Article

Measurement of Street Network Structure in Strip Cities: A Case Study of Lanzhou, China

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Abstract: As the foundation and skeleton of urban space, the street network is significant to the urban travel environment and socio-economic activities. To reveal the structural characteristics of the street network, this paper proposes a measurement index system to study the street network structure and urban travel characteristics. To illustrate the relationship between spatial accessibility of streets in strip cities and residents’ travel and service demands, we take Lanzhou, a typical strip city, as an example for network analysis and study the hierarchical structure of physical, functional, and environmental characteristics of the street topological network. The results show that Lanzhou City has formed a radial network structure with traffic-oriented streets as the backbone and interconnected living streets. However, the development of old and new urban areas is still uneven. In terms of street function distribution, streets with a high degree of diversity are more attractive to population clustering and show a polycentric clustering feature in space related to the regional functional orientation and travel characteristics. Much of the structural difference in the centrality core-periphery of the street network under pedestrian and vehicular travel patterns are influenced by the street’s type and function. In addition, as part of the contribution, we provide an evaluation methodology that enables the analysis of street network centrality. These findings advance our understanding of strip city development.

Keywords: strip city; street network structure; functional characteristics; centricity

1. Introduction

Since reforms were undertaken in China and the opening of the economy, the acceleration in urban development has led to an increase in demand for mobility. Multiple modes of travel, including walking, bicycles, buses, and private cars converge together on the street space. Consequently, the traditional efficiency-oriented street spaces can no longer meet the increasingly diverse needs of the new era of travel, thereby resulting in urban traffic congestion, poor accessibility, and imbalance between jobs and housing. The urban street network, a skeleton of a city, has both physical and social attributes and is a crucial factor for sustainable urban development. As a key part of the urban public space, urban streets are the physical places where people live, interact, and move around [1]. Thus, the layout of urban streets directly affects the spatial distribution, facilities, environment, and gathering of the population herein. Furthermore, the street network serves the demands of human activities as it is the main carrier of the flow of material elements in urban space that supports the orderly and efficient operation of urban social activities [2]. In addition, modern cities mostly develop obvious polycentric features based on their street networks, which are characterized by identifiability, adaptability, and complexity [3]. The hierarchy, layout, and functional–structural characteristics of strip cities have a continuous impact on the spatial and temporal sustainability of the urban population and facilities. As street networks confer spatial distribution, attractiveness, and order to cities, they are crucial to the sustainability of a city.
Strip cities are constrained by the natural environment, including rivers and valleys. Linear street networks are mostly distributed vertically, with urban traffic arteries forming the main skeleton; the facilities used for various urban functions are randomly arranged along the main axis. The special topography and spatial distribution of streets in strip cities promote close connectivity between people and nature, culture, and society [4]. However, currently, many strip cities in China are at a crucial stage of development; therefore, topographically constrained cities inevitably result in several urban problems, including low-quality urban sprawl [5], traffic congestion [6,7], inefficient land use patterns [8], and functional polarization. Addressing all these problems should be a top priority of government and society.

At present, a total of 44 strip cities at and above the prefecture level are distributed throughout China, accounting for 15% of the total number of Chinese cities [9]. The spatial distribution of strip cities possesses canonical geographical characteristics. Strip cities distributed along the coastline of southern and eastern China include Sanya, Shenzhen, and Qingdao; those along the rivers in the river network areas of western and southern China include Lanzhou, Xining, and Xianyang, and strip cities in the plateau and mountain terrains include Gannan, Yinchuan, and Lhasa. The spatial structure of strip cities confers certain common problems. First, the strip form is due to natural environmental constraints [10]. Second, the unique narrow urban form of strip cities increases the pressure on the urban infrastructure the traffic pressure in the direction of the long axis of the city. Furthermore, it is difficult to maintain the job–housing balance and the dynamism between polycentric gathering and dispersing of the population [11,12]. At present, most Chinese cities are undergoing a process of rapid urbanization, leading to a large population concentration within these cities. The attractiveness of the population towards cities drives the expansion of their street networks in the direction of making functional complexes.

The street network connects various spaces in the city and constitutes the urban fabric as it performs several functions, including regulating living areas and transportation; the streets are the most closely connected public space for people. As early as 1984, according to the geometric design of roads handbook, in the United States, urban roads were divided into expressways, trunk roads, and local streets. Road mileage and traffic flow at different levels show a certain distribution pattern [13,14]. Functionally, the urban street network contains several thousand network nodes and complex internal structures [15,16]. They are not only the predominant factors affecting transportation costs but conferring spatial mobility, also the necessary public spaces for residents. Paths with higher spatial accessibility are constantly constructed, which influences the urban layout. The rationalization of the street network structure is the base for the efficient functioning of the city and yet is often overlooked; streets are more relevant to the daily life of citizens and various pedestrian activities [17]. Consequently, the concept of a street should not only focus on the efficiency of the flow of the “Dao” (road in Chinese) but also on the spatial perception of people on the “Jie” (street in Chinese). Thus, it is necessary to identify and measure the street network structure of specific urban forms from a network science perspective to help us better understand urban space.

For the street network structure, several studies and reviews have been published previously. Lammer et al. analyzed the topological characteristics of the street network structure of more than 20 major cities in Germany and quantitatively computed the hierarchical characteristics of the road structure [18]. A study on Italian street network construction, through the analysis of the basic characteristics of street networks and the relationship between network structure and traffic flow [19,20], provides a theoretical basis for optimization of the control strategies for street structures. It is widely accepted that the street network structure is morphologically categorized into four typical types of the grid, circular radial, free-form, and hybrid [21–23]. Previous studies have summarized the advantages, disadvantages, and adaptability of each of these different layouts. Some studies also propose three major theoretical structural features to classify street networks, including, function, grade, and layout. These authors opine that street network structures do not refer
to any of the above three bases alone but are an organic combination of the three [24,25]. Jiang Bin and Tsiotas et al. constructed urban street networks and analyzed different characteristic indicators using different construction methods [26,27]. The impact of street transportation on the daily life of the residents has been studied intensively. The structure and temporal evolution of spatial networks involve intercity trains and subways [28–31], urban traffic [32,33], public transport [34,35], pedestrians, and bicycles [36,37] on different spatial scales that affect the spatial form and functions of the city. Moreover, several of these features vary widely among different systems [38]. In recent years, accumulating evidence provides quantitative descriptive indicators of the complexity of street network structures and they have been used to study the real street network structure in several cities [39].

The urban street network largely determines the city’s spatial layout, economic activities, and social travel environment and has a particular hierarchical structure. There are differences in the perspective of the study and the selected measures. Most existing studies on the quantitative measurement of street network hierarchy are based on graph theory and network science, focusing on the following three levels. First, the traffic characteristics and fractal patterns of the streets themselves are emphasized from the perspectives of morphology [23,40], hierarchy [41,42], and type [43]. Second, in addition to the properties of the streets themselves, the place-based functions formed by the commercial, green space, and public space on both sides of the streets are often used to measure the role of the spatial development of streets in influencing the distribution pattern and degree of aggregation of population, leisure, and employment [44,45]. More extensively, streets use the dynamics and complexity of topological networks to measure the physical and spatial manifestations of human activities in cities [46,47], which quantitatively and objectively reflect the direct and complex interactions of various socioeconomic, technological, and environmental factors. Moreover, the street network is the backbone of the city, not only as the basis for its emergence and accompanying growth and evolution but also subject to the constraints of urban spatial scale and morphology. Significantly, the narrow geospatial characteristics of strip cities make it challenging to measure the street network structure. Therefore, in this paper, under the system of urban transportation theory, it is not only necessary to measure the own hierarchy, type, and morphological description of the street network that contains it, but also to construct a coherent system of street function and complex network structure indicators from the perspective of human perception in the street space using network science.

The main contribution of this paper is to incorporate the physical, functional, and external environmental characteristics of the street network into the measurement index system in a specific strip urban form. The users of the street and their activities exist as a close whole in the physical entity of the street space, thus constituting the “performer” and “performance content” of the entire street space. At the same time, we proposed a multivariate measurement method of street network characteristics to reduce the difficulty of labeling urban streets using the topological accessibility of complex networks of streets. In addition, we conduct a case study of Lanzhou City, a typical strip city in China, using a system of metrics and centrality measures to locate areas of agglomeration and dispersion in urban travel patterns, and analyze the impact of street space on residents’ travel and service demands.

2. Materials and Methods

2.1. Study Area

Lanzhou is a typical strip city in China, with a downtown area of 230.34 km². In 2020, the resident population of Lanzhou City was 2,776,000; the population density was 11,600 people/km² [48]. In this case report, the central built-up area of Lanzhou City was selected as the study area. As shown in Figure 1, the city is in a mountainous valley, with mountains to the north and south of the Yellow River, which crosses the central city from west to east. The north–south expansion of this city is restricted by the mountainous valley,
and the street network is characterized by a limited number of longitudinal arterial roads and many horizontal connecting roads. The concentration of traffic flow on the longitudinal arterial roads led to a certain level of mismatch between the limited longitudinal traffic resources and the huge traffic demand. This mismatch has been a common limitation of strip cities; however, it confers the advantage of better organization of urban transportation systems in such cities. In recent years, the government has made a strategic choice for the optimization of network structure to cope with the continuous demand growth of traffic, guide decentralization of the urban functions, and promote high-quality economic development. Moreover, the Government of Lanzhou embarked on constructing a skeleton network system of one horizontal trunk, two links, two rings, and eight vertical trunks. In 2020, Lanzhou City had a complete skeleton road network system, 1428.68 km long. Thus, a mature street network spanning the central city and crossing the Yellow River has been constructed.

![Location and layout of Lanzhou City](image1)

**Figure 1.** The location and layout of Lanzhou: (a) Location of Lanzhou City in Gansu Province; (b) Location of the study area in Lanzhou City; (c) Street layout of the study area.

2.2. Data and Pre-Processing

In this study, data from the China National Basic GIS ([http://www.ngcc.cn/ngcc/](http://www.ngcc.cn/ngcc/)) accessed on 16 December 2020 and 1:4 million administrative boundary and water systems were analyzed. Roads, secondary roads, and highway vector data, along with the labels were obtained using the open-source OSM ([http://www.openstreetmap.org](http://www.openstreetmap.org)) platform [16]. Using the Google Earth map tool, remote sensing satellite images of Lanzhou City were extracted at a spatial resolution of 10 m. Consequently, spatial information and street networks for all sections were constructed. In addition, the 2019 POI data (containing seven attributes, including name, type, address, longitude, latitude, contact number, and administrative district) of the main urban area of Lanzhou City were obtained from Amap and divided into 12 major categories, including medical, leisure, life, company, transportation, automobile, finance, restaurant, scenic spot, shopping, science, education, and culture, and residential [49]. Each major category consisted of several sub-categories. A total of 163,925 POI points were extracted. The data of bus and rail transit stations and routes in Lanzhou City in 2019 (including station ID, station name, station latitudinal and longitudinal coordinates, line ID, line name, line type, line distance, line start station name, line end station name, start time, end time, and passing station ID) were obtained based on the cleaned data from the Baidu Map and Amap.

Since the open-source data contained information on roads that did not meet the criteria of the study sample, including broken roads and internal roads of communities,
and owing to the possible topological errors, we simplified the projected street network data by converting two-lane roads into single-lane roads, interrupted roads at the fold to form sections without intersections, and interrupted urban interchanges. Subsequently, the roads in this analysis were not natural streets interrupted exactly by the actual intersections. Finally, a total of 2009 street segments were included as the sample road network data for the analysis of street spatial.

2.3. Street Network Structure Systems

Following the experience of previous studies, the characteristics of strip cities and the possibilities of data acquisition were combined [44,50]. In this paper, three first-level indicators of the physical, functional, and environmental characteristics of the street itself, which are the spatial components of the street, were selected as a characterization of the street network structure. Specifically, physical street streets were characterized using street type, passage time, and network density. Functional density and diversity degree can accurately reflect the functional characteristics of streets. Proximity centrality and betweenness centrality, on the other hand, are common indicators of complex network characteristics. The indicator system and its meanings are shown in Table 1.

Table 1. Indicator system for evaluating the structure of the street network.

| Primary Indicator                  | Secondary Indicator         | Meaning                                                                 |
|-----------------------------------|-----------------------------|-------------------------------------------------------------------------|
| Physical structure of the street  | Type of street [31]         | Traffic-oriented and life-oriented streets.                               |
|                                   | Passage time [36]           | Maximum street passage time between intersections.                       |
|                                   | Street network density [22] | The ratio of street length to area.                                     |
| Functional structure of the street| Functional density [27]     | The number of facility points per 100 m within a cell, reflects the distribution of facilities. |
|                                   | Functional diversity [45]   | The diversity state of POI within a cell is reflective of the diversity in land-use patterns. |
| Environmental structure of the street | Proximity centrality [33]   | Difficulty in searching the rest of the street network within the radius. |
|                                   | Betweenness centrality [39] | Probability of flowing traffic for the search radius.                   |

2.4. Methods

2.4.1. Physical Characteristics of the Street

Street network density refers to the ratio of street length to the area within a network; the network density can be expressed as the ratio of the total number of street lengths present in the network, G (100 m × 100 m), to the area of G space cell. The formula for this calculation was as follows:

\[ d_j = \frac{\sum l_i}{S_j} \]  

(1)

where \( l_i \) is the length of in the spatial cell of network G. \( S_j \) is the area of the G cell.

2.4.2. Functional Structure of the Street

The function of the street is the main factor that attracts people to move on the street. The functions mainly include dining, accommodation, transportation, traveling, shopping, and entertainment. Although most of the street functions in modern cities are diverse, i.e., multiple functions are distributed across one street to meet the daily needs of residents [30], given the overall urban street space, there are several large streets with one main service function collaborating with streets having other functions to form a complete street space. In this paper, we use POI points to characterize the main functions of the street space. Specifically, as shown in Figure 2, the POI facilities within 50 m of the centerline buffer of
the street network were divided into street space facilities by the frequency density–type ratio model (FD-CR) and the street functions were extracted and identified.

![Diagram of street network function identification](image)

**Figure 2.** Street network function identification: (a) Street network centerline; (b) Street 50 m buffer zone; (c) The POI type in the street 50 M buffer zone; (d) Identify Street functions.

The FD-CR model (Frequency density-types ratio model) was chosen for the identification of the street function. The calculation formula was as follows:

\[
FD_i = \frac{n_i}{N_i}
\]

(2)

\[
CR_i = \frac{FD_i}{\sum_{j=1}^{m} FD_j}
\]

(3)

where \(CR_i\) denotes the type ratio of the \(i\) type of POI within a street spatial unit, which in turn is the ratio of the frequency density of the \(i\) type of POI within this street unit to the total frequency density of all types of POIs; \(FD_i\) denotes the frequency density of the \(i\) type of POI within a street spatial unit, which is the ratio of the \(i\) type of POI within this street buffer space to the total number POIs of this type; \(n_i\) denotes the number of the \(i\) type of POI in a street unit; and \(N_i\) denotes the total number of POIs of the \(i\) type in the study area.

The FD-CR model was used to calculate the frequency density and type ratio for each POI within all block units. Subsequently, we compared the ratios of each type of facility within individual street spaces. Based on the literature, a threshold value of \(CR_i = 50\%\), was used to determine the functional type of street space units.

- For streets with \(CR_i > 50\%\), they were considered as a single type, and that type was the main function of the spatial unit of that street.
- For streets with \(CR_i \leq 50\%\), they were considered as the hybrid type. Herein, the first two POI types with the highest values of type ratios in that street spatial unit were regarded as the main function of the block unit, and the secondary function types with equal proportions were included within the main function for statistical analysis.
- For streets with \(CR_i \approx 0\) or null, the street was categorized as 'unclassified'.

**Functional Diversity**

The functional analysis of street types suggested that more than 80% of the streets in the street network possessed hybrid functions. The diversity degree of the hybridity of specific streets was supplemented by the functional hybridity index. The POI hybridization rate combined with the natural breakpoint method and the average nearest neighbor method was used to estimate the degree of functional facility diversity in different areas.

Given that previous studies have quantified the functional hybridity and rationalized the migration and interpretation according to the object of the analysis, the entropy of the street random variable \(x\), in this investigation was calculated as follows:

\[
H(x) = -K\sum_{i=1}^{n} (FD_i \times n\log FD_i) \quad (i = 1, 2, \cdots, n)
\]

(4)
where $H(x)$ denotes the POI functional hybridity of the street; $n$ denotes the number of types of POI; $p_i$ denotes the proportion of a certain type of POI to the total number of POIs in the street; $FD_i$ is the probability of occurrence of random event $i$ ($0 < p_i \leq 1$); $K$ is the calculation coefficient, generally 1.

The following formula was used for computing the functional diversity of the street:

$$ Diversity = \text{Sum}(H_{\text{Medical, Leisure, Transportation, ...}}) $$

(5)

**Functional Density**

Functional density reflects the density of various types of functional POIs in street and characterizes the possibility of providing different types of services in the street space. Generally, the higher is the functional density, the easier it is to fulfill the daily needs of the people, thereby making a street popular. The following formula was used for calculating the functional density of a street:

$$ Density = \frac{N_i}{L_i} $$

(6)

where density denotes the functional density of the $i$th street; $N_i$ denotes the total number of POIs 50 m within the buffer of the $i$th street; $L_i$ denotes the length of the $i$th street, and $i$ denotes the street number (all integers, 1, 2, 3, 4 . . . $n$).

**2.4.3. Centrality of the Street Network**

When people travel by different modes of transport, they may have varied perceptions and awareness of the street network configurations [51]. As shown in Table 2, we analyzed two modes of transport, namely, walking, and vehicular, and selected 0.8 km, 2 km, 10 km, and global travel distance as thresholds to calculate the centrality of the street network with walking and vehicular travel modes, respectively.

Table 2. Relationship between travel patterns, distance, and time of residents.

| Travel Patterns | 0.4 km | 0.8 km | 1.2 km | 2 km | 5 km | 10 km |
|-----------------|--------|--------|--------|------|------|-------|
| Walking         | 5 min  | 10 min | 15 min | 25 min | 62.5 min | 125 min |
| Vehicle Travel  | 10 min | 16 min | 20 min |      |      |       |

**Proximity Centrality**

Proximity centrality ($NQPDA$) is a measure of freedom from the control of others, representing the ease of travel from the street network to the rest of the road network within the search radius [33]. Road networks with high proximity usually have a higher degree of topological integration and centrality and are more attractive for traffic flow. $NQPDA$ was calculated as follows:

$$ NQPDA(x) = \sum_{y \in R_x} \frac{p(y)}{d(x, y)} $$

(7)

where $p(y)$ is the weight of node $y$ within search radius $R$. For continuous space analysis, $p(y) \in [0, 1]$; for discrete space analysis, $p(y)$ is assigned the value of 0 or 1; $d(x, y)$ is the shortest topological distance from node $x$ to node $y$, and $NQPDA(x)$ is the proximity.

**Betweenness Centrality**

The intermediate centrality ($TPBi$) is usually used to measure the probability that a street will be passed by traffic within the search radius, with a higher value representing a more passable street, which accordingly carries more passable pedestrians and vehicular traffic [34]. The calculation formula is as follows.
### 3. Results

#### 3.1. Physical Characteristics of Streets Based on Travel

3.1.1. Street Type and Structure

All street networks of Lanzhou City were included in this study. The street network in Lanzhou City was divided into two major categories of traffic-oriented streets and life-oriented streets [52,53]. As shown in Figure 3, the total number of traffic-oriented streets, including expressways, main streets, minor roads, and tertiary streets only accounted for 3% of the total number of streets. The service-oriented streets and residential streets accounted for 46% and 26% of the total number of streets, respectively. Thus, the proportion of life-oriented streets was substantially greater than that of traffic-oriented streets. The length of service-oriented streets, including both traffic-oriented and life-oriented streets, accounted for 26% of the total length, and the average length was 120.81 m. However, the average length of expressways and main streets reaches 7143.22 m and 3947.93 m, accounting for 8% and 6% of the total street length. Lanzhou City space consisted mainly of traffic-oriented streets that formed a skeleton network. Life-oriented streets were the branches that connected these networks. Residents could reach the traffic-oriented streets by walking through several short streets. The longest lengths of riverfront roads and bypass expressways were along the direction of urban development and primarily included expressways and trunk roads. The total length of walking paths connecting traffic-oriented streets and service-oriented streets was the lowest. As shown in Figure 3, several streets less than 300 m in length in the central city of Lanzhou relate to traffic-oriented streets, resulting in the formation of a dense radial network structure.

The maximum value of street network density in Lanzhou was 3.5779, the average value was 0.93 with a standard deviation of 0.47; the concentration value was between 0.72 and 1.07, which suggested that the medium density space was evenly distributed. The street space with a density greater than 1.8 was considered as a high-density area and showed main distribution in the central area of the city; the space unit was closely connected to the main trunk. Travel time showed a high correlation with the distribution of street network density. The areas with high density also exhibited greater traffic efficiency, such as in Xiguan Cross and Dongfanghong Square, which indicated that the traffic microcirculation was smoother in these areas.
Figure 3. Statistical chart of street network type, length, and number.

3.1.2. Maximum Passage Time

The ideal maximum speed of street passage was estimated without considering the waiting time and congestion at street intersections. According to the Urban Road Engineering Design Specification (CJJ37-2012), for an expressway, the design speed is 60 km/h; 40 km/h for the main trunk; 30 km/h for secondary and tertiary roads; and 20 km/h for other life-oriented streets. We calculated the maximum passage time as the ratio of street length to the speed.

As shown in Figure 4, the shortest passage time from one street to another in Lanzhou City was less than three minutes, while the average passage time for most streets was less than 10 min. These results indicated a good connectivity structure of the street network in Lanzhou City. In addition, the maximum passage time from one street to another was less than 60 min. The streets with long passage times mainly include expressways and trunk roads, such as the North–South Binhe Road and the North Ring Expressway. These streets are the main arteries of traffic lateral penetration of Lanzhou City as they carry the main traffic flow of the city.

Figure 4. Maximum street passage time.
3.2. Functional Structure Characteristics of the Street

3.2.1. POI-Based Identification of Street Functions

Based on the collected data, the POIs within the 50-meter buffer zone of the streets were divided into 12 categories according to their functions; among them, the top three were shopping service (25.92%), catering service (22.18%), and life-support service (17.84%) as shown in Figure 5.

![Figure 5. Statistical chart for the number of POIs for street functions.](image)

FD-CR model analysis showed that the maximum value of type ratio of street function in Lanzhou City was 7, the average value was 1.94, which indicated that the overall street network in Lanzhou City functioned as a hybrid. Herein, 14% of these street networks had a single function, which mainly included shopping service, business, or residential areas, while greater than 80% of the streets encompassed two or more major functions, including residential, shopping, or/and leisure. Moreover, most shopping-oriented streets were compatible with catering services, and traffic-oriented functions with other functions catering, business, and residential spaces.

3.2.2. Functional Structural Characteristics of the Street

As shown in Figure 6, we show the spatial distribution of the functional diversity of the street network in Lanzhou. In the Chengguan District of Lanzhou City, an old urban area, the streets with high functional diversity are mainly concentrated between Zhongshan Road, Yantan Road, Minzhu East Road, and Donggang West Road; these are mostly in an east–west orientation. The streets with high functional diversity of north–south arterial roads included the Yanyuan Road in Gaoxin District. The urban beehive area connecting Chengguan District and Qilihe District was linked by Xijin West Road, which was the main traffic-oriented road with high functional diversity. A high overall functional diversity and density of the street network on the east and west sides of the Xiguan Cross were observed. Since fewer traffic streets were connecting different parts of the city, they tended to have higher functional diversity, including the Anning East Road connecting Anning District with Chengguan District and Qilihe District, and Pengjiaping East Road in Pengjiaping District. These findings suggested that in a strip city, urban trunks connecting urban clusters exhibit traffic-oriented functions and exert their effects on the facilities and populations in these streets. Streets with low functional diversity were concentrated to the outer edges of the city, along the Yellow River area, and within scattered low-grade streets.
3.2.3. Differential Characteristics of the Spatial Distribution of Street Functions

The analyses for estimating kernel density and functional density of POI facilities at the street level, as shown in Figure 7, demonstrate the density of the main POI categories in medical services, recreation and leisure, living services, and business facilities. The distribution of recreation and leisure facilities at the street level was relatively scattered, with an obvious polycentric distribution pattern. The distribution of business entities at the street level was relatively concentrated, thereby indicating the unbalanced single-kernel distribution trend in urban development. The distribution of medical service facilities was of a cluster-belt type, leading to a high degree of integration between the Qilihe District and the Chengguan District. The east–west direction was linked by the axis of Xijin Road, while the north–south direction was vertically connected by the Donggang Area and the Yanta Area. The distribution of living service facilities was more scattered, and the kernel formation was not obvious. In addition, the distribution of traffic service facilities in the streets formed a decentralized cluster, which could better connect the residential, commercial, and office spaces. The scattered group distribution was conducive to the full-coverage mode of expansion of the city’s multi-center outward and radiation in a row. Lanzhou City has actively developed public transportation in recent years, resulting in a high density of public transport stations in the central city, with full coverage in all areas except for the Pengjiaping Development Zone. In addition, BRT was constructed in the Anning District to connect the Anning District with Qilihe District. In the Chengguan District, several dedicated bus routes have been designated, contributing to a greater willingness of the residents to travel by public transport. In addition, a comparison of the distribution densities of traffic facilities and car service facilities in the streets showed a clear complementarity between the public transportation and private cars in the city, with most private car services distributed along the periphery of the city, such as in Yantan and Xigu.

Figure 6. Street network functional diversity.
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Figure 7. Kernel density map for street functions. (a) Healthcare; (b) Recreation; (c) Life Services; (d) Transportation Services; (e) Company Business; (f) Financial Services; (g) Catering Services; (h) Car Service; (i) Shopping Service; (j) Accommodation Services; (k) Educational Facilities; (l) Residential areas.

3.3. Street Structure Centrality Characteristics

Proximity centrality analysis determined that the closer were the nodes of the street network to the central area of the city, the higher was the proximity centrality measure. At the periphery of the street network, the value of proximity centrality decreased with an increase in distance. The majority of the streets in the network had significant proximity centrality, i.e., most of the streets closer to the central city had the characteristic of being closer to other streets in the network. Street proximity centrality showed “center-periphery” distribution pattern, with areas having a high value mainly concentrated in the central city, while the low-value areas were along the periphery of the road network. Therefore, from the perspective of global proximity centrality, the central city traffic road network contributed more to the whole traffic network of Lanzhou. In terms of travel scales, areas with high centrality were found to be mainly concentrated in regions with high street network density in the old city with walking and bicycle travel patterns. The new urban area, including the Anning and Xigu districts, were mainly traffic-oriented streets, whereas the number of life-oriented streets was insufficient and unevenly distributed. As a result, the travel mode of people in these areas often included vehicular transport to reach their destinations. Therefore, the internal street microcirculation network needs to be optimized further. The distribution center of the global proximity centrality was roughly the same as the network center of the Lanzhou City traffic road network, which indicated that streets
with higher centrality values within the central city area were more easily accessible to other streets. In addition, for the vehicular travel mode, the proximity centrality of the beehive area in Lanzhou, represented by Xijin Road, was significantly higher than that of the old city and other areas, which indicated that the high degree of traffic convergence in the beehive area due to vehicles led to a high incidence of traffic congestion.

Betweenness centrality reflected the probability of traffic flowing through the street. As shown in the right panel of Figure 8, most of the street grid cells in Lanzhou City exhibit a highly discrete spatial distribution for walking mode. Pedestrian flows only gathered in some streets in the old city of Chengguan, and the gathering characteristics were not obvious. This highly discrete spatial distribution reflected the local scale of the walking mode [54]. For the betweenness centrality of vehicular travel patterns, the grid cells with large values were concentrated in urban trunk roads and traffic-oriented streets and showed a strip distribution along major roads, which coincided with the layout of major roads, including Shenan Road, Anning East Road, Xijin Road, Tianshui Road, Donggang East Road, and Yanyuan Road. The spatially discrete characteristics of betweenness centrality indicated that the main trunks formed in Lanzhou play a crucial role in connecting the shortest paths.

Figure 8. Street network street proximity centrality spatial distribution. (a) Proximity centrality; (b) Betweenness centrality.
4. Discussion

Street space is the core carrier of urban activities and interactions and develops together with the city’s social, economic, and environmental aspects. The street network plays an essential role in the urban strip form. It effectively links several functional centers of the city into a whole and significantly influences residents’ daily travel habits and patterns. As urbanization grows and the population and economic scale of the strip city expands further, new streets will be built. With the expansion and increased density of the street network, the efficiency of transporting goods and people will increase, and the function of the street space will be enriched. Therefore, it is essential to understand the interdependence of urban street network structure and the travel characteristics of urban residents.

In this study, we propose a system and method for measuring street network structure in terms of human travel characteristics and spatial perceptions on the street, which allows for a more comprehensive assessment of the street network structure through physical characteristics of the street, functional characteristics, and characteristics of the external environment of the street. Because there is a specific hierarchical structure among these indicators, they are interrelated. First, the grade and length of a street determine the time it takes for vehicles and pedestrians to pass through the street. At the same street network density, the longer people spend on the street can attract people to stop or stay, providing opportunities for businesses on both sides. Second, in the same street space, vehicles and pedestrians often coexist, and the accessibility of street amenities directly influences whether to choose that street, which is often more attractive with a variety of features. Third, with different travel patterns and service demands, if a polycentric urban space can be formed, it can effectively reduce the frequency of long-distance trips that rely on vehicle travel, which also relieves urban traffic pressure. In addition, we also found that the difference in the centrality of the street topology network “core-periphery” structure is primarily influenced by the type and function of the street, depending on the travel pattern. Therefore, when constructing the topology network evaluation index, we incorporate the characteristics of the street space itself and the external environment into the same measurement index system, which can measure the topological accessibility of the street network more entirely and make up for the shortage of existing studies.

In a case study of Lanzhou, a typical strip city in China, the physical, functional, and environmental characteristics of the street network jointly determine people’s activities in the urban street space, forming the aggregated and discrete distribution characteristics of the urban space. It also confirms the validity of the polycentric theory of the strip city [55,56]. In addition, the urban street network is developed together with the urban space and influences the city through self-organization and external effects [57,58]. Specifically, the physical characteristics of the street network can provide the foundation for and influence the daily travel of residents, especially the density and length of the living streets are an essential reflection of the pedestrian-friendly streets. The function of streets is a crucial attraction place, and streets with a high diversity of street functions tend to be more accessible, promoting a polycentric structure of discrete and clustered residential, employment, and amenity functions in strip cities and facilitating the efficient operation of urban street spaces. However, we also find that the existing street network relies on longitudinal arterials connecting multiple life-oriented streets to form a dense radial mesh. However, the development of old and new urban areas is still uneven. There is a need to open the street micro-circulation network by increasing the connectivity between the living streets and the traffic streets to benefit the city’s development.

This study constructs and analyzes in detail the physical, functional, and environmental characteristics of the street topology network in a strip city, and the results clearly show the hierarchical pattern of streets in the strip city polycentric. Compared with the traditional street network structure, the improved indicators and research methods can reflect the accessibility and friendliness of the street network more directly from the characteristics of people’s travel patterns. It helps planners and city managers to build a more connected city through the optimization of street space. However, the article has some shortcomings,
which will be remedied in subsequent research. First, we constructed a street network evaluation index that is interrelated and has a specific influence relationship, but we did not analyze the interactive influence mechanism of this evaluation index, which may affect the reliability of the evaluation index selection. Secondly, under the condition of an already relatively perfect complex network, we analyzed the centrality relationship between street network nodes and edges under different travel patterns. We did not profoundly explore the hierarchical structural characteristics of street intersections and sections and their influence on urban travel patterns, revealing the inner mechanisms of street network configuration relationships that deserve further exploration. In addition, future research should consider the overall performance of street network structure indicators, as it can assign the weights of these three indicators to form an overall index that can assist the spatial development and planning decisions for urban streets.

5. Conclusions

The main objective of this paper is to measure the network structure characteristics of strip city streets under travel patterns and functional configurations. Therefore, we propose a metric measurement system that reflects the physical, functional, and environmental characteristics of streets to reflect the spatial parameters of street places using topological network accessibility. The study confirms the importance of street networks for aggregating facilities and travel patterns in strip cities, which is conducive to improving the functional compounding of street spaces and enhancing street accessibility in cities.

This study finds that three indicators, physical, functional, and environmental characteristics of the street network, are interrelated and influence each other, affecting the development of urban travel and place space. Revisiting the street topology network accessibility from the perspective of travel patterns can provide a reference for optimizing street space and rationalizing facility configuration in strip cities. Therefore, as a complex of transportation and living space, street space should guarantee the efficiency of urban transportation and pay attention to the mix of street space functions. The reasonable distribution of facility functions in street space can help attract people to gather and disperse, thus building a complete street network. In addition, compared with the single street network analysis, the topological hierarchical network analysis method is an effective means to develop the urban space from traffic space to place space, effectively reflecting the street network’s complexity characteristics. These findings advance our understanding of the development of strip cities.

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References

1. Tawil, M.; Reicher, C.; Jafari, M.; Baeumer, K. Assessment of public space efficiency in relation to spatial development in Amman: Exploring indicators to sustainable models of future city life. *Sustain. Dev.* 2016, 9, 104–117. [CrossRef]

2. Liu, Y.; Xu, S.; Li, G.; Liua, W. Research on countermeasures of local culture-based sustainability of urban block patterns. *Energy Procedia* 2019, 157, 312–322. [CrossRef]

3. Xie, F.; Levinson, D. Measuring the structure of road networks. *Geogr. Anal.* 2007, 39, 336–356. [CrossRef]

4. Li, X.; Qian, Y.; Zeng, J.; Wei, X.; Guang, X. The Influence of Strip-City Street Network Structure on Spatial Vitality: Case Studies in Lanzhou, China. *Land* 2021, 10, 1107. [CrossRef]

5. Gradiaru, S.R.; Kienast, F.; Psomas, A. Using multi-seasonal Landsat imagery for rapid identification of abandoned land in areas affected by urban sprawl. *Ecol. Indic.* 2019, 96, 79–86. [CrossRef]

6. Arnott, R.; Rave, T.; Schöb, R. *Alleviating Urban Traffic Congestion*; MIT Press Books: Cambridge, MA, USA, 2005; Volume 1.

7. Jain, V.; Sharma, A.; Subramanian, L. Road traffic congestion in the developing world. In Proceedings of the 2nd ACM Symposium on Computing for Development, Atlanta, GA, USA, 11–12 March 2012; pp. 1–10.

8. Lyne, M.C.; Nieuwoudt, W.L. Inefficient land use in KwaZulu: Causes and remedies. *Dev. S. Afr.* 2019, 8, 193–201. [CrossRef]

9. Yuan, M.; Song, Y.; Huang, Y.; Hong, S.; Huang, L. Exploring the association between urban form and air quality in China. *J. Plan. Educ. Res.* 2018, 38, 413–426. [CrossRef]

10. Peng, J.; Du, Y.; Liu, Y.; Hu, X. How to assess urban development potential in mountain areas? An approach of ecological carrying capacity in the view of coupled human and natural systems. *Ecol. Indic.* 2016, 60, 1017–1030. [CrossRef]

11. Ta, N.; Chai, Y.; Zhang, Y.; Sun, D. Understanding job-housing relationship and commuting pattern in Chinese cities: Past, present and future. *Transp. Res. Part D Transp. Environ.* 2017, 52, 562–573. [CrossRef]

12. Zhang, D.; Wang, X. Effects of jobs–residence balance on commuting patterns: Differences in employment sectors and urban forms. *Transp. Res. Rec.* 2015, 2500, 80–92. [CrossRef]

13. Wohluter, K. *Geometric Design of Roads Handbook*; CRC Press: Boca Raton, FL, USA, 2019.

14. Wang, Z.; Li, L.; Li, Y. From super block to small block: Urban form transformation and its road network impacts in Chenggong, China. *Mitig. Adapt. Strateg. Glob. Change* 2015, 20, 683–699. [CrossRef]

15. Zhao, L.; Deng, M.; Wang, J.Q.; Peng, D.L. Structural property analysis of urban street networks based on complex network theory. *Geogr. Geo-Inf. Sci.* 2010, 26, 11–15.

16. Boeing, G. A multi-scale analysis of 27,000 urban street networks: Every US city, town, urbanized area, and Zillow neighborhood. *Environ. Plan. B Urban Anal. City Sci.* 2020, 47, 590–608. [CrossRef]

17. Ki, D.; Lee, S. Analyzing the effects of Green View Index of neighborhood streets on walking time using Google Street View and deep learning. *Lands. Urban Plan.* 2021, 205, 103920. [CrossRef]

18. Lämmer, S.; Gehlsen, B.; Helbing, D. Scaling laws in the spatial structure of urban road networks. *Phys. A Stat. Mech. Appl.* 2007, 363, 89–95. [CrossRef]

19. De Montis, A.; Barthélémy, M.; Chessa, A.; Vespiignani, A. The structure of interurban traffic: A weighted network analysis. *Environ. Plan. B Plan. Des.* 2007, 34, 905–924. [CrossRef]

20. Yan, Y.; Zhang, S.; Tang, J.; Wang, X. Understanding characteristics in multivariate traffic flow time series from complex network structure. *Phys. A Stat. Mech. Appl.* 2007, 477, 149–160. [CrossRef]

21. Fei, S.; Wei, W. urban road network structure analysis. *Urban Plan.* 2007, 8, 68–73.

22. Sharifi, A. Resilient urban forms: A review of literature on streets and street networks. *Build. Environ.* 2019, 147, 171–187. [CrossRef]

23. Knoop, V.L.; De Jong, D.; Hoogendoorn, S.P. Influence of road layout on network fundamental diagram. *Transp. Res. Rec.* 2014, 2421, 22–30. [CrossRef]

24. Reed, P.S. Toward Form: Louis I. Kahn’s Urban Designs for Philadelphia, 1939–1962. Ph.D. Thesis, University of Pennsylvania, Philadelphia, PA, USA, 1989.

25. Afsin, N. Questioning Urban Design Dimensions of the Cul-De-Sacs in the Walled City of Famagusta. Master’s Thesis, Eastern Mediterranean University (EMU)-Doğu Akdeniz Üniversitesi (DAÜ), Gazimağusa, Cyprus, 2016.

26. Tsiotas, D.; Polyzos, S. The topology of urban road networks and its role to urban mobility. *Transp. Res. Procedia.* 2017, 24, 482–490. [CrossRef]

27. Jiang, B. A topological pattern of urban street networks: Universality and peculiarity. *Phys. A Stat. Mech. Appl.* 2017, 384, 647–655. [CrossRef]

28. Zhu, Z.; Zhang, A.; Zhang, Y. Connectivity of intercity passenger transportation in China: A multi-modal and network approach. *J. Transp. Geogr.* 2018, 71, 263–276. [CrossRef]

29. Chen, S.; Claramunt, C.; Ray, C. A spatio-temporal modelling approach for the study of the connectivity and accessibility of the Guangzhou metropolitan network. *J. Transp. Geogr.* 2014, 36, 12–23. [CrossRef]

30. Qu, L.; Tai, Y.; Nadin, V. The changing scale and spatial structure of chinese city regions a case study on the development of Panyu district in Guangzhou metropolitan area. In Proceedings of the 2012 6th International Association for China Planning Conference (IACP), Wuhan, China, 17–19 June 2012; pp. 1–11.

31. Derrible, S.; Kennedy, C. Characterizing metro networks: State, form, and structure. *Transportation* 2010, 37, 275–297. [CrossRef]
32. Amini, B.; Peiravian, F.; Mojarradi, M.; Derrible, S. Comparative traffic performance analysis of urban transportation network structures. *arXiv* 2015, arXiv:1507.03612.
33. Liu, W.; Li, X.; Liu, T.; Liu, B. Approximating betweenness centrality to identify key nodes in a weighted urban complex transportation network. *J. Adv. Transp.* 2019, 2019, 9024745. [CrossRef]
34. Scheurer, J.; Porta, S. Centrality and connectivity in public transport networks and their significance for transport sustainability in cities. In Proceedings of the World Planning Schools Congress, Global Planning Association Education Network, Mexico City, Mexico, 13–17 July 2006.
35. Fielbaum, A.; Jara-Diaz, S.; Gschwender, A. Optimal public transport networks for a general urban structure. *Transp. Res. Part B Methodol.* 2016, 94, 298–313. [CrossRef]
36. Zuo, T.; Wei, H. Bikeway prioritization to increase bicycle network connectivity and bicycle-transit connection: A multi-criteria decision analysis approach. *Transp. Res. Part A Policy Pract.* 2019, 129, 52–71. [CrossRef]
37. Szell, M.; Mimar, S.; Perlman, T.; Ghoshal, G.; Sinatra, R. Growing urban bicycle networks. *arXiv* 2021, arXiv:2107.02185.
38. Zhang, H.; Lan, T.; Li, Z. Fractal evolution of urban street networks in form and structure: A case study of Hong Kong. *Fractals* 2020, 28, 1250060. [CrossRef]
39. Zhang, H. Uncovering Road Network Structure through Complex Network Analysis. Ph.D. Thesis, Hong Kong Polytechnic University, Hong Kong, China, 2011.
40. Han, B.; Sun, D.; Yu, X.; Song, W.; Ding, L. Classification of urban street networks based on tree-like network features. *Sustainability* 2020, 12, 628. [CrossRef]
41. Moroni, S.; Rauws, W.; Cozzolino, S. Forms of self-organization: Urban complexity and planning implications. *Environ. Plann. B Urban Anal. City Sci.* 2020, 47, 220–234. [CrossRef]
42. LOBsang, T.; Zhen, F.; Zhang, S. Can Urban Street Network Characteristics Indicate Economic Development Level? Evidence from Chinese Cities. *ISPRS Int. J. Geo-Inf.* 2020, 9, 192. [CrossRef]
43. Qian, Y.S.; Wang, M.; Kang, H.X.; Zeng, J.W.; Liu, Y.F. Study on the road network connectivity reliability of valley city based on complex network. *Math. Probl. Eng.* 2012, 2012, 430785. [CrossRef]
44. Zong, L.; He, S.; Lian, J.; Bie, Q.; Wang, X.; Dong, J.; Xie, Y. Detailed Mapping of Urban Land Use Based on Multi-Source Data: A Case Study of Lanzhou. *Remote Sens.* 2020, 12, 1987. [CrossRef]
45. De Tré, G.; Van Britsom, D.; Mathé, T.; Branselaer, A. Automated cleansing of POI databases. In *Quality Issues in the Management of Web Information*; Springer: Berlin/Heidelberg, Germany, 2013; pp. 55–91.
46. Boeing, G. Street network models and indicators for every urban area in the world. *Geogr. Anal.* 2021. [CrossRef]
47. Hillier, B. Centrality as a process: Accounting for attraction inequalities in deformed grids. *Urban Des. Int.* 1999, 4, 107–127. [CrossRef]
48. Lu, C.; Pang, M.; Zhang, Y.; Li, H.; Lu, C.; Tang, X.; Cheng, W. Mapping Urban Spatial Structure Based on POI (Point of Interest) Data: A Case Study of the Central City of Lanzhou, China. *ISPRS Int. J. Geo-Inf.* 2020, 9, 92. [CrossRef]
49. Wang, L. Planning for cycling in a growing megacity: Exploring planners’ perceptions and shared values. *Cities* 2020, 106, 102857. [CrossRef]
50. Dökmeci, V.; Berköz, L. Transformation of Istanbul from a monocentric to a polycentric city. *Eur. Plan. Stud.* 1994, 2, 193–205. [CrossRef]
51. Kloosterman, R.C.; Musterd, S. The polycentric urban region: Towards a research agenda. *Urban Stud.* 2001, 38, 623–633. [CrossRef]
52. Barthelemy, M.; Bordin, P.; Berestycki, H.; Gribaudi, M. Self-organization versus top-down planning in the evolution of a city. *Sci. Rep.* 2013, 3, 2153. [CrossRef]
53. Sholihah, A.B.; Heath, T. Assessing the quality of traditional street in Indonesia: A case study of pasar baru street. *Procedia-Soc. Behav. Sci.* 2016, 234, 244–254. [CrossRef]