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Algorithm for Determining the Curvature of the Project Line of a Truck Haul Road and the Rate of Change in Its Curvature

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Abstract It is recognized that a visually smooth and clear road, successfully integrated into the landscape, providing a constant or smoothly variable traffic mode, reduces the tension and fatigue of drivers, thereby contributing to their efficiency. That also reduces transport costs by choosing the most optimal traffic mode. These qualities can be achieved through spatial design method, which consists in creating conditions for safe driving at high speeds. Until now, the spatial road design method has been mainly based on the empirical rules of tracing when using visual images or models for the smoothness and clarity of the designed route of a truck haul road. Based on this method, one makes the necessary corrections to the road by evaluating the original images. Therefore, the effectiveness of the methodological foundations of spatial design of truck haul roads is further increased by providing clarity and visually acceptable curvature of spatial curves, which requires significant development and continued search to find new effective solutions. The work aims to develop an algorithm to evaluate the visual smoothness and clarity of the project line curvature of a truck haul road and the rate of change in its curvature. The article reveals a set of quantitative indicators that sufficiently and completely characterize the visual smoothness and clarity of the central projections of elementary spatial and plane curves. The presented algorithm and the indicators determined based on this algorithm; allow estimating both the visual smoothness and clarity of curves of truck haul roads. The proposed recommendations for the design of spatial curves are checked and refined based on the developed algorithm.

Keywords The Curvature of the Formation Line, Truck Haul Road, Visual Smoothness, Design of Spatial Curves

1. Introduction

When setting the research problem, it was assumed that the greatest curvature $K_{c,н}$ can be one of the indicators of the visual smoothness of the road curves [1-7]. At that, the greatest curvature is understood as its greatest value on the studied curved section of the line [8-15]. To prove the possibility of using the $K_{c,н}$ indicator, it is necessary to establish a relationship between the visual smoothness of the roadway edges and the corresponding curvature graphs.

The work objective consists in developing an algorithm to evaluate the visual smoothness and clarity of the curvature of a truck haul road project line and the rate of change in its curvature.

2. Methods

As an example, a typical section of the highway was considered. It consists of three elements, namely, a straight, a spatial curve, and a straight (Figure 1). Figure 2 shows a perspective image of this road section.

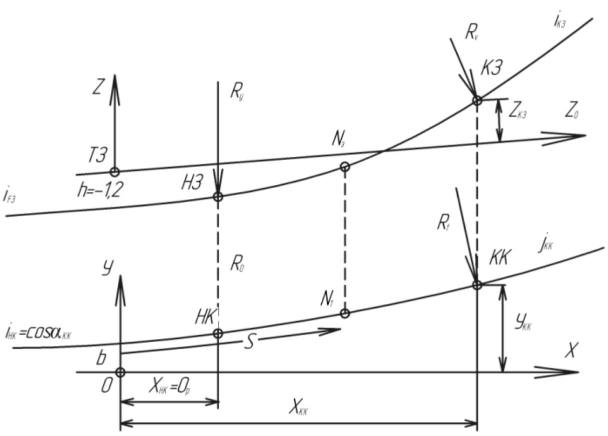


Figure 1. Parallel projections of the spatial line (road axis) on the profile and horizontal planes

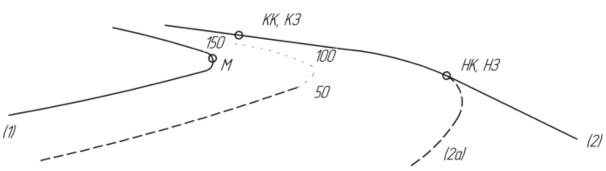


Figure 2. Perspective image of the road section, whose axis is shown in Figure 1

When determining the mathematical models of the road sections, the following notation is used:

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

b – the distance of the T3 relative to the tangent to the start point of the horizontal projection of the estimated curve;

D_p , D_v – the distances from the YOZ plane to the points of curves in the HK plan and the H3 profile, respectively, m;

i – the longitudinal route inclination;

R_p – the curve radius in the plan, m;

R_v – parabola parameter in the longitudinal profile, m;

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

Taking X-axis tangent t_l to the curve origin in the plan, the road section shown in Figure 2 can be set by intervals using the following systems of equations:

at $0 < s < s_{нk}$

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

at $s_{нk} \le s \le s_{kk}$

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

at $s_{kk} \le s$

$$\left.\begin{aligned} x &= x_{kk} + (s - s_{kk})Cos\alpha_{kk} \\ y &= y_{kk} + (s - s_{kk})Sin\alpha_{kk} \\ z &= z_{kk} + (s - s_{kk})Sin\beta_{kk} \end{aligned}\right\} \quad (3)$$

Where $\alpha = \frac{S-D_p}{R_p}$ $\alpha = \frac{S-D_p}{R_p}$ is the road turning angle in the plan, radian;

$\alpha_{kk} = \frac{S_{kk}-D_p}{R_p}$ is the road turning angle in kk point, radian;

$\beta_{kз} = \frac{S_{kз}-D_v}{R_v}$ – is the road turning angle in the profile in kз point, radian.

Table 1 shows the calculation results of the curvature for a curve with the parameters: R_p =500 m; $R_v = 5{,}000\ m$. Coordinates: $b_{л,kр} = 5.0\ m$; $b_{п,kр} = -2.0 m$; h= - 1.2 m. $D_p = D_v$ =60 m. The argument increment step ΔS=10 m.

Table 1. Coordinates of curvature graphs $K_{C(s)}$

S	0	10	20	30	40	50	60	60	70	80
$b_{л,кр}$		-	-	-	-	-	0	5,4	19,2	93.8
$b_{п,кр}$		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
$b_{л,кр}$	488.0	275.3	67.5	24.2	11.4	6.3	3.9	2.6	0.0	0.0
$b_{п,кр}$	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 Figure 3.

The relationship between the visual smoothness of the roadway edges and the corresponding curvature graphs can be identified according to Figures 2 and 3. 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 HK-KK interval, 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 from the graph $K_{C,2}(s)$ it is seen that it is the point HK (the point of the maximum curvature of line 2, in this case, is in the O-HK interval on the part of the curvature that is not used for curving the turning angle.

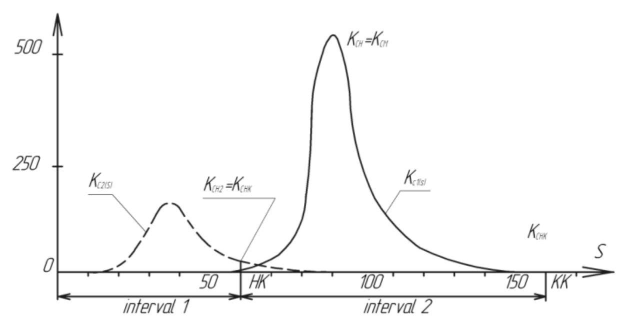


Figure 3. Curvature graphs of the central projections of the left (1) and right (2) edges of the roadway. HK, M, and KK are the points of greatest curvature (K $_{С,П}$)

Thus, the analysis leads to the following conclusions:

1) line 1 is most curved at point M, i.e.

$$K_{C,\text{н},1} = K_{C,\text{м}};$$

2) line 2 is most curved at point HK, i.e.

$$K_{C,\text{н},2} = K_{C,\text{н}k};$$

3) $K_{C,\text{н},2} < K_{C,\text{н},1}$;

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

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

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

The partial values of the curvature $K_{C,\text{м}}, K_{C,\text{н}k}$, и $K_{C,kk}$ are further considered separately since they have an independent value when quantifying the visual smoothness of spatial curves.

The values of $K_{C,\text{м}}$ that characterize smooth lines are determined experimentally.

At the initial stage of the present study, it was assumed that the degree of smoothness of the central projections of spatial curves can be characterized by the maximum curvature $K_{C,\text{м}}$. Indicator $K_{C,\text{м}}$ (or $K_{C,E}$) is not sufficient to quantify the visual smoothness of the curves. The rationale for this provision is given below.

Let us assume that in the system of equations (2), the values b, h, D_p, D_v and the ratio of the parameters R_v: R_p=m are constant. In this case, it can be assumed that $K_{C,\text{м}} = f(R_p)$.

As can be seen from Figure 4, any value of $K_{C,\text{м}}$, greater than C, M, min can be obtained for two values of radii R_1 *and* R_2, if $D_p > 0$. The authors set a task to find out whether the road sections that have different radii R_1 *and* R_2 differ qualitatively in their perspective view. For this purpose, several pairs of perspective views of road turns were made and evaluated, whose radii (R_1 *and* R_2)) were different, but the smoothness index $K_{C,\text{м}}$ was almost the same.

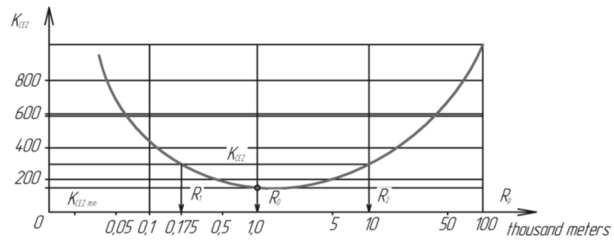


Figure 4. Dependence graph $K_{C,\text{м}} = f(R_p)$. Initial parameters: b=1.5 m; h=-1.2 m; $D_p = D_v = 40$ m

One of the pairs of images of the mentioned series is shown in Figure 5. The qualitative difference between these two images is very pronounced. Only the road section shown in Figure 5b was recognized as visually smooth. Since the maximum curvature values that characterize the smooth edges of the roadway in Figure 5 are almost the same (306 and 322), it was concluded that the indicator $K_{C,\text{м}}$ is not sufficient. It does not often reveal visually unsatisfactory lines. Therefore, the task was to identify an additional quantitative indicator.

Figure 6 shows that the maximum values of the road curvature rate are different (53.4 and 5.2). The visually unsatisfactory right edge of the roadway in Figure 5a is characterized by a value of $K'_{c,\text{м}}$ larger than that for the corresponding line in Figure 5b.

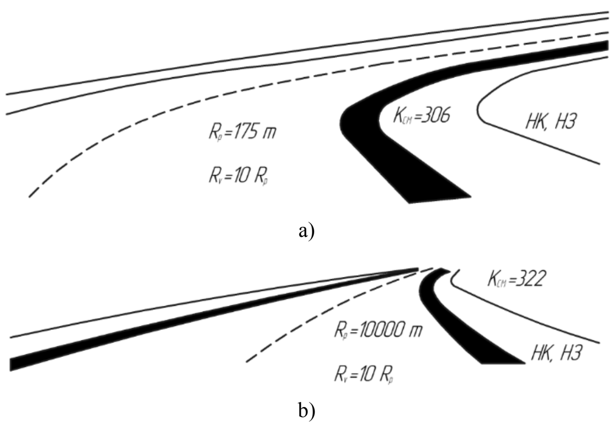


Figure 5. Perspective images of road sections. (Indicators of the smoothness of the turn $K_{C,M}$ differ little, the shape of the right edges of the roadway differs markedly)

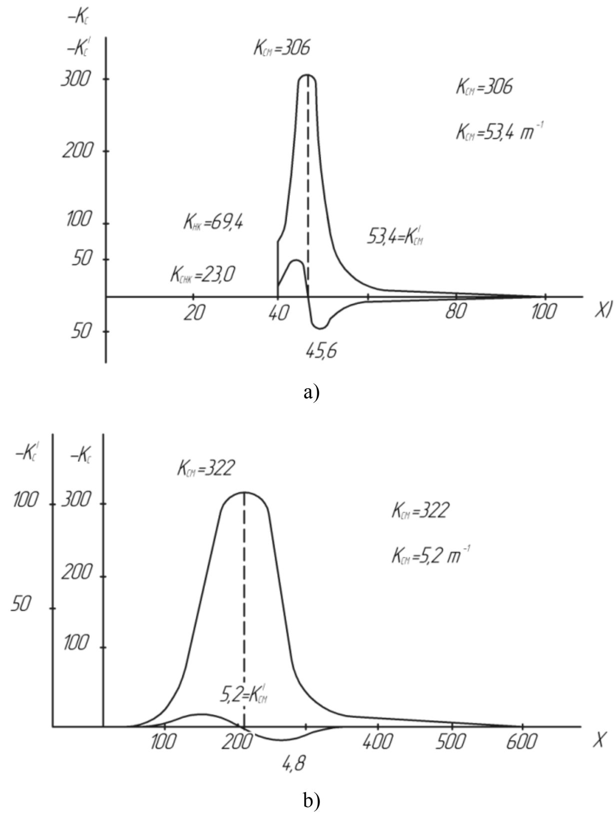


Figure 6. Graphs of the $K_{C,M}=f_1(x)$ and $K'_{C,M}=f_2(x)$, corresponding to the right edges of the roadway $K'_{c,\text{м}}$ is the second characteristic, showing the shape of the lines being studied

The curvature of the right edge of the curve, drawn with a radius R=10800 m, increases to a maximum value (322) gradually over a longer section of the road.

This analysis suggests that the qualitative difference between the right-hand edges of the roadway is quantitatively characterized by the maximum road curvature rate $K'_{c,\text{м}}$, therefore it must also be taken into account when evaluating the visual smoothness of the curves.

The range of values $K'_{c,\text{м}}$ allowable in terms of visual smoothness condition is determined experimentally.

It can be seen from Figure 6 that the breaks in the graph of curvature $K_{C,\text{м}}$(x) correspond to the start and end points of circular curves.

Considering the right edge of the roadway in Figure 5a, one can notice a significantly sharp transition from a straight line to a curve. This place is characterized by the jump of curvature $\Delta K_c = 69.4$ On the contrary, for a curve drawn with a radius of 10000 m, $K_{C,\text{н}k} = 0.9$. The right edge of the roadway beyond the point of the curve is perceived as very smooth.

Based on these conclusions, the authors assumed that depending on the magnitude of the discontinuities of the curvature graphs ΔK_c, the start and end points of the circular curves may appear to be places of visual smoothness violations.

The line smoothness indicators $K_{C,\text{н}k}$, and $K_{C,kk}$ can be used to justify the need for using "aesthetic" transition curves, as well as to determine the extent of the curves in the plan that is sufficient to meet the visual smoothness condition.

The allowable curvature jump values $\Delta K_c = K_{C,\text{н}k}$ are determined experimentally.

It is known that at small turn angles, the difference in the radii of curvature of the circle and the parabola is insignificant, therefore the arcs of the circles corresponding to the turn angles of the order up to 10^0 or 0.18 radians can be replaced by arcs of parabolas (Figure 7). Such a replacement is advisable because the formulas for determining the parameters of parabolic curves are much simpler when employing circular spatial curves. Let us estimate errors that occur in the case of such replacement.

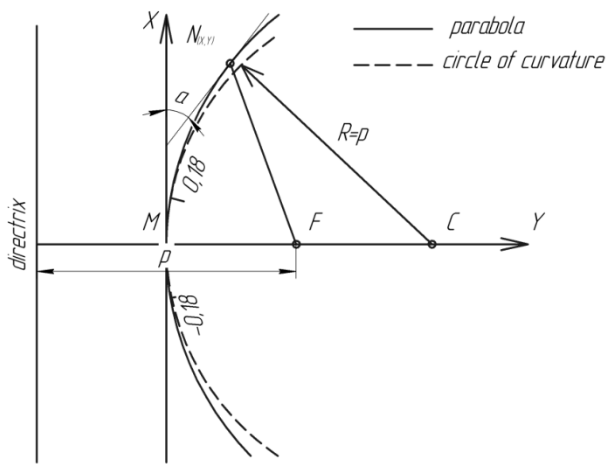


Figure 7. Arcs of a circle approximated by the arc of a parabola: F – focus; C – the center of the circle of curvature; p – focal parameter; R – radius of the circle of curvature

Let's assume that the section of the spatial curve corresponding to interval 2 in Figure 3 is drawn in the plan and the longitudinal profile along the parabolas. In this case:

$$x = x$$
$$y = b + \frac{(x-D_p)^2}{2R} \quad (4)$$
$$z = h + ix + \frac{(x-D_v)^2}{2R}$$

The derivatives of the coordinate equations (4) of parabolic curvature by x are as follows:

$$x' = 1, x'' = 0,$$
$$y' = \frac{x - D_p}{R_p}, y'' = \frac{1}{R_p},$$
$$z' = i + \frac{x - D_v}{R_v}, z'' = \frac{1}{R_v}$$

Inserting the values of the derivatives, we get

$$K_c = \frac{x^3[\frac{b}{R_v} - \frac{h}{R_p} - \frac{\delta_H(D_v - D_p)}{2R_pR_v}]}{\{\left[\frac{x^2-D_p^2}{2R_p} - b\right] + \left[\frac{x^2-D_v^2}{2R_v} - h\right]^2\}^{3/2}} \quad (5)$$

where δ_H is the offset of the points HK and H3, m.

$$\delta_H = D_v - D_p \quad (6)$$

Denoting a constant value

$$\frac{b}{R_v} - \frac{h}{R_p} - \frac{\delta_H(D_v - D_p)}{2R_pR_v} = A \quad (7)$$

and a variable

$$\left[\frac{x^2-D_p^2}{2R_p} - b\right] + \left[\frac{x^2-D_v^2}{2R_v} - h\right]^2 = V \quad (8)$$

we obtain the curvature formula

$$K_c = \frac{Ax^3}{V^{3/2}} \quad (9)$$

Differentiating the dependence (9) by x, one obtains a formula for calculating the road curvature rate

$$K_c' = \frac{3Ax^2(2V - V'x)}{2V^{5/2}} \quad (10)$$

Given the dependence (9), K_c' can be expressed through K_c

$$K_c' = K_c[\frac{3}{x} - \frac{1.5V'}{V}] \quad (10a)$$

The curvature formula (5) allows supplementing the assessment of the conclusions of Safonov V.V., who believed that the degree of change in the curvature radius is unsuitable as a criterion of visual smoothness since of all the influencing factors, only the size and shape of the curves are taken into account. From the above-mentioned formula, it can be seen that the curvature depends on the displacement of the point of the plan and profile δ_H curvature, which characterizes their mutual location, as well as on the values b, h, D_v, D_p which determine the position of the spatial curve in relation to the center of the projection.

To determine the parameter of the maximum curvature point, the value of K_c' in the formula (10) equates to zero.

Since $\frac{3Ax^2}{2V^{5/2}} \neq 0$ then:

$$2V - V'x = 0 \quad (11)$$

The value of V' is obtained by differentiating the dependence (8) by x

$$V' = \frac{2x}{R_p}\left[\frac{x^2-(D_p^2+2bR_p)}{2R_p}\right] + \frac{2x}{R_v}\left[\frac{x^2-(D_p^2+2bR_v)}{2R_v}\right] \quad (12)$$

Substituting the values V and V' into equation (11), after simplifications we get:

$$x^4\left[\frac{1}{R_p^2} + \frac{1}{R_v^2}\right] = \frac{(D_v^2+2bR_p)^2}{R_p^2} + \frac{(D_v^2+2bhR_v)}{R_v} \quad (13)$$

Denoting

$$D_p^2 + 2bR_p = x_p^2 \quad (14)$$
$$D_v^2 + 2bhR_v = x_v^2 \quad (15)$$

and taking

$$R_v = mR_p \quad (16)$$

One obtains the maximum curvature point parameter from dependence (13)

$$x_M = \sqrt[4]{\frac{m^2x_p^4 + x_V^4}{m^2+1}} \quad (17)$$

If $R_p = \infty$(straight line in plan), then

$$x_M = \sqrt[4]{(2bR_v)^2 + (D_v^2 + 2hR_v)^2} \quad (17a)$$

If $R_v = \infty$(straight line in the longitudinal profile), then

$$x_M = \sqrt[4]{(D_p^2 + 2bR_p)^2 + (2hR_p)^2} \quad (17b)$$

The maximum curvature of the central parabolic curve is determined from the dependence (5) at the parameter x_M.

If the parameter is defined by formula (17) $x_M < x_{Hk}$, then the central projection of the spatial curve in the interval HK-KK has no vertex and the point of greatest curvature $K_{c,H}$ will be located to the right of the point HK (Figure 3).

When x_M>x_kk, the greatest curvature will be to the left of the KK point.

The experience of analytical evaluation of visual smoothness has shown that the curvature of the central projection of the spatial curve at the points of its extremes EZ and EY relative to the coordinate axes z_c and Y_c (Figure 8) differs little from the maximum curvature at the points of the vertices M. On this basis, $K_{c,E}$ can be considered as an approximate value of $K_{c,M}$.

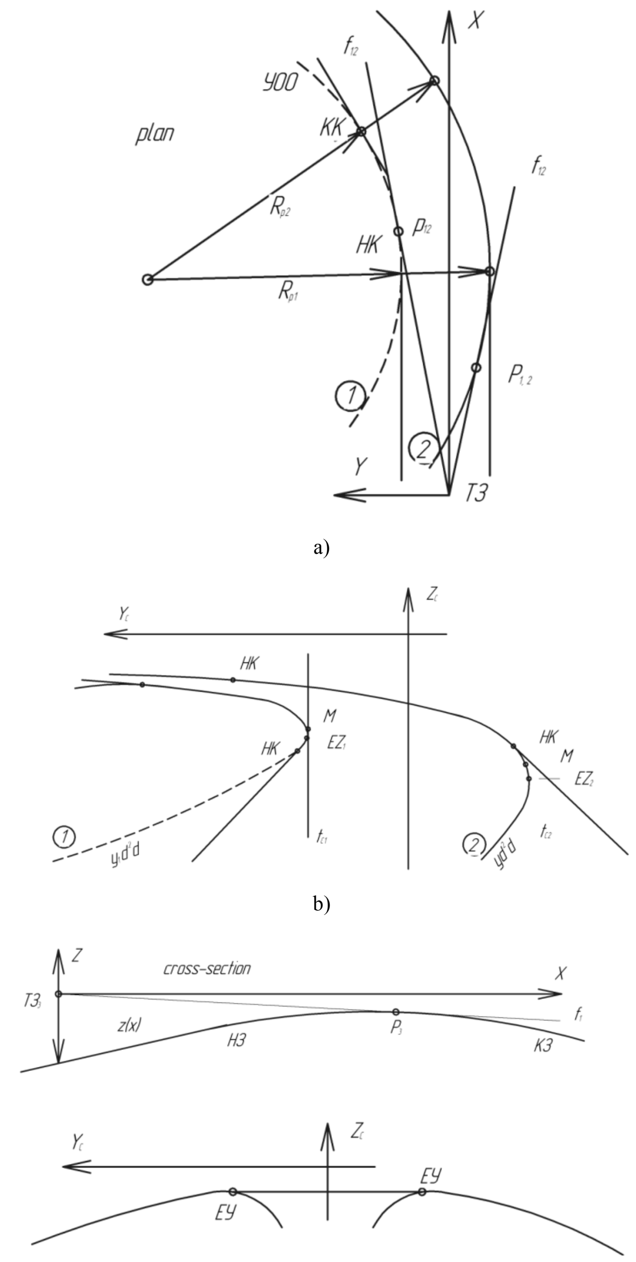


Figure 8. The points of contact P_1 of the visual rays t_1 to the horizontal projections of the spatial curves (a) are projected into the points of extrema EZ relative to the Z_c -axis of the perspective image (b). Similarly, the points of contact P_3 of the visual rays t_3 to the profile projections of the spatial curves (c) are centrally projected to the points of extrema EY relative to the Y-axis (d)

At the points of extremes EZ and EY (Figures 8b and 8d), the tangents t_c are parallel to the corresponding coordinate axes z_c and Y_c. The slopes of these tangents relative to the z_c and Y_c axes are expressed by the derivatives Y_c' and Z_c' from the perspective image coordinate equations. Substituting the extremum condition $Y_c' = 0$, we get

$$K_{c,\mathrm{EZ}} = \frac{y_c''}{z_c'^2} \tag{18}$$

The condition Z_c'=0 implies that

$$K_{c,EY} = -\frac{z_c''}{y_c'^2} \tag{19}$$

Obviously, the line $Y_c(z_c)$ can have extremes relative to the z_c or Y_c axis provided that the visual point is in a centrally projected spatial curve. At that, the points of extremums EZ or EY that miss from the contact points P_1 и P_3 may also be located on the part of the curve that is not used for turning at a certain angle (EZ, 2, in Figure 8b).

Since $a/x^2 \neq 0$, the parameter of the point EZ can be set by substituting in the equation:

$$xy' - yx' = 0 \tag{20}$$

Solving this equation with respect to the variable x, we get

$$X_{EZ} = \sqrt{D_p^2 + 2bR_p} \tag{21}$$

The curvature at the extremum point EZ can be determined by putting the value of the parameter X_{EZ} in formula (5):

$$K_{C,EZ} = \frac{X_{EZ}^3[\frac{b}{R_v} - \frac{h}{R_p} - \frac{\delta_{\text{н}}(D_v - D_p)}{2R_pR_v}]}{[\frac{x_{EZ}^2 - D_v^2}{R_v} - h]^3} \tag{22}$$

$at\ \delta_{\text{н}}$=0, expressing $R_v = mR_p$, one obtains

$$K_{C,EZ} = \frac{X_{EZ}^3 m^2}{(b-hm)^2 R_p} \tag{23}$$

Further denoting

$$\frac{m^2}{(b-hm)^2} = n_1 \tag{24}$$

one gets:

$$K_{C,EZ} = \frac{n_1 X_{EZ}^3}{R_p} \tag{25}$$

If there is a straight section in the longitudinal profile, then $R_v = \infty$; and from the formula (13) we get

$$K_{C,EZ} = \frac{X_{EZ}^3}{h^2 R_p} \tag{26}$$

By solving the equation in a similar way

$$xz' - zx' = 0 \tag{27}$$

we obtain

$$X_{EZ} = \sqrt{D_V^2 + 2hR_v} \tag{28}$$

This parameter value defines the visibility boundary on the convex curve in the longitudinal profile. The curvature at this point is

$$K_{C,EY} = \frac{X_{EY}^3[\frac{b}{R_v} - \frac{h}{R_p} - \frac{\delta_{\text{н}}(D_v - D_p)}{2R_pR_v}]}{[\frac{x_{EY}^2 - D_p^2}{2R_p} - b]^3} \tag{29}$$

When $\delta_{\text{н}} = 0$, given that $R_v = mR_p$

$$K_{C,EY} = \frac{X_{EY}^3}{m(b-hm)^2 R_p} = -\frac{n_2 X_{EY}^2}{R_p} \quad (30)$$

$$\text{where } n_2 = \frac{1}{m(b-hm)^2} \quad (31)$$

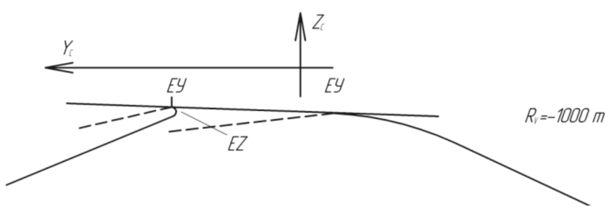
At $R_p = \infty$ (straight section in plan)

$$K_{C,EY} = -\frac{X_{EY}^3}{b^2 R_v} \quad (32)$$

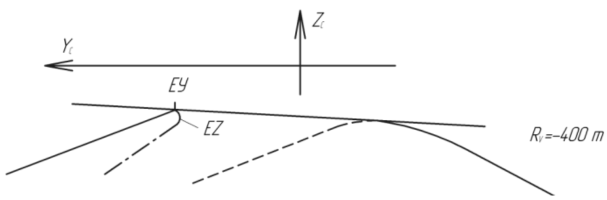
The central projections of spatial curves obtained by combining a planar curve with a convex vertical curve can have both extremes relative to the z_c and Y_c axes (Figure 9).

At that, the following relations are possible: $x_{EZ} < x_{EY}$ (Figure 9a), $x_{EZ} = x_{EY}$, $x_{EZ} > x_{EY}$ (Figure 9b).

Since the x_{EY} parameter defines the visibility boundary in the longitudinal profile, then if $x_{EZ} > x_{EY}$, then both EZ and the vertex point M are in the invisibility zone. Using the curvature at a point located in the invisibility zone, as an indicator of smoothness, does not make practical sense. Therefore, for $x_{EZ} > x_{EY}$, the curvature determined by formulas (29), (30), or (32) is used as such indicator.



a)



b)

Figure 9. Possible location of the points EZ and EY: a) EZ is in front of EY; b) EZ is behind EY

The values of the curvature at the points HK and KK are determined by the formula (5) for the parameters x_{HK} and x_{kk}.

Obviously, to the left of the HK point

K_C=0, while to the right of HK point:

$$K_{C,HK} = \frac{x_{HK}^3[\frac{b}{R_v} - \frac{h}{R_p}]}{(b^2+h^2)^{3/2}} \quad (33)$$

The curvature graph at the point HK loses continuity, and the gap value is $\Delta K_c = K_{C,HK}$. Depending on the gap value, the line can be visually smooth or non-smooth.

When using simplified formulas, it is important to assess the reliability of the visual analysis conclusions made based on approximate analysis of indicators $K_{C,EZ}$ instead of the exact one. To do this, it is necessary to determine how the ratio

$$\frac{K_{C,M}}{K_{C,EZ}} = N_1 \quad (34)$$

changes depending on the curve parameters.

Based on formulas (5) and (23) and taking that $D_p = D_v = 0$, we obtain

$$N_1 = \frac{J^3[\frac{b}{m} - h]^3}{\{[b(J^2-1)]^2 + \left[\frac{J^2 b}{m} - h\right]^2\}^{3/2}} \quad (35)$$

where

$$J = \frac{x_M}{x_{EZ}} = [\frac{m^2}{m^2+1} \cdot \frac{b^2+h^2}{b^2}]^{1/4} \quad (36)$$

Considering the dependencies (25) and (34), a simple formula is obtained for determining the maximum curvature

$$K_{C,M} = N_1 K_{C,EZ} = \frac{N_1 n_1 X_{EZ}^3}{R_p} \quad (37)$$

It is seen that for left curves $N_1 \leq 1.08$, while for right curves at the concave longitudinal profile (m$\leq$ 25) the value $N_1 \leq 1.11$. It can be assumed that in these cases

$$K_{C,M} \approx K_{C,EZ} \quad (38)$$

Consequently, the possibilities of using the approximate maximum curvature index $\boldsymbol{K_{C,EZ}}$ are quite broad, and the reliability of the conclusions concerning the visual smoothness based on this approach is quite acceptable for practical purposes.

3. Conclusions

A set of quantitative indicators that quite completely characterize the visual smoothness and clarity of the central projections of elementary spatial and planar curves is determined. These indicators include curvature $K_{C,i}$, the radius of the curve in the plan R_p, the maximum curvature $K_{C,M}$, and the maximum curvature rate.

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

Indicators $K_{C,i}$, and R_p are used to check visual clarity, while indicators $K_{C,HK,}$ $K_{C,M}$ or $K_{C,EY}$, $K_{C,kk,}$ and $K'_{C,M}$ are used to assess the degree of visual smoothness of curves.

The above algorithm makes it possible to compile a computer program to determine the mentioned indicators. The largest values of K_C, and K'_c, m are calculated from a series of K_C and K'_cvalues calculated at a certain step ΔS (or Δx) of changing the argument s and x.

The indicators determined based on this algorithm allow evaluating both the visual smoothness and clarity of curves of the truck haul road.

The allowable displacements in terms of visual clarity condition of the circular curve points of the plan and the longitudinal profile are determined.

The tasks of experimental research necessary for using the results of theoretical study in design practice include the following:

- determining the intervals of the indicators of smoothness $K_{C,нk}$, $K_{C,м}$, $K_{C,kk}$, and K'_c at which the lines are visually perceived as smooth, sharp, or broken;
- determining general conditions for visual smoothness and clarity of curves;
- creating a method for quantifying the visual smoothness and clarity of spatial curves;
- checking and refining recommendations for designing spatial curves;
- developing auxiliary tools for visual analysis and selection of optimal parameters of spatial curves.

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