The Study on the Measurement and Enhancement Strategies of Urban Street Space Quality Based on Street View Images: A Case Study of Streets in the Central Urban Area of Xi'an

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Abstract
Identifying the spatial quality characteristics of urban streets is crucial for achieving scientific planning and effective management. This provides a basis for optimizing urban spatial layouts and promotes the intelligent and sustainable development of cities. However, most previous studies have been limited to specific neighborhoods, lacking a systematic analysis of street quality across large urban areas. Therefore, this study integrates spatial pattern data and street landscape image data from the main urban area of Xi 'an, constructing a quantitative database for street spatial quality. It establishes a measurement system from both objective physical space and subjective perception. The system covers four primary dimensions: safety, comfort, richness, and convenience, with fourteen evaluation indicators. The system uses the entropy value method to assign weights and completes a large-scale quantitative assessment of street spatial quality. The study results indicate: (1) The spatial quality of streets in the main urban area of Xi' an generally shows a 'high in the center, low in the periphery' layered distribution pattern. The central urban area has significant advantages in street interfaces, visual environments, and traffic organization, while the peripheral new districts face issues such as insufficient greenery, enclosed spaces, and single-function configurations. (2) Through K-means clustering, this study identifies four types of street spatial qualities: safety-oriented, ecological comfort, interface vitality, and pedestrian convenience. It further analyzes the causes and mechanisms of these types from four aspects: location conditions, land use, planning policies, and historical evolution. (3) The study also used the Cohen's s Kappa coefficient to test the consistency between model outputs and subjective perception levels. The results showed that the integrated model outperformed the single objective index model in terms of recognition accuracy, confirming the necessity of incorporating perception dimensions. (4) Enhancing the spatial quality of streets requires a multi-dimensional collaborative strategy, including enriching street interfaces, enhancing road surveillance and lighting design, and improving green spaces and pedestrian facilities. The framework for measuring street spatial quality proposed in this paper is highly scalable and adaptable, both methodologically and practically. It not only provides a basis for targeted measures to improve the quality of streets in Xi' an's main urban area but also offers a feasible path and technical support for other cities to advance the refined governance and human-centric optimization of public spaces.

Key words: street space quality; street scene image; subjective and objective fusion; cluster analysis

1. Introduction

As urbanization accelerates and urban governance concepts evolve, enhancing the quality of urban public spaces has become a critical support for achieving livable, resilient, and sustainable cities. Streets, being the most human-centric urban units, not only serve as basic traffic corridors but also play a vital role in connecting diverse urban activities, fostering social interactions, and shaping the city's image. The quality of street spaces directly impacts residents' daily experiences, travel preferences, and the overall vitality of the city, making it a core issue in urban planning and governance (Xuan & Zhao, 2022).

Traditionally, the assessment of street space quality has primarily focused on the physical environment, emphasizing 'visible structure' indicators such as road section design, greenery layout, and the continuity of street interfaces (Wan, Lu, & Sun, 2022). However, this method, which emphasizes structural objectivity, often overlooks the subjective feelings and emotional responses of space users, making it difficult to fully capture the comprehensive impact of street spaces on residents 'psychological and behavioral aspects. In the current trend of urban governance that increasingly emphasizes' people-oriented 'and' perception-focused 'approaches, there is an urgent need to develop a multi-dimensional evaluation system that integrates subjective experience with objective measurement, breaking through the limitations of existing theories and methods (L. Zhang, Ye, Zeng, & Chiaradia, 2019). Meanwhile, with the rapid advancement of street image technology and computer vision algorithms, the recognition of urban street space characteristics is becoming more automated and refined (Ye, Zeng, Shen, Zhang, & Lu, 2019). Street images, as spatial data that approximate the human eye's perspective, offer the advantage of high-frequency, low-cost acquisition of street visual landscape features. By integrating deep learning and perception modeling technologies, these images can achieve quantitative analysis of street spaces in terms of safety, livability, and aesthetics, significantly expanding the depth and breadth of evaluation metrics (Tang & Long, 2019; Yu, Zhang, & Zeng, 2019). Therefore, the data-driven measurement framework based on street view images has become a key development direction in the current research on urban spatial quality.

However, existing research still has several shortcomings: Firstly, most studies focus on typical street segments with small sample sizes, lacking systematic coverage of large-scale urban areas, which makes it difficult to reveal the overall distribution and spatial heterogeneity of street space quality. Secondly, discussions on the integration of subjective and objective factors are mostly theoretical, without a mature and stable empirical approach. Thirdly, there is currently a lack of a comprehensive research chain that effectively links measurement results to the identification of street space types, the analysis of formation mechanisms, and the formulation of subsequent optimization strategies, which affects its practical application in urban governance.

This paper selects the main urban area of Xi'an City, China, as the research area and proposes a framework for evaluating street spatial quality that integrates street scene image recognition, subjective perception modeling, and the measurement of street physical characteristics. The framework systematically analyzes the distribution pattern, type characteristics, and formation mechanisms of street space. The main innovations of this study include: first, integrating street scene images with GIS spatial data to construct a multi-level indicator system that encompasses both subjective and objective dimensions, thereby enhancing the accuracy of street spatial quality assessment; second, using the K-means clustering method to identify different types of street space, revealing the combined differences in safety, comfort, interface vitality, and functional accessibility among these types; third, based on multiple factors such as location characteristics, land use, policy orientation, and historical culture, the study deeply analyzes the formation mechanism of street spatial quality and proposes practical optimization paths and spatial zoning suggestions.

2. Literature review

In recent years, with the advancement of big data and automated analysis technologies, the measurement of urban street space quality has shifted from traditional subjective surveys and manual observations to a quantitative evaluation method based on multi-source data integration. As a vital part of urban public spaces, streets not only influence travel behavior but also directly impact urban vitality and residents 'quality of life. Early theories, proposed by Lynch, Jacobs, and others, focused on the linear continuity, human scale, and visual appearance of streets. Today's research leverages deep learning, street view imagery, and GIS technology to automate the measurement of various elements of streets, including greenery, building facades, skylines, and pedestrian activities (Harvey & Aultman-Hall, 2016).

Traditional evaluation methods primarily rely on questionnaires and on-site observations to capture the perceived environment and visual effects of streets. While these methods can directly reflect user experiences, their limited sample sizes and subjective assessments make them unsuitable for large-scale application. To address this issue, researchers have developed automated evaluation methods based on street view images and geospatial data in recent years. These methods use deep learning and computer vision to segment street view images semantically, automatically extracting indicators such as green visibility, road width, building proportions, and sky perspective factors, forming a quantitative physical measurement system (Biljecki & Ito, 2021; Tang & Long, 2019). In contrast, other studies focus on integrating physical indicators with pedestrian perceptions, validating the accuracy of automatic measurements through expert ratings, questionnaires, or social media sentiment analysis (Du & Huang, 2022). Additionally, research based on indicator systems often draws from the 5D framework, which includes density (Density), diversity (Diversity), design (Design), destination accessibility (Destination Accessibility), and transportation distance (Distance to transit), and has been expanded to include dimensions such as social, safety, and cultural aspects, such as the 5D+3S model (Wan et al., 2022; L. Zhang et al., 2019).

Despite progress in quantifying street space quality, current research often focuses on measuring physical space in a single dimension, particularly on extracting and analyzing structural features such as green coverage, building density, and street interfaces. However, incorporating residents' subjective perceptions has lagged behind, facing issues such as insufficiently systematic indicator construction, inadequate coupling between dimensions, and limited validation methods (Han, Wang, Seo, He, & Jung, 2022). Even studies that attempt to integrate subjective and objective elements are often confined to specific street segments or small experimental areas, lacking systematic and standardized analysis for larger-scale urban spaces. Moreover, the current methods for collecting subjective perception data still heavily rely on costly manual surveys or limited sampling, which cannot meet the demands for high-frequency, dynamic, and extensive street assessments (Ogawa, Oki, Zhao, Sekimoto, & Shimizu, 2024). Therefore, there is an urgent need to develop a street space quality measurement system that balances physical characteristics with subjective experiences, is scalable, and practical. This would not only enhance the precision of urban governance but also provide robust data support and decision-making for smart city development and public space optimization. Based on this background, this paper intends to carry out a systematic study integrating intelligent analysis and perception verification mechanism of street view images, focusing on filling the deficiencies of existing research in the construction of multi-dimensional index system, spatial heterogeneity identification and strategy optimization path, which has important theoretical significance and practical value.

3. Study areas and data sets

3.1 Research area

This study selects Xi 'an City in China as the subject of empirical analysis. Located in the middle of the Guanzhong Plain, Xi' an is situated between 107°24′00″E and 109°29′24″E, and 33°25′12″N and 34°27′00″N. It borders the Wei River to the north and the Qinling Mountains to the south, forming the heart of the 800-li Qin Plain. Known as the 'ancient capital of thirteen dynasties,' Xi 'an has a city-building history of over 3,100 years and a capital-building history of over 1,100 years. Thirteen dynasties, including the Western Zhou, Qin, Han, Sui, and Tang, have established their capitals here. This study focuses on the main urban area of Xi' an, which includes six administrative districts: Xincheng, Beilin, Baqiao, Yanta, Lianhu, and Weiyang (Figure 2). The district comprises 55 sub-districts and covers a total area of 836.02 square kilometers (Lin, Xiping, Junyi, Yongyong, & Zhiyuan, 2025).

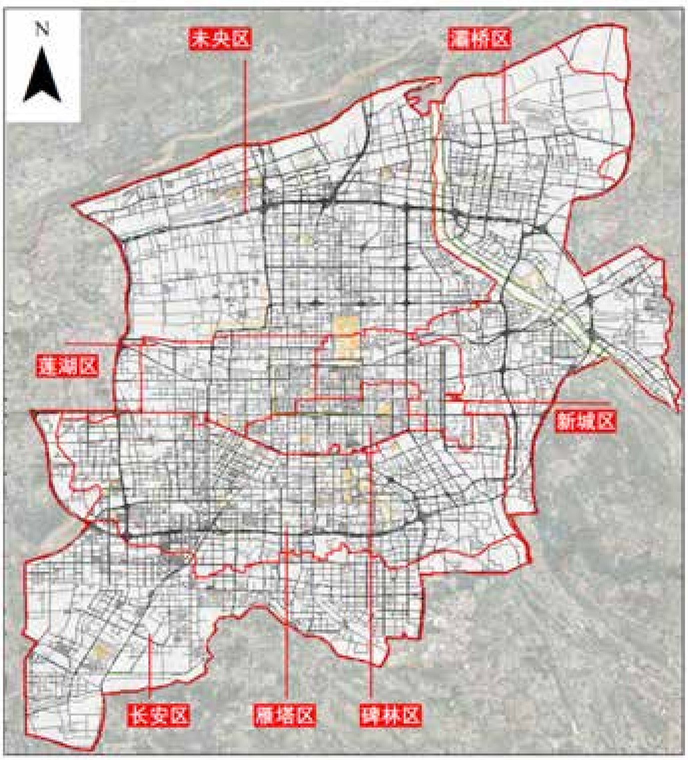

Figure 1. Scope of the study

3.2. Data sets and variables

The institute's data encompasses a variety of sources, including basic road information, spatial quality assessments, and administrative divisions. The basic road information is sourced from the 2021 updated OSM platform (https://openstreetmap.org/). POI data are collected via Python 3.8 from Baidu and AutoNavi Maps, and have been corrected. Street view images are primarily sourced from Baidu Panorama Map, with 360 Maps providing supplementary data for missing areas. Sampling points are set at intervals of 100 m, capturing human-viewed images from 90°,180°,270°, and 360° angles (1024×512 resolution). Image semantic segmentation tools are used to extract the proportions of building interfaces, sky, and greenery. Administrative division base maps are sourced from the National Basic Geographic Information Public Service Platform and are uniformly projected into a consistent coordinate system using ArcGIS 10.7.

Table 1 Multi-source, multi-scale data types, sources and processing

data name	data sources	acquisition time	data handling
Road network data	Open Street Map	December 2024	After the road centerline is simplified and extracted by manual, the topology is checked and verified with reference to the Gaode satellite image
Street View data	Baidu Open Street View Map platform	December 2024	The Baidu Street View API was called to collect 289,664 static panoramic images with a spacing of 50 m, and the image size was 1024x512 pixels. Then the Mask2Former semantic segmentation model was used to segment the street view images.
Interest point (Point of Interest, POI) data	Baidu Map	December 2024	The geographic information interest point (POI) data was obtained from Baidu Map API. According to the research needs, 18 kinds of POI data such as food, hotel and shopping were obtained within the research scope and its surrounding area. The data contained industry categories, names, addresses, administrative areas and other information.
MIT Place Pulse Data set	MIT Media Lab Developed Place Pulse projects	December 2024	The Microsoft Trueskill algorithm was used to calculate the corresponding perception scores of six dimensions, and the model was trained to predict the scores of six perception dimensions on the streets in the central urban area of Xi 'an.

4. Research methods

4.1 Subjective perception score acquisition

In this study, to more accurately capture residents' subjective perceptions of the street space environment, the Place Pulse 2.0 dataset and its accompanying subjective perception model, developed by MIT Media Lab, were introduced as the core tool for generating perception scores. Place Pulse constructed a street scene perception evaluation system covering six dimensions—safety, security, livability, vitality, wealth, and sociality—by conducting paired comparisons and scoring global street scenes. The scoring results were then quantified and ranked using the Microsoft Trueskill algorithm (L. Wang, Han, He, & Jung, 2022).

In the implementation of this study, street view images from the main urban area of Xi 'an were selected as input data. Using a pre-trained Place Pulse perception model, scores were assigned to each image across multiple perceptual dimensions. To enhance the model's performance in localized applications, the model was fine-tuned and refined based on a small amount of manual scoring results. For each sampling point, four street view images were collected from four directions (90°,180°,270°,360°). Scores were assigned to each image and a weighted average was calculated to obtain the overall subjective perception score for that sampling point.

Subsequently, the study utilized GIS tools to map the scoring results onto street grid units, achieving a spatial visualization of scene perception. Ultimately, by calculating the weighted average of the scores from multiple sampling points on each street, the study derived the representative subjective evaluation of that street. This scoring system not only provides a clear reflection of residents' overall impressions of the street environment but also offers crucial data and theoretical support for future analyses that integrate with objective physical indicators.

4.2 Objective perception score acquisition

The objective perception scoring system proposed by this institute primarily relies on semantic segmentation analysis of street view images and geospatial data processing. It aims to achieve automated and standardized quantitative evaluation of the physical characteristics of urban street spaces. The research team first used the Baidu Street View Open Platform API to set up sampling points at intervals of 50 meters in the main urban area of Xi'an City. They collected static street view images from four directions (90°,180°,270°,360°), with a uniform image size of 1024×512 pixels, to ensure data consistency and improve subsequent processing efficiency.

Subsequently, using the deep learning model Mask2Former, pixel-level semantic segmentation was performed on the images to automatically identify the proportions of greenery, sky, buildings, roads, and motor vehicles (Cheng et al., 2021). Based on this proportion information, a quantitative index system reflecting the spatial characteristics of streets was constructed, including dimensions such as road accessibility, motor vehicle interference intensity, visibility of greenery and sky, and street interface morphology (W. Zhang, Chen, & Tian, 2025). The image analysis results were matched with the road space network, and using GIS analysis tools, the measurement values were mapped to each street segment. An objective perception score at the street scale was formed based on the weighted average of the sampling points in each street segment.

To enhance the robustness and representativeness of the index system, the study integrates POI data to supplement the identification of street safety facilities (such as surveillance cameras) and functional interfaces (such as ground-floor openness). It also considers factors such as building openness, material diversity, and pedestrian accessibility, thereby constructing a more comprehensive framework for evaluating street physical characteristics (Miaoyi, Zhonghao, & Feng, 2021). The final scoring results not only reflect both structural and functional aspects but also lay a solid foundation for the integration of subjective perception results in subsequent analyses. This further supports the multi-dimensional modeling of street spatial quality and the identification of regional differences.

4.3 Construction of street quality index system

In constructing an evaluation system for assessing the quality of street spaces, this paper adheres to the urban design philosophy of 'people-oriented,' balancing practicality and interpretability. It integrates the objective attributes of physical space with residents' subjective perceptions, forming a diverse and systematic evaluation framework. This system primarily relies on street scene images, spatial data, and perception models as core information sources, aiming to comprehensively reflect the overall performance of street spaces from multiple perspectives, including function, environment, and experience.

On the objective level, the evaluation system focuses on the structural characteristics and functional environment of streets, covering key indicators such as spatial openness, traffic interference, green space ratio, street interface complexity, and pedestrian accessibility. It emphasizes the physical safety, comfort, and connectivity of streets (R. Wang, Huang, & Ye, 2024). On the subjective level, the system incorporates Place Pulse's perception scores, focusing on psychological dimensions like security, livability, vitality, and social interaction. This approach addresses the individual experience differences that traditional physical measurements often overlook, reflecting the environmental impact on residents' emotions and behaviors.

To achieve the organic integration of two dimensions, this paper uses a unified street segment spatial unit as the foundation and standardizes both subjective and objective indicators through Z-score normalization, enabling the comparison and analysis of indicators with different scales within the same system. By integrating the results of principal component analysis and correlation tests, the eight core indicators are categorized into three primary dimensions: spatial efficiency, visual environment, and user experience, forming a hierarchical model for measuring street quality. This model not only highlights the multi-level characteristics of street space but also lays the theoretical groundwork for subsequent cluster analysis and spatial difference studies.

By integrating multi-source data and constructing a dual-dimensional framework, this paper transforms the spatial structure from 'visible' to 'felt' life experiences, advancing street quality research from a single physical measurement to a more comprehensive evaluation method. This approach provides practical pathways and assessment tools for creating urban spaces with a focus on humanistic care and refined governance (Wei, Tingting, & Jie, 2024). To validate the effectiveness of integrating subjective and objective dimensions in measuring street spatial quality, the paper further calculated the consistency between the fusion model and the single objective model in terms of street classification levels and subjective perception levels. The results showed that, based on Cohen's Kappa coefficient, the consistency between the single objective index model and subjective perception was -0.092, while the consistency between the subjective perception and the fusion model was -0.074 (Blackman & Koval, 2000; Warrens, 2015). Although neither model achieved a high level of consistency, the fusion model demonstrated better matching, confirming the importance of incorporating the subjective perception dimension in enhancing model accuracy and aligning with residents' experiences.

Table 2 Construction environment indicators and calculation methods

dimension	metric	computational method	weight	direction
safety	Vehicle interference	The degree of influence of motor vehicle traffic on pedestrian activity is measured by the number of vehicles in the unit.	0.0015	-
	Road surveillance	Assess the safety of a street, known as the "eyes on the street," by counting the number of surveillance facilities or pedestrians and shops on either side of the street.	0.1814	+
	sense of security	Based on the Place Pulse model, the "safety" dimension of street view images is scored, and the weighted average of multi-angle image scores is obtained to obtain the perceived safety score of street segments.	0.0138	+
degree of comfort	Visibility in the sky	The proportion of the visible part of the sky in the street space is calculated to reflect the degree of visual openness. The proportion of the sky in the total pixels is calculated through the analysis of street view images.	0.1663	+
	High ratings	The proportion of green vegetation in the street view is calculated to reflect the greening degree of the street. The proportion of green pixels in the total pixels is calculated through street view image analysis.	0.0792	+
	Sense of oppression	Based on the negative score results of "livability" and "safety" dimensions of Place Pulse model, the weighted calculation was carried out, and the lower the value, the stronger the sense of depression.	0.0162	-
	aesthetic feeling	The perception score of "aesthetics" dimension of Place Pulse model reflects residents' subjective evaluation on the visual image of the street, and the higher the score is, the stronger the aesthetic sense is.	0.0082	+

	Interface transparency	Measures the transparency of the facade of buildings on both sides of the street, i.e. the proportion of transparent or translucent parts (such as Windows, porches). Through street view image analysis, the proportion of transparent area to total facade area is calculated.	0.2699	+
rich	Interface richness	Evaluate the detail and diversity of the facade of buildings on both sides of the street. This can be measured by calculating the types and numbers of facade elements, such as decoration, material changes, etc.	0.0881	+
	Liveliness	The “activity” dimension of Place Pulse model is used to score the perception, which reflects residents’ subjective evaluation on the visual image of the street. The higher the score, the higher the activity.	0.0264	+
	Boredom	The perception score of the “boredom” dimension of Place Pulse model reflects residents’ subjective evaluation on the visual image of the street. The higher the score is, the higher the boredom degree is, which is a negative factor.	0.0096	-
	Walkable accessibility	Measures how easily pedestrians can get from the street to various facilities (such as stores, public transport stops). It is usually calculated by calculating the number and distance of various facilities within a certain range around the street, combined with the street connectivity index.	0.1320	+
convenience	Function mixing	The diversity of land use around the street is evaluated. The information entropy formula is usually used to calculate the proportion and distribution of different functions (such as residential, commercial, office, etc.) of land use around the street.	0.0013	+
	A sense of affluence	Based on the “sense of wealth” dimension score of Place Pulse model, the building material, facade decoration complexity and high-end commercial POI density are taken as auxiliary factors for comprehensive calculation.	0.0060	+

5.Results and analysis
5.1 Street quality identification results
To more deeply uncover the regional differences in the spatial quality of different streets within Xi ‘an’s main urban area, this study uses administrative districts as the basic analysis units. It employs the entropy value method to calculate comprehensive evaluation scores, conducting a systematic quantitative statistical analysis of the street quality in the five core urban districts: Xincheng District, Lianhu District, Beilin District, Weiyang District, and Yanta District. The study reveals that there are significant differences in street spatial quality among these five districts, reflecting a typical ‘layer differentiation’ spatial structure where the central urban area outperforms the peripheral new districts.

In terms of overall performance, the street space quality scores of Xincheng District and Lianhu District rank at the top, with average comprehensive scores of 10.39 and 10.38, respectively. Both districts have scores that are close to each other and significantly outperform other administrative regions. This indicates that the central urban area has a clear advantage in street space interface design, environmental openness, greening levels, and pedestrian infrastructure construction, reflecting the long-term efforts of historical urban areas in refined urban management and planning. Additionally, the score standard deviations for the two districts are 2.69 and 2.96, respectively, indicating a high degree of balance in street space quality within the region, without significant polarization. The overall quality is maintaining a stable and balanced development trend.

The Beilin District, an old district with a rich historical and cultural heritage, also excels in street space quality, scoring an average of 10.00, ranking it among the top districts. The standard deviation of its score is 2.53, lower than that of Lianhu District, indicating relatively minor internal differences in street quality. However, the district's highest score of 26.58 significantly surpasses other districts, highlighting the outstanding performance of some historically significant and culturally rich streets in terms of visual appeal, environmental comfort, and interface diversity, showcasing the unique advantages of cultural streets. However, the lowest score in the district is only 5.77, significantly below the average of other districts, suggesting an uneven distribution of street quality within the district. The disparity in spatial quality between historical protection areas and ordinary streets warrants close attention during urban renewal efforts.

As key areas of urban expansion in Xi'an City in recent years, Weiyang District and Yanta District have an average street space quality score of 9.57 and 9.23, respectively, which is significantly lower than that of traditional central urban areas. While some streets in these districts have high scores, with the highest score exceeding 22 points, indicating a relatively good level of construction in certain areas, the overall standard deviation of street scores in these two new districts is relatively low, at 2.49 and 2.21, respectively, suggesting a noticeable trend towards homogenization in the design and construction style of street spaces. Notably, the lowest scores in Weiyang District and Yanta District are 4.60 and 4.69, respectively, far below the lowest scores in other administrative regions. These low scores are primarily concentrated in the urban fringe areas, highlighting issues such as strong motor vehicle interference, insufficiently transparent street interfaces, and inadequate green coverage, which require targeted improvements in future urban renewal efforts.

Further analysis of the distribution of street quality scores across different administrative districts reveals that high-quality streets are widely distributed in Xincheng District and Lianhu District, with generally superior spatial environments. In contrast, Weiyang District and Yanta District exhibit a dense concentration of medium to low-quality streets. This significant differentiation in spatial quality is closely linked to differences in urban development history, functional positioning, and policy resources, reflecting distinct development strategies in street spatial structure, land use methods, and functional layout across districts.

In summary, this study uses a comprehensive evaluation method to conduct a quantitative comparative analysis of the spatial quality of streets in various administrative districts of Xi 'an's main urban area. It highlights significant differences in spatial quality between traditional urban areas and emerging new districts. When formulating policies for future street quality improvements, it is essential to fully respect and integrate the specific development characteristics of each district. The central urban area should continue to enhance the optimization of interface details and the diversity of landscapes. For the peripheral new districts, the focus should be on increasing environmental openness, reducing traffic disturbances, and improving overall spatial comfort. This approach aims to promote the gradual coordinated development of street spatial quality across different regions, achieving balanced optimization and sustainable progress in the urban spatial environment.

Figure 2 Street quality identification results

Table 3 Street quality by district

canton	average value	standard deviation	maximum value	low
new city zone	10.39	2.69	24.83	5.22
Lianhu District	10.38	2.96	25.76	5.20
Beilin District	10.00	2.53	26.58	5.77
Weiyang District	9.57	2.49	22.45	4.60
Yanta District	9.23	2.21	23.12	4.69
Baqiao District	9.22	2.33	23.84	4.65
Chang'an District	8.83	1.77	24.38	4.46

5.2 Identification and characteristic analysis of street quality space types
In exploring the internal structural characteristics of street space quality in Xi 'an's main urban area, this paper uses the four core dimensions —— safety, comfort, richness, and convenience, established in the street space quality evaluation system, to classify the street spaces within the study area using the K-means clustering analysis method. Based on the performance differences of various streets across these dimensions, they are categorized into four types: 'safety-oriented streets,' 'ecological comfort streets,' 'interface vitality streets,' and 'pedestrian convenience streets.' The specific features of each type of street are as follows:

(1) Safety-oriented streets
These streets excel in safety, typically equipped with comprehensive road surveillance systems, offering a strong sense of security and relatively low motor vehicle interference. They are commonly found in densely populated or commercially active areas, providing robust public security. However, they fall short in terms of visual transparency (such as sky views) and green coverage, with room for improvement in the transparency and diversity of street interfaces. Therefore, future planning for these streets should focus on enhancing safety facilities while also improving ecological landscapes and visual quality.

(2) Ecological comfortable streets
These streets excel in green ecological indicators and visual environmental quality, featuring high green plant coverage, wide-open views, and a pleasant overall spatial experience. They are generally well-received by residents and are commonly found around green corridors, parks, and ecological scenic boulevards. However, they fall short in terms of pedestrian accessibility and mixed-use functionality, with insufficient interaction at street interfaces. Future urban renewal efforts should focus on enhancing functional complementarity and improving the pedestrian system to boost spatial vitality and usage efficiency.

(3) Interface dynamic street
Interface dynamic streets are renowned for their transparency, richness, and spatial vibrancy. They feature diverse building facades and strong visual appeal, creating a highly interactive and vibrant street environment. These streets are typically found in core commercial districts, historical and cultural areas, or tourist hotspots, making them ideal venues for cultural, commercial, and entertainment activities. However, high traffic volumes and a certain level of environmental pressure can also negatively impact the quality of experience. Therefore, while maintaining the vitality of the interface, enhancing traffic order and spatial transparency will be key areas for future optimization.

(4) Pedestrian-friendly streets
This type of street excels in pedestrian accessibility, mixed land use, and facility configuration. It features a well-planned spatial layout that is highly pedestrian-friendly, making it an essential part of daily commuting and living activities. Such streets are commonly found around urban commercial centers, transportation hubs, and comprehensive service areas. However, they generally lack visual appeal and greenery, with the street interface's attractiveness and visual comfort needing improvement. Future improvements should focus on enhancing visual experiences and ecological environments to comprehensively improve the quality and appeal of street spaces.

5.3 Analysis of the formation mechanism of street space quality types
The quality of street space is a key indicator for assessing the overall quality of urban public spaces, and its development is influenced by multiple factors. Based on the classification of street space types in Xi 'an's main urban area, this paper further explores the underlying mechanisms behind the differences in street quality from four perspectives: spatial location, land use, planning policies, and historical context.

(1) Differences in spatial location and endowment
The quality of street spaces is often closely tied to their location. Traditional central urban areas, such as Xincheng District, Lianhu District, and Beilin District, boast well-developed street systems and comprehensive commercial services and public facilities, offering superior location advantages. These factors naturally enhance the street vitality and pedestrian-friendliness of these areas. Moreover, early investment in public safety infrastructure has led to a dense distribution of 'safety-oriented streets' in central urban areas. In contrast, peripheral areas like Yanta District and Weiyang District, due to their later urban expansion, have less developed infrastructure, and the development of street safety and vitality is still in its early stages.

(2) Characteristics of land use mode and functional layout
The formation of different types of street spaces is closely linked to the intensity of land use and functional configurations. Pedestrian-friendly streets are typically found in commercial nodes, transportation hubs, and public service areas, where the land use is highly mixed, facilities are densely packed, and the focus is on enhancing pedestrian experience. Ecological comfort streets are mainly located around parks, green spaces, ecological axes, and new residential areas, characterized by low land density, high green coverage, and an open visual environment. Interface vitality streets, which rely on cultural and commercial land, feature interactive and visually diverse building facades, making the spatial interfaces highly attractive.

(3) Urban planning policy and governance orientation
In recent years, Xi 'an's planning policies have increasingly emphasized the quality of public spaces and the

refinement of urban governance. This has led to the updating of street safety facilities, the enhancement of interface images, and the optimization of pedestrian systems in the central urban area, resulting in a significant and stable improvement in overall spatial quality. Although the new urban areas initially focused on ecological space construction and created some ecologically comfortable streets, the lack of effective supporting policies has led to lagging development in other areas, resulting in a noticeable quality gap. In the future, it is necessary to enhance the vitality of the new district interfaces and pedestrian convenience through policy measures, promoting the coordinated development of the city's overall spatial layout.

(4) Historical development background and spatial heritage inheritance
The quality of street space is significantly influenced by the city's historical development and cultural heritage. Traditional urban areas, such as Beilin District and Lianhu District, are rich in cultural resources and humanistic landscapes. The streets in these areas have evolved over time, with highly dynamic spatial interfaces, making them an essential part of the urban landscape. In contrast, new urban areas lack historical and cultural support, and their street space design relies more on modern planning concepts, resulting in relatively weak visual and interface performance. Therefore, the renewal of street spaces should aim to protect historical and cultural heritage while integrating modern functional optimization, achieving an organic blend of tradition and modernity.

The formation of the spatial quality types of main urban streets in Xi'an City is essentially the result of the combined effects of various factors, including spatial location, land use, policy guidance, and historical and cultural elements. The location characteristics provide a foundation for development, land use enhances spatial functions, planning policies drive quality improvements, and historical heritage enriches the cultural significance of the spaces. Future urban street governance should, based on an understanding of these mechanisms, develop a multi-dimensional and balanced optimization strategy to promote the continuous improvement and coordinated development of urban public space quality.

6.Conclusion
This study, using the main urban area of Xi'an as a case, developed a framework for measuring urban street spatial quality that integrates intelligent recognition and perception scoring mechanisms of street scenes. It systematically integrates physical environmental elements with subjective perception factors, conducting a comprehensive and systematic analysis from the construction of evaluation indicators, data processing, spatial type identification to the analysis of formation mechanisms. Based on this framework, the study has reached the following key conclusions:

The subjective and objective integration evaluation system proposed in this paper has achieved significant breakthroughs in both theory and methodology for measuring the quality of street space. In terms of indicators, it expands the traditional measurement centered on physical structure to a multi-dimensional system that includes residents' perceptions. Technically, it leverages street view images and machine learning models to construct a large-scale, automated evaluation process, significantly enhancing the accuracy and applicability of street space quality analysis. By using Z-score standardization and entropy value weighting, a scientific, systematic, and hierarchical comprehensive index of street quality has been developed, providing a stable and reusable technical framework for spatial quality research.

(2) The spatial quality of the main urban area's streets generally follows a' high in the center, low on the periphery 'pattern. Traditional central areas, such as the new district and Lianhu District, excel in safety, interface diversity, green coverage, and pedestrian accessibility, with significantly higher average scores compared to peripheral new districts like Weiyang District and Yanta District. These structural differences are closely linked to the city's development stage, resource allocation, and policy priorities, highlighting the uneven distribution of urban spatial quality.

Through cluster analysis, four typical street types were identified: 'safety-oriented streets,' 'ecological comfort streets,' 'interface vitality streets,' and 'pedestrian convenience streets.' Each type of street excels in different aspects, such as the completeness of safety facilities, the openness of visual landscapes, the vibrancy of interface interactions, and the integration and accessibility of functions. This classification highlights the diverse development paths of urban street spaces in terms of composite functions, structural forms, and service performance. The results provide a clear direction for future district governance and differentiated improvements.

(4) The classification and distribution of street spatial quality are influenced by multiple mechanisms, including location conditions, land use patterns, urban planning policies, and historical and cultural heritage. The spatial location determines the level of street infrastructure and the layout of supporting facilities. The structure of land use enhances the expression of spatial attributes, policy support accelerates the pace of quality improvement, and historical heritage profoundly influences the formation of street interfaces and forms. Urban street space optimization should be based on these factors, adopting comprehensive measures to achieve dynamic integration between planning logic and spatial practice.

(5) To evaluate the model's effectiveness, the study used Cohen's s Kappa coefficient to compare the consistency between different models and subjective perception levels. The results showed that the consistency between the single objective index model and subjective perception was -0.092, while the consistency between the integrated subjective-objective model and subjective perception improved to -0.074. Although the overall consistency level still needs improvement, the integrated model performed better, further confirming the positive impact of incorporating subjective perception factors in enhancing the explanatory power and accuracy of measurement models. This finding underscores the importance of a 'people-oriented' and 'perception-led' approach in future urban spatial quality assessments.

7.Discussion

This study introduces a street space quality measurement system that integrates subjective and objective perspectives. It overcomes the limitations of traditional urban space evaluation models in both theory and methodology, significantly enhancing the ability to identify the interaction between human perception and the spatial environment. By integrating street view images, subjective perception models, and multi-dimensional evaluation indicators, the study not only achieves a broad and high-precision assessment of urban street space quality but also demonstrates the positive impact of incorporating subjective factors on improving evaluation accuracy. Compared to a single objective model, the Kappa coefficient between the subjective level and the subjective-objective integration model is superior, although overall consistency has not yet reached a significant level, it shows potential for improving recognition accuracy. Additionally, the results of street type identification reveal the diverse patterns of urban street space functions and environmental characteristics, providing practical guidance for urban zoning governance and detailed updates.

Despite achieving some success, the research still has several shortcomings. Firstly, the quality of street view images is affected by shooting time, occlusion factors, and update frequency, leading to unclear or incomplete images in some areas. Secondly, subjective perception data primarily relies on the Place Pulse model, which has strong cultural biases in its training samples, making it difficult to fully reflect the actual perceptions of urban residents in China. Thirdly, the current method of integrating subjective and objective scores uses a simple averaging approach, lacking more robust weight optimization or structural modeling strategies. Lastly, while the classification of street spatial types has some application value in policy-making, it has not yet been effectively linked with land use, socio-economic characteristics, and governance units, resulting in a certain degree of disconnection between measurement and governance. Therefore, future research should enhance the model's adaptability to local conditions, expand the sources of diverse data, introduce mechanisms for behavioral responses and logic for matching governance scenarios, and promote the evolution of street spatial quality research from technical tools to governance mechanisms.

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