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A Systematic Approach to Designing High-Speed Railway Track: European Perspective

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Abstract

This paper presents a systematic methodology for designing European-standard railway tracks, considering topographical and geological factors. The objective is to analyse various scenarios and assess the feasibility of constructing European-standard railway tracks in Ukraine. The study is based on an analysis of scientific developments in the field of railway design and construction across different track gauges.

KEY WORDS: *railway, transport corridor, high-speed railway, railway route, track gauge*

1. Introduction

The EU's transport infrastructure strategy [1] focuses on improving the quality of transport infrastructure through new investments and the efficient use of existing infrastructure to enhance accessibility, mobility, and safety.

Since 2000, the EU has provided €23.7 billion in co-funding to support investments in high-speed rail infrastructure. Currently, Europe has 9,000 km of high-speed lines in operation. It is important to note that some lines are under construction or in the design phase, bringing the total number of lines and their length to around 15,000 km as of 2023. The EU aims to triple the number of kilometres of high-speed rail lines by 2030. At the same time, the Commission notes that Europe has a network of national high-speed lines built without proper cross-border coordination: high-speed lines crossing national borders are not among the national construction priorities, even though international agreements have been signed and the Trans-European Transport Network (TEN-T) Regulation provisions require core network corridors [2].

Today, high-speed rail lines (HSR) around the world operate with trains reaching speeds of up to 350 km/h [3]. The European Commission and the European Investment Bank have developed a strategy to integrate the railway networks of Ukraine, Moldova [4], and the European Union. A mathematical model for forecasting high-speed rail demand is described in paper [5]. There is a growing trend of expanding freight traffic on HSR. The potential and possibilities for using freight HSR in Europe are described in work [6]. This may require some modernization of rolling stock [7], but it allows for a significant shift from road to rail transport [8, 9], which, among other benefits, provides an opportunity to reduce environmental pollution [10].

Specifically, for Ukraine, as a country bordering EU states and taking steps towards integrating into the broader European transport network, there is a need to construct a new 1435 mm gauge mainline network. This network will operate in parallel with the existing 1520 mm gauge network based on two key principles: firstly, the 1435 mm gauge will be designated for high-speed transport, and secondly, the development of the 1435 mm gauge mainline network will be carried out in stages.

The main cities in Ukraine from which trains will run abroad will be Kyiv, Kharkiv, Lviv, and Odesa. According to the new project, trains will travel at speeds of up to 350 km/h. The new route will significantly reduce travel time to the capital [11].

The creation of HSR in Ukraine is a timely necessity and opens up vast prospects for the country's development. The purpose of this work is to reveal the prerequisites for the creation of HSR in Ukraine, as well as their significance for integration with the European network.

2. Methods and Results

The design standards for the high-speed railway are based on current regulatory and directive documents in the railway transport sector and recommendations from the following: European regulatory documents in the field of high-speed rail transport; European infrastructure compatibility requirements approved by Directive 96/48/EC as amended by Directive 2004/50/EC; as well as other regulatory documents and scientific studies [12-14].

The high-speed railway is designed as a double-track line with a gauge of 1435 mm for a maximum (design) speed of passenger trains up to 350 km/h with a static axle load not exceeding 170 kN. The HSR infrastructure is designed for electric traction using an alternating current system of 2×25 kV, 50 Hz.

The separation points (stations, passing points, dispatch points), their locations, track layouts, and technical equipment are crucial aspects of HSR formation, as they largely determine the level of operational viability. Analyzing global experience, two approaches can be highlighted: the Japanese and Western European. The Japanese approach is characterized by almost complete isolation of HSR track equipment from conventional railways. This necessitated the construction of new passenger stations along the entire HSR route with a full set of equipment. To ensure passenger convenience when transferring from existing network trains to high-speed ones, these stations are, whenever possible, co-located with conventional railway stations.

The Western European approach involves using existing stations, usually renovated and expanded. Passenger operations are conducted at existing passenger complexes, with some high-speed trains entering these complexes via special connections.

Since the HSR option under consideration in Ukraine is of European standard (1435 mm), while all other existing tracks have a gauge of 1520 mm, it is recommended to adopt the Japanese approach, with the isolation of HSR track equipment from conventional railways.

It is important to note that in countries outside the EU that have HSR, such as Japan, South Korea, Taiwan, the USA, and China, their own regulatory frameworks have been developed and are in operation. These frameworks ensure the processes of development, design, construction, production, operation, and maintenance of HSR, its components, and devices. In Japan and the USA, these regulatory frameworks were developed independently and differ in some respects from EU standards. South Korea developed its HSR under significant influence from France, Taiwan from Japan, and China successfully accumulated and adapted the experience of several leading countries in the field of high-speed rail.

The main criteria for choosing the route direction were based on a balanced consideration of such fundamentally important requirements as maximizing the reduction of HSR length, ensuring optimal technical, operational, and construction indicators of the line (minimizing the number of curves, large artificial structures, earthworks, building wear, etc.), reducing the area of occupied land, and ensuring compliance with environmental and sanitary standards in the HSR impact zone [15].

The route was laid deviating from the shortest path only in difficult topographical conditions and to bypass populated areas, historical reserves (such as Poltava), large bodies of water, and so on. Based on the analysis, the most rational option was identified and recommended for further development.

Based on available satellite imaging data, a digital terrain model (DTM) was created for further route design. Figures 1 and 2 show the route of the Lviv–Ternopil–Shepetivka and Shepetivka–Zhytomyr–Kyiv sections using special markers.

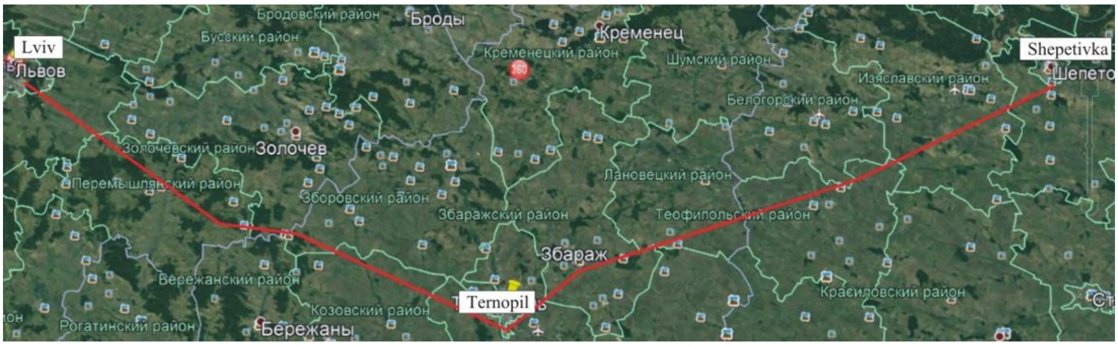

Fig. 1 Route Lviv–Ternopil–Shepetivka (the figure was created based on Google Earth [16])

Fig. 2 Route Shepetivka–Zhytomyr–Kyiv (the figure was created based on Google Earth [16])

The HSR route is generally laid with deviations from the shortest direction only in difficult topographical conditions and to bypass populated areas, large bodies of water, and other obstacles. Existing communication corridors were used for routing.

The selection of the principal alignment for the projected high-speed railway is influenced by socio-economic, natural, technical, and other factors and conditions, many of which are closely interconnected.

The primary purpose of the new high-speed railway line is to facilitate large volumes of passenger transport between two or more cities and their surrounding areas with minimal time loss for passengers. The inclusion of large populated areas along the chosen route determines the passenger transport volume and operational revenue. The dense urban development of intermediate settlements and the presence of numerous engineering communications necessitate routing the railway line outside city limits. As an example, the high-speed railway sections Lviv–Ternopil and Ternopil–Shepetivka are shown (Figs. 3 and 4).

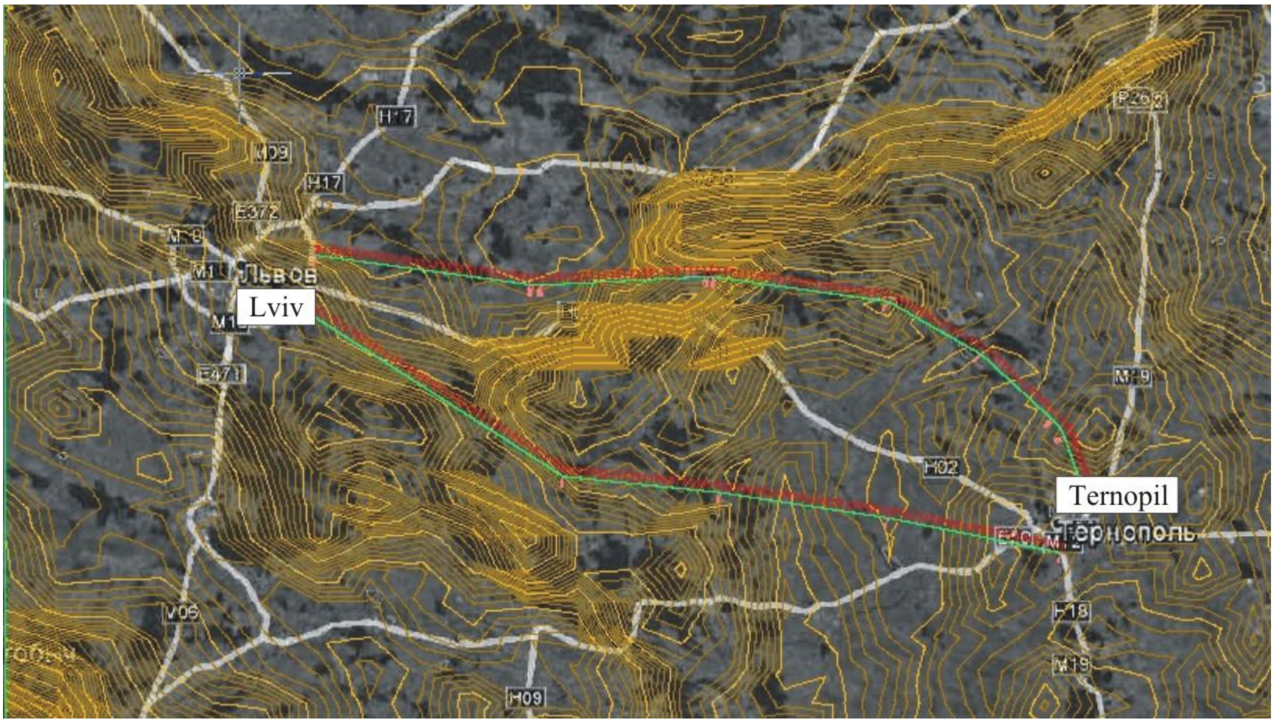

Fig. 3 Variants of the high-speed railway section Lviv–Ternopil

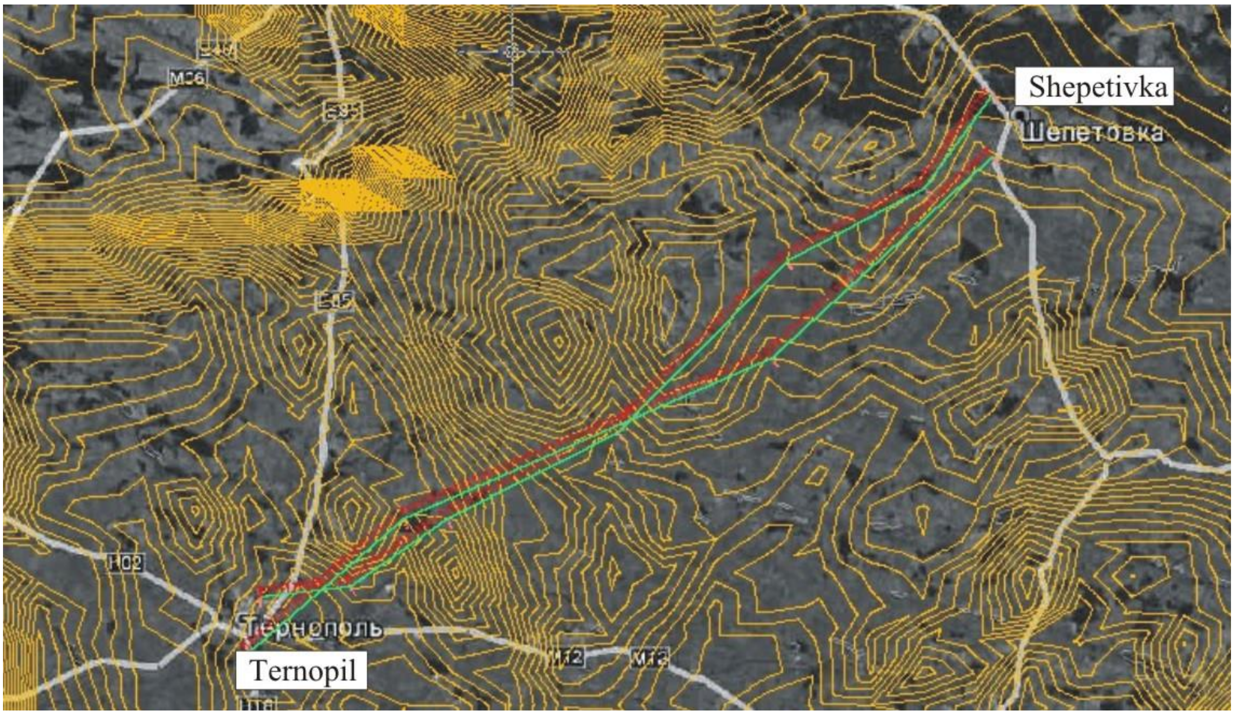

Fig. 4 Variants of the high-speed railway section Ternopil–Shepetivka

The rational variant for further development is determined based on the results of a techno-economic comparison. In modern conditions, a systematic approach should be applied, which involves finding the optimal route alignment. Since finding the absolute extremum for engineering tasks is an extremely complex problem, "optimal" here and further refers to a solution that has a criterion value close to the minimally possible.

When describing the terrain, DTM is used as the basis, with primary and auxiliary scales introduced to more accurately represent the terrain relief [17], Fig. 5. The obtained scale system adequately reflects the relief structure in the search zone and facilitates the optimization process. The criterion for optimization is the adjusted construction and operational costs. The adopted optimization method allows the calculation of adjusted costs algorithmically with the necessary accuracy and detail, enabling its use at various stages of design and for solving various design tasks related to routing.

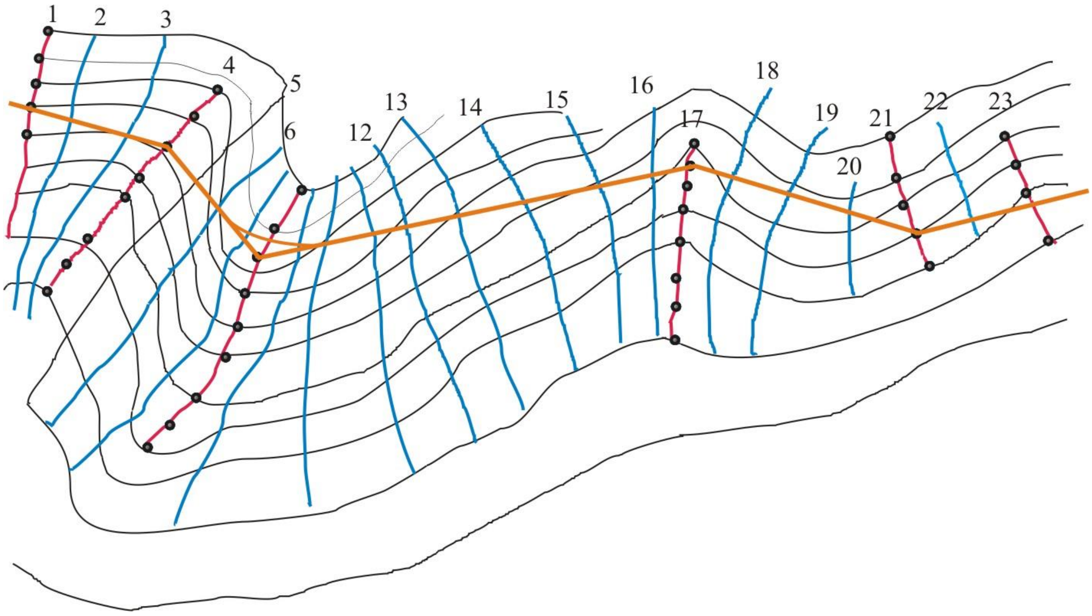

Fig. 5 Scale system for route variants

Studies have shown that stepwise algorithms are the most effective for solving this problem, as they allow for algorithmic calculation of the criterion and constraint checking. Among the known stepwise algorithms, it is advisable to use random search algorithms for route optimization tasks, as they outperform gradient methods in terms of speed when calculating the criterion. Developed modifications of these algorithms enable finding solutions sufficiently close to optimal in complex terrain and with challenging constraints.

From the perspective of nonlinear programming, the route optimization problem can be formulated as follows. The object (route) being optimized is described by a vector whose dimensionality equals the number of primary scales. The components of the vector are points on the primary scales where the turning points are located. These components change discretely within a hyper parallelepiped, and the vector is subjected to constraints expressed parametrically or algorithmically. For each permissible vector, an algorithm is defined for calculating the quality criterion (adjusted costs), which involves finding a longitudinal profile close to optimal [18]. The goal is to find such a vector for which the criterion value is close to optimal.

Calculations were performed for several sections designed using typical methods. Fig. 6 shows an example of route variants for typical and optimized design.

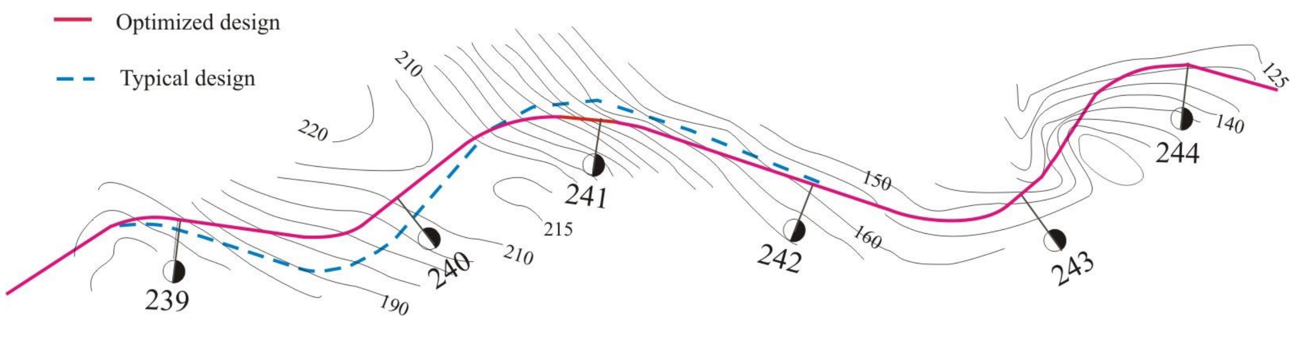

Fig. 6 Route variants for typical and optimized design

3. Conclusions

To establish the optimal route alignment for the new European-standard HSR being considered in Ukraine for the future, a new method of automatic route design based on random search algorithms has been developed and implemented. This method allows for designing a route close to optimal within a section, with fixed initial and final points in both plan and profile. The criterion for evaluating the route variants is adjusted costs.

The method considers the main technical requirements for the plan and profile as per design standards. It is practically independent of the methods for calculating adjusted costs and accounting for constraints, and can be applied to solve various design and research tasks related to routing.

The adopted DTM accurately represents the terrain within the routing corridor with relatively little information and allows for the presentation of a route variant as a vector with discrete variable components, and a profile variant as a vector of design elevations, with the number of components equal to the number of DTM lines. This representation of the optimized objects significantly speeds up the task resolution by limiting the range of variation. The use of automatic route design allows for a reduction of adjusted costs by up to 10 % and helps avoid irrational designs.

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