Innovative Approaches to Railway Track Alignment Optimization, in Curved Sections

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Abstract: The efficient advancement of railway transportation is impossible without the integration of cutting-edge innovations. This study places emphasis on the application of computer modeling for railway track alignment, enabling the determination of an optimal strategy for rectifying curves within the plan. This approach ensures enhanced accuracy and effectiveness in curve realignment efforts. The calculations involved in plan correction are not only essential for addressing track deviations but also for solving a set of challenges associated with increasing permissible travel speeds. Particular significance is attributed to the reconstruction of track alignment, especially for international routes transitioning from wide (1520 mm) to standard European gauge (1435 mm). The incorporation of innovative technologies for railway curve correction, along with line plan optimization across multiple track sections, facilitates the realization of maximum stipulated velocities while ensuring safety, smoothness of motion, and passenger comfort. The investigation results detailed in this paper were conducted with support from a grant provided by The National Research Foundation of Ukraine under the project, "Scientific Justification of the Introduction of the European Track on the Territory of Ukraine in the Post-War Period".

Keywords: railway; innovative activity; innovative technologies; railway curves, transport corridor

1 Introduction

Global experience attests that effective railway transport development is unattainable without the implementation of innovations. Ukraine, akin to other European nations, is embracing various innovative technologies in the reconstruction of railway alignments. Noteworthy, among these innovative technologies, are the following:

- GPS navigation for ensuring precise railway track construction, thereby reducing deviations from the designated route and enhancing train travel safety

- Employment of automated process control systems during railway construction and reconstruction, allowing the maintenance of required line plan parameters and reducing deviations from specified standards
- Laser scanning of railway tracks, enabling accurate measurement of track parameters, including radius, leading to the creation of a precise track plan and identification of areas necessitating curve rectification
- Utilization of modern geodetic techniques, facilitating accurate measurement of railway track geometry and ensuring more precise curve realignment within the plan
- Deployment of autonomous machinery for plan-wise curve correction, substantially reducing the time and cost required for such adjustments
- Utilization of computer modeling for railway track alignment, allowing the determination of optimal strategies for curve rectification.

These advancements collectively contribute to a more precise and efficient approach to railway track alignment, aligning with the contemporary standards and expectations for modern rail systems.

Each innovation has its specific sphere of application. In 2020, the Strategic Research and Innovation Program for European Rail Transport was published by the European Rail Research Advisory Council (ERRAC). Its endeavors are geared towards furnishing innovative solutions that assist the railway sector in becoming more efficient, safer, and environmentally sustainable [1]. The seamless operation of railway transport hinges on the technical condition of rolling stock, railway track, and its alignment within the plan [2-5]. Consequently, for modern railways, the implementation of innovative methods in track repairs and ongoing maintenance on sections equipped with high-precision coordinate systems, ensuring track alignment with the designated position, becomes practically indispensable.

2 Statement of the Problem

Calculations for track alignment rectification typically occur in cases of track deviations, which can result from various factors [6-10]. Such calculations are also required for adjusting plan parameters (curve radius, length of transition curve, superelevation) when addressing the complex challenge of increasing permissible travel speeds along a given route [11-14]. Additionally, the reconstruction of track alignment is necessary for substantial changes in its parameters, such as transitioning to a different gauge. The latter is particularly pertinent today for international routes traversing Ukraine, where a transition from the broad (1520 mm) to the standard European (1435 mm) gauge is planned [15] [16].

Accurate information about railway track alignment is linked to measurements of quantities defining track geometry, which can be classified into global and local categories. Global measurements determine the position of elements within the global system of geographic coordinates, while local measurements establish the position of elements relative to other elements (e.g., elevation of the outer rail at a specific kilometer of the track) or temporary deviations of parameters from their design values (e.g., various track deformations). Depending on the measurement method applied, global or local parameters are determined, or both simultaneously. For instance, an innovative method for determining the position of the track axis using Global Navigation Satellite System (GNSS) receivers was proposed in the study [17].

If the actual characteristics of the track alignment deviate from the design parameters, this can lead to either speed limitations or exceeding the norms, which, in turn, would result in decreased levels of safety and travel comfort, as well as increased forces of interaction between the train wheels and the elements of the track superstructure. These increased forces contribute to the wear of rails, as well as other components of the track superstructure, and the wheels and elements of the rolling stock [18].

Scientific research aimed at improving curve parameters, minimizing wear in curves, and realigning curves to enhance speed continues. In the paper [19], problematic issues regarding the selection of horizontal radius and length of transition curves are discussed in detail, including an analysis of radius diagrams and angular diagrams. Various types of transition curves are assessed considering the presence of obstacles. The influence of track irregularities on the optimal length of transition curves and the level of maximum speed is demonstrated indirectly.

In the dissertation [20], a scientific approach is presented that considers the cost difference between constructing new tracks or reconstructing railways, involving the elimination of obstacles related to connections: transition curve - circular curve - transition curve. Curvature plots and angle-turn diagrams were utilized to determine when individual curves should be replaced with compound curves. The definition of the most suitable length for transition curves is provided, allowing for the realization of the highest permissible speed.

In order to enhance accuracy and calculation speed, a methodology for curve survey calculation has been proposed based on the coordinate method and the least squares method [21]. When minimizing shifts during curve realignment, the radius of the circular curve, coordinates of the circle center, lengths of transition curves, and coordinates of characteristic points of the curve are computed.

An analysis of curves on Indian railways [22] has revealed that over time, curves can deviate from their initial position due to the following reasons. Firstly, unbalanced loading on both the inner and outer rails caused by exceeding the elevation of the outer rail at low speeds or a deficiency of elevation at high speeds, instead of the equilibrium speed for which the elevation was intended. The second reason involves the influence of significant horizontal forces exerted on the rails by trains. These horizontal forces alter the curvature profile, reducing or increasing curvature at specific locations, thereby altering radial acceleration and consequently disrupting the smoothness of train movement. Hence, to restore smooth vehicle movement on these curves, curve realignment and adjustment of its parameters become necessary.

Currently, the issue of reconstructing railway tracks within the global reference system is of great relevance. Its essence lies in determining the position of railway track axes within a Cartesian or local coordinate system [23]. To achieve such representation of the track's centerline, many countries have developed methods primarily utilizing the Global Navigation Satellite System (GNSS). The accuracy of this type of measurement can reach one centimeter under favorable conditions. The authors have previously described the methodology they developed, and this article presents a method for determining corrections to measured horizontal GNSS coordinates that account for the presence of the superelevation in curves.

A technical system enabling the resolution of tasks related to optimal reconstruction of curved tracks to increase train speed with minimal investment has been proposed by the authors in their work [24]. Consideration is given to providing passenger comfort while increasing speed on curved track sections.

In the study [25], the question of determining the horizontal radius of the railway track is addressed. The method is based on altering the incline angles of the moving chord in the Cartesian coordinate system. By assessing the influence of chord length on obtained radius values, it has been established that chord length does not play a significant role in radius determination and does not limit the application of this method. Simultaneously, attention is drawn to the accuracy of radius determination and its relevance to transition curve sections.

The initial data significantly impact the results of permissible train speeds. In the work [26], the utilization of modern geodetic technologies for determining track geometry is proposed. The author in [27] considers the issue of determining the horizontal radius of the railway track's axis to obtain unknown geometric characteristics of the track as not definitively resolved. This is explained by the fact that geometric characteristics were determined using approximate methods. Hence, a new concept for determining track radius through altering the slope angle of the moving chord has been introduced. To employ this method, the coordinates of points in a Cartesian system are required for a given railway section.

Numerous scientific studies have been dedicated to justifying the form of transition curves for the introduction of high-speed train travel. For instance, in [28], a new form of transition curve adapted to operational requirements imposed on the railway is presented. Parameters of two types of transition curves used in Hungary and Austria are defined in the paper [29]. It is demonstrated that the convenience of using transition curves in the form of the clothoid is unjustifiably limited in Hungarian regulations for speeds up to 120 km/h.

In the scientific study [30], the authors examined the change in track gauge width on curves for various secondary and main railway lines in Hungary with low and high transport volumes. The analyzed curves encompassed transition curves and circular curves. The variation of the gauge width parameter as a function of elapsed time was investigated by calculating distribution functions.

The pursuit of novel methods for surveying line plans and calculating curve realignment to place them in their design positions continues. In the study [31], a reconstruction method for existing railways with constrained optimization based on point cloud data is presented. Drawing from the theory of intelligent algorithms, the concept of the Particle Swarm Optimization (PSO) algorithm is introduced, along with the method of directed search. After obtaining point cloud data of the track's alignment, a target function with constraint conditions was established and integrated with railway surveying technology. The complexity and reconstruction time for solitary and continuous curves containing multiple basic curve units are analyzed. Utilizing measurement data, design data, and synthetic data as inputs, this research demonstrated the suitability, reliability, and practicality of its application.

A review of scientific works reveals that methods proposed by various authors are valuable for the reconstruction of existing railways, but their effectiveness may be contingent on specific operational conditions. Numerous studies have been dedicated to optimizing individual or constituent curves, adjusting their parameters (radius, transition curves, superelevation, etc.), yet the optimization of the entire track plan for a section or multiple sections remains underexplored.

This paper places emphasis on the application of computer modeling for railway track alignment, enabling the determination of an optimal strategy for rectifying curves within the plan. This approach ensures enhanced accuracy and effectiveness in curve realignment efforts, not only for local sections but also across the entire track section.

3 Methods

To explore the aforementioned phenomena, the software tool RWPlan, developed at the Ukrainian State University of Science and Technologies, was utilized in the course of this study. The foundation of this development was laid by I. Korzhenevich [32]. The calculations of speed limits and the construction of curve profiles are performed within the program using the algorithm by D. Kurhan, while computations concerning the elevation of the outer rail in curves for train flows and the consideration of speed constraints are carried out by N. Hmelevska. The innovative approach within the RWPlan software lies in its capability to employ various surveying methods for line plans, utilized both within railway administration and project organizations. The software also allows for the analysis of not just individual curves, but also track sections or multiple sections, optimizing the project plan according to various criteria while ensuring the attainment of the maximum permissible speed [14].

For existing plan design methods, a clear system of criteria for optimal positioning of the project curve has not yet been established. The task is formulated as follows: it is necessary to determine the position of the project curve that ensures the minimum amount of realignment work for track correction within the main earthwork platform, taking into account specified constraints (fixed points, shift directions, etc.). Clearly, with the aim of enhancing design quality and reducing construction costs, this criterion should indeed be considered during calculations. However, there are certain circumstances that must be taken into account in the optimization process.

It is often believed that the minimum realignment work would be achieved when the algebraic sum of alignment deviations equals zero. Previous studies have indicated that such a condition holds true when the length of the circular curve between the ends of the transitions constitutes no less than 2/3 of the total curve length. For short curves, primarily composed of two transition parts and a circular section amounting to less than 1/3 of the total length, an algebraic sum of deviations equating to zero does not yield the minimum realignment work, especially if the track is severely misaligned within the transition curves. The minimum realignment work can be achieved when the entire curved section results in the minimum sum of absolute values of shifts.

In this study, the authors have applied the proposed methodology for optimizing the project plan, taking into account various criteria, namely: minimum sum of absolute shift values, minimum sum of squared shift values, minimum sum of curve realignment costs. This approach allows for the incorporation of the aforementioned observations.

Hence, the sequence of calculations in the optimization of lengthy track sections consists of the following steps:

1. Coordinate survey is established based on the curve parameters. Segmentation of the long track section is achieved using angle diagrams and the radius of the segment.
2. Optimization of each curve is carried out in either the involute or coordinate models, employing one of the four optimization criteria: minimum sum of squared shifts, absolute shifts, absolute root shifts, or minimum costs.
3. Upon calculating each fragment, model parameters are gradually revealed and the survey of individual fragments is amalgamated for the entire section. When integrating interdependent curves, the maximum curvature difference between these elements is controlled. If the difference exceeds the predetermined limit, the program adjusts the radius values to satisfy

this restriction. Throughout the optimization process, the potential elevation adjustment of the outer rail within the transition curve is monitored.

4. Calculation and evaluation of the shift magnitudes for the entire section are executed. The limitation magnitude and the prescribed shift at the end of the section are taken into account in all cases, while other restrictions are incorporated during the optimization process. It is possible to incorporate shift magnitude constraints for specific segments.

5. The maximum permissible travel speeds for the proposed design are computed, followed by an analysis of the outcomes using the pre-established criterion.

4 Results and Discussion

Let us consider an example of calculations using the algorithm presented above for the Kyiv-Hrebinka-Poltava-Lozova route (Ukraine), Fig. 1. The positional layout of the track plan was determined under the condition of route modernization, aiming to achieve the highest possible speed while remaining within the existing embankment. The maximum allowable horizontal displacements of the track (alignment corrections) depend on various factors, such as the track's construction, its condition [33] [34], the presence of infrastructure devices, including power supply systems, signaling systems, etc. [35-40]. Following a thorough terrain analysis, it was stipulated that permissible shifts in the range of 0-250 mm would be acceptable in this scenario.

Figure 1

Railway section Kyiv - Lozova

As a result of the track plan and traction calculations, data were obtained for the following variants:

1. Without section reconstruction.
2. Station reconstruction is carried out to enhance travel speeds, with no alteration to the track plan.
3. In addition to station reconstruction, modifications are made to the elevation of the outer rail in curves, ensuring maximum speeds with minimal rail wear. In this case, the track's positional layout, radii, and lengths of transition curves remain unchanged.
4. Alongside station reconstruction, the track is placed in a new design position, guaranteeing maximum feasible speeds while maintaining the track within the existing embankment.

Trains of various types operate on this section. The calculations are presented for trains of the Hyundai type, which are designed for high-speed travel. The travel time of trains does not significantly differ between directions; therefore Table 1 provides the time only for the direct direction.

As evident from the results, on the Hrebinka-Poltava section, station reconstruction yields a significant effect (16 minutes). The implementation of outer rail superelevation calculated according to regulations allows for an additional saving of 4 minutes. Laying the track in the projected position results in a time saving of 10 minutes compared to the 2nd variant. On the Poltava-Lozova section, station reconstruction has a relatively modest effect (7 minutes). However, by adjusting the outer rail superelevation, an additional 18 minutes can be saved. Furthermore, aligning the track in the projected position leads to a substantial reduction in time (26 minutes) compared to the 2nd variant.

Table 1

Train travel time for Hyundai trains in the forward direction by variants

Direction	**Distance, km**	**Train travel time by variants, minutes**			
		1	**2**	**3**	**4**
Kyiv - Hrebinka	148	67	59	55	51
Hrebinka - Poltava	186	134	118	114	108
Poltava - Krasnohrad	81	68	64	51	48
Krasnohrad - Lozova	95	70	61	56	51
Poltava - Lozova	**176**	**138**	**125**	**107**	**99**
Hrebinka - Lozova	**362**	**272**	**243**	**221**	**207**

When calculating the design variant for each curve, the feasibility and potential for speed enhancement were considered. Variants that require adjustments within the range of up to 250 mm were explored, avoiding significant realignments. Graphical fragments depicting radius, superelevation, and maximum permissible train speeds on the Poltava-Krasnohrad section for the design variant are presented in Figs. 2 and 3.

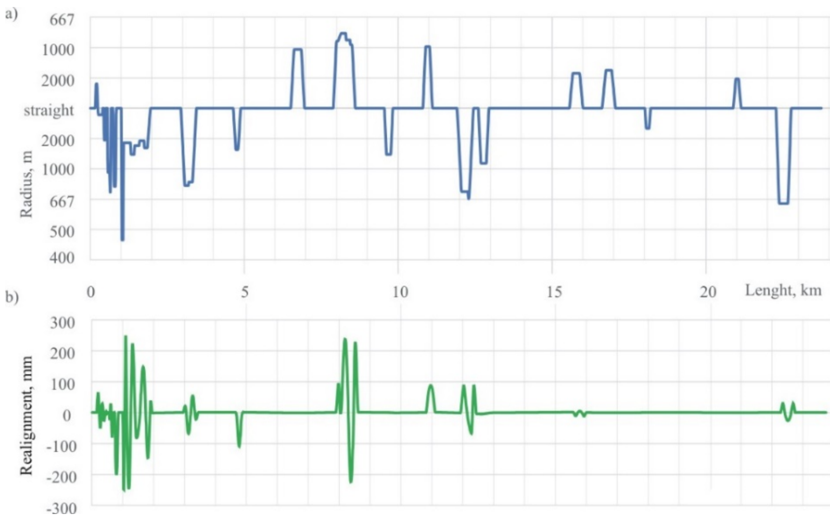

Figure 2

Segment of the Poltava – Krasnograd section: a) track plan; b) track alignment

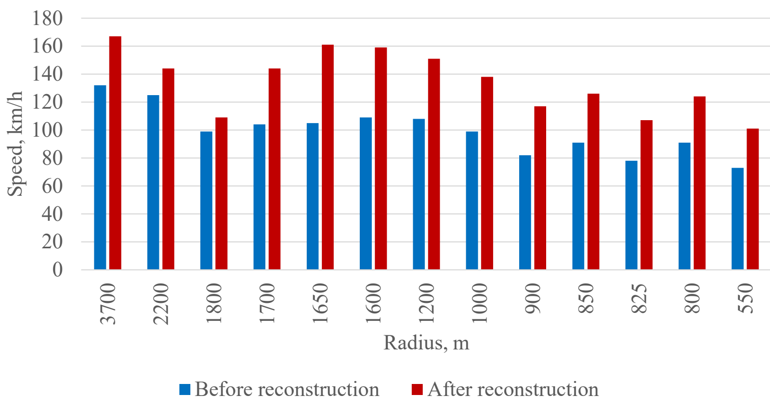

Figure 3

Permissible movement speeds on the Poltava – Krasnograd section

By optimizing the outer rail superelevation while considering the maximum permissible speed and rail wear, an optimal solution has been achieved. In all variants, the acceleration of passenger trains does not exceed 0.7 m/s^2, while for freight trains, it remains within ±0.3 m/s^2.

Conclusions

Based on both theoretical and experimental research, it has been determined that the implementation of innovative technologies, for railway curve alignment in the plan, will allow establishing plan parameters and optimal train speeds. This will result in reduced wear of rails and train wheels, decreased track maintenance efforts, minimized energy or fuel consumption for freight and passenger transportation and contribute to enhancing safety, smoothness, and passenger comfort.

The analysis of technical and technological challenges arising from the incompatibility of standards between Ukrainian and European railway infrastructures has demonstrated that the proposed algorithm for the sequential alignment of the track plan during the optimization of long sections can be applied, including during the transition from the broad (1520 mm) to the standard European (1435 mm) gauge.

The calculation results and the developed methodology can be used for, theoretically, justifying maximum permissible train speeds, while simultaneously ensuring the standards of strength, stability, durability and the reliability of railway track and rolling stock components. This theoretical groundwork also serves as a basis for implementing European standard railway curve alignment technologies, for the facilitation of high-speed train travel.

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