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Dynamic Occlusion Modeling and Clearance Control of the Visual Field of Curved Highway Roadside Landscape

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Abstract: In order to solve the control of the degree of anti-occlusion of the roadside landscape of the expressway curve according to the drivers' visual characteristics during high-speed driving, a dynamic space model of the visual process of curved highway roadside landscape was established, and the calculation equation of roadside landscape visual field was derived. The dynamic occlusion ratio was defined by space coordinates, and the judgment model was proposed for the de-occlusion of the roadside landscape visual field. According to the standard design parameters of the G4 Highway Hunan section, the occlusion laws were analyzed by MATLAB for different widths and different heights of obstructions as well as the same widths and heights of obstructions at different positions in the roadside landscape visual field, thus the control value and control content of anti-occlusion clearance for the roadside landscapes were proposed. The results show that the anti-occlusion clearance control range of the roadside landscape is 270 m at the design speed of 120 km/h, 220 m at 100 km/h, and 170 m at 80 km/h. The control value of clearance width is 25 m, and the control value of clearance height is recommended to be 20 m. Within the scope of highway land expropriation, it is recommended to land expropriation 25 m wide from the road boundary. The research provides model support for building the closeness and openness of highway roadside landscape.

Keywords: curve roadside; landscape; visible window; dynamic visual occlusion space models; clearance control

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Citation: Xiao, J.; Zha, X.; Yang, L.; Wei, J. Dynamic Occlusion Modeling and Clearance Control of the Visual Field of Curved Highway Roadside Landscape. *Sustainability* **2023**, *15*, 3200. https://doi.org/10.3390/su15043200

Academic Editors: Jia-Rui Lin, Yu-Shen Liu, Xiaoping Zhou, Ge Gao, Anthony Tzes and Yi Fang

Received: 27 November 2022
Revised: 29 January 2023
Accepted: 31 January 2023
Published: 9 February 2023

1. Introduction

With the vigorous promotion and development of the concepts of Green Highways or Tourism Highways, the roadside landscape of highways has been paid increasing attention. Many research results showed that an impressive highway roadside landscape might be beneficial for reducing traffic accident rates, the ratio of obstruction of the roadside landscape is an important element of a good roadside landscape. Ganguly et al. [1] used the visual occlusion method to assess the visual needs of highway alignment and found that complex curves affected the driver's roadside visual needs. The studies by Jeong [2] et al. and Mo, K. et al. [3] showed that a driver is likely to concentrate on driving by seeing a comfortable roadside landscape, whereas they feel confused and depressed by seeing a complex roadside landscape. Park et al. [4] found that there was a clear correlation between roadside facility density and traffic accidents according the study of roadside tree spacing, pole density, etc. Lankathilakeal [5] studied and found that roadside plants, structures and other areas in the curve area hinder the driving line of sight much more than straight lines. Qi et al. [6] found that the obstructions on the roadside of the curve will have a significant impact on the average speed of the vehicle when the driver drives the truck through the curve through real vehicle test, and proposed that the side obstructions should be considered in the design of speed limit for curve sections. Xie [7,8] and Shang [9,10] found highway landscape based on the environment of the prairie-highway has a significant impact on the driver's dynamic vision, such as saccade amplitude, fixation duration, etc. from the real vehicle experiment. Huang et al. [11] studied the landscape pavement of emergency lane and its impact on driver's vision and driving safety. Zhang [12] proposed that the blocked roadside landscape would leave a hidden danger to traffic safety. Wang et al. [13] simulated the spatial scale sensitivity of drivers to roadside structures through mathematical model simulation, in which highly sensitive was found within 50 m; sensitive for 50–100m; and less sensitive beyond 100 m. Xu et al. classified [14] three highway landscape sensitive areas by establishing a model and determined that the total size of the highway landscape sensitive area is 545 m for a two-way four-lane highway. The distances of the first, second, and third sensitive areas are 55 m, 260 m, and 230 m, respectively; and the distance to the subgrade edge in the first sensitive area is 15 m.

Since the roadside landscape of a highway can be realized by borrowed scenery and at the same time, for traffic safety, the driver cannot be distracted by the excessively rich landscape, the occlusion of the roadside landscape and the control of the degree of occlusion are the main studied topics in the visual field of roadside landscape. Therefore, based on the analysis of the visual field occlusion of the two highways in the Hunan section, i.e., Highways G4 and G60, we established a spatial model and an occlusion judgment model for the roadside landscape of a curving highway to control the roadside landscape clearance.

2. Analysis of Visual Field Occlusion by Roadside Landscape on High-Risk Curved Highways

Highways passing through mountains and ridges are a beautiful landscape. Therefore, the roadside landscape of such highways shows richness due to the change of terrain. The closeness and openness of the roadside landscape depended on how much this richness is blocked by the features of the highway, i.e., the degree of occlusion. Japanese landscape scholar Yoshinobu [15] divides the road space into "openness" and "closed feeling" Based on the characteristics of fast moving and the ratio of road width W and scene height H, the visual field occlusion by roadside landscape of a highway can be classified into three types: closed, balanced, and open.

The analysis of the high-risk section (Source: Hunan Expressway Network Risk Assessment Data from 2013 to 2015 (data from Hunan Provincial Department of Transportation).)of Highways G4 and G60 in Hunan section shows that, as for Highway G4, closed-type is 62.9%; balance-type is 14.5%; and open-type is 22.6%. As for Highway G60, close-type accounts for 41.4%; balance-type accounts for 27.4%; and open-type accounts for 31.2%. The proportion of closed roadside landscapes in the Highway G4 exceeds 60%, while the sum of balance- and open types of the Highway G60 is about 60%, indicating that the former roadside landscape is much more closed than the latter. In other words, Highway G4 has a higher proportion of visual field occlusion by roadside landscapes. Statistics on three types of roadside landscapes in high-risk curved road sections show that the road sections with more accident rates have higher roadside landscape closeness. For example, the downward section of K 1784~ K 1787 in the Highway G4 reaches 19 accidents per kilometer, along with the ratio of the S-curve closed-type roadside landscape is as high as 93.3%. The upward section of the Highway G60 K 1049~ K 1050 reaches 17 accidents per kilometer, accompanying a 60.0% of closed-type roadside landscape, which is the highest proportion in Highway G60. The down section of K 1389~ K 1392 has as many as 19 accidents per kilometer with a closed-type rate of 53.3%.

The Highway G4 Hunan section has a relatively long period of construction and operation time. Except for the urban road section of K 1497 ~K 1499 and the upward and downward sections of K 1814 ~K 1817 being the bridge section with a relatively open roadside landscape, the rest of the road section are of high occlusion rate from plants to the roadside landscape. The roadside landscape is relatively closed due to the more close-type distribution, leading to a simple driving environment for drivers who thus are prone to fatigue.

The Highway G60 Hunan section are mainly due to the occlusion of the roadside landscape by tunnels and high cutting slopes, whereas in the road sections with many bridges, the roadside landscapes are all open type.

3. Visual Field Modeling of Roadside Landscape on a Curved Highway

3.1. Scope of the Visual Field Modeling of Roadside Landscape on a Curved Highway

In the process of vehicle movement, the visual field of the roadside landscape on a curved highway is shown in Figure 1. It is an enclosed cone that is composed by the tangent line between the left side of the driver's visual height (h) and the central separation zone, the visual field at the driver's right side, and the visual distance depth. The visual field occlusion of the roadside landscape on a curved highway is defined as that under a certain speed condition, if the driver does not move his head and only looks forward on the road, there is an occluder in the driver's visual field, which prevents the driver from seeing the roadside landscape from the roadbed on his right side or partially blocks the roadside landscape, thus affecting the integrity of the roadside landscape.

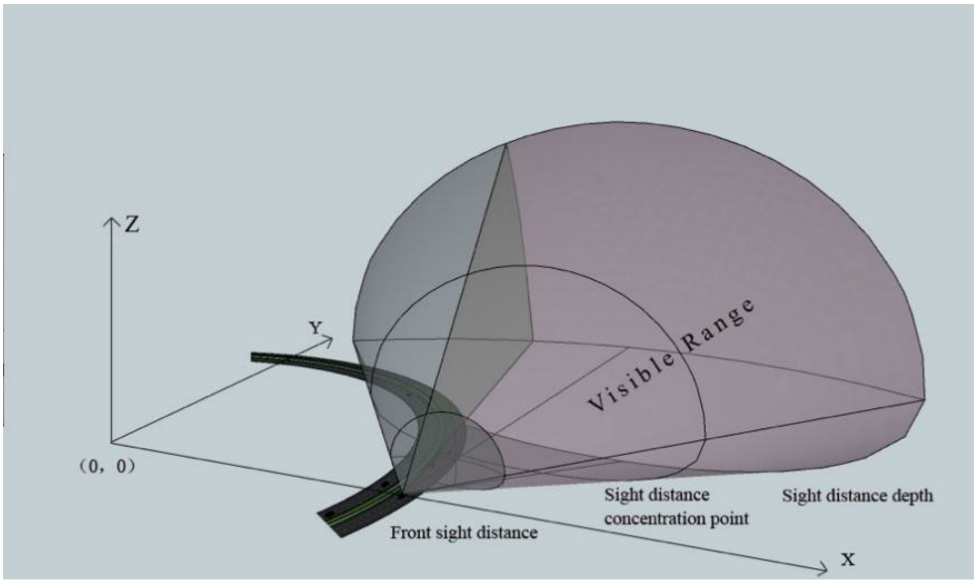

Figure 1. Visual field of the roadside landscape on a curved highway.

3.2. Dynamic Spatial Model of the Visual Field of the Roadside Landscape on a Curved Highway [16]

As shown in Figure 2, taking the center of the circular curve of the highway as the origin (0, 0, 0), the coordinates of the point A where the driver is located are (0, −(R + w1 + w2), h); at the same time, taking the viewing plane as the reference plane, the visual field volume of the roadside landscape at point A is:

$$V_A = \frac{4}{3}\pi L^3 \cdot \frac{\alpha + \alpha_1}{360} \cdot \frac{\beta_1 + \beta_2}{360} = \frac{4}{3}\pi L^3 \cdot \frac{\alpha + \arccos\frac{R+w_1}{R+w_1+w_2}}{360} \cdot \frac{\beta_1 + \arctan\frac{h}{L_1}}{360} \quad (1)$$

where V_A is the visual field volume of the roadside landscape at point A (m^3); α is the horizontal angle of view (°), which varies with the speed; α_1 is the angle of view that is not blocked by the central separation zone (°); L is the sight distance (m), which varies with the speed. The sight distance L here refers to the depth of the visual distance, which is divided into the front visual distance L_1, the visual distance concentrated point ($L_1 + L_2$), the visual distance depth ($L_1 + L_2 + L_3$); β is the vertical viewing angle (°), which is the sum of β_1 and β_2; β_1 is the upper vertical angle of view on the viewing plane (°); β_2 is the lower vertical angle of view on the viewing plane (°), that is, the vertical angle of view that is not blocked by the visual distance in front of the vehicle; h is the apparent height (m), 1.2 m for a car, 2.0 m for a truck; R_0 is the highway curve radius (m), simulated by the minimum radius of circular curve; R is the curve radius of the edge line of the highway subgrade (m); w_1 is the width from the edge of the subgrade in the inner curve to the edge of the outer curve (m); w_2 is the width from the edge of the outer curve to the coordinate position of the car (m); v is the speed of the vehicle (km/h).

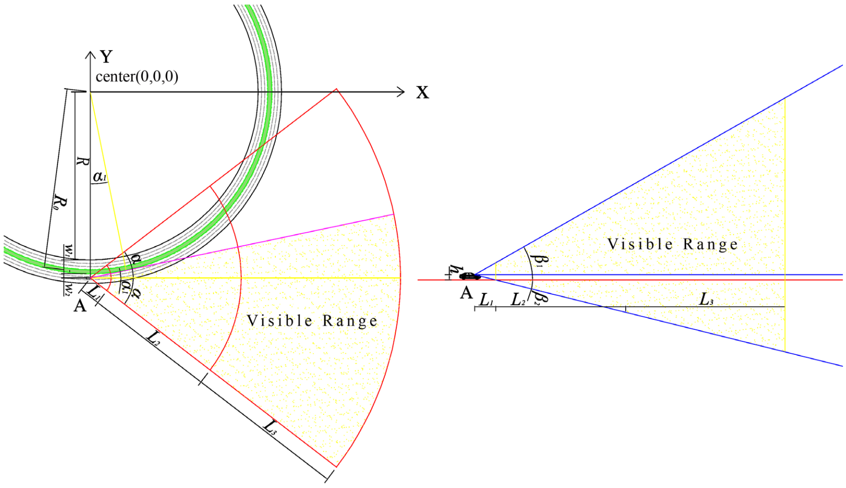

Figure 2. Schematic representation of the visual field volume of the roadside landscape on a curved highway.

3.3. Modeling for Occlusion Judgment of the Visual Field of the Roadside Landscape on a Curved Highway [17]

3.3.1. The Occlusion Model of the Roadside Landscape Visual Field at the Starting Point

As shown in Figure 3, assuming that the occluder (the maximum section projected into the visual field is a rectangle) is of width D and height H. If one point of the occluder is in the relative coordinates of (x_z, y_z, z_z), while the other three points are (x_z, y_z–D, z_z), (x_z, y_z–D, z_z + H), (x_z, y_z, z_z + H), where z_z = 0 m, then y_z is:

$$y_z = -\sqrt{(R + w_1 + w_2)^2 - x_z^2} \tag{2}$$

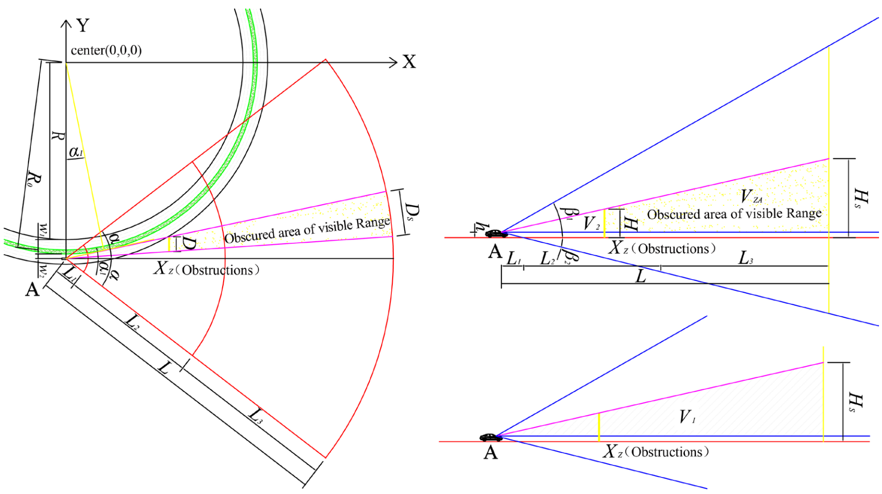

Figure 3. Schematic representation of the occluded volume in the visual field of the roadside landscape (point A).

The occlusion volume of a point A is calculated by the difference between the large triangular pyramid V_1 with an approximate rectangular bottom surface and a small triangular pyramid V_2 with a rectangular bottom area.

The calculation formula for the volume V_1 was obtained from the following. From the triangular ratio relationship, we get:

$$\frac{H}{H_s} = \frac{x_z}{L} \Rightarrow H_s = \frac{HL}{x_z} \tag{3}$$

$$\frac{D}{D_s} = \frac{x_z}{L} \Rightarrow D_s = \frac{DL}{x_z} \tag{4}$$

where D and H are the parameters (m) of the projection of the width and height of the occluder on the two sides of the approximate rectangular bottom surface at the end of the sight distance (L), respectively.

$$V_1 = \frac{1}{3} D_s H_s L = \frac{1}{3} \frac{DL}{x_z} \frac{HL}{x_z} L = \frac{1}{3} \frac{DHL^3}{{x_z}^2} \tag{5}$$

The formula for calculating the volume V_2:

$$V_2 = \frac{1}{3} DHx_z \tag{6}$$

Therefore, the occlusion volume of the point A is:

$$V_{zA} = \frac{1}{3} \frac{DHL^3}{{x_z}^2} - \frac{1}{3} DHx_z \tag{7}$$

where D is the width (m) of the occluder; H is the height (m) of the occluder; x_z is the X coordinate value (m) of the occluder.

Therefore, the occlusion ratio at the point A is:

$$z = \frac{V_{zA}}{V_A} \tag{8}$$

3.3.2. The Model of the Occlusion of the Roadside Landscape Visual Field When a Vehicle Travels to Any Point

When a vehicle moves from point A to point B, the occluded volume of the visual field of point B at time t_i is shown in Figure 4.

When the driver travels from point A to point B, the driving angle is δ, and the driving distance arc length L_a is:

$$L_a = v \cdot t_i = \frac{\pi}{180} \cdot (R + w_1 + w_2) \cdot \delta \tag{9}$$

Thus:

$$\delta = \frac{v \cdot t_i}{R + w_1 + w_2} \cdot \frac{180}{\pi} \tag{10}$$

Then, the coordinates of point B are:

$$\begin{gathered} \left((R + w_1 + w_2) \cos\left(90 - \frac{v \cdot t_i}{R+w_1+w_2} \cdot \frac{180}{\pi}\right), \right. \\ \left. -(R + w_1 + w_2) \sin\left(90 - \frac{v \cdot t_i}{R+w_1+w_2} \cdot \frac{180}{\pi}\right) \right) \end{gathered} \tag{11}$$

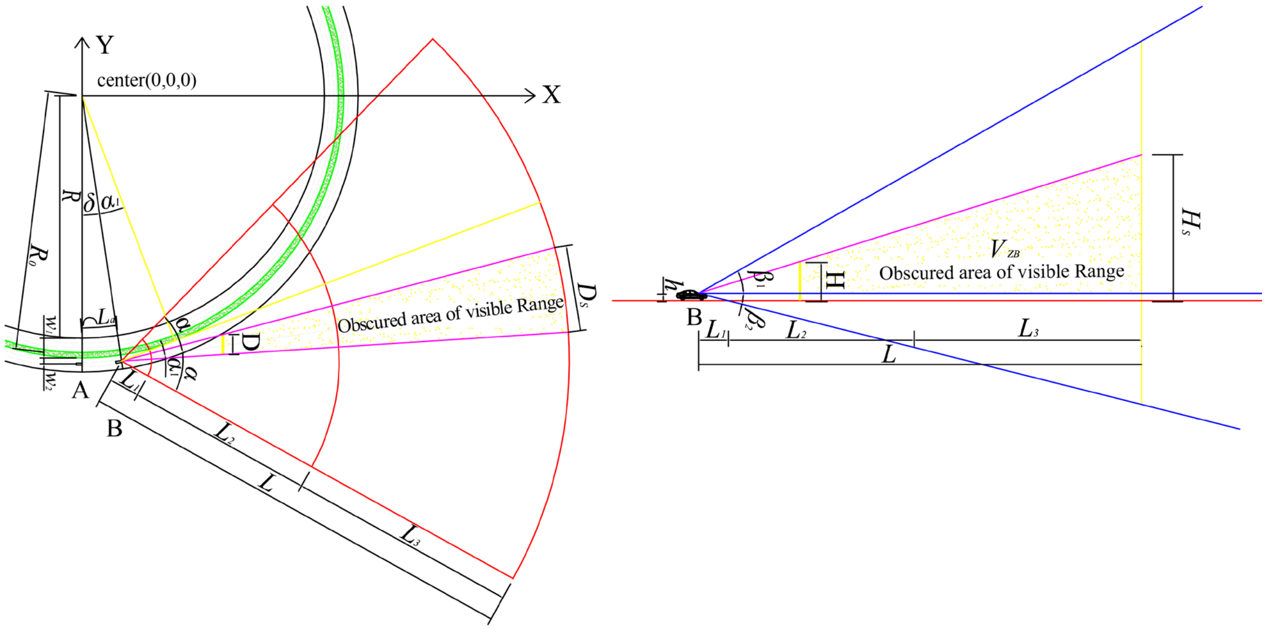

Figure 4. Schematic representation of the occluded volume of the visual field of the roadside landscape on a curved highway (volume at time t_i).

Through trigonometric function transformation, the coordinates of the simplified point B are:

$$\begin{array}{c}\left((R+w_1+w_2)\sin\left(\frac{v\cdot t_i}{R+w_1+w_2}\cdot\frac{180}{\pi}\right),\right.\\ \left.-(R+w_1+w_2)\cos\left(\frac{v\cdot t_i}{R+w_1+w_2}\cdot\frac{180}{\pi}\right)\right)\end{array} \tag{12}$$

$$\begin{array}{c}V_{zB}=\frac{1}{3}\frac{DHL^3}{\left[X_z-(R+w_1+w_2)\sin\left(\frac{vt_i}{R+w_1+w_2}\cdot\frac{180}{\pi}\right)\right]^2}\\ -\frac{1}{3}DH\left[X_z-(R+w_1+w_2)\sin\left(\frac{vt_i}{R+w_1+w_2}\cdot\frac{180}{\pi}\right)\right]\end{array} \tag{13}$$

where t_i is the travel time (s) when the vehicle moves from point A to point B.

Therefore, the occlusion ratio at point B is:

$$z=\frac{V_{zB}}{V_A} \tag{14}$$

3.3.3. Occlusion Judgment Model for Roadside Landscape Visual Field

If the width D and height H of the occluder are given, because in the process of vehicle motion, the occlusion and volume of the occluder to the driver change, they are related to the driving speed of the vehicle, the radius of the circular curve, and the coordinates of the initial point A of the vehicle. They are constantly changing.

The change of the width D of the occlusion is recorded as D_j, whose value can be judged and obtained by calculating the intersection of the driver's line of sight and the occluder's segment line in the top view; and the change of the height H of the occluder is recorded as H_j, whos evalue can be judged and obtained by calculating the intersection of the driver's line of sight and the occluder's segment line the straight view.

(1) D_j value calculation and occlusion judgment

As shown in Figure 5, it is assumed that the vehicle travels to the point $B(x_0, y_0)$ of the curve, and the top view of the occluder is equivalent to a line segment, and its two ends are D_1 $(x_1, y_{1)}$ and D_2 (x_2, y_2). If the coordinates of D_1 and D_2 use the spatial coordinates assumed by the occluder, namely, D_1 (x_z, y_z, z_z) and D_2 $(x_z, y_z - D, z_z)$, then the occlusion width D_j can be obtained by calculating the intersection point $J(x_j, y_j)$.

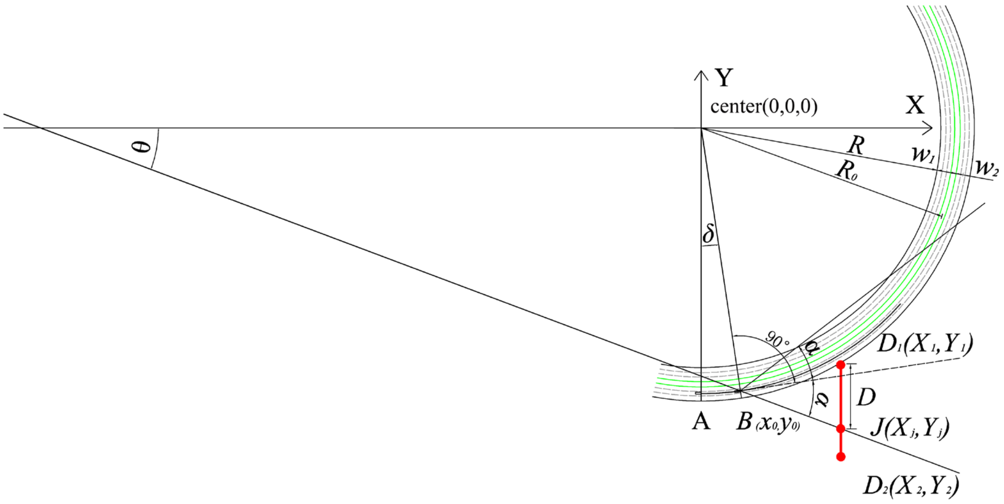

Figure 5. Occlusion judgment of the occlusion width D_j value.

The equation BJ of a straight line passing through point B can be known from the geometric relationship:

$$\theta = 90 - (\delta + 90 - \alpha) = \alpha - \delta = \alpha - \frac{vt_i}{R + w_1 + w_2} \cdot \frac{180}{\pi} \tag{15}$$

$$k = \tan(-\theta) \tag{16}$$

Then, the ray equation passing through point B is:

$$y = k(x - x_0) + y_0 \tag{17}$$

The equation for line segment D1,D_2 is:

$$x_1 = x_2 = x_z \Rightarrow x = x_1 \tag{18}$$

Find the intersection point J. The equations of the simultaneous Equations (17) and (18), as well as the coordinate formula of point B, can obtain the coordinates of the intersection point J(x_j, y_j) as:

$$\begin{cases} x_j = x_1 = x_z \\ y_j = k(x_1 - x_0) + y_0 = \tan\left(\frac{vt_i}{R+w_1+w_2} \cdot \frac{180}{\pi} - \alpha\right)(x_1 - x_0) + y_0 \\ = \tan\left(\frac{vt_i}{R+w_1+w_2} \cdot \frac{180}{\pi} - \alpha\right)\left[x_z - (R + w_1 + w_2)\sin\left(\frac{vt_i}{R+w_1+w_2} \cdot \frac{180}{\pi}\right)\right] \\ -(R + w_1 + w_2)\cos\left(\frac{vt_i}{R+w_1+w_2} \cdot \frac{180}{\pi}\right) \end{cases} \tag{19}$$

Make the following judgments:

If $y_j > y_1$ and $y_j < y_2$, it is partially occlusion, and $D_j = y_j - y_1$ is obtained. From the coordinate system shown in Figure 5 and the actual roadside landscape, it can be known that the D1 and D2 coordinates are both located in the fourth quadrant, and the Y axis coordinate values have the same sign.

If $y_j \leq y_1$, there is no occlusion, at this time $D_j = 0$.

If $y_j \geq y_2$, it is fully occlusion, at this time $D_j = y_2 - y_1$.

The calculation steps of D_j value were given above, and the occlusion volume when the vehicle travels to a certain point can be obtained by substituting into Equation (13).

(2) H_j value calculation and occlusion judgment

As shown in Figure 6, it is assumed that the vehicle travels to the point B(x_0, h) of the curve, and the straight view of the occluder is equivalent to a line segment, and its two ends are H_1 (x_1, H) and H_2 (x_2, 0), the occlusion width H can be obtained by finding the intersection point $J(x_j, z_j)$.

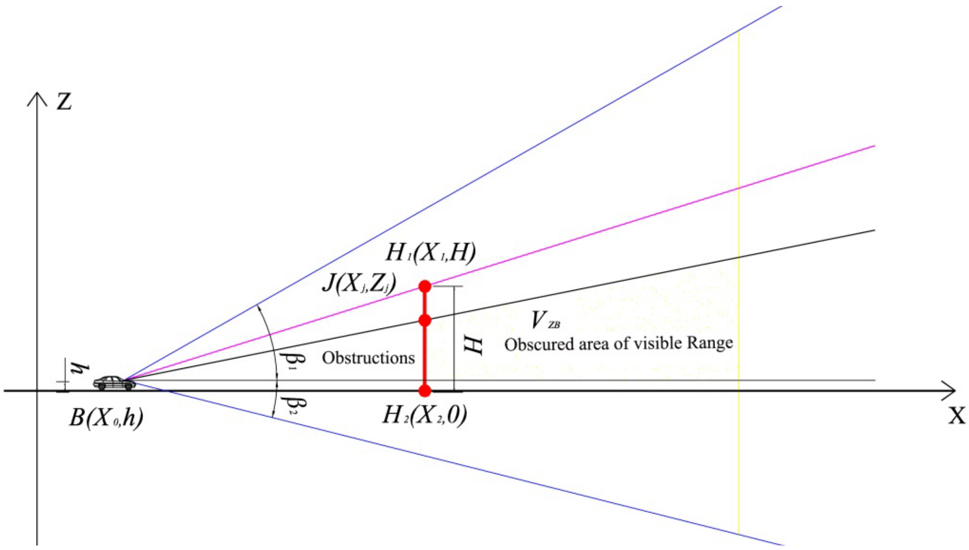

Figure 6. Occlusion judgment of the occlusion height H_j.

The ray equation passing through point B can be known from the geometric relationship, and the slope is:

$$k = \tan(\beta_1) \tag{20}$$

Then, the ray equation passing through point B is:

$$z = k(x - x_0) + h \tag{21}$$

The equation for line segment H_1, H_2 is:

$$x_1 = x_2 = x_z \Rightarrow x = x_1 \tag{22}$$

Find the intersection point J. Based on the simultaneous Equations (21) and (22) and the coordinate formula of point B, the intersection point $J(x_j, z_{j)}$ can be obtained as:

$$\left\{\begin{array}{c} x_j = x_1 = x_z \\ z_j = k(x_1 - x_0) + h = \tan(\beta_1)(x_1 - x_0) + h \\ = \tan(\beta_1)\left[x_z - (R + w_1 + w_2)\sin\left(\frac{vt_i}{R+w_1+w_2} \cdot \frac{180}{\pi}\right)\right] + h \end{array}\right. \tag{23}$$

Make the following judgments:

If $z_j \geq H$, the occlusion height is H. From the coordinate system shown in Figure 6 and the actual roadside landscape, it can be known that the H_1 and H_2 coordinates are both located in the first quadrant, and the Y axis coordinate values have the same sign.

If $z_j < H$, the occlusion height is z_j.

The above is the calculation step of the H_j value, and the occlusion volume when the vehicle travels to a certain point can be obtained by substituting into the Equation (13).

4. Calculation of the Occlusion of the Visual Field of the Roadside Landscape on a Curved Highway

4.1. Parameter Selection

4.1.1. Value of Section Width

According to the "Technical Standards for Highway Engineering" (JTG B01-2014) [18,19], the road width of the highway is the standard value, so that it is a universal reference value to select the G4 Highway Hunan section for this study. To this end, the cross-section width of the G4 Highway as shown in Figure 7 is selected for verification, in which the width w_1 from the edge of the inner curve roadbed to the outer edge of the outer curve of the middle belt is 16.25 m, and the width w_2 from the outer edge of the outer curve of the middle belt to the coordinate position of the car is 5.625 m.

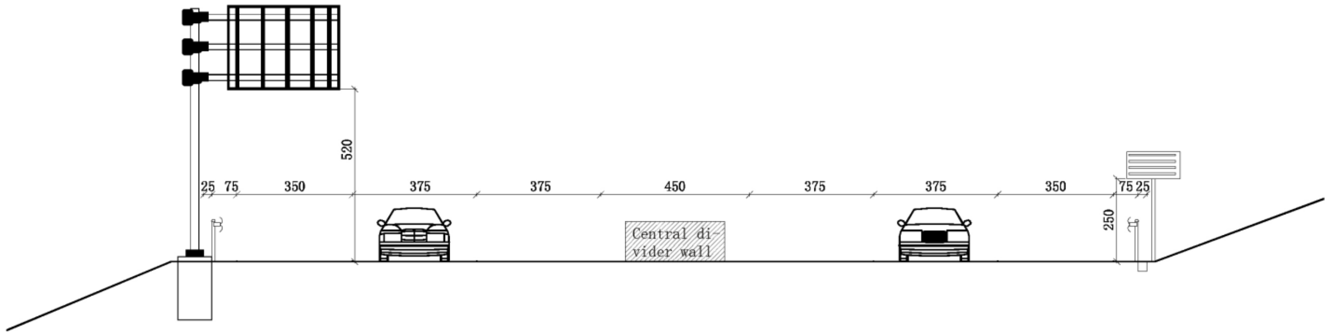

Figure 7. Typical standard cross section of G4 Hunan section (unit: cm).

4.1.2. Regular Data Value

The design speed v and the radius R of the curve are taken according to the regulations in the "Design Specification for Highway Route 19" (JTG D20-2017). The horizontal viewing angle α [20], the vertical viewing angle β [21], the front visual distance L_1 [21,22], the point L_2 [21,22] and the visual distance depth L_3 [21,22] take values from Table 1. The vertical viewing angle β_1 on the vertical field of view is 30° [23], and the viewing distance L is valued according to the depth of the viewing distance [22]. The apparent height h is taken as a value of 1.2 m for a car.

Table 1. Values of v, R, α, β, L.

Travel speed v (km/h)	40	60	80	100	120	140
General value of minimum radius of circular curve R_0 (m)	100	200	400	700	1000	—
Horizontal viewing angle α (°)	55	43	30	20	12	—
Vertical viewing angle β (°)	The clearest field of vision angle of a person's vertical field of view is 1.5~3°; the clear field of view is about 10° above and below the horizon; the angle of good clear field of view is 10° to 30° below the horizon; and the maximum field of view is 60° on the horizon down to 70°					
Vertical viewing angle β_1 (°) over vertical field of view	is 60°, the best vertical viewing angle is 26~30°, and the driver's vertical scanning range is basically 5~10°					
Vertical viewing angle β_2 (°) under vertical field of view	The angle between the line connecting the apparent height and the visual distance in front of the road vehicle and the viewing plane					
Front visibility L_1 (m)	—	25	33	42	50	—
Viewing distance from concentrated point L_2 (m)	—	180	300	420	540	—
Visibility depth L_3 (m)	—	370	500	660	820	1000

4.1.3. Occlusion Parameter Values

(1) The value of the height H of the occluder

The most frequent roadside obstructions are roadside plants, followed by cutting slopes. Among them, the roadside plants are divided into arbor (over 31 m for victor arbors, 21–30 m for big arbors, 11–20 m for medium arbors, 6–10 m for small arbors), shrubs (3–6 m for big shrubs, 1–3 m for small shrubs), and open vegetation (ground cover, flowers, and grass less than 1 m in height) [24]; according to G4 and G60 Highways' survey data, the cutting slopes in the Hunan section are divided into high slopes (above 10 m), medium slopes (5~10 m), and low slope (below 5 m). Other obstructions, such as the height of the sound barrier is generally 2~3.5 m; the height of the guardrail is 1.2~1.8 m; the height of the monitoring equipment is 6 m; and the height of the sign is generally 3.5~5.5 m.

Since the plants planted on the roadside of the highway are mainly small arbors and shrubs and the high slope will be avoided as much as possible in the design due to the large amount of excavation and serious disasters such as landslides, in this study, the height H of the occluder was selected as 3 m, 5 m, 10 m, 15 m, and 20 m as the calculated values.

(2) The value of the width D of the occluder

According to the highway land use scope confirmed in the "Highway Engineering Technical Standards" (JTG B01-2014) [18], it's defined as outside the outer edge of the drainage ditch on both sides of the embankment, if there is no drainage ditch outside the toe of the embankment (slope protection road), or on the cutting slope outside the outer edge of the top intercepting ditch, if there is no intercepting ditch outside the top of the slope, it is the land not less than 1 m in distance; in the conditional section, for the highway and the first-class highway it shall not be less than 3 m and for the second-class highway it shall not be less than 2 m.

In the design of the G4 Highway Hunan section, the land use range is 2 to 3 m beyond the drainage ditch at the foot of the subgrade fill, and 5 m beyond the top of the excavation slope; plus the side slope within the road boundary, the distance from the road boundary to the road and the boundary markers is about 5 to 30 m. Therefore, in this study, the width D of the occluder was selected as 3 m, 5 m, 10 m, 20 m, and 30 m as the calculated values.

(3) The value of the position of the occluder

The position of the occluder is determined by xz and is mainly selected by L_2 (viewing distance concentration point) and L_3 (viewing distance depth). See the values in Table 1. When the design speed is 120 km/h, select x_z as 300 m and 700 m; when the design speed is 100 km/h, select x_z as 200 m and 400 m; when the design speed is 80 km/h, select x_z as 200 m and 400 m; and when the design speed is 60 km/h, select x_z as 100 m and 300 m.

4.2. Analysis of Calculation Results

We substituted all parameter values into the visual field space model in Section 3.1 and the occlusion judgment model in Section 3.2 through MATLAB for calculation, and the rules of the verification results are as follows:

For the change of the occlusion volume and the change of the occlusion ratio, the larger the width of the occlusion object, the higher the height, and the longer the occlusion time. The occlusion process becomes an inverted "V" shape change; and from the occurrence of occlusion to the occurrence of the peak values of the occlusion volume and occlusion ratio, it takes 6 to 8 s.

(1) When the design speed of the main line is the same, the width of the obstruction at the same position is the same, but the height is varying:

Set the design speed of the main line to be the same (v = 100 km/h), the obstructions at the same position (x_z = 400 m), and the width of the same (width D is selected as 3 m, 10 m, 20 m, 30 m respectively as calculated values). When the heights are varying (3 m, 5 m, 10 m, 15 m, and 20 m are selected as the calculated values for the height H respectively), the verification results are shown in Figure 8.

Comparing Figure 8, it can be seen that the larger the occluder width, the larger the occlusion volume and the occlusion ratio. The peak occlusion ratio of obstructions with wide width (D = 30 m) and high height (H = 20 m) reached more than 62.2%; for obstructions with narrow width (D = 3 m) and high height (H = 20 m), the peak value of the occlusion ratio is only 8.9%, and its occlusion effect is relatively small; for the occlusions with wide width (D = 30 m) and short height (H = 3 m), the peak value of occlusion ratio is 9.4%. This indicates that the influence of the occluder width value is greater than that of the height value.

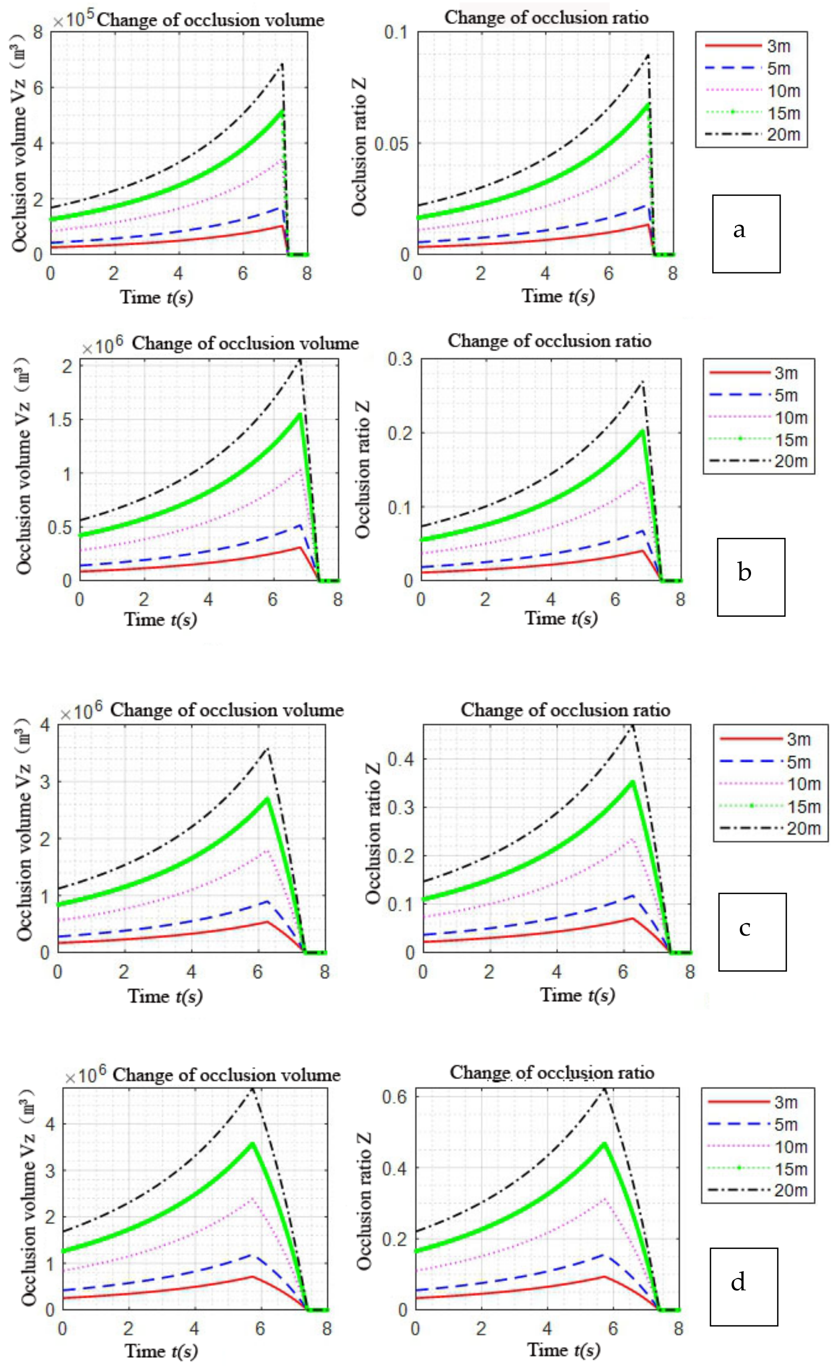

Figure 8. Simulation of the change of the occlusion volume and occlusion ratio of the roadside landscape by the occlusions of different heights under the same main line design speed, the same position, and the same width: (**a**) Obstruction of different heights when D = 3 m; (**b**) Obstructions of different heights when D = 10 m; (**c**) Obstructions of different heights when D = 20 m; (**d**) Obstructions of different heights when D = 30 m.

From Figure 8d, one can see that when the width of the occluder (D = 30 m) is wider, the occlusion ratio reaches 50% when the height is about 16.9 m, and the occlusion is serious.

(2) When the design speed of the main line is the same, the height of the obstruction at the same position is the same, but the width is varying:

The design speed of the main line is the same (v = 100 km/h); the obstructions at the same position (x_z = 400 m); the height is the same (the height H is selected as 3 m, 5 m, 10 m and 20 m respectively as the calculated value); and the width is inconsistent (The width D is selected as 3 m, 5 m, 10 m, 20 m, 30 m respectively as the calculated value), the verification result is shown in Figure 9.

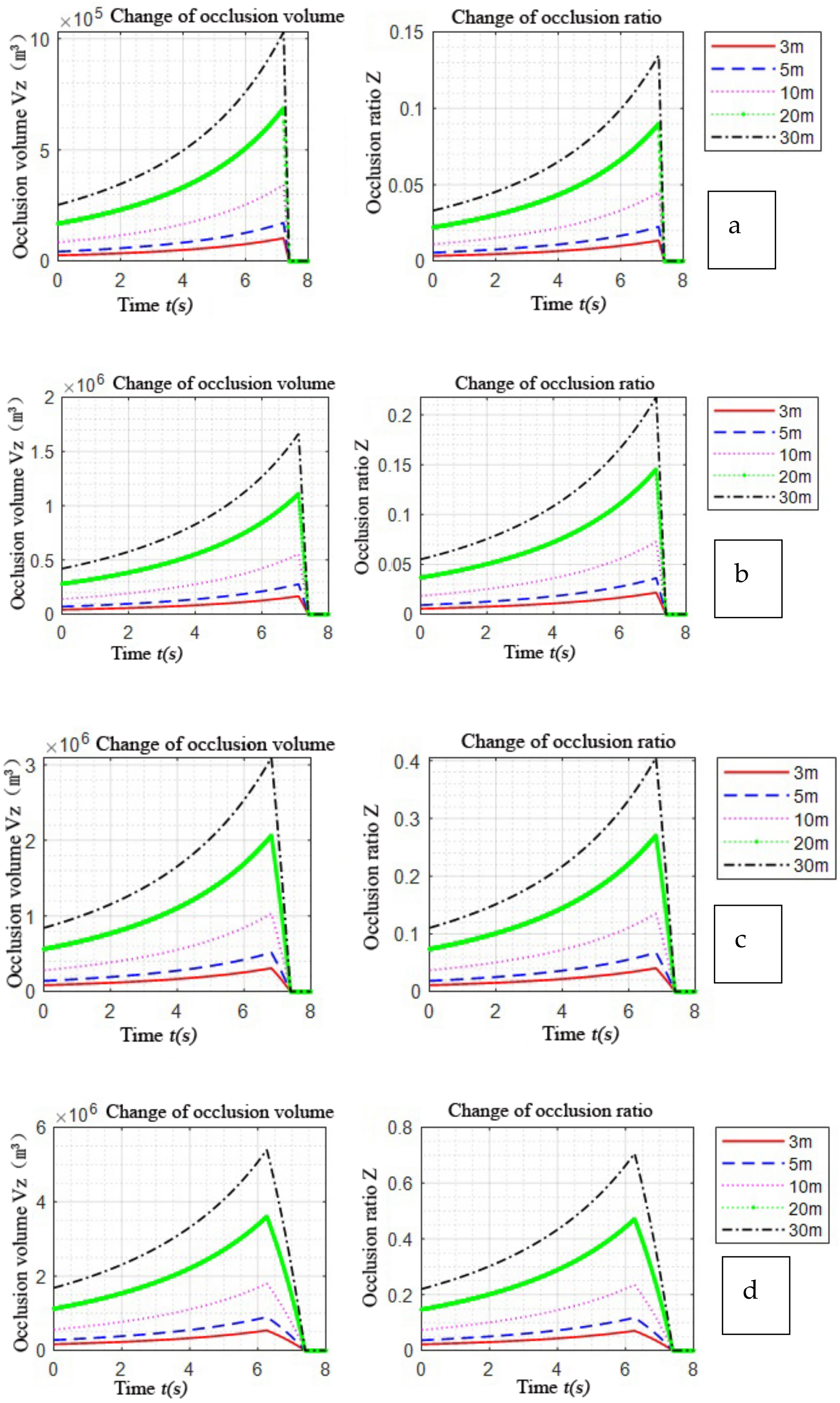

Figure 9. Simulation of the change of the occlusion volume and occlusion ratio of roadside landscape by occlusions of different widths under the conditions of the same main line design speed, the same position, and the same height. (**a**) H = 3 m with different widths of obstruction; (**b**) H = 5 m with different widths of obstruction; (**c**) H = 10 m with different widths of obstruction; (**d**) H = 20 m with different widths of obstruction.

Comparing Figure 9, it can be seen that the higher the height of the occlude is, the larger the occlusion volume and the occlusion ratio are. The peak occlusion ratio of obstructions with a high height (H = 20 m) and a wide width (D = 30 m) reaches about 70.1%; the peak value of the occlusion ratio is about 13.5%, and its occlusion effect is relatively small; for the occlusions with high height (H = 20 m) and narrow width (D = 3 m), the peak value of the occlusion ratio is about 7.6%. It shows that the height value of the occluder has a certain influence on the occlusion of the visible field, but the effect is not as obvious as the value of the width of the occluder, and it is also affected by the distance of the occluder.

From Figure 9d, we can see that when the height of the occluder (H = 20 m) is high, the occlusion ratio reaches 50% when the width is 22.8 m, and the occlusion is serious.

5. Curved Highway Roadside Landscape Visual Field Antiblocking Clearance Control

After calculating the values of various standard cross-section parameters of the highway, according to the analysis results of the visual field of the curved roadside landscape being occluded, we are seeking solutions to effectively utilize the roadside landscape and relieve the driver's fatigue by effectively controlling the roadside clearance of the curved highway. It is reasonable to take into consideration of the closeness and openness of the roadside landscaping into the design process to create a highway with a pleasant view and a degree of appropriate openness and closeness.

The volume value of the roadside landscape visual field increases as the driving speed increases. Table 2 shows the calculation results of the width and height of the occluder when the roadside landscape is completely occluded at different driving speeds.

Table 2. Viewing field volume and full occlusion width and height values of curved roadside landscape at different speeds.

Travel speed v (km/h)	60	80	100	120
Roadside landscape visual field volume V (m^3)	2,998,163	5,102,255	7,982,705	9,995,608
When the roadside landscape is completely blocked, the width of the blocking object D (m)	121.7	127.2	106.9	86.4
When the roadside landscape is completely blocked, the blocking height H(m)	70.4	98.5	127.9	154.7

Due to the large visual field and wide range of the roadside landscape, in the clearance control, the width and height of the fully occluded obstructions are large, and the volume of the obstructions is large. The visual field of the side landscape is relevant to the driver's dynamic vision, and the driver's degree of attention is different. Some visual fields are sensitive areas, while others are considered as background areas. Therefore, the range of clearance control selects the sensitive area as the reference. According to the relevant research results, the range formed by the visual distance in front of the vehicle (L_1) isset as the first-level landscape sensitive area ($W_{g)}$, and the obstructions in this area can easily block the roadside landscape. For the total width of the first-level landscape sensitive area, it is 53 m when the driving speed is 60 km/h, 55 m when the driving speed is 80 km/h, 45 m when the driving speed is 100 km/h, and 35 m when the driving speed is 120 km/h [22]. At the same time, the driver's vertical saccade range is basically in the range of 5~10°, so the visual field in this range is most likely to be occluded. Thus, 5° is selected as the reference value [25].

According to the above discussion, the clearance control of curved highway roadside landscape includes clearance control, clearance width control, and clearance height control, as shown in Figure 10. Among them, the clearance control range is the vertical distance from the driver's viewpoint to the tangent between the inner viewing plane and the median of the curve; the clearance width control is the projection of the roadside landscape visual field onto the viewing plane, the vertical distance from the intersection of the tangent line of the inner viewing plan and the median of the curve and the roadside edge line to the outer boundary of the first-level visual sensitive area; and the clearance height control is the vertical distance of 5° from the ground to the viewing plane on the projected elevation of the roadside landscape viewing area.

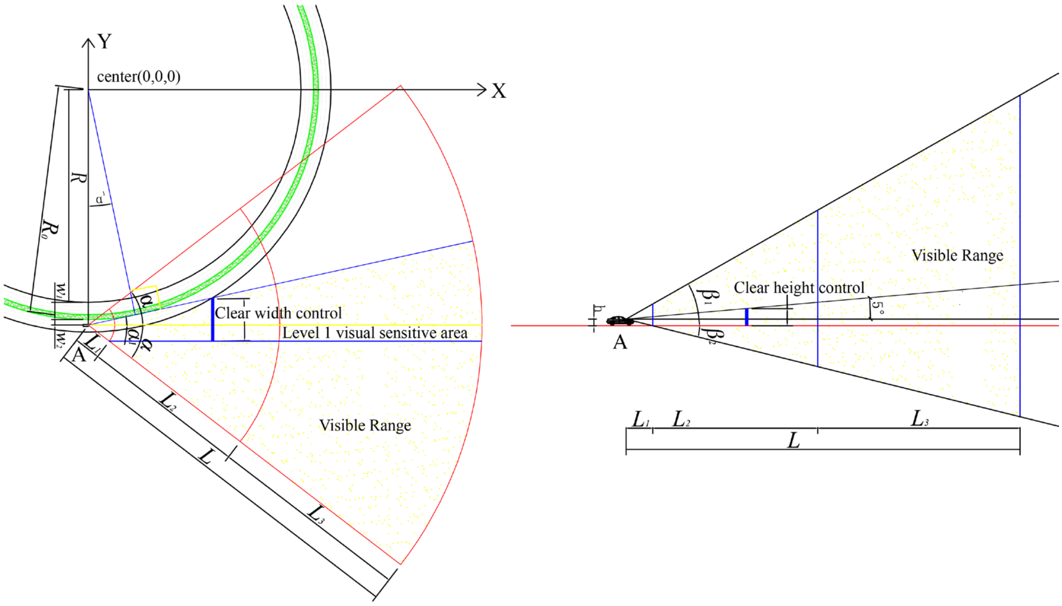

Figure 10. Schematic diagram of roadside landscape clearance control for a curved highway.

From Figure 10, based on calculations, the clear width and clear height of roadside landscape obstructions at different driving speeds are shown in Table 2. At the same time, according to relevant research, the driver's preview time should be greater than the time required for the process of visual information, perception, recognition, decision-making, and response, and the minimum preview time should not be less than 1 s [26]. Therefore, if the occlusion time exceeds 1 s, it will have an impact. Therefore, it is considered that when the roadside landscape is occluded, the width and height of the occluder can be regarded as severe occlusion as long as the peak occlusion ratio exceeds 50% for more than 1 s. According to the calculation results of Figures 8 and 9, when the driving speed is 100 km/h, when the width of the occluder reaches 22.8 m and the height is 16.9 m, the occlusion ratio reaches more than 50% for more than 1 s.

According to Table 3, the clearance control range of roadside landscape is recommended to be 270 m when the design speed is 120 km/h, 220 m when the design speed is 100 km/h, and 170 m when the design speed is 80 km/h; the recommended clearance width control value is 25 m; the recommended clearance height control value is 20 m. Within the scope of land acquisition for highways, it is recommended to acquire land 25 m wide from the road boundary.

Table 3. Control values of clearance width and clearance height of roadside landscape obstructions at different speeds.

Travel speed v (km/h)	60	80	100	120
Clearance control range (m)	119.9	168.5	217.1	265.9
Obstruction clear width control value (m)	45.0	46.4	42.3	39.7
Obstruction clear height control value (m)	11.7	15.9	20.3	24.5
Width of occluder at 50% occlusion (m)	24.3	25.1	22.8	21.4
The height of the occluder at 50% occlusion (m)	9.7	13.2	16.9	20.4

In order to ensure the proper openness and closeness of the highway and obtain a roadside landscape with beautiful scenery and pleasant natural landscape, we do not plant tall trees and shrubs but mainly use the ground cover with low shrubs. With that, the roadside landscape is open, to enrich the highway by borrowing the scenery landscape [27]; as for roadside landscapes with monotonous landscapes and many artificial landscapes, it is recommended to use tall trees and shrubs for appropriate shielding, to reduce the distraction of drivers; [28,29] and as for some roadside landscapes with prominent regional culture and not suitable for distraction, it is recommended to use shrubs that are not high or do not plant continuously to reduce the width of the cover to leak the scene [30].

6. Conclusions

Aiming at studying the occlusion of the visual field of the curved highway roadside landscape and the control of the degree of occlusion, the visual field spatial model and the visual field occlusion judgment model of the curved highway roadside landscape are established from the perspective of dynamic visual 3D. Taking the G4 Highway Hunan section as a case study, by simulating the influence of occluders of different sizes and positions on the visual field of the curved roadside landscape, an example verification is carried out, and the following main results and conclusions are obtained:

The curved roadside landscape is selected as the modeling object; the spatial coordinates are established with the center of the circular curve of the curved highway as the origin; and the geometric spatial model of the visual field of the curved roadside landscape is established. According to the width and height of the occluder, the dynamic occlusion ratio is constructed by the spatial coordinates, and the occlusion judgment model for the curved highway roadside landscape visual field is proposed.

We simulated the occlusion of different sizes and positions of occluders in the visual field of the curved roadside landscape and used the established occlusion judgment model to check and analyze the design case of the G4 Highway Hunan section. The larger the value of the width and height of the occlude, the longer the occlusion time it is, as the occlusion process becomes an inverted "V"-shaped change rule; and it takes 6 to 8 s from the occurrence of occlusion to the peak of the occlusion volume and occlusion ratio.

According to the verification results, the corresponding clearance control requirements are put forward for the anti-occlusion of the highway curving roadside landscape visual field. We recommended that the clearance control range of roadside landscape is 270 m when the design speed is 120 km/h, 220 m when 100 km/h, and 170 m when 80 km/h; the control value of clearance width is 25 m; and the control value of clearance height is 20 m. Within the scope of land acquisition for expressways, it is recommended to acquire land 25 m wide from the road boundary.

Author Contributions: Conceptualization, J.X.; methodology, X.Z.; software, L.Y.; validation, J.X. and J.W.; formal analysis, J.X. and X.Z.; investigation, J.X. and J.W.; resources, X.Z.; data curation, J.X. and L.Y.; writing—original draft preparation, J.X.; writing—review and editing, X.Z.; visualization, J.X.; supervision, X.Z.; project administration, J.X.; funding acquisition, X.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Informed Consent Statement: Not applicable.

Data Availability Statement: All stimulation and calculation results are available upon requests.

Acknowledgments: Thanks to the comprehensive laboratory of Changsha University of Science and Technology for the assistance provided; thanks to the Hunan Provincial Expressway Administration for the assistance in data collection.

Conflicts of Interest: The authors declare no conflict of interest.

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