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Intelligent Design System for Logging Truck Roads

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Abstract: *The possibility of improving the quality of design solutions is associated with taking into account the visual perception of roads. The road traffic situation depends on the wrong perception of the logging truck road direction by drivers or on the overestimation of dangerous traffic speeds. On the other hand, slowing down the lumber-truck speed before the seemingly sharp road turns affects the operational efficiency of the logging transport. Therefore, the perspective view of the road should strongly orient the driver, i.e., be visually clear and changing clearly, ensuring the constancy or smooth reduction of the traffic flow mode. At that, the need for a successful spatial solution of the road increases. It is established that the perspective road view correctly orients the vehicle driver, i.e., it is visually clear, provided that the lines outlining the roadway edges and the trackway joining edges are curved in the perspective image in the same direction as in the road plan. The study aims at determining a set of quantitative indicators (curvature, radius of the horizontal curve, maximum curvature, maximum curve curvature rate) to optimize the visual smoothness and clarity of the central projections of elementary spatial and plane curves. The performed studies allow fully characterizing the visual smoothness and clarity of the central projections of elementary spatial and plane curves. The suggested algorithm makes it possible to develop software to determine the above-mentioned indicators. The indicators determined based on this algorithm allow evaluating both the visual smoothness and clarity of curves of logging truck roads.*

Keywords: *spatial curves, building a road, visual clarity, curved section, algorithm.*

I. INTRODUCTION

The projects of logging truck roads include straight lines, transition curves, described in recent years most often by the clothoid, and circular curves as elements of the route plan [1]-[14]. When analyzing perspective images, the curved lines can also be subdivided depending on the direction of their curvature into left and right, while the transition curves – by their relation to the direction of movement of the logging rolling-stock, into inlet and outlet curves. The longitudinal profile is usually designed using horizontal and inclined straight lines, concave and convex parabolas (or circular curves). Usually used elements of the route plan and road profile can form 28 mutual combinations [15]-[18]. Thus, by combining the elements of the plan and the profile, one gets certain elements of the route in space.

The work objective is to determine a set of quantitative indicators (curvature, radius of the horizontal curve, maximum curvature, maximum curve curvature rate) to optimize the visual smoothness and clarity of the central projections of elementary spatial and plane curves.

I. RESEARCH METHODS

The spatial curve, whose graphical model is shown in Fig. 1, can be analytically described by the following system of equations:

$$\left.\begin{aligned} x &= x(s) \\ y &= y(s) \\ z &= z(s) \end{aligned}\right\} \qquad (1)$$

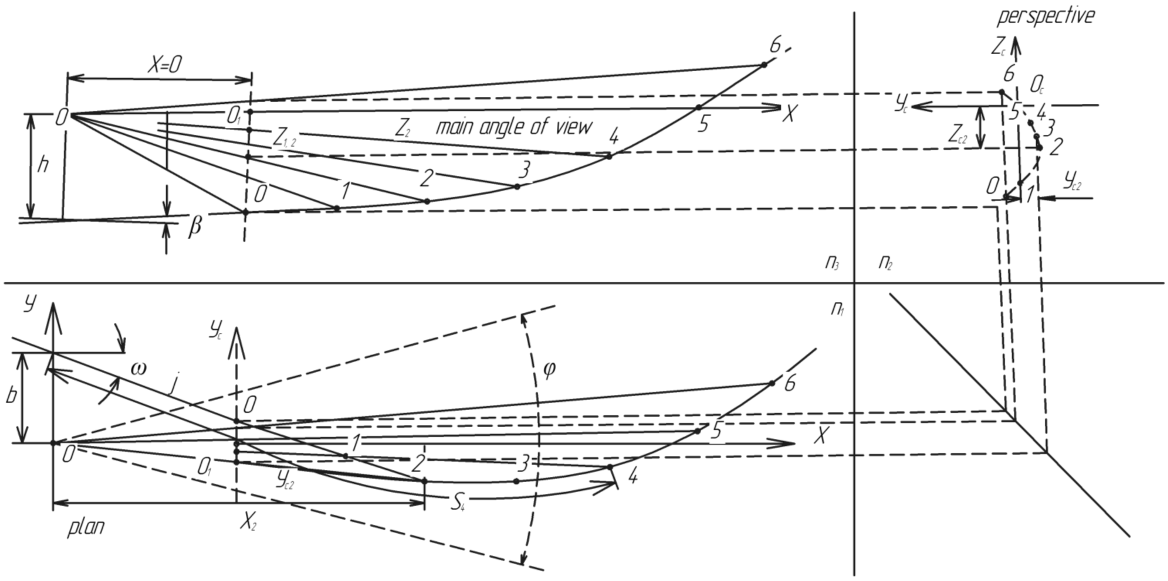

Fig. 1 Diagram of the central projection of the spatial curve. T3 – point of ~~view~~ sight (projection center), П – projection planes (1 – horizontal, 2 – frontal, 3 – profile), a – distance from T3 to the image plane Yc Oc Zc (П2), φ – the angle of the image sector, (b, h) – coordinate of the beginning of the projected line, β, ω – angles of inclination of the projected line relative to the X-axis in the profile and plan, l, j – angular coefficients corresponding to the angles β, ω

Path S, calculated from the logging truck driver's point of sight (PO), is taken as the parameter. The selected PS is taken as the origin of the right coordinate system 0, while the main ray of sight is directed along the X-axis. The image plane Y_c O_c Z_c is assumed to be perpendicular to the X-axis.

The coordinates of the central projection (Y_c Z_c) of any of the lines defining the roadbed (surface edges, edges, axis), the image plane, which is located at a distance from the point of sight, are determined by a system of equations.

$$\left.\begin{aligned} y_c &= \frac{ay}{x} \\ x_c &= \frac{az}{x} \end{aligned}\right\} \qquad (2)$$

In the system of equation (2), the values x, y, and z, according to the system of equations (1), denote the equations of coordinates x(s), y(s), and z(s) of the spatial curve. Hence, the coordinates of the perspective of the spatial curve are functions of a single parameter s.

In the case of parametric assignment of a plane curve, its curvature is expressed by the formula

$$K_c = \frac{z_c' y_c'' - z_c'' y_c'}{(y_c'^2 + z_c'^2)3/2} \qquad (3)$$

The values of the derivatives y_c', y_c'', z_c', z_c'' are obtained by differentiating the equation of perspective coordinate by the s parameter (system 2).

Where

$$y_c' = (\frac{ay}{x})' = \frac{a(xy' - yx')}{x^2} = \frac{ap}{x^2} \qquad (4a)$$

$$y_c'' = (\frac{ap}{x^2})' = \frac{a(xp' - 2px')}{x^3} \qquad (4b)$$

$$z_c' = (\frac{az}{x})' = \frac{a(xz' - zx')}{x^2} = \frac{aq}{x^2} \qquad (4c)$$

$$z_c'' = (\frac{aq}{x^2})' = \frac{a(qx' - 2qx')}{x^3} \qquad (4d)$$

The following notations are used in the dependencies (4):

$$xy' - yx' = p \qquad (5a)$$

$$xz' - zx' = q \qquad (5b)$$

Derivatives of these values with respect to s are

$$p' = (xy' - yx') = xy'' - yx'' \qquad (6a)$$

$$q' = (xz' - zx') = xz'' - zx'' \qquad (6a)$$

After converting and simplifying the numerator of the expression (3), one gets

$$y_c^{"} z_c' - y_c' z_c^{"} = \frac{a^2(p'x - 2px')q}{x^3 \cdot x^2} - \frac{a^2 p}{x^2} \cdot \frac{(q'x - 2qx')}{x^3} = \frac{a^2(qp'x - 2qpx' - q'px + 2qpx'}{x^5} = \frac{a^2(qp' - pq')}{x^4}$$
$$= \frac{a\left[(xz' - zx')\left(xy^{"} - yx^{"}\right) - (xy' - yx')\left(xz^{"} - zx^{"}\right)\right]}{x^4}$$
$$= \frac{a^2(x^2 z' y\text{-xzx'y} - xyz'x\text{+yzx'x} - x^2 y' z\text{+xyx'z} + xzy'x\text{-yzx'x}]}{x^4}$$
$$= \frac{a^2[x^2 z' y\text{-y'z}) + xy(x'z\text{-z'x}) + xz(y'x\text{-x'y}) + yz(x'x\text{-x'x})]}{x^4}$$
$$= \frac{a^2[x(z'y\text{-y'z}) + y(x'z\text{-z'x"})\text{+z(y'x"-x'y")}]}{x^3}$$

Converting and simplifying the denominator of expression (3) gives

$$(y_c'^2 + z_c'^2)\frac{3}{2} = \{[\frac{a(xy'-yx')}{x^2}]^2 + [\frac{a(xz'-zx')}{x^2}]^2\}^{3/2} = \frac{a^3[(xy'-yx')^2+(xz'-zx')^2]^{3/2}}{x^6}.$$

Hence, the curvature is expressed as

$$K_c = \frac{x^3[x(z'y\text{-y'z})\text{+y(x'z} - z'x)\text{+z(y'x} - x'y")]}{a[(xy' - yx')^2 + (xz' - zx')^2]^{3/2}} \quad (7)$$

Denoting

z’y”-y”z”=u (8a)

x’z”-z’x”=v (8a)

y’x”-x’y”=w (8c)

formula (7) can be represented as follows:

$$K_c = \frac{x^3(xu + yv + zw)}{a(p^2 + q^2)^{3/2}} \quad (9)$$

Denoting further

xu+yv+zw=U (10a)

$p^2 + q^2 = V$ (10b)

One gets

$$K_c = \frac{x^3 U}{aV^{3/2}} \quad (11)$$

The image plane is usually taken at a distance of 1 m. Therefore, further, *a=1*.

When controlling the visual clarity of spatial curves, it is important to determine the direction of curvature of their central projections. If the center of curvature lies on a positive semidirect normal, then the curvature is considered a positive. If it lies on the negative semidirect normal, then the curvature is negative [9], [10], [19], [20].

In the case of a fixed position of the point of sight above the roadbed, the curvature direction can be determined more easily. If the center of curvature is located to the left of the central projection of the curve, then the curvature calculated by the formula (7) is positive. If the center of curvature is to the right – the curvature is negative.

The road curvature rate is expressed by the first derivative of the curvature K_c by the parameter s. Based on the formula (11), one gets:

$$\frac{dK_c}{ds} = K_c' = \frac{x^2(3UVx' + U'Vx - 1{,}5UV'x)}{V^{5/2}} \quad (12)$$

Dependence (12) can also be represented as:

$$K_c' = K_c\left[\frac{3x'}{x} + \frac{U'}{U} - \frac{1{,}5V'}{V}\right]. \quad (13)$$

In this relationship, K_c' is expressed by K_c.

In formulas (12) and (13), U’ and V’ are the derived functions U(s) and V(s) with respect to the parameter s. Their values are as follows:

$$U' = x'y + y'v + z'w + xu' + yv' + zw' \quad (14a)$$

$$V' = 2(pp' + qq' \quad (14b)$$

$$u' = z'y"' - y'z"' \quad (15a)$$

$$v' = x'z"' - z'x'" \quad (15b)$$

$$w' = y'x'" - x'y"' \quad (15c)$$

Algorithm for determining K_c and K_c'

Formulas Number of formulas

The following values are determined

$x = x(s)$ $x' = x'(s)$ $x^{"} = x"(s)$ $x''' = x'''(s)$ 3.7a b, c, d

$y = y(s)\ y' = y'(s)$ $\qquad$ $y'' = y''(s)\ y''' = y'''(s)$ 3.7b b, c, d
$z = z(s)\ z' = z'(s)$ $\qquad$ $z'' = z''(s)\ z''' = z'''(s)$ 3.7c b, c, d

$x(s),\ y(s), z(s)$ represent the equations of the spatial line. The strokes indicate their derivatives by s.

Next, the following values are determined:

$$p = xy' - yx' \qquad p' = xy'' - yx''$$
$$q = xy' - yx' \qquad q' = xz'' - zx''$$
$$u = z'y'' - y'z'' \qquad u' = z'y''' - y'z'''$$
$$v = x'z'' - z'x'' \qquad v' = x'z''' - z'x'''$$
$$w = y'x'' - x'y'' \qquad w' = y'x''' - x'y'''$$

Then the following values are calculated:

U=xu+yv+zw
V=p2 +q2
$U' = xu' + yv' + zw' + x'u + y'v + z'w$
$V' = 2(pp' + qq')$

Next:
$K_c = \frac{x^3 U}{V^{3/2}}$

Finally, K_c' is calculated
$K_c' = K_c[\frac{3x'}{x} + \frac{U'}{U} - \frac{1.5V'}{V}]$

When setting the research problem, the authors assumed that the greatest curvature, K_c,н, can be one of the indicators of the visual smoothness of the road curves. At that, the greatest curvature is understood as its greatest value on the studied curved section of the line. To prove the possibility of using the K_c,н indicator, the authors established a relationship between the visual smoothness of the roadway edges and their corresponding curvature graphs.

III. RESULTS AND DISCUSSION

As an example, let consider a typical section of the route consisting of three elements: a straight line, a spatial curve, and another straight line (Fig. 2). Fig. 3 shows a perspective image of this section.

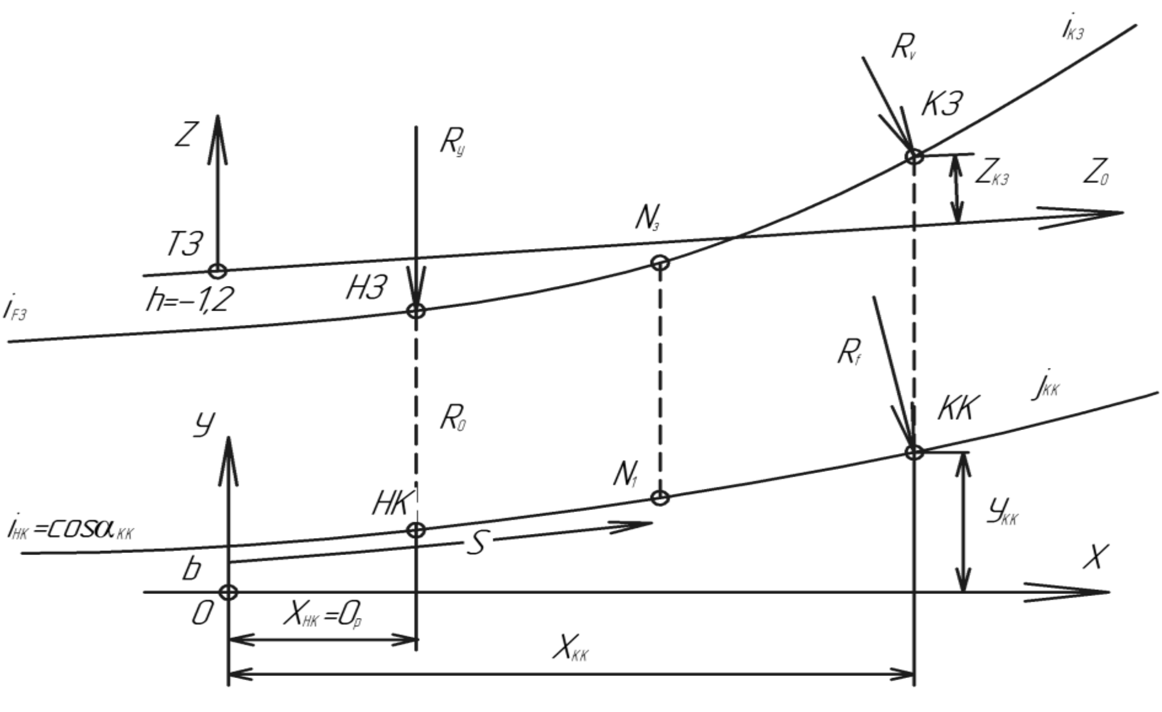

Fig. 2 Parallel projections of the spatial line (road axis) on the profile and horizontal planes

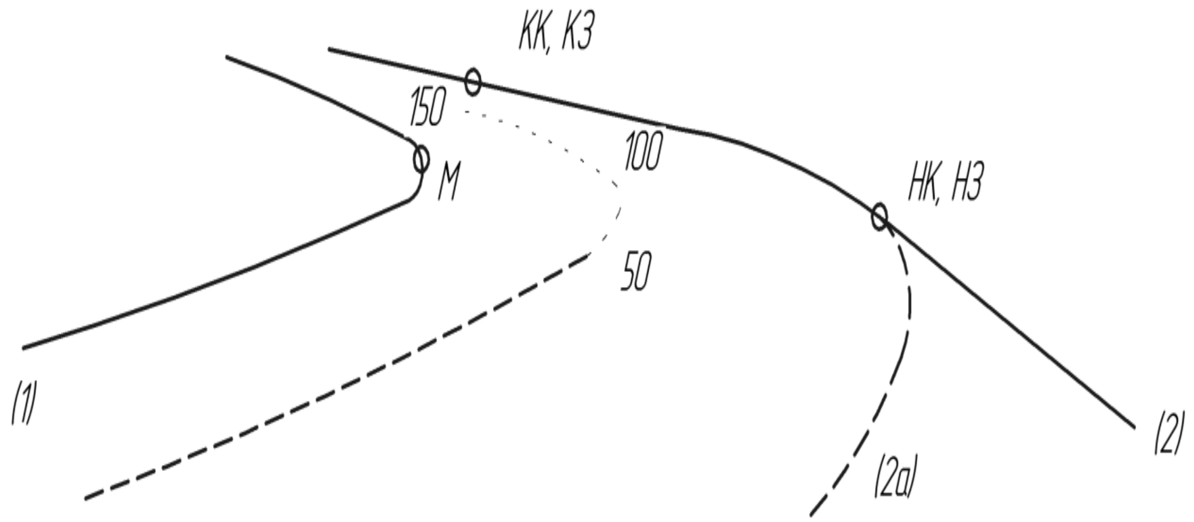

Fig. 3 Perspective image of the road section, whose axis is shown in Fig. 2

When determining the mathematical models of the road sections, the following designations were used:

b, h – rectangular coordinates of the estimated curve in the YOZ plane, m: (h – the height of the point of sight (driver's eyes) relative to the tangent to the onset of the profile projection of the estimated spatial curve;

b – the distance of the point of sight relative to the tangent to the onset of the horizontal projection of the estimated curve;

D_p , D_v – the distance from the YOZ plane, respectively, to the points of the onset of the curves in the NK plan and the NZ profile, m;

i – the longitudinal slope of the route;

R_p – the radius of the horizontal curve, m;

R_v – parabola parameter in the longitudinal profile, m;

S – parameter (horizontal projection of the path with the onset in the YOZ plane), m.

If we take the X-axis of the tangent t1 to the onset of the horizontal curve, then the section of the route shown in Fig. 2 can be set in intervals using the following systems of equations:

at $0 < s < s_{нk}$

$$\left.\begin{aligned} x &= s \\ y &= b \\ z &= h \end{aligned}\right\} \qquad (16)$$

at $s_{нk} \leq s \leq s_{kk}$

$$\left.\begin{aligned} x &= D_p + R_p Sin\alpha \\ y &= b + R_p(1 - Cos\alpha) \\ z &= h + is + \frac{(s - D_v)^2}{2R_v} \end{aligned}\right\} \qquad (17)$$

at $s_{kk} \leq s$

$$\left.\begin{aligned} x &= x_{kk} + (s - s_{kk})Cos\alpha_{kk} \\ y &= y_{kk} + (s - s_{kk})Sin\alpha_{kk} \\ z &= z_{kk} + (s - s_{kk})Sin\beta_{kk} \end{aligned}\right\} \qquad (18)$$

where $\alpha = \frac{S - D_p}{R_p}$ is the rotation angle of the horizontal route, radian;

$\alpha_{kk} = \frac{S_{kk} - D_p}{R_p}$ is the rotation angle of the route at the point kk, radians;

$\beta_{kз} = \frac{S_{kз} - D_v}{R_v}$ Is the rotation angle of the route in the profile at the point KZ, radians.

Table 1 shows the results of calculating the curvature according to the formula (7) for a curve with the parameters R_p=500 m; $R_v = 5000$ m.

Coordinates are as follows: $b_{л,kр} = 5{,}0\,m$; $b_{п,kр} = -2{,}0\,m$; h= - 1,2 м. $D_p = D_v$ =60 m. The increment step of the argument is ΔS=10 m.

TABLE I. COORDINATES OF CURVATURE GRAPHS $K_{C(s)}$

S	0	10	20	30	40	50	60	60	70	80
$b_{л,kр}$		-	-	-	-	-	0	5.4	19.2	93.8
$b_{п,kр}$		0.38	4.87	34.5	128.0	66.0	34	34.1	15.2	8.1
S	90	100	110	120	130	140	150	160	160	200
$b_{л,kр}$	488.0	275.3	67.5	24.2	11.4	6.3	3.9	2.6	0.0	0.0
$b_{п,kр}$	4.9	3.1	2.2	1.6	0.9	0.8	0.7	0.6	0.0	0.0

Based on this data, curvature graphs of the left and right edges of the roadway are drawn in Fig. 4.

To identify the relationship between the visual smoothness of the roadway edges and the corresponding curvature graphs, one should pay attention to Figs. 3 and 4. It can be seen that the inner edge (line 1) is less smooth than the outer edge (line 2). The greatest curvature of this line corresponds to the interval NK-KK, which is also shown by its curvature graph $K_{C,1}(s)$. The point of the greatest curvature 2 is difficult to determine visually, but the graph $K_{C,2}(s)$ shows that it is the point NK (in this case, the point of the maximum curvature of line 2 is within the interval O-NK on the part of the curvature that is not used for rounding the rotation angle.

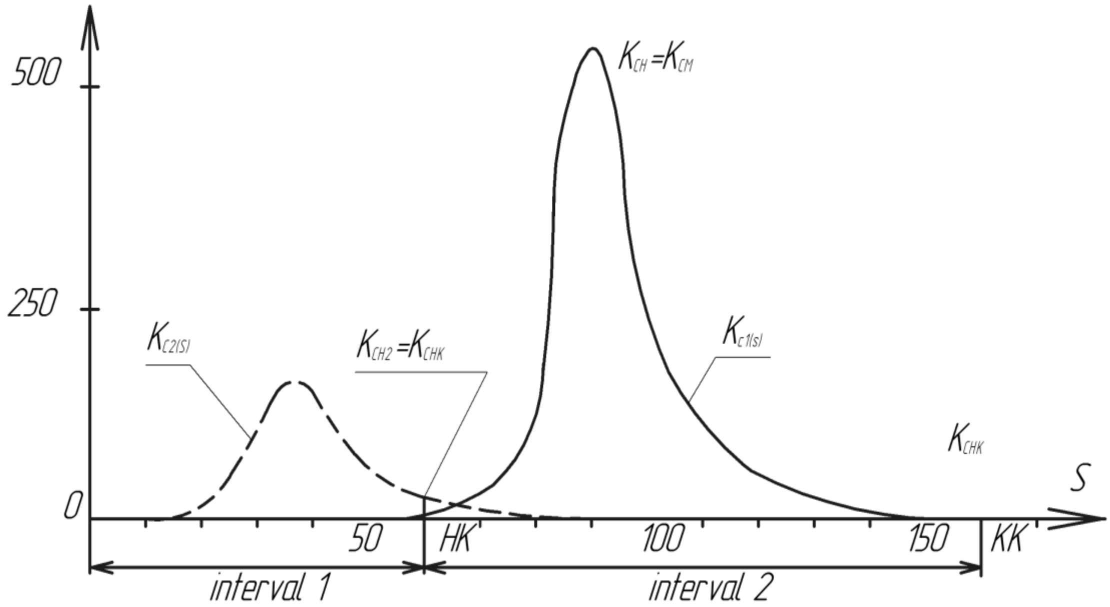

Fig. 4 Curvature graphs of the central projections of the left (1) and right (2) edges of the roadway. HK, M, KK – the points of greatest curvature ($K_{C,п}$)

Thus, the analysis leads to the following conclusions:

1) line 1 is most curved at point M, i.e.
$K_{C,н,1} = K_{C,м}$;

2) line 2 – at the point NK, i.e.
$K_{C,н,2} = K_{C,нk}$;

3) $K_{C,н,2} < K_{C,н,1}$;

4) line 2 is smoother than line 1 according to the qualitative assessment;

5) smaller value of the greatest curvature $K_{C,н,2}$ corresponds to a smoother line 2.

This indicates that the maximum curvature $K_{C,м}$Which corresponds to the point of the vertices M of the curves can be used as a quantitative indicator of visual smoothness.

The partial values of the curvature $K_{C,м}, K_{C,нk}$, and $K_{C,kk}$ They are considered further separately since they have an independent value when quantifying the visual smoothness of spatial curves.

IV. CONCLUSIONS

It is established that the perspective road view correctly orients the vehicle driver, i.e., it is visually clear, provided that the lines describing the roadway edges and trackway joining edges are curved in the perspective image in the same direction as in the horizontal road plan. On this basis, the condition of the geometric relationship of the perspective image and the plan of the logging truck road is formulated, which allows analytically checking the visual clarity of curved sections.

A set of quantitative indicators that sufficiently characterize the visual smoothness and clarity of the central projections of elementary spatial and plane curves is revealed.

In cases where the point of maximum curvature is in a zone of invisibility, the curvature at a point located on the border of visibility, in particular, $K_{C,EY.}$ Is taken as a smoothness indicator.

Indicators $K_{C,нk,}$ and $K_{C,м}$ are used to test visual clarity, while indicators $K_{C,нk,}$ and $K_{C,м}$ or $K_{C,EY}$, $K_{C,kk,}$ and $K'_{c,м}$ Are employed to assess the degree of visual smoothness of the curves.

The proposed algorithm makes it possible to develop software to determine the above-mentioned indicators. The largest values of K_C, м и K'_c, м are calculated from a series of values of K_C and K'_cCalculated using a certain step ΔS (or Δx) of changing the argument s and x.

The indicators determined by this algorithm allow evaluating both the visual smoothness and clarity of curves on logging truck roads.

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