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The Prospect of Using the Dual Gauge Line for the Ukraine–Hungary Railway Connection

Mykola Kurhan[1], Szabolcs Fischer[2*], Dmytro Kurhan[1]

[1] Department of Transport Infrastructure, Dnipro National University of Railway Transport named after Academician V. Lazaryan, Lazaryan st. 2, Dnipro, 49010, Ukraine
[2] Department of Transport Infrastructure and Water Resources Engineering, Faculty of Architecture Civil Engineering and Transport Sciences, Széchenyi István University, Egyetem tér 1, Győr, 9026, Hungary
[*] Corresponding author, e-mail: fischersz@sze.hu

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Abstract
There are several international transport corridors in Hungary. Záhony railway station is one of the largest hubs in Europe, providing a railway connection between Ukraine and the European Union. Two different railway tracks meet and come together here, such as the standard (1435 mm) and broad (1520 mm) gauges. The availability of a developed infrastructure of the dual gauge on the territory of Hungary presupposes the corresponding development of the railway connection by Ukraine. In order to effectively use the dual gauge line and solve problems of special design, it is necessary to ensure the appropriate train flows. This research aims to provide scientific support for express analysis of the railway routes' competitiveness between Ukraine and the European Union to define the determining factors. The application of such approaches provides a tool for establishing the prospects for the development of existing railway lines, considering their features. Scientific approaches to creating methods for determining the priority areas of railway transport have been further developed. Apart from involving such essential indices as average speed and traffic volumes, the authors added the possibility of considering the presence of lines with such design features as single-track sections, non-electrified, dual gauge, etc., on the route. The theoretical background is applied as a tool for rapid calculations for increasing the competitiveness of the Chop–Záhony dual gauge line.
Keywords
railway, dual gauge, transport corridor

1 Introduction

Hungary's geographical location allows controlling transport routes between Eastern, Western, and Southern European countries. Hungary has several international transportcorridors, including the Fifth Pan-European Corridor: Venice–Trieste–Koper–Ljubljana–Budapest–Záhony–Chop–Lviv (Chop is the location Csap, as well as Lviv is Lemberg, in the Hungarian language).

Záhony railway station, through which the above transport corridor passes, is one of the largest hubs in Europe, providing a railway connection between Ukraine and the European Union. Two different railway tracks meet and come together here, such as the standard (1435 mm) and broad (1520 mm) gauges. Záhony staging point is an area of more than 80 km^2, which has special equipment for loading/unloading and storage of various freights, including bulk, such as grain. The network of station railway tracks consists of 260 km of standard gauge and 140 km of broad gauge track. The maximum design axle load is 225 kN and 250 kN, respectively. The productive capacity for reloading the goods at Záhony station is 18 million tons per year (Oktatási portál, 2020).

Between Záhony and Eperjeske railway stations, there is a sorting railway interchange, which provides further transportation of freights through Hungary with access to other European countries: Eperjeske–Hegyeshalom with access to Austria, Eperjeske–Bajánsenye with access to Slovenia, Eperjeske–Kelebia with access to Serbia, Eperjeske–Lökösháza with access to Romania, Fig. 1.

A few years ago, the Hungarian Railways (MÁV) repaired the dual gauge line to Záhony station (Geosynthetic Kft., 2012; NIF Zrt., 2015) (see Figs. 2 and 3). The repair goal was to eliminate the factors that limited the throughput of

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Fig. 1 Directions of transit from Ukraine through Hungary (own drawing)

Fig. 2 Repair of the dual gauge line with the replacement of wood sleepers with reinforced concrete ones (Geosynthetic Kft., 2012)

Fig. 3 Construction of crossing and switch interchange on the dual gauge line (Hungary) (NIF Zrt., 2015)

the line and to ensure the movement of freight trains from the Ukrainian direction with a load of 245 kN per axle. In order to reduce the intensity of the accumulation of residual deformations associated with high loads and design features of the dual gauge line (Kurhan et al., 2019a; Kurhan and Kurhan, 2018), a layer of geotextile was put during the repair. For the current line state control, geotextile had a special aluminum reflective surface type Detex 250, which makes it possible to detect the subgrade's deformations using a special radar device (Geosynthetic Kft., 2012).

The availability of a developed infrastructure of the dual gauge on the territory of Hungary presupposes the corresponding development of the railway connection by Ukraine. Today, the railway network of the Zakarpattia region has 18 crossing points, which are located on the state border with neighboring countries (Hungary, the Slovak Republic, and Romania). The length of the state border of the Zakarpattia region with Hungary is 133.1 km, through which two railway crossings Chop–Záhony and Diida–Berehdarot (i.e.,-Beregdéda–Beregdaróc) were opened within the framework of the Fifth Pan-European Transport Corridor.

When switching to the European track, passenger trains coming from Ukraine lose about two hours when changing wheelsets on the borders of Ukraine with Hungary, Poland, Romania, and Slovakia, or a transfer is required. The only European track between Transcarpathian Mukachevo and Budapest will significantly save passengers time. Ukrzaliznytsia's cars reach the Hungarian capital Budapest: Kyiv–Budapest, Kyiv–Belgrade, Lviv–Budapest as part of a train passing through the Chop–Záhony crossing, and then attach to the Budapest-Belgrade and Budapest-Venice trains.

To improve the connection with Hungary in 2018, Ukrzaliznytsia together with the Hungarian Railways launched the Intercity No. 34 "Latorytsia" train Mukachevo–Budapest. The train travels 383 km in 7 hours via Mukachevo, Chop, Nyíregyháza, Debrecen, Ferenc Liszt International Airport, and Budapest (see Fig. 4).

Fig. 4 The "Latorytsia" Mukachevo–Budapest train route (own drawing)

An alternative option to this train is two transfers in Chop and Záhony with delays at the border. Mukachevo – Budapest connection makes it possible to reduce travel time due to the absence of changing bogies of cars, which is certainly convenient for passengers and will facilitate the development of direct rail connections by the European track with Slovakia, the Czech Republic, and other EU countries.

Chop Station has a dual gauge connection with two countries – Hungary and Slovakia. It is the Chop–Záhony line (Hungary) with 12 km and Chop–Čierna nad Tysi–Dobrá (Slovakia) with 14 km. If the line from Ukraine to Slovakia has direct current (DC) electrification along its entire length, then the direction to Hungary has DC electrification to the Chop station (Fig. 5), the non-electrified line Chop–Záhony (Fig. 6) and alternating current (AC) electrification from Záhony station.

It should be noted that in Ukraine there are options to change the principles in the organization of passenger traffic and the transition to the hub model. Kyiv, Dnipro, Zaporizhzhia, Kharkiv, Odesa, and Lviv are considered transport hubs. It is planned to develop a suburban and interregional communication system in these cities (Szkoda and Tulecki, 2008). In current conditions, the project of connecting at least two lines of the dual gauge track with the subsequent creation of an intermodal hub could be attractive. For example, Mukachevo and Mostyska (almost 300 km) could be connected by a European track, by building a large transshipment hub in Lviv. Naturally, such plans require significant investments.

Fig. 5 The dual gauge line at the Chop station (Ukraine) (Hibberd, 2006)

Fig. 6 Traffic on the Eperjeske – Szalóka dual gauge line (Hungary) (Trainphoto, n.d.)

2 Literature review

The negation of the dual gauge design compared to the standard one affects the dynamic interaction processes between the track and rolling stock. The unevenness of the load under the different rails and the asymmetry of the further stress distribution in the ballast and the subgrade are especially noted (Kurhan et al., 2019a; Kurhan and Kurhan, 2018; Villalba Sanchis et al., 2021).

Modern scientific research shows geogrids' effectiveness in reducing the intensity of the accumulation of residual deformations in the railway track space (Fischer, 2021; Fischer, 2022).

Gailiene et al. (2018) describe the peculiarities of the track/rolling stock interaction in the horizontal plane on the dual gauge lines. In particular, including the proposed improvements in calculating the increase of the outer rail in the curves to reduce the unbalanced (i.e., non-compensated) acceleration on the example of Lithuanian 1453–1520 mm dual gauge lines.

The use of dual gauge does not contradict the installation of the continuous welded rail (i.e., CWR tracks), as the more modern and leading structure compared to the panel (ballastless) track. However, it is clear that such a main question concerning the reliability of the continuous welded rail, as its stability under the impact of temperature forces, must be solved concerning the presence of four (or three) rails instead of two in the rail-sleeper grid (ladder). For example, such problems have been solved in several scientific papers (Cuadrado et al., 2008; Arbuzov, 2013; Villalba Sanchis et al., 2018).

In some European countries the availability of both a standard railway gauge (1435 mm) and the Iberian gauge (1668 mm) requires this factor to be taken into account when solving the problem of finding the optimal route (Almech et al., 2019).

An example of the use of the dual gauge is the international project "Rail Baltica" from the state border of Lithuania and Poland to Kaunas. A new European standard gauge (1435 mm) was constructed on the "Rail Baltica" railway line in a length of 120 km, and next to it, there was the updated existing railway line with the 1520 mm track gauge. Since 2016, regular passenger services were launched from Kaunas (Lithuania) to Białystok (Poland) (Kurhan et al., 2019b).

Among the numerous studies devoted to the choice of priority directions of international transport, one should single out the scientific work (Tarapata, 2015), which presents the theoretical foundations and empirical results of analysis and modeling of transport networks in the example of Poland using structured networks. Gnatenko et al. (2018) highlight the workstreams of the railway system, which depend on the introduction of interoperability. Szkoda and Tulecki (2008) propose decision-making models concerning evaluating the efficiency of the Europe-Asia transport system. The technology of rolling stock transition when changing the track gauge 1435–1520 mm at the crossing Medyka (Poland)–Mostyska (Ukraine) is studied. It is shown that technical and economic analysis, analysis of life-cycle costs, and analytical network process can be applied to assess the effectiveness of the technology. Mężyk and Zagożdżon (2019) outline the main reasons for the gap in high-speed rail networks between Western and Central Europe and analyzes the differences that depend on geographical, economic, social, political, and organizational factors.

As for scientific work on the choice of technology for the transfer of freights at the changing points of track gauge, authors can build upon (Kurhan and Kurhan, 2018; Kurhan and Kurhan, 2019), which compares such technological processes as freight transfer; changing bogies at car exchange points; use of special rolling stock equipped with bogies with adjustable-gauge wheelsets; continuation of the existing broad gauge 1520 mm from the borders of Ukraine to the territory of Europe; continuation of the European gauge 1435 mm from the borders of Europe to the territory of Ukraine and the use of the dual gauge 1435–1520 mm.

Further prospects for mutual integration of Ukraine's railways into the European transport network will depend on the actual status of international transport corridors, the availability of rolling stock to provide transportation at fixed speeds, solving many political, economic, technical-technological problems of passenger traffic and freight turnover between Ukraine and Europe (Kurhan and Kurhan., 2018; Fischer, 2015).

3 Methods

In order to effectively use the dual gauge line and solve problems of special design, it is necessary to ensure the appropriate train flows. The implementation of such a task primarily depends on technical and economic feasibility. Therefore, the primary purpose of this research is to provide scientific support for express analysis of the railway routes' competitiveness between Ukraine and the European Union to define the determining factors. Furthermore, the application of such approaches provides a tool for establishing the prospects for developing existing railway lines, considering their features.

The basis for the analysis of prioritizing areas for the development of the railway connection is the route Lviv–Berlin, which may have several different implementation options. Three main options will be considered: I – Lviv-Warsaw-Berlin; II – Lviv–Krakow–Berlin; III – Lviv–Budapest–Berlin (Table 1).

Option I. The development of the European standard gauge 1 435 mm on the Lviv-Rava-Ruska-Warsaw route was being discussed in Lviv during the project presentation "National Transport Strategy until 2030". The aim of the "Eurorail Warsaw-Lviv” project is to establish an efficient international railway connection between Poland and other EU countries in the context of active growth of political,

Table 1 Main characteristics of options

Line	Length [km]	Travel time [hour : minute]	Average route speed [km/h]
Option I			
Berlin–Poznan	239	02:47	85.9
Poznan–Warsaw	326	04:28	73.0
Warsaw–Lublin	171	02:07	78.9
Lublin–Lviv	209	05:00	41.8
Result	945	14:22	65.5
Option II			
Berlin–Wroclaw	296	04:14	69.9
Wroclaw–Krakow	236	03:19	71.2
Krakow–Przemyśl	205	02:50	72.4
Przemyśl–Lviv	90	03:00	30.0
Result	827	13:23	61.8
Option III			
Berlin–Prague	349	04:13	82.8
Prague–Vienna	401	04:03	99.0
Vienna–Budapest	215	02:37	82.2
Budapest–Mukachevo	383	06:09	62.3
Mukacheve–Lviv	225	03:46	59.7
Result	1573	20:48	75.6

economic, and social relations. Furthermore, introducing a dual gauge track would allow trains to run non-stop from Lviv to European cities.

The total distance from Warsaw to Lviv is about 330 km. The line with 66 km within Ukraine Bryukhovychi–Rava–Ruska includes five intermediate stations (Klepariv, Briukhovychi, Kulykiv, Zhovkva, Dobrosin) and provides access to Poland. Laying European tracks to Lviv can promote to form of a transport-freight handling hub in the Lviv region.

To be able to build a new dual gauge railway, in particular on the Rava–Ruska–Lviv line to the railway station Briukhovychi near Lviv, it is necessary to perform a set of works: to lay 58 km of new dual gauge widening the main section of a roadbed, reconstruct five stations and reconstruct eighteen artificial structures. The choice of Briukhovychi as the destination of the European track is not accidental. Despite the developed broad-gauge infrastructure around Lviv railway station, its reconstruction requires significant investments.

Option II. One of the most important destinations connecting Germany and other Western European countries with Ukraine is the Cretan Transport Corridor No. 3. The total length of the railway on Poland's territory is 611 km. In addition to the transit role, the corridor is vital in domestic traffic, since it crosses the industrialized region of Silesia with significant mining and metallurgical enterprises.

It is worth mentioning that while preparing for Euro 2012 in Poland, work was executed to modernize the railway track in the areas of Opole–Wroclaw–Legnica, Legnica–Wegliniec, Opole–Zabrze–Katowice–Krakow–Przemysl–Medica, which will facilitate the organization of passenger traffic, including in the direction of Lviv–Mostyska and further to Warsaw. To solve this problem in Ukraine, work on the dual gauge project 1520/1435 in the direction of the Lviv–Rodatychi–State Border should be completed.

Currently, all lines of the railways included in the corridor are double-track. They are designed for trains with speeds up to 120 km/h, but due to the unsatisfactory state of infrastructure, the speed is limited to 60–80 km/h for a significant distance. Therefore, the corridor is electrified almost along the entire direction, except for the Wegliniec-Zgorzelec line.

Option III. The description of this option was provided in the Introduction part.

3.1 The first stage

In the first stage, the authors analyzed the condition of priority directions (length of double-and single-track lines, type of traction, time of operations at transition of rolling stock from a track of 1520 mm to 1435 mm, and vice versa, traffic volumes).

Based on the analysis of scientific papers devoted to the choice of prioritizing areas of international transport, the method (Vaičiūnas and Steišūnas, 2017) was adopted as a basis, which was further developed in Kurhan et al. (2019b). The method is reduced to assessing the importance of routes by the criterion of geometric mean (see Eq. (1)).

$$R_i = \sqrt[n]{\prod_{j=1}^{n} R_{ij}} , \qquad (1)$$

where R_i – the value of the generalized rating of the i-th route; n – the number of criteria; R_{ij} – the value of the j-th relative criterion of the i-th route, which is defined by Eq. 2.

$$R_{ij} = \frac{X_{ij}}{\sum_{j=1}^{k} X_{ij}} , \qquad (2)$$

where X_{ij} – the j-th criterion for the i-th route; k – number of routes.

Three criteria were considered in Vaičiūnas and Steišūnas (2017): the ratio of the area of the country, the number of inhabitants in the country, and the gross domestic product in the country to the train running time within the corresponding country.

Given that the routes from Berlin to Lviv cross several countries, other criteria have been proposed for Eq. (2), namely:

- the average motion speed X_1, reflecting in a certain way the state of the railway infrastructure (Table 1);
- the volume of passenger traffic/the travel time X_2 ratio reflecting loading/gravity area and traffic volumes
- the route characteristics coefficient X_3, which takes into account the length of double-track and single-track lines, the type of traction and the operating time during the transition of rolling stock from the track 1520 mm to 1435 mm, and vice versa.

An important parameter is the average route speed, determined by the distance between stations and the train time movement. Therefore, carrying out actions to reconstruct railway sections, update their condition, modernize infrastructure, etc., leads to a change of route speed, as a rule, towards an increase.

One of the fundamental principles underlying the assessment of options for transportation distribution is the formation of passenger flows and the passenger's speed movement.

To calculate the projected volume of passenger traffic, considering both transit flows of passengers through the territory of a country and the population in the cities covered by the corresponding route, the authors applied the method (Kurhan and Kurhan, 2019) and the initial data shown in Fig. 7.

The annual number of transported passengers, with regard to the intermediate stations between cities, was determined by Eq. (3).

$$P_{N_1-N_m} = \left[\sum_{r=1}^{m} \frac{1}{\left(C_{N_r} + T_{N_r}\right)} \right]^{-1}, \tag{3}$$

where $P_{N_1-N_m}$ – prediction of the annual number of transported passengers, concerning the intermediate stations N_r between cities N_1 and N_m, thousand people; C_{N_r} – urban population, thousand people; T_1, T_2 – transit passenger traffic through the stations in the forward and reverse directions, thousand people.

The results of calculations according to Eq. (3) are presented in Table 2.

To characterize the route from the standpoint of existing infrastructure, the authors proposed a method for determining index , which consists of five partial coefficients (see Eq. (4)).

$$K_0 = k_1 k_2 k_3 k_4 k_5, \tag{4}$$

where k_1, k_2 – coefficients that take into account the length of double-track lines and the type of traction on the transportation route, respectively; k_3, k_4 – coefficients that take into account the length of single-track sections and the type of traction on the transportation route, respectively;

Fig. 7 Population (in circles), distance (over the line) and travel time (under the line)

k_5 – coefficient that considers the operating time at border stations during the transition of rolling stock from the track of 1520 mm to 1435 mm and vice versa.

Calculation equations for coefficients k_1– k_5 are obtained based on the comparative analysis of the traffic capacity of railway lines – double-track and single-track, with electric and diesel traction, taking into consideration demurrage at border stations (Table 3).

Considering the above and the calculations by Eq. (4), relative criteria were determined to show the route's importance (Table 4).

Each route has a particular place according to the value of the relative criterion (Table 5).

Table 2 Characteristics of routes

Route	Distance, km	Travel time, hours	Projected passenger traffic vol., 1000 people
Berlin-Warsaw-Lviv	920	13.1	285.3
Berlin-Krakow-Lviv	827	14.2	439.3
Berlin-Budapest-Lviv	1426	21.3	564.3

Table 3 Calculation equations for determining partial coefficients

Indices	Calculation equation
The part of double-track railways on the route	
electric traction	$k_1 = 2.0553x^2 + 0.9312x + 1.032$
diesel traction	$k_2 = 1.3517x^2 + 0.9296x + 1.018$
The part of single-track railways on the route	
electric traction	$k_3 = 0.098x^2 + 0.3928x + 1.001$
diesel traction	$k_4 = 0.0524x^2 + 0.2971x + 1.00$
The proportion of time for operations when changing the track gauge relative to the travel time between end stations	$k_5 = 4.4286x^2 – 4.8114x + 2.319$

Table 4 Relative criteria showing the importance of the route

Route	Average route speed, km/h	Ratio of passenger traffic to travel time, thousand persons/h	Route characteristics coefficient
	X_{i1}	X_{i2}	X_{i3}
Berlin-Warsaw-Lviv	64.3	23.6	5.61
Berlin-Krakow-Lviv	72.4	30.9	6.69
Berlin-Budapest-Lviv	75.6	26.5	6.46

Table 5 Priority of routes according to relative criteria

Route	Place in relation			Criterion of geometric mean, $R_1 \cdot 100$	Priority of a route
	Average route speed	Volumes of traffic to travel time	Coefficients of route characteristics		
Berlin–Warsaw–Lviv	3	3	3	2.639	3
Berlin–Krakow–Lviv	2	1	1	4.639	1
Berlin–Budapest–Lviv	1	2	2	4.012	2

It is worth noting that the task mentioned above of prioritizing the destinations was solved without considering economic indices for transportation. At the same time, the implementation of large-scale investment projects (new construction, reconstruction of railways, etc.) requires more complex calculations and the use of more precise methods of assessing efficiency.

3.2 The second stage

The Net Present Value (NPV) of discounted cash flow is used as an economic criterion in the work. To compare the above options, the authors used a model for predicting and evaluating the effectiveness of railway transport between countries. Concerning all the costs by the *NPV* index (Kurhan and Kurhan, 2019), which is the difference between total income (D_t) and all types of expenses taking into account the time factor (K_t - investments, costs in $ZLoc_t$ - locomotive fleet, $Zcar_t$ - car fleet, C_t - current operating costs, and S_t - costs, depending on the type of technological operations and the time of freight cars presence at the station splicing of different gauges (see Eq. (5)).

$$NPV(t) = \sum_{t=0}^{T_p} \left(D_t - K_t - ZLoc_t - ZCar_t - C_t - S_t \right) \eta_t \qquad (5)$$

Uncertainty and risks in assessing the effectiveness of options were taken into consideration through the modified discount rate, which is included in the calculation of the discount factor of different time costs η_t.

According to Eq. (5) and the method described in Kurhan and Kurhan (2019), calculations were performed for three routes: I – Kyiv–Warsaw–Berlin, II – Kyiv–Krakow–Berlin, III – Kyiv–Budapest–Berlin. The results are shown in Figs. 9 and 10.

In the first case, the creation of an intermodal hub in Lviv was considered. Based on Fig. 8, the third option is not effective because it requires the construction of the dual gauge railway from Mukachevo to Lviv with 225 km.

If a hub to Mukachevo is created for Kyiv–Budapest, Kyiv–Prague, and Kyiv–Vienna trains passing through the Chop–Zakhon crossing, there is no need to continue the European track to Lviv, and the third option becomes effective even at volumes of one pair of passenger trains per day (see, Fig. 9).

4 Conclusions

Scientific approaches to creating methods for determining the priority areas of railway transport have been further developed. Apart from involving such important indices as average speed and traffic volumes, the authors added the possibility of considering the presence of lines with such design features as single-track sections, non-electrified, dual gauge, etc., on the route.

The theoretical background is applied as a tool for rapid calculations for increasing the competitiveness of the Chop–Záhony dual gauge line, as a component of the Lviv–Berlin direction.

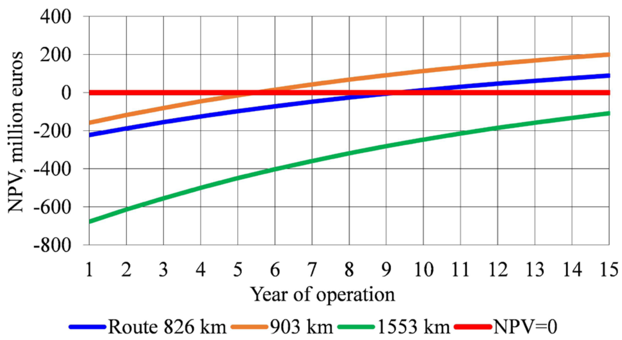

Fig. 8 The period when the NPV appears depending on the length of routes with the volume of passenger traffic two pairs of trains per day (Lviv HUB)

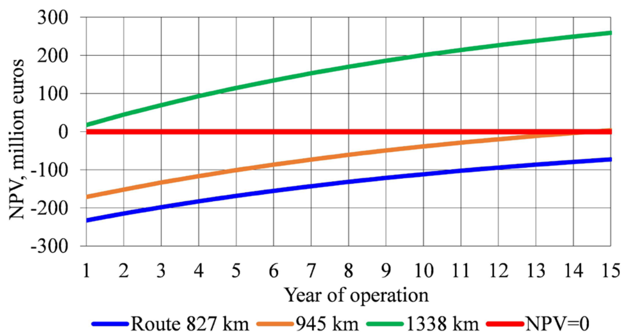

Fig. 9 The period when the NPV appears for route III at different volumes of traffic (Mukachevo HUB)

Analysis of the results showed that at the cost of reconstruction of the railway infrastructure of 3.0–4.0 million euros/km, the organization of passenger traffic can be effective with two-three pairs of passenger trains per day if Lviv is taken as a hub (options I and II) and at volumes of one–two pairs of trains per day if the hub is Mukachevo (III option).

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