Considering various conditions during determination of railway curve superelevation

V P Beltiukov and A V Andreev

Emperor Alexander I St. Petersburg State Transport University (PSTU), 9, Moskovsky pr., Saint Petersburg, 190031, Russia

E-mail: Oddman@bk.ru

Abstract. The calculation of the established railway curve superelevation, until recently, was carried out on the basis of two conditions: the condition of equal wear of both rails and the condition of passenger ride comfort. With the introduction of the Interim guideline on determining the railway curve superelevation and speeds limits in curves, this condition was abolished in favor of a more complex condition for ride comfort. Unfortunately, the condition of ride comfort does not take into account many factors that can influence the determination of the optimal railway curve superelevation. Among such factors are economic factors. In the URRAN methodology, for example, among others, the life cycle cost is considered. For track facilities, it is more relevant to consider the concept of overhaul cycle cost, since it is during the overhaul cycle that the curves are operated. The article proposes, along with the Interim guideline, in which safety factors are considered, to consider the definition of the railway curve superelevation, taking into account the life cycle cost.

1. Introduction
Ensuring the same vertical wear and settlement of both rails requires that the sum of the normal pressures on the high side of curve rail (or normal reactions $E_h$) from all wheels of all trains traveling along a given curve during the accepted time interval be equal to the sum of the normal pressures from the same trains to the inside of curve rail (or its normal reactions $E_i$). It is customary to consider in this case a design scheme with a carriage without springs (Figure 1).

Additionally, it is assumed that the carriage is symmetrically positioned in the track, and the influence of the wind is neglected. To ensure the stated condition, it is necessary that:

$$\sum E_h = \sum E_i$$

(1)

where $\sum E_h$ - total loads on the high side of curve rail;
$\sum E_i$ - total loads on the inside of curve rail.
Based on the equality of the total loads (Formula 1), a formula was derived to determine the elevation of the railway curve superelevation based on the condition of equal wear of both rails during the passage of the train traffic ($h_{traf}$). In the method for calculating the railway curve superelevation [1], the formula looked like this:

$$h_{traf} = \frac{12,5 \bar{v}_{top}}{R}, \text{mm}. \quad (2)$$

In this case $\bar{v}_{top}$ – weighted average speed of trains, obtained on the basis of the top speeds of trains circulating on the study railroad; $R$ – curve radius.

2. Materials and methods

Professor G. M. Shakhunyants and Professor O. P. Ershkov in the 60s proposed adding an additional term ($\Delta h$) [2], which would take into account the influence of the bolster part to the wheelset and the work of the carriage springs. In future, the carriage members were taken into account only during determination of railway curve superelevation based on the ride comfort. Formula 2 was abolished with the release of an Interim guideline on determining the railway curve superelevation and speeds limits in curves [3].

Considering the ride comfort during the carriage following the curved section of the track is carried out using the non-compensated acceleration that occurs when the centrifugal force appears.

Years of research experience shows that high values of these accelerations are unpleasant for passengers. The value of the railway curve superelevation, calculated from the weighted average speed, may be insufficient to reduce the non-compensated accelerations that occur when passenger train pass along the curve, the speed of which is higher than the freight train. It is required to set such a railway curve superelevation that the value of the non-compensated acceleration that occurs when the train passes at top speed does not exceed the permissible value for the effect on the passenger.

To simplify the calculation, such a limitation of the non-compensated acceleration of the rolling stock elements is adopted according to the considered scheme, in which the non-compensated acceleration of the passenger does not exceed the permissible medical standards.

Consideration of safety (ride comfort) can conflict with the condition of an equal load on both rails during operation, which leads to a more intensive growth of failures in a curve track section.

In the period from 2016 to 2018, Russian Railways performed an analysis of the non-compensated accelerations and railway curve superelevation in connection with the suspicion of irrational railway curve superelevation on the railway.
The Hexa company, the Railway Vehicle and Track Interaction Testing Center and JSC "VNIKTI" considered the optimal railway curve superelevation for five directions of the railway: Samara – Chelyabinsk, Irkutsk – Chita, Moscow – Smolensk, Aleksandrov – Orekhovo-Zuevo, Yaganovo – Voskresensk. To consider the optimal railway curve superelevation, the values of vertical and lateral loads in the curves were determined using load complexes at various non-compensated accelerations. Studies have shown that minimum loads occur at a non-compensated acceleration of 0 m/s^2. It follows from this that under the most comfortable conditions for passengers there will be an equal distribution of loads on outer and inner rail, which indicates the minimum load on one rail (left or right).

But it should be said that the minimum loads does not mean the minimum costs when operating a railway curve. To determine the minimum cost, it is worth considering the concept of overhaul cycle cost.

3. Considering overhaul cycle cost during determination of railway curve superelevation

The overhaul cycle of the upper track is a part of the life cycle during which the maintenance and repair of the railway track takes place. The overhaul cycle cost is the sum of the costs at the laying of track, maintenance and intermediate repairs of the track, dismantling of track.

Compared to similar stages during the life cycle of an object (implementation, operation and decommissioning and disposal), the overhaul cycle has the difference at the stage of dismantling of track, the elements of the permanent way can be used in the future, that is, after the stage of dismantling of track in another railway track start the laying of track.

When considering the overhaul cycle cost, it was assumed that the amount of costs will be taken without taking into account the further relaying of track in another railway track. Minimization of the life cycle cost based on the URRAN system [4] will give the optimal maintenance of the railway track.

This principle can also be used to optimize the overhaul cycle. The minimum of the overhaul cycle cost will indicate that the costs at all stages of the cycle will be optimal. If we consider the overhaul cycle cost in relation to the non-compensated acceleration, then we can say that the non-compensated acceleration will be optimal if the minimum the overhaul cycle cost is observed.

When determining the railway curve superelevation, taking into account the overhaul cycle cost, one should not forget about the limiting values of non-compensated accelerations from the condition of the comfort of the passengers. ride.

In general, the railway curve superelevation, taking into account safety (ride comfort), will be determined by the following formula:

$$h_{\text{max,pass}} = 12.5 \frac{v_{\text{max,pass}}^2}{R} - a_d \cdot 163, mm.$$  \hspace{1cm} (3)

where

- $v_{\text{max,pass}}$ - maximum speed of passenger trains, km / h;
- $a_d$ - non-compensated acceleration limit (0.7 m/s^2).

The limit of non-compensated acceleration for passenger traffic can be increased to 1.0 m/s^2 for a number of types of passenger rolling stock with improved dynamic properties.

To take into account the technical and economic component when calculating the railway curve superelevation in the Interim guideline [3], the railway curve superelevation for freight trains are calculated. Taking into account the technical and economic components, in this case, the limiting values of the non-compensated acceleration will be ± 0.3 m/s^2, depending on the considered maximum or minimum speed of freight trains.

To optimize the overhaul cycle, the railway curve superelevation should be considered, taking into account the overhaul cycle cost, on the equal basis with the railway curve superelevation, determined according to the Interim guideline [3], which will determine the optimal railway curve superelevation.

For consideration of the overhaul cycle cost, when determining the railway curve superelevation, the non-compensated acceleration is determined so that the overhaul cycle costs would be minimal.
To solve this problem, the function of the dependence of the overhaul cycle cost on non-compensated acceleration was determined. When calculating the overhaul cycle cost, the main track maintenance-of-way works and track repair works performed during the overhaul cycle were considered.

The cost of track maintenance works was calculated as the sum of the cost of overhauls (track relaying), track raising and ballast cleaning repairs. A set of track repairs for each railroad section was selected based on the class of the railway track according to Specifications [5]. The costs of the works were taken on the basis of aggregated estimates. The calculation of the track maintenance works costs showed that the costs in track with the same overhaul scheme (a set of track repairs) are approximately equal and almost do not depend on the non-compensated accelerations in the curve. Therefore, the determination of the dependence of the overhaul cycle cost on the non-compensated acceleration was reduced to the determination of the dependencies of the costs for the maintenance-of-way works on the non-compensated acceleration.

Before determining the final dependence of the costs for the maintenance-of-way works on the non-compensated acceleration, the dependences of the costs for each individual work on the non-compensated acceleration were determined. During the study, it turned out that the function that would best reflect the dependence is an exponential function of the following form:

$$ y = Ae^{Bx} $$

where $x$ – value of non-compensated acceleration for a specific curve, m/s$^2$.

The study also showed that when considering different costs for the execution of work, the function could be with the opposite sign, which in turn could mean that for different works, costs may be unevenly distributed between the activities carried out on the high side and inside of curve rail.

After determining the coefficients $A$ and $B$ by the least square method [6], the final function was defined to determine the dependence of the cost of the maintenance-of-way works on the non-compensated acceleration. The resulting function was equal to the sum of the functions of the dependence of costs on the non-compensated acceleration. To simplify the determination of the non-compensated acceleration, at which the minimum cost of the maintenance-of-way works will be observed, the exponential function has been replaced by a parabolic function. Figure 2 shows the graphs of the dependence of the costs of the maintenance-of-way works on the non-compensated acceleration and the obtained optimal non-compensated acceleration.

$$ f(x) = Kx^2 + Mx + N $$

$$ y = Ae^{Bx} $$

$$ y = Ce^{-Dx} $$

**Figure 2.** Charts of the dependence of costs on optimal non-compensated acceleration

After determining the optimal non-compensated acceleration from the point of view of the maintenance-of-way works ($a_{d/\text{opt}}$), the optimal non-compensated acceleration was determined taking into account the track maintenance.
Based on the determined non-compensated acceleration, the railway curve superelevation were calculated using the following formula:

\[ h_{OCC} = 12,5 \frac{v_{Top}^2}{R} - a_{d,opt} \cdot 163, \text{mm}, \]  

(5)

where \( a_{d,opt} \) – optimal value of non-compensated acceleration for a specific track, determined based on the overhaul cycle cost, m/s².

In formula 5, as in formula 2, the weighted average train speed is taken as the speed. The weighted average speed is taken in order to determine such a railway curve superelevation, at which the average conditions of the transportation process will be taken at the optimal non-compensated acceleration.

For example, the railway curve superelevation were determined taking into account the overhaul cycle cost on the curve of the longevity welded track with R65 rails, fastenings of the ARS type, reinforced concrete sleepers on crushed stone ballast.

Table 1 shows the results of calculating the railway curve superelevation, taking into account the overhaul cycle cost:

| Curve No. | \( h_{act} \), mm | \( a_{d,opt} \), m/s² | \( R \), m | \( v_{Top} \), km/h | \( h_{OCC} \), mm |
|-----------|------------------|------------------|------|----------------|----------------|
| 1         | 104              | -0,038           | 590  | 51,20          | 61,73          |
| 2         | 102              | -0,038           | 595  | 51,85          | 62,67          |
| 3         | 105              | -0,038           | 618  | 48,61          | 53,98          |
| 4         | 114              | -0,038           | 598  | 49,22          | 56,84          |
| 5         | 91               | -0,038           | 599  | 58,01          | 76,41          |
| 6         | 99               | -0,038           | 585  | 54,94          | 70,69          |
| 7         | 82               | -0,038           | 616  | 42,27          | 42,44          |
| 8         | 98               | -0,038           | 588  | 43,63          | 46,65          |

To simplify the work with the railway curve superelevations, the railway curve superelevation was rounded in multiples of 5 mm according to the rules of mathematics.

When considering the overhaul cycle cost, one should not forget about the safety of train traffic. To simultaneously consideration safety components and technical and economic components, a calculation was made according to the Interim guideline [3]. The calculation results are shown in Table 2. The railway curve superelevation, determined using the Interim guideline [3], is noted as the value \( h_{calc} \). On the basis of two values of railway curve superelevation, the optimal railway curve superelevation (\( h_{opt} \)) was determined, which would simultaneously considerate safety and the overhaul cycle cost.

| Curve No. | \( h_{act} \), mm | \( h_{OCC} \), mm | \( h_{calc} \), mm | \( h_{opt} \), mm |
|-----------|------------------|------------------|------------------|------------------|
| 1         | 104              | 60               | 80               | 80               |
| 2         | 102              | 65               | 80               | 80               |
| 3         | 105              | 55               | 70               | 70               |
| 4         | 114              | 55               | 80               | 80               |
| 5         | 91               | 75               | 55               | 75               |
| 6         | 99               | 70               | 45               | 70               |
| 7         | 120              | 40               | 50               | 50               |
| 8         | 98               | 45               | 60               | 60               |
From Table 2 we can conclude that in most cases the railway curve superelevation determined by the Interim guideline [3] is taken as the optimal railway curve superelevation. But at the same time there are two cases (curves No. 5 and No. 6), in which the optimal railway curve superelevation are the railway curve superelevation, determined based on the overhaul cycle cost. This fact suggests that the use of the concept of the overhaul cycle cost can help in determining the best railway curve superelevation, considering various conditions.

Among other things, we would like to note that the results obtained differ greatly from the actual railway curve superelevation ($h_{act}$). This fact suggests that an irrational railway curve superelevation has been established in these curves. It is not rational both from the point of view of safety and from the point of view of technical and economic components.

4. Conclusion
The study carried out to account for various conditions of the railway curve superelevation showed that the existing Interim guideline [3] does not take into account all aspects of the permanent way economy. The technical and economic components in the Interim guideline [3] are poorly reflected.

When considering the overhaul cycle cost, it is possible to determine the optimal non-compensated acceleration, which in turn will allow the railway curve superelevation to be determined based on the economic components. It is not rational both from the point of view of safety and from the point of view of technical and economic indicators.

References
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