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Research article

Three-dimensional characterization and calculation of highway space visual perception

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ABSTRACT

To quantify the impact of three-dimensional highway spatial characteristics on drivers' visual perception, this study analyzes the measurement points of highway spatial visual perception from the perspectives of spatial visual depression and spatial visual continuity based on spatial perception theory. Based on the hemispherical field of view, a spatial enclosure calculation method improved by "Distance/Height value" is proposed. A three-dimensional quantification model of the build-to-line ratio, including the vertical direction, was established using the relative relationship between the maximum section plane and the road area. Finally, a 3D real-scene model of the demonstration highway section was established, the proposed three-dimensional quantization method of visual perception of highway space was applied, and the road area landscape construction and promotion strategy is proposed based on the quantitative calculation results. The results show that: the overall landscape space of the highway section is undulating and that there is a lack of visual continuity. It is advisable to plant an appropriate amount of vegetation on the side of the road at 0 m–250 m and 500 m–700 m of the road section to reduce the fluctuation of its enclosure and enhance its spatial continuity. The improved quantitative results of the spatial enclosure degree and the three-dimensional build-to-line ratio can well characterize the spatial visual depression and the spatial visual continuity and can provide a basis and support for road space reorganization and the improvement of landscape construction.

1. Introduction

Highways and landscapes constitute various forms of highway space (Hu et al., 2012), and different forms of space produce different spatial visual characteristics (Hu et al., 2013). Three-dimensional spatial visual characteristics have a direct impact on the psychological feelings of drivers during driving, and also have an important impact on their driving experience and driving safety (Francesco 2013; Imalka and Sunanda 2020), it is important to consider the three-dimensional spatial visual perception characteristics of highways for highway landscape planning and design (Li et al., 2020; Liu et al., 2020). Accurate characterization and calculation of a driver's visual perception of highway space has become a real problem for highway space reorganization and landscape design.

Research on the visual perception of space has mainly focused on urban space, and most studies are based on the D/H index, where H represents the scale of a street or square, D is the scale at which people appreciate a building, and the different ratios of the two can lead to psychological feelings of dispersion, cohesion, and closure (Qin 2008). Later, Benedikt (1979) introduced the visual field into the field of architecture and Batty (2001) improved it so that the visual field could be obtained by computerized raster operations. Fisher-Gewirtzman (2003) extended the visual field analysis from two to three dimensions, making it more compatible with the spatial visual perceptual properties of humans (Fisher et al., 2003). Porta et al. (2005) counted the proportion of various visual elements of the interface constituting the street space based on the street view map and quantitatively analyzed the facade continuity, sky nudity, visual complexity, etc. Zhou Yu et al. (2016) quantitatively studied the relationship between human perception-street-side interface morphology based on interface density and build-to-line ratio and proposed the "near-line rate" index (Zhou and Wang 2018). Kurdoglu (2013) quantified the perceptual judgment of road users while driving by showing images to quantify the study. In addition, some scholars have interconnected mathematical methods with landscape evaluation,

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combined with the Delphi method (Huang et al., 2014) and expert rating method (Yan 2014; Wang et al., 2015), used statistics and psychophysics to improve the objectivity and accuracy of evaluation, and conducted research on highway landscape perception. Dai (2016) verified the evaluation indexes of highway landscape and visual coordination, including the compatibility of side slopes with the background and the compatibility of structures with the environment. Han (2019) constructed a triadic theory of highway landscape perception: a sense of safety, a sense of environment, and a sense of landscape. Huang et al. (2013) analyzed and calculated the ratio of greenery, sky, and road surface in a driver's driving view image and concluded that a landscape tending to a golden ratio of 0.618 can provide a comfortable visual perception experience for drivers. Based on the visual perception characteristics of drivers, Su et al. (2016) proposed a strategy for creating a landscape in the middle division zone, side slopes, and interchanges.

With the development of modern 3D information technology such as 3D GIS and 3D real-world modeling, there are new technical methods and analysis platforms for the visual analysis of 3D space (Belén et al., 2016), and scholars have proposed some quantitative methods for spatial visual perception and used them in urban spaces (Vitor and Oliveira 2013; Harvey 2014). The study of road spatial visual directivity through street interface build-to-line ratio was initiated, and some scholars proposed a GIS-based method to identify ideal street wall lines of roads (Sandro and Mirko 2019). Zhang (2010) used a cone to simulate the range of the human visual field and quantitatively characterized the degree of human visual closure by calculating the proportion of the sky on the base of the cone. Niu (2011) improved the Fisher-Gewirtzman visual field analysis model and proposed a calculation method for the degree of visual closure. Compared with urban space, the form of highway space is often simpler; therefore, research theories and quantitative methods of the visual perception of these spaces can be used to quantitatively study the visual perception of highway space.

Based on this, this study takes the road space as the research object, and proposes the a 3D spatial enclosure and 3D build-to-line ratio of highway space from the driver's psychological perception and drawing on the relevant theories of spatial visual perception research. Based on the 3D GIS platform, a specific quantitative analysis of highway space visual perception was conducted, and a highway landscape creation strategy based on highway space visual perception was proposed. To provide a technical reference and theoretical basis for highway spatial planning and landscape design.

2. Methods

2.1. Visual perception of highway space

Highway space refers to the space environment divided from nature by an interface composed of pavements, roadside vegetation, mountains, and structures, etc. (Dong et al., 2020). In highway space, the visual subject is the driver. After the visual experience in the highway space, the driver generates visual impressions according to the overall form of the highway space, the interface form and the relationship between the interfaces and the types and proportions of various elements (Wang et al., 2021), and generates psychological feelings, such as a sense of security, excitement, tension, and loneliness (Belén et al., 2018). As for the highway space, because the planning attributes of its constituent elements such as roadside mountains, retaining walls, and traffic ancillary facilities, are weak (Wartmann et al., 2021), the form of the highway space can be changed through landscape improvement (Yi 2021), resulting in different visual perception characteristics of the highway space and different psychological feelings of drivers. To accurately measure the visual perception of highway space, it is necessary to select and quantify the characterization factor corresponding to the visual perception characteristics of highway space (Chen 2021). After summarizing the literature, the application of spatial visual depression and spatial visual continuity as factors can better characterize the spatial visual characteristics of highways.

The quantification of the visual closure of space was first proposed in urban space, that is, the ratio of the distance D from the visual subject to the roadside building to the building height H (Qin 2008). Some scholars, combined with a questionnaire survey (Qin et al., 2012), obtained the impact of the road spatial interface relationship on the psychological feeling of the visual subject, as shown in Table 1.

Subsequently, the D/H index was introduced into highway landscape space, and many studies have verified it based on this index (Yu 2021). The results show that this index can reflect the visual closure of the highway space, that is, spatial visual depression (Yang 2018; Fang 2014). However, the D/H index also has shortcomings. 1) The external space environment of the highway is mostly composed of vegetation groups. There are often multiple layers of vegetation within the driver's field of vision, and there are differences in the vegetation height and distance from the observer. It is difficult to accurately obtain the values of D and H when judging the enclosure degree (Kaplan 2016); 2) this index is completely based on a two-dimensional road cross-section, which theoretically simplifies the real visual perception of human eyes (Fan et al., 2021).

Spatial visual continuity is also an important aspect in research on street spatial visual perception (Meng et al., 2020), which is mainly affected by the continuity of building interfaces on both sides of the street (Bingge et al., 2020). Similarly, highway spaces also have a continuous side interface. Therefore, the visual continuity of the highway space is directly affected by side interface continuity. Spatial visual continuity can be quantified by calculating the morphological characteristics of an interface on the opposite side. The most commonly used index for characterizing visual continuity is the build-to-line ratio (Tang and Long 2019). The build-to-line ratio is derived from the concept of "street wall" in urban planning (Kaplan 2016). The build-to-line ratio is calculated according to the sum of the intersection length of the ideal street wall boundary and the projection plane of roadside buildings on the two-dimensional plane and the length of the street, that is, the build-to-line ratio of street interface = the length of ideal street wall interface/street length × 100%. The higher the build-to-line ratio, the more neat the street interface, the higher the visual continuity, and the stronger the visual guidance (Yang and Chen 2019).

2.2. Highway three-dimensional spatial enclosure based on visual repression

When we consider spatial visual repression from the perspective of three-dimensional space, through further analysis of the D/H index, we found that it actually subdivides the human visual field plane and the object blocking the line of sight infinitely in the vertical direction, so that the visual field plane and the object can be regarded as a line segment perpendicular to the ground. Assuming that the distance between the object blocking the line of sight and the view field plane remains unchanged, the higher H, the higher the projection of the line of sight on the view field plane, as shown in Figure 1 (a). When the height is constant, the smaller the distance D between the viewpoint and the object blocking the line of sight, the higher the projection of the line of sight on the field

Table 1. D/H index and spatial feeling of road interface.

D/H index range	Space feeling
D/H < 1	The road space will give people a sense of urgency and show a closed phenomenon
D/H = 1	The road space has a sense of cohesion and stability
D/H = 2	The cohesion and evacuation of road space are not obvious
D/H > 3	The road space have a sense of evacuation

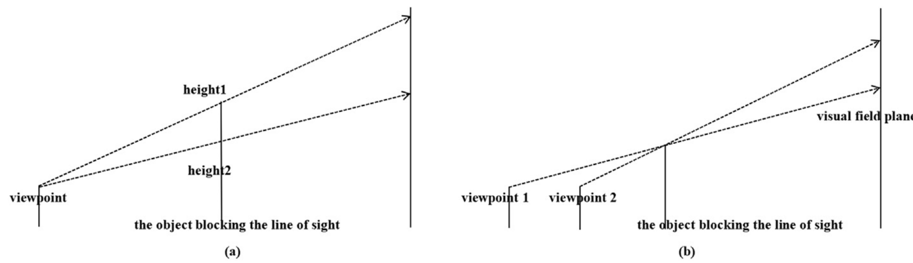


Figure 1. Characterization of D/H value on visual closure.

of view, as shown in Figure 1 (b). The D/H value reflects the size of the projection of the object, blocking the line of sight in the view area.

According to this principle, we can establish a virtual three-dimensional surface consistent with the actual field of view of the human eye. By drawing numerous lines of sight from the viewpoint of the virtual surface, the projection area of the object that blocks the line of sight on the virtual surface is obtained. Considering that the areas of the virtual surface and the projection surface are linearly related to the line of sight of the visual subject, the feeling of visual closure can be characterized by "the projection area on the virtual surface/virtual surface area". It is defined as a spatial enclosure, which is used to quantify spatial visual depression. The larger the ratio, the stronger is the spatial visual depression. The calculation and analysis methods of the spatial enclosure are described below.

(1) Select view-area model

In 3D visual analysis, it is necessary to establish a view-field plane to receive the projection of the object blocking the line of sight (Fan 2021). There are three common view field shapes: (1) a plane along the line-of-sight direction of the visual subject and perpendicular to the earth; (2) a cylindrical facade centered on the viewpoint and perpendicular to the earth; and (3) a hemispherical surface with the viewpoint as the center and the edge perpendicular to the earth. By constructing three different view field models for comparative analysis, the results show that when the view field is defined as a plane, the line-of-sight occlusion rate is smaller, and the line-of-sight occlusion rate calculated using the cylindrical facade or hemispherical plane as the view field is similar in value. Considering that when the roadside vegetation is dense, the highway-top interface also blocks the line of sight, and the hemispherical surface is selected as the view basis for establishing the spatial enclosure analysis model.

Based on the above conclusion, the spatial enclosure can be calculated using formula (a).

$$I = S_{\text{Projection}} / S_{\text{hemisphere}} \quad \text{(a)}$$

I is the spatial enclosure, $S_{\text{projection}}$ is the projection area formed by the line of sight blocked by the object in the view hemisphere, and $S_{\text{hemisphere}}$ is the surface area of the view hemisphere. The calculation diagram is shown in Figure 2.

It should be noted here that in an actual driving environment, the driver's line of sight generally points to the front and side front, even if he looks back through the rearview mirror and only focuses on the vehicle from the rear. However, to quantify the highway interface shape more objectively and concisely, this study establishes a hemispherical model from an all-round perspective to describe the field of view, which will not affect the calculation results through the analysis of geometric symmetry and similarity principle.

(2) Determining the optimal view-field radius

To improve the calculation efficiency of the model, we need to choose a smaller view field radius so that the spatial enclosure result can be equivalent to the calculation result of the actual sight distance of the human eye (approximately 3000 m) with a small error. Research on the spatial enclosure has proven that when the D/H value is between 2 and 3, the drivers start to feel the enclosure of the space; when the D/H value is less than 2, the driver can strongly feel the closeness and oppression of the roadside interface (Qin 2008, 2012; Yang and Chen 2019). It can be considered that the drivers can feel an obviously enclosed interface when D/H = 2. Therefore, to determine the appropriate view field radius, two simplified three-dimensional models of typical highway spaces with D/H = 2:1 are constructed: 1) pavement width d = 26 m and side interface height h = 13 m, which are used to represent a typical two-way four-lane highway; 2) pavement width d = 34 m, side interface height h = 17 m, which is used to represent a typical two-way six-lane highway, according to the view radius of 50 m–3000 m, the analysis of highway spatial enclosure is carried out. The analysis process is illustrated in Figure 3.

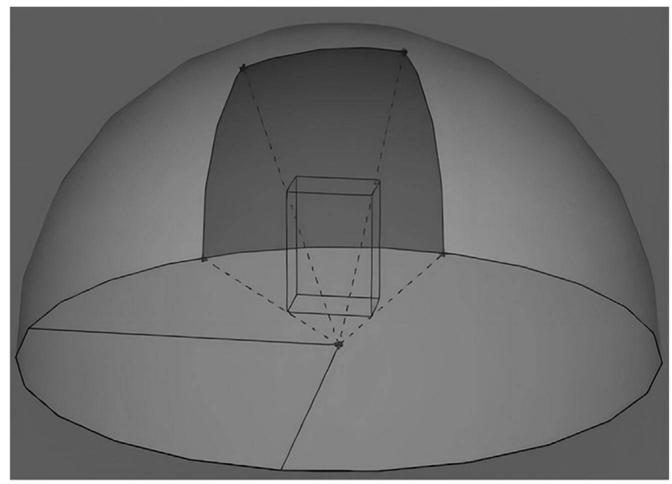


Figure 2. Calculation diagram of spatial enclosure based on hemispherical model.

According to the analysis of the results in Table 2, when the view field radius is small, for two roads with different widths, the wider road has a smaller spatial enclosure and the narrower road has a larger spatial enclosure. However, when the field of view radius is more than 100 m, the calculated spatial enclosure degree of the two types of highways is the same when the field of view radius is the same. Therefore, to improve analysis efficiency, the view field radius was set to 100 m.

(3) Determining characterization threshold

As the calculation method of the spatial enclosure degree is similar to the D/H index in principle, and the D/H value has been applied in the actual engineering of highway landscapes, highway space types with different visual closure degrees divided based on D/H values are shown in Table 3 (Qin et al., 2012). Therefore, we can refer to the characterization of the D/H value for the degree of visual closure to determine the

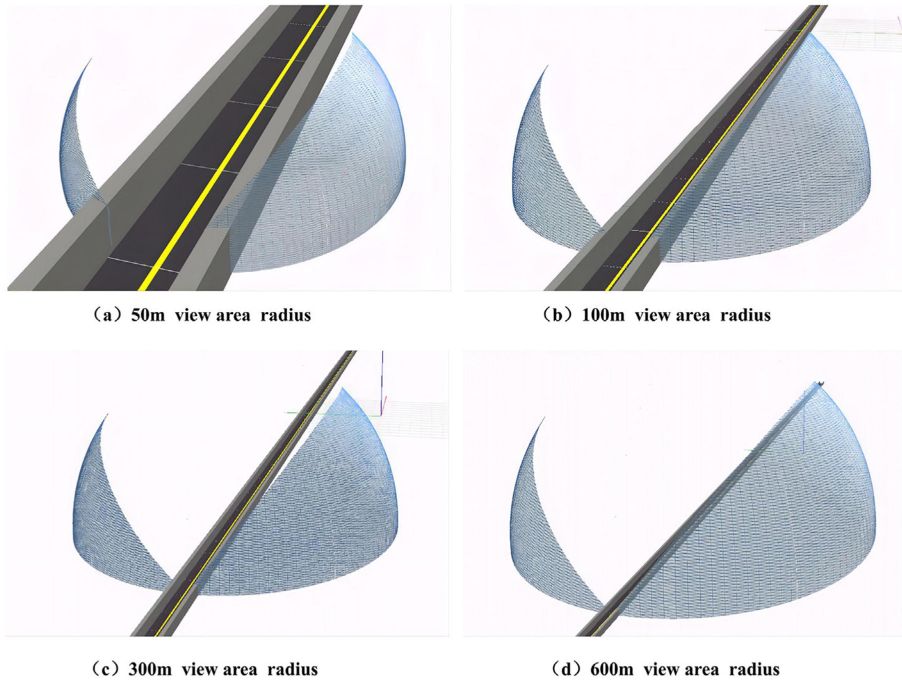


Figure 3. Analysis model of highway spatial enclosure with different radius view field.

Table 2. Influence of different view field radius on calculated value of spatial enclosure.

view area radius(m)	Highway model I		Highway model II	
	$S_{projection}/S_{hemisphere}$	Benchmark ratio (%)	$S_{projection}/S_{hemisphere}$	Benchmark ratio (%)
50	0.525	4.9	0.511	7.5
80	0.541	2.0	0.533	3.5
100	0.550	0.4	0.550	0.4
200	0.551	0.2	0.551	0.2
300	0.552	0.0	0.552	0.0
600	0.552	0.0	0.552	0.0
1000	0.552	0.0	0.552	0.0
3000	0.552	0.0	0.552	0.0

Table 3. Highway space with different visual closure based on D/H value.

Range of D/H value	Visual closure
D/H < 2	closed
2 < D/H < 3	enclosed
3 < D/H < 4	semi-open
D/H > 4	open

characterization threshold of the $S_{projection}/S_{hemisphere}$ for the degree of spatial enclosure.

By constructing a spatial model, simulating the highway space with D/H = 2, D/H = 3, and D/H = 4, construct a hemispherical view plane with a radius of 100m centered on the viewpoint and calculate the $S_{projection}/S_{hemisphere}$ respectively:

Among them, the D/H = 2:1 highway model, $S_{projection}/S_{hemisphere} = 11/20$; D/H = 3:1 highway model, $S_{projection}/S_{hemisphere} = 7/20$; D/H = 4:1 highway model, $S_{projection}/S_{hemisphere} = 3/20$.

Therefore, when the $S_{projection}/S_{hemisphere}$ value is greater than 11/20, it is considered that the vision of the highway space is closed; when the $S_{projection}/S_{hemisphere}$ value is between 7/20 and 11/20, it is considered that the vision of highway space is enclosed; when the $S_{projection}/S_{hemisphere}$ value is between 3/20 and 7/20, it is considered that the vision of highway space is semi-open; and when the $S_{projection}/S_{hemisphere}$ value is less than 3/20, it is considered that the highway space is visually open, as shown in Table 4.

2.3. Three-dimensional build-to-line ratio of highway space based on visual continuity

Considering that the side interface of highway space is mostly vegetation and irregular mountains, and there are many concave convex changes in the vertical dimension, the characterization of the visual continuity of highway space by the calculation results of the two-dimensional build-to-line ratio will be quite different from the real visual effect. Therefore, according to the calculation method of the build-to-line ratio in the two-dimensional plane, this study expands it to the vertical dimension; that is, the position of the ideal side interface is determined from the three-dimensional model, and the build-to-line ratio of the three-dimensional angle is calculated according to the sum of the area where the ideal side interface intersects with the roadside object and the area of the highway, as shown in Figures 4 and 5.

Calculation formula of 3D build-to-line ratio:

$$K = \sum_{i=1}^{n} S_{side-i}/S_{road} \times 100\% \tag{b}$$

where, K is the 3D build-to-line ratio, S_{side-i} is the interface area of the ith object constituting the ideal-side interface, and S_{road} is the area of the

Table 4. Characterization threshold of highway spatial enclosure.

Range of D/H value	Range of $S_{projection}/S_{hemisphere}$	Spatial visual depression
≤2	≥11/20	closed
2 ~ 3	11/20 ~ 7/20	enclosed
3 ~ 4	7/20 ~ 3/20	semi-open
≥4	≤3/20	open

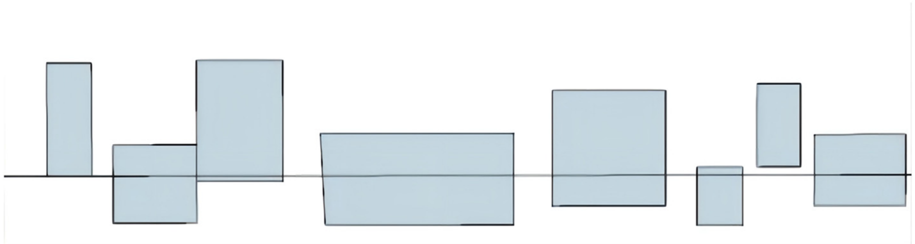


Figure 4. Schematic diagram for calculation of 2D build-to-line ratio.

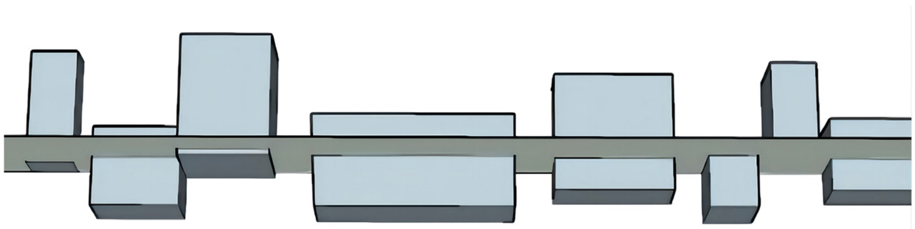


Figure 5. Schematic diagram for calculation of 3D.

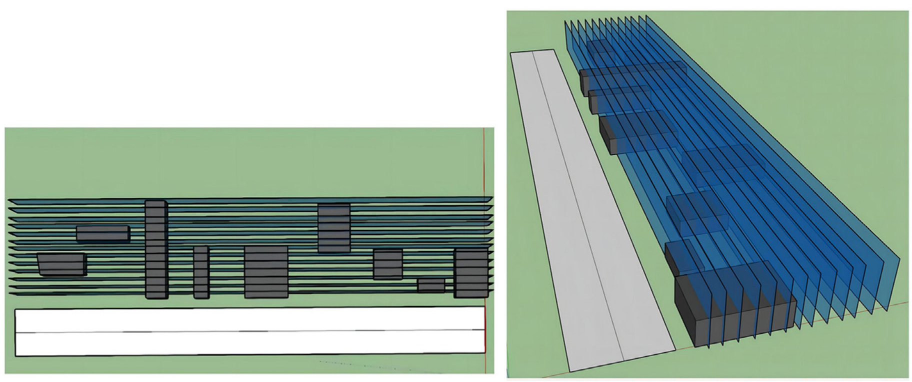


Figure 6. Schematic diagram of calculation process of 3D build-to-line ratio.

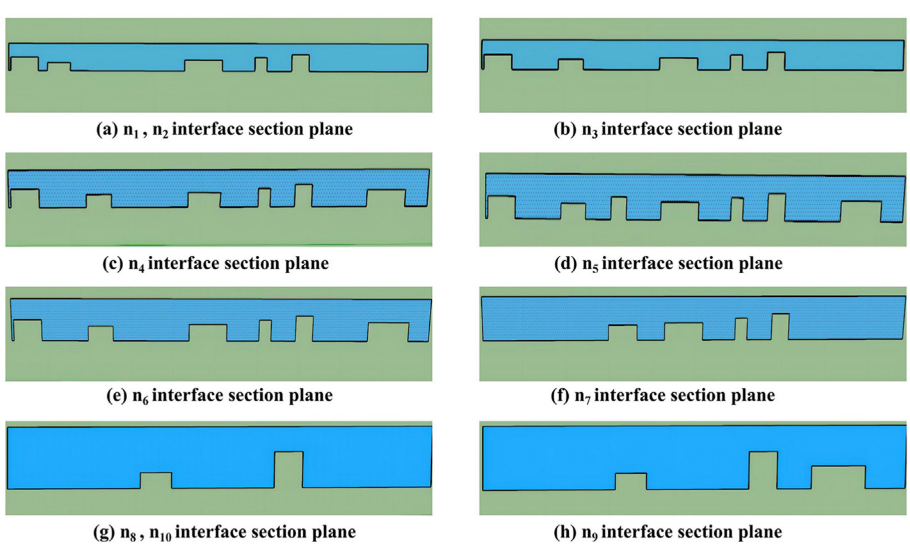


Figure 7. Sectional plane of each interface intersecting with roadside objects.

Table 5. Area value of each intersecting section plane.

Interface number	Sectional area (m^2)
n_1	753
n_2	753
n_3	778
n_4	991
n_5	1145
n_6	1040
n_7	592
n_8	289
n_9	515
n_{10}	289

Table 6. Characterization threshold of three-dimensional build-to-line ratio of highway space.

Range of 3D build-to-line ratio	Spatial visual continuity
≥70%	strong visual continuity
40%–70%	general visual continuity
≤40%	weak visual continuity

road where the side interface is located. For a highway, owing to its large scale and many central separators, it is appropriate to take the area of half the road for calculation. It can be seen from formula (b) that the key point of calculating the 3D build-to-line ratio is to determine the location of the ideal side interface and the area of the ideal side interface. The specific steps are as follows.

(1) Based on the road centerline, n_1–n_{10} a series of interfaces perpendicular to the road are gradually constructed outward in 2m steps on both sides based on the road red line, as shown in Figure 6.
(2) Conduct a three-dimensional intersection calculation between each constructed interface and roadside object to obtain the intersecting section plane and record the area value of each section plane, as shown in Figure 7 and Table 5.
(3) Because the denser the interface, the easier it is to feel the shape of the side interface, the position of the structural interface with the largest total area of the section plane is the ideal side interface position of the road. It can be seen from Table 5 that the section area where structural interface n_5 intersects the roadside object is the largest; therefore, the interface n_5 is the position of the ideal side interface of the road.
(4) The road area on which the side interface was located was calculated. As shown in Figure 6, the road is 15 m wide, 120 m long and 1800 m^2 in area. It can be seen from Table 5 that the maximum intersection area is 1145 m^2. According to formula (b), the three-dimensional build-to-line ratio on one side of the current section is 1145/1800 × 100% = 63.6%.

In the study of urban streets, it is considered that when the build-to-line ratio is greater than 80%, the interface wall is clear and the spatial visual continuity is strong; when the build-to-line ratio is 50–80%, the existence of the interface wall can be roughly felt, and the spatial visual continuity is general; when the build-to-line ratio is less than 50%, the spatial concave convex change is obvious and the visual continuity is weak. Owing to the high speed in the highway space, it can still be considered visually continuous when the roadside vegetation spacing is small. Therefore, in the highway space, the threshold value for characterizing visual continuity with the build-to-line ratio should be appropriately reduced based on urban streets, as shown in Table 6.

3. Results

3.1. Highway real scene 3D modeling based on tilt photography

Taking the G211 Highway in Shaanxi Province as the research object, a 1000 m section was selected for real-scene model construction. G211 Highway is a two-way four-lane highway with a subgrade width of 16 m. The roadside vegetation of the demonstration section is sparse, and there are some farmlands, buildings, and power facilities outside the highway. Considering that the

(a) Real 3D model of G211 Highway

(b) Local magnification of 3D real scene model

Figure 8. 3D real model of highway space.

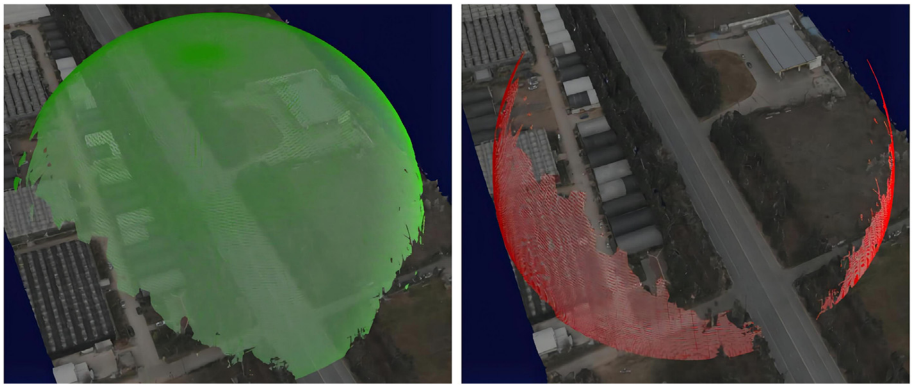


Figure 9. Analysis of highway spatial enclosure.

highway has a large spatial scale and the driver's line of sight moves fast while driving and has a weak sense of detail, in terms of the 3D data acquisition method, compared with manual 3D data and point cloud 3D data based on laser scanning (Jocea et al., 2015; Bulgakov et al., 2015), the real scene 3D data obtained based on tilt photography are selected to complete the real scene 3D modeling of highway space.

The construction of tilt photography real scene model needs to go through the process of on-site tilt image acquisition, image data processing and model production (Xu et al., 2015; Yu 2021), which have been very mature. The specific process and model processing details can be found in Yu (2021), and the final three-dimensional real-scene model of the highway is shown in Figure 8.

3.2. Analysis of three-dimensional spatial enclosure

The spatial enclosure degree of the G211 highway obtained through three-dimensional modeling using tilt photography, was analyzed. Because the length of the highway model was 1000 m, 19 observation points were set at an interval of 50 m, and each observation point was constructed with 100 m a viewing radius. The visible part of the semi-sphere model was set as green, and the invisible part was set as red, as shown in Figure 9. The $S_{projection}/S_{hemisphere}$ and corresponding spatial visual depression at each observation point on the G211 highway are shown in Table 7.

Table 7. Analysis results of G211 Highway spatial enclosure.

Position of observation point (m)	$S_{projection}/S_{hemisphere}$	Spatial visual depression
50	0.05	open
100	0.08	open
150	0.06	open
200	0.07	open
250	0.17	semi-open
300	0.27	semi-open
350	0.22	semi-open
400	0.25	semi-open
450	0.26	semi-open
500	0.15	semi-open
550	0.11	open
600	0.06	open
650	0.05	open
700	0.08	open
750	0.18	semi-open
800	0.31	semi-open
850	0.34	semi-open
900	0.37	enclosed
950	0.35	enclosed

According to the analysis results of the G211 highway spatial enclosure, in this highway space, the spatial enclosure degree experienced a process of rise-decline-rise. The value of the $S_{projection}/S_{hemisphere}$ in the initial section is between 0.05–0.1, the value of the $S_{projection}/S_{hemisphere}$ in the second section is between 0.15–0.25, the value of the $S_{projection}/S_{hemisphere}$ in the third section is between 0.05–0.2, and the value of the $S_{projection}/S_{hemisphere}$ in the end section is between 0.3–0.35. It can be seen that although the spatial enclosure of this section of the highway fluctuates greatly, the overall value is small.

3.3. Analysis of three-dimensional build-to-line ratio

According to the above three-dimensional build-to-line ratio calculation method, the three-dimensional build-to-line ratio of the G211 highway model obtained by three-dimensional modeling of tilt photography was calculated. The three-dimensional build-to-line ratio calculation process is shown in Figure 10.

Next, three representative highway spaces were taken as examples to analyze the characterization effect of the three-dimensional build-to-line ratio: 1) highway space with low and dense roadside vegetation and large road width; 2) the roadside vegetation is low and sparse, and the road width is small; 3) for the highway space with tall and dense roadside vegetation and wide road width, the length of the three highway spaces is 200 m, as shown in Figure 11.

The calculation results of three-dimensional build-to-line ratio are listed in Table 8. According to the analysis results of the three-dimensional build-to-line ratio of the three-highway space, the third type of highway space has the highest three-dimensional build-to-line ratio of more than 70%, with a clear interface wall and strong spatial continuity. The driver can experience clear visual guidance when driving in this highway space. The three-dimensional build-to-line ratio of the left interface was lower than that of the right interface, mainly because of the existence of an intersection.

Although there were significant differences in the vegetation density of the side interface between the first and second highway spaces, there was little difference in the overall three-dimensional build-to-line ratio. This is mainly because of the narrow width of the road in the second highway space, which makes it have spatial visual continuity similar to the first highway space when the ideal side interface area is small. The first and third highway spaces have the same road width, but the ideal side interface area of the third highway space is larger; therefore, it has a stronger spatial visual continuity.

4. Discussion

4.1. Create highway landscape according to the spatial enclosure

The three-dimensional spatial characteristics of highway straight-lines and curved sections are different, and the corresponding landscape construction

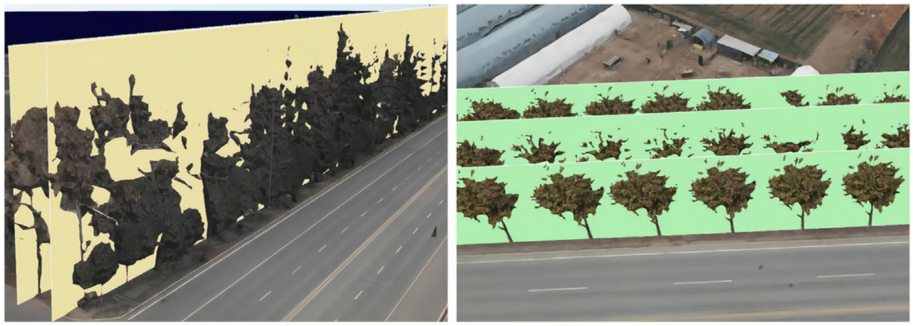


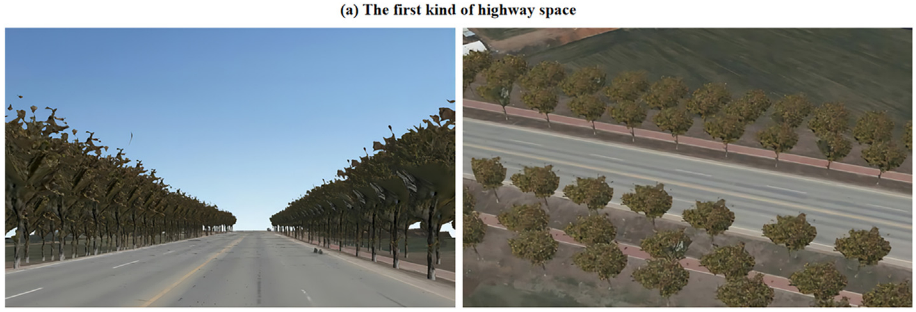
Figure 10. Calculation of 3D build-to-line ratio.

methods are also different. For the straight-line segment, an observation point can be set at a certain distance according to the actual need to analyze the spatial enclosure degree, draw the analysis results into the spatial enclosure degree trend diagram, and determine which spatial type its spatial form belongs to according to the spatial enclosure degree trend diagram, as shown in Figure 12. If it is a flat space, driving for a long time will tire the driver. It is advisable to set up some landscape sketches in it, or change the space form by planting vegetation on the roadside to avoid the monotony of the same enclosure; if it is an undulating space, the change in space enclosure degree should be avoided too sharply, and the highway space with scattered length and rhythm should be further created by means of landscape improvement. If it is a rising space, there is no need for redundant landscape improvement, and the driver has better driving experience in this space.

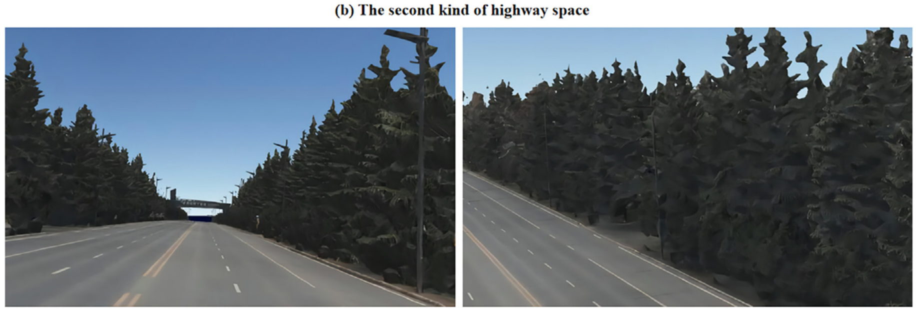
For the horizontal curve section, the enclosure analysis was performed at the horizontal curve and its front and rear sections. The horizontal curve is an important position for the drivers to obtain a good perception of the off-road landscape. The off-road landscape should be allowed to enter the driver's field of vision as much as possible, which is called "borrow scenery" in landscape science.

Therefore, the degree of enclosure on the horizontal curve should be sufficiently open. If the analysis results indicate that it is an enclosed or closed space type, roadside vegetation should be transplanted. For the sections before and after the horizontal curve, if the analysis results show that the enclosure degree is open or semi-open, it should be considered to arrange them as a relatively closed space type through landscape improvement to limit the driver's line of sight to the highway space.

(a) The first kind of highway space



(b) The second kind of highway space



(c) The third kind of highway space

Figure 11. Three types of highway space for three-dimensional build-to-line ratio analysis.

Table 8. Analysis results of 3D build-to-line ratio of three types of highway space.

Highway space type		Maximum sectional area (m^2)	Half road area (m^2)	3D build-to-line ratio (%)
Highway space1	left side interface	112	220	50.9
	right side interface	107	220	48.6
Highway space2	left side interface	69	160	43.1
	right side interface	72	160	45
Highway space3	left side interface	155	220	70.5
	right side interface	165	220	75

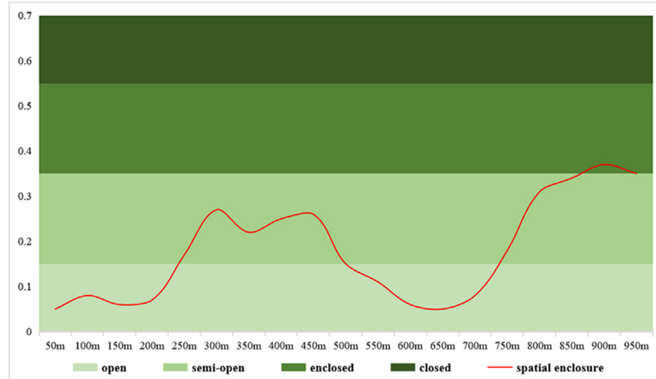


Figure 13. Trend of spatial enclosure of G211 Highway.

Through such landscape construction, drivers can experience a sudden sense of openness when reaching the horizontal curve.

The analysis results of the G211 Highway spatial enclosure degree were counted and drawn into a spatial enclosure degree trend diagram, as shown in Figure 13. A landscape spatial sequence for the highway was planned.

According to the trend diagram of the spatial enclosure of the G211 Highway, it is initially open, and then the enclosure degree goes through the process of rising, falling, and rising until it approaches the enclosure state at the fast end. It can be seen that the original landscape space belongs to undulating type. Although the undulating landscape space can bring better driving experience to the driver, the overall enclosure of the G211 Highway is small, and it is almost a completely open space in the valley, so the driver cannot feel a sense of space on the highway. In addition, the degree of enclosure of the G211 Highway has experienced two ups and downs within 1000 m, with frequent changes, which makes drivers feel nervous. It can reduce the fluctuation of the enclosure degree by planting appropriate vegetation on the roadside of 50 m–250 m and 500–700 m sections, building a rhythmic highway space, or planing it as a rising landscape space sequence by adjusting the overall enclosure degree trend.

4.2. Create highway landscape according to the three-dimensional build-to-line ratio

Three-dimensional build-to-line ratio analysis is applicable to the straight section of a highway. For the straight-line section of the highway with traffic function as the main function, if the calculation results show that the three-dimensional build-to-line ratio of the highway space is low, it is appropriate to plant dense vegetation on the roadside to make the three-dimensional build-to-line ratio reach more than 70% to enhance the continuity of the highway space and guide the driver's line of sight while driving. At the same time, the sudden rise and fall of the three-dimensional space will break the rhythm and continuity of highway space vision and affect the visual experience effect of drivers. For such sections, the height and thickness of the side interface should have a certain transition by means of landscape improvement, so that a continuous change in spatial vision can occur within a reasonable range to form a stable and fluctuating trend of the three-dimensional build-to-line ratio. It can also be combined with the trend chart of the degree of spatial enclosure to jointly create a rhythmic and dynamic highway space through two means.

For the straight-line section of the highway with the roaming function as the main function, the requirements can be appropriately reduced to ensure that the three-dimensional build-to-line ratio is 40%–50%, which can not only ensure the continuity of the highway space and guide the driver's line of sight, but also add more spatial transparency to the driver's spatial vision and enrich its roaming experience. In addition, for artificial structures such as retaining walls and hard slopes, although the highway space has a high build-to-line ratio and strong visual continuity, the texture is too stiff, which will reduces the driver's sense of safety. It is appropriate to soften them by planting grasses and shrubs.

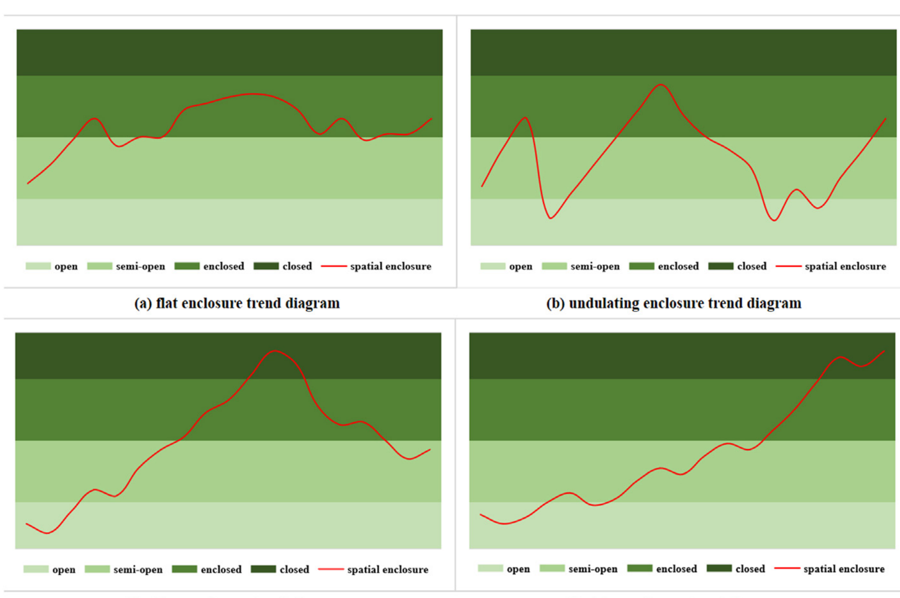


Figure 12. Trend type of highway spatial enclosure.

According to the statistical analysis results of the three-dimensional build-to-line ratio of the G211 highway, the three-dimensional build-to-line ratio of the G211 highway in the 250 m–500 m section and 700 m–1000 m section is approximately 40%–45%, and the highway space has certain visual continuity. In the 0 m–250 m and 500–700 m section, because there was no vegetation on the roadside, the three-dimensional build-to-line ratio was approximately 0. When driving in this highway space, the driver cannot perceive the directivity and line-of-sight guidance provided by the side interface. The continuity of space gives people a sense of visual stability and a sense of psychological security. A lack of continuity can easily cause a negative space experience. In addition, it can be seen from the real three-dimensional model of the G211 Highway that most of the roadside range is houses, electric towers, and other artificial buildings, without good landscape elements, and the roaming nature is weak. Therefore, for the 0m–250m and 500 m–700 m sections of the G211 Highway, it is appropriate to plant dense and moderate vegetation on the roadside to enhance spatial continuity. The specific height and planting position can be simulated by manual modelling, and then planted in an actual project. In addition, for the "negative elements" affecting visual continuity such as houses and power towers, it is appropriate to heighten and densify the roadside vegetation at these locations during landscape improvement, so that the "negative elements" do not appear in the driver's field of vision.

5. Conclusion

In this study, the characterization and quantification methods of highway spatial visual depression and spatial visual continuity were studied. By improving the "D/H" value, a calculation method of spatial enclosure based on hemispherical view surface is proposed; By improving the two-dimensional build-to-line ratio, a three-dimensional build-to-line ratio calculation method including vertical axis is proposed. Three-dimensional characterization and quantitative calculation of highway spatial perception have been realized, and the characterization effect of human visual perception has been improved.

In addition, this study established a landscape construction method based on three-dimensional spatial perception: obtain the real three-dimensional data by means of tilt photography, model the highway based on the 3D GIS technology platform, draw the spatial enclosure degree trend diagram according to the calculation results of spatial enclosure degree, analyze the highway space type and analyze the spatial continuity according to the calculation results of the three-dimensional build-to-line ratio. Finally, according to the analysis results, the corresponding construction and improvement of highway spatial sequence rhythm are carried out. A complete set of technical processes and methods for highway space construction and landscape improvement was established.

Subsequently, through the application and analysis of the G211 Highway, the feasibility of the above quantitative method of highway space visual perception was verified, and a landscape construction strategy based on the project was proposed. The calculation results are accurate and scientific and can be used for highway space reorganization and landscape improvement.

However, this study refers to the relevant theories and research on visual perception of urban space due to the lack of research on visual perception of highway space, and selects the characterization factors of visual perception of highway space from the driver's psychological feeling. In the follow-up research, scientific psychological methods should be further used to analyze the relationship between the visual characteristics of highway spaces and the psychological feelings of drivers, so as to better form a research closed loop.

Declarations

Author contribution statement

Xingli Jia: Conceived and designed the experiments; Performed the experiments; Aanalyzed and interpreted the data; Wrote the paper.

Ye Zhang: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Ao Du: Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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