the meantime, it is important to understand that every street in every district should seek its appropriate level of street vitality; over-vitalized or under-vitalized streets can undermine the healthy development of the neighborhood in question. In particular, the pursuit of high street vitality in historic districts may lead to gentrification and increased tourism that, paradoxically, end up reducing the vitality that made them popular [3]. The many cases of urban revitalization, such as Barcelona, Bucharest's Old Center and Krakow, etc., are inevitably experiencing these issues, which reminds policymakers to strive to include all communities involved in the process of urban revitalization in search of an appropriate level of vitality [4].

### *5.3. Limitations and Prospects*

There are several limitations of this study specific to the selection of the dataset and the construction of the quantitative indicator system. First, the concept of street vitality is too broad and complicated to be completely represented by geospatial data and attached numerical values. The Baidu Heat Map, to a certain extent, reflects relative population density and the dynamic spatial distribution of crowds. We have to be aware that the complexity of street vitality in social, economic and cultural dimensions cannot be

measured by the Baidu Heat Map, which can only be viewed as an approximation of the density of peoples' activity in space. Furthermore, the Baidu Heat Map cannot reflect the types of activities and the subjective feelings of the crowds (i.e., perception, satisfaction, belongingness), which are crucial to the study of street space [70]. Qualitative work such as street-level observations and field questionnaire surveys would be required to fill this gap. Also, Big Data is limited with regard to developing a good understanding of the complexities of everyday life. In addition, as the Baidu Heat Map is based on the location information obtained by mobile phone users who access Baidu application products, and it fails to represent all age and social groups (especially those who do not use Baidu apps or cell phones). Thus, using the Baidu Heat Map in this study can generate biased results and findings [30]. Future research needs to integrate multiple sources of data, such as public review data, TikTok records and social media check-in data, and other datasets to fill the gaps in the existing studies. Hence, as mentioned in Section 2.1 above, the definition of street vitality can significantly differ between Western and Eastern countries, and the methodology employed by this study is limited to measuring street vitality in the Asian context. It could generate different conclusions when applying the same methodology to historic districts in Western countries.

Second, we built up the quantitative indicator system of diversity and accessibility in terms of the physical environment. However, with the growing penetration of information and communication technologies and the outbreak of the COVID-19 global pandemic, the daily life patterns of people have experienced major changes. A series of activities (e.g., working, studying, communicating, sharing and checking in) can now be performed in virtual spaces [71]. As a consequence, the paradigm of urban study should not merely focus on physical space, but include studies on virtual spaces as well. As mentioned in previous studies, the city is not only regarded as a spatial container, but a living organism which consists of human and non-human actors, the surrounding environments, and the networks between them [30,72]. Therefore, the measurement of diversity and accessibility could be extended to virtual spaces, where they display the diversity of personal attitudes towards the living environment.

## 6. Conclusions

This study aims to propose a recontextualization of the conventional theories in terms of diversity and accessibility, revealing the spatiotemporal traits of street vitality in the DTMD, a typical historic district in Xi'an, China, involving the Baidu Heat Map data. The functional density, mixed-use index and amenities density indicators were incorporated into the evaluation of the diversity dimension. The street network configurations of closeness and betweenness, the density of road intersections, and the distance to public transportation are included in the evaluation of the accessibility dimension. Moreover, we adopted the OLS models and GWR models to analyze the effect of the diversity and accessibility characteristics on street vitality, as well as on the driving force or inhibiting factors spatially.

The results suggest that the temporal characteristics of street vitality in the DTMD is in line with the time orders of daily life, following the "slow rise—smooth fluctuation—rapid decline" pattern. Moreover, the results show that accessibility tends to play a more important role than diversity in inducing street vitality. This study confirms the significant impact of street network configuration on vitality, particularly concerning closeness and intersection density. In terms of diversity, the functional density was observed to have positive impacts on street vitality, while the opposite effect was observed for amenity density, and the effect of the mixed-use index was found to be concentrated in low-density functional areas. This study has the following theoretical and practical contributions. Theoretically, through looking at the DTMD's case, this study enriches the literature by advancing studies of the revitalization of historic districts with Big Data methods and technologies. In addition, this study can be considered a practical operationalization and verification of anecdotal-style theory in historic districts in the Asian context. In practice,

the results found here may allow fellow researchers and practitioners to estimate the potential of historic districts to be vital ones, contributing to a further discussion about what constitutes a vibrant historic district.

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**Data Availability Statement:** The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy restrictions.

**Conflicts of Interest:** The authors declare that they have no conflict of interest.

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