CORRELATION OF TECHNICAL SOLUTIONS AND CONSTRUCTION COSTS OF HSR

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ABSTRACT

The article highlights the urgency and specificity of high-speed railways in Russia. The specifics of accounting for the cost of construction of HSR are indicated. The necessity of evaluating project solutions based on the technical and economic comparison of options is substantiated. Present and prospective technical solutions and technologies for construction of HSR are given, possibilities for further transition to the overpass method of their erection are considered.

A comparative analysis of the estimated cost of construction of HSR-2 Moscow–Kazan and similar analogues, whose projects are implemented in international practice, are presented. The authors argue that the high-speed railway line Moscow–Kazan is unique, technically complex, the first in Russia infrastructure project of this level. Compliance with the requirements of the terms of reference, regulatory documents and the application of best practices of foreign countries have a determining effect on the estimated cost of construction. In comparison with the railways of the common network with train speeds of up to 200 km/h, the HSR-2 project significantly exceeds the share of the main construction sites (by more than 36 %).

The presented data confirm that the cost of project solutions with the increase in the speed of trains by more than 200 km/h is interdependent from the increase in the requirements for safety and continuity of movement of high-speed railway transport.

Keywords: *railway, high-speed highway, construction, technical and economic comparison, cost of line, cost of technical solutions, roadbed, ballastless track superstructure, HSR in the world.*

Background. *The development of high-speed transport is impossible without state support, which is confirmed by the world experience in building high-speed railways.*

The decision to build the world's first high-speed railway (Tōkaidō Shinkansen) on the other end of the continent – in Japan was made in 1956. The proposed project of HSR of normal gauge met considerable resistance, including among conservative railway workers, as well as from the automobile and aviation lobbies. And very few specialists believed that in the regular commercial operation it is possible to ensure the movement of trains at a speed of 250 km/h [1].

In the 1960s, in response to the commencement of construction of HSR in Japan, the French government carried out large-scale research on development of new technologies in railway transport (magnetic and air-cushion trains and high-speed trains for conventional railways). In 1976, the authorities allocated money for a large-scale implementation of the TGV project. The passenger traffic on the TGV lines was opened in 1981, which marked the beginning of the operation of the first HSR in Europe.

In China, by 1993, the average speed of passenger trains was 48 km/h, railways began to give way in the popularity rating to air travel and road transport. Taking this into account, the Ministry of Railway Transport developed a strategy to increase the speed of train traffic by creating high-speed lines. The construction of China's HSR began 40 years after the launch of the first Japanese line, but today the country has the longest network of high-speed railroads on the planet (more than 20000 km).

The future Moscow–Kazan main line unites existing in the world, as well as promising technical solutions and technologies in the field of high-speed rail transport. The HSR-2 project in the Russian Federation is developed with the involvement of specialists from China («Er Yuan» corporation) in full compliance with the requirements of regulatory documents. The project documentation and the results of engineering surveys are the object of analysis of the state expertise of the FAI Glavgosexpertiza of Russia, in addition, the project is undergoing a departmental examination of JSC Russian Railways, scientific and methodological support is provided by the leading transport universities of the country (RUT (MIIT), PSTU), technological and price audit is conducted with the involvement of foreign companies (France, Germany, Italy).

Objective. *The objective of the authors is to consider correlation of technical solutions and construction costs of HSR.*

Methods. *The authors use general scientific methods, comparative analysis, evaluation approach, graph construction.*

Results.

Technical and economic comparison

Continuous improvement in the world practice of technical solutions and technologies for creation of HSR infrastructure contributed to the emergence of many competitive options, including those meeting the requirements of the HSR-2 Moscow–Kazan. For example:

- *choice of the type of construction of the ballastless track superstructure (Pic. 1) (two-section monolithic RHEDA 2000, LVT, Zublin; on a slab track of continuous type B gl, CRTS II, PORR);*
- *choice of technology to strengthen the foundation of the roadbed (reinforcement of soil with concrete piles of the type CFA (CFG), bored piles under the protection of casing, reinforcement of soils using MIP technology (mixed-in-place), RDV – vibrocompression, FDP (full displacement pile), ROB – vibrating concrete columns);*
- *determination of brands of switch turnouts;*
- *types of span structures of railway bridges;*
- *types of fasteners (Pic. 2) (WJ-8, DFF300 Vossloh, SFC Pandrol, CM-1).*

In the «On the composition of sections of project documentation and requirements for their content» (approved by Decree of the Government of the Russian Federation of February 16, 2008 No. 87) [2], the compulsory development of project solutions is not mandatory. However, some normative documents (codes of rules) indicate that the adoption of basic technical solutions should be justified by developing options by comparing technical and economic indicators [3, 4.9, 4, 4.2, 5, 5.2]. In accordance with the requirements specification for the design of HSR-2, Moscow–Kazan, a variant development of design solutions was carried out, that is, the adoption of constructive, technical and technological solutions, by means of a technical and economic comparison of options.

The rate of improvement of modern technologies in construction is not inferior to the growth rates of information and computer technologies. The best indicator of the trend is innovative high-speed rail. Designing of HSR is proceeding along the path of accumulation and use of the best experience of foreign countries and application of innovative technologies that ensure operational safety in difficult climatic conditions of construction.

Cost and rationing of project solutions

The estimated cost of construction (hereinafter – the cost) is one of the main points in the analysis of design decisions. More and more often the question «how much?» is transformed into the question «wl so much?». At the same time, the answer to the la question essentially depends on many factors, tl main of which remain [6]:

• organizational – a customer, a designer, contractor, suppliers of materials and equipme simultaneously participate in formation of the price construction products, in case of financing tl construction of the facility from the federal budg funds – examination (expert);

• territorial – is associated with complex geologic (unfavorable physical and geological environmen geographic (terrain, proximity of large cities, whic leads to increased costs of renting or redemption territories for diversion) and climatic (permafros buried ice, thermokarsts) construction conditions;

• transport – characterized by the remoteness the construction site from raw materials, which lea to an increase in transportation costs for delivery materials and structures;

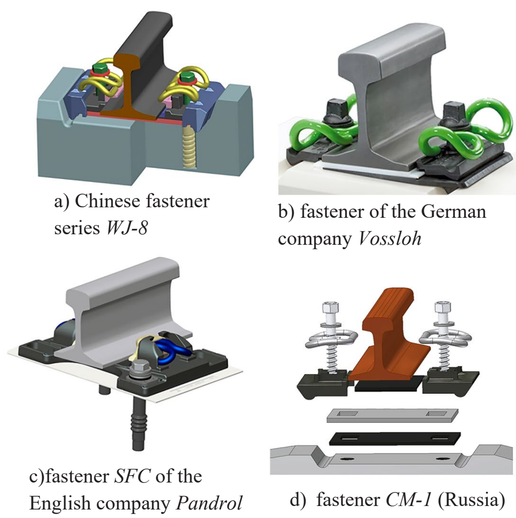
• technical – presence of out-of-class bridge tunnels, weak grounds under the roadbed, need f.. additional measures for engineering protection of the territory from karst phenomena can lead to a significant increase in the cost of 1 km of the projected line;

• technological – use of innovative solutions requires the use of high-performance construction equipment (crane lifting equipment, front-end machines for loading span beams, beam carriers, imported drilling rigs, rail-laying train on a pneumatic wheel), which allows not only to shorten construction time, but also significantly improve the quality of construction products.

During the design of HSR-2, Moscow–Kazan, a multifactor analysis of design solutions with territorial reference to the construction site was carried out. Within the framework of the article, the cost of the technical decisions taken in the project documentation on the main pricing sections: «Roadbed», «Artificial structures» and «Ballastless track superstructure» will be considered. At the same time, an attempt is made to answer the previously asked question: «Why so much?».

The main technical parameters of the projected high-speed railway Moscow–Kazan railway are presented in Table 1, the passage of the HSR-2 route is shown in Pic. 3.

Pic. 1. Types of construction of a ballastless track superstructure.



Pic. 2. Rail fastening systems of ballastless track superstructure.

The zone of gravitation of HSR-2 Moscow–Kazan unites the territories of seven constituent entities of the Russian Federation: Moscow, Moscow region, Vladimir region, Nizhny Novgorod region, Chuvashia Republic, Mari El Republic and Tatarstan.

The intersection of HSR-2 with existing and planned roads, railways and communications is provided only in different levels. Protection of crossed pipelines and underground communications is arranged on the entire width of the right-of-way.

Section «Roadbed»

The roadbed of HSR-2 canopy, with the exception of separate points, is designed for two tracks and must satisfy the following requirements of STU [7], which have a determining effect on the cost:

• the maximum accumulated residual deformation of the main site of the roadbed with a ballastless structure of track superstructure for the entire period of its useful life should provide the possibility of eliminating the drawdown by adjusting the fasteners and not exceed 15 mm;

Table 1

The main technical parameters of the HSR-2 Moscow–Kazan

No.	Name of the main technical parameters	Meas. unit	Value
1	Operational length of main tracks in two-dimensional measurement:	km	790
1.1.	1,2 stages: st. Moscow-Technical Kurskaya–st. Zheleznodorozhnaya 23 km	km	27
1.2.	3, 4 stages: st. Zheleznodorozhnaya 23km–st. Vladimir HSR (incl.)	km	172
1.3.	5, 6 stages: st. Vladimir HSR (excl.)–st. Airport (incl.)	km	224
1.4.	7, 8 stages: entrance to Nizhny Novgorod (block-post 410 km (incl.)–st. N. Novgorod HSR (incl.)–st. Airport HSR (excl.)	km	20
1.5.	9, 10 stages: st. Airport HSR (excl.)–st. Cheboksary HSR (incl.)	km	229
1.6.	11, 12 stages: st. Cheboksary HSR (excl.)–st. Kazan HSR(incl.)	km	118
1.7.	15 stage: construction of an administrative and technical building for accommodation (DCU) at the station Vladimir HSR	object	1
2	Ballastless track superstructure with a track gauge of 1520 mm	km	712
3	Ballast track superstructure with a track gauge of 1520 mm	km	78
4	Maximum speed of high-speed passenger trains	km/h	400
5	Value of the greatest slope of the longitudinal profile of the main tracks	‰	24
6	Minimum radius of the curve in the plan for speeds not less than 400 km/h	m	10000
7	Value of the inter-track distance between the axes of the main tracks at speeds up to 400 km/h mm	mm	5000
8	Number of stopping points	pcs	16
9	Out-of-class bridges across large rivers (Klyazma, Oka, Sura, Volga)	pcs	5
10	New traction substations	pcs	14
11	Time between Moscow and Kazan is not more than	hourc	3 hous 30 min.

Pic. 3. Passage of the route of HSR-2 Moscow–Kazan.

• depending on the moisture content, strength and deformation properties of soils, the homogeneity of their occurrence the basement of the roadbed should be subdivided into strong, insufficiently strong and weak;

• in accordance with clause 2.3.1 and Table 3.2 of STU Roadbed in areas of insufficiently strong and weak basements, their strengthening is necessary to comply with the requirements for embankment subsidence;

• the difference in the subsidence of the roadbed and the artificial structure (bridge, culvert, tunnel, etc.) in the zone of their interface should not exceed 5 mm;

• requirements for soils of embankments and protective layers are presented in section 3.1 of STU Roadbed, respectively, in the project documentation it is planned to fill the embankment with draining soil;

• higher requirements are set for compaction of the soils of HSR-2 roadbed: the soil compaction factor for the 1st and 2nd protective layers should not be less than 1,00, the compaction factor of the soil of the embankment should be not less than 0,98.

The construction of the roadbed according to the design documentation of the HSR-2 Moscow–Kazan consists of:

• the base of the roadbed (RB), natural or strengthened on the sites of weak soils;

• mass of the embankment (it is poured off by draining soil);

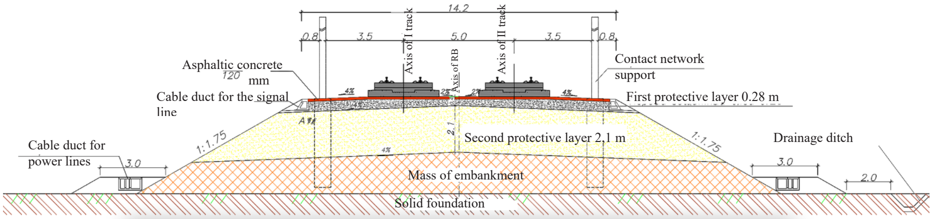
• the second protective layer with a height of 2,1–2,3 m (it is poured from coarse-grained sands, sand-gravel mixtures (SGM), enriched sand-gravel mixtures (ESGM));

• the first protective layer with a height of 0,28 m (arranged from crushed stone-sand-gravel mixtures (CSSGM) in accordance with the granulometric composition determined by STU);

• asphalt-concrete coating with a height of 0,12 m.

A typical transverse profile of the roadbed is shown in Pic. 4.

At the stage of performing engineering surveys on the exploration of soil building materials within the route, it was found that there were no suitable soils that meet the requirements of STU for depositing the first and second protective layers and the mass of the



Name of works and expenses	Meas. unit	Cost of meas. unit in the price level of I quarter of 2017 thous. rub. without VAT
Moscow region		
Protective asphalt pavement h = 12 cm	m^2	1 392,58
The device of the first protective layer of CSSGM	m^3	1 521,39
The device of the second protective layer	m^3	602,42
Construction of the mass of embankment	m^3	557,79
Vladimir region		
Protective asphalt pavement h = 12 cm	m^2	1 410,35
The device of the first protective layer of CSSGM	m^3	1 449,65
The device of the second protective layer	m^3	580,27
Construction of the mass of embankment	m^3	537,14

Pic. 4. Cost of elements of a typical design of the roadbed of HSR-2 Moscow–Kazan.

embankment of the roadbed. For each stage of the HSR-2 project, a variant analysis of logistic schemes for delivery of soil from the supplier's quarry to the place of production was made (Pic. 5). Optimum, economically feasible solutions are reflected in the transport schemes agreed with the customer.

In connection with the absence of prepared ground mixtures of the 1st protective layer (CSSGM) within the projected route, the project documentation provides for delivery of the components of the mixture to temporary cargo yards and preparation of CSSGM in the construction conditions.

Within the borders of the passage of HSR-2, negative physico-geological phenomena are widespread: marsh, karst, gully erosion, bank washing, soil flooding, flooding. Of the dangerous exogenous geological processes, karst and landslide are most evident. According to the engineering survey reports, the following anti-deformational measures in the zone of the basement of the roadbed are planned to meet the requirements of STU (Pic. 6):

- *reinforcement of the base with prismatic piles on sections with speeds of up to 250 km/h;*
- *bored non-reinforced concrete piles using continuous hollow screw (CFG) technology, with a flexible grillage device (piles diameter 0,5–0,6 m, spacing between them – 3–5 pile diameters);*
- *bored reinforced concrete piles, with the construction of reinforced concrete grillage, the diameter of the piles is 1,25 m;*
- *jet grouting in the areas of karst distribution.*

In the technical and economic comparison of variants of anti-deformation measures, the use of concrete piles, the technology of a continuous hollow screw CFA (CFG), is the most popular. In this way it is planned to strengthen more than 90 % of the basement of the roadbed throughout the entire route.

The main design solutions for the «Roadbed» section were adopted taking into account the technical and economic comparison of options, the possible number of which is limited by the need to comply with the requirements of regulatory documents to ensure the safety of train traffic at the maximum set speeds. At the same time, compliance with these requirements has a significant impact on the cost of the construction of the roadbed, which is more than 19 % of the total cost of construction of HSR-2 (Pic. 13).

Section «Track superstructure»

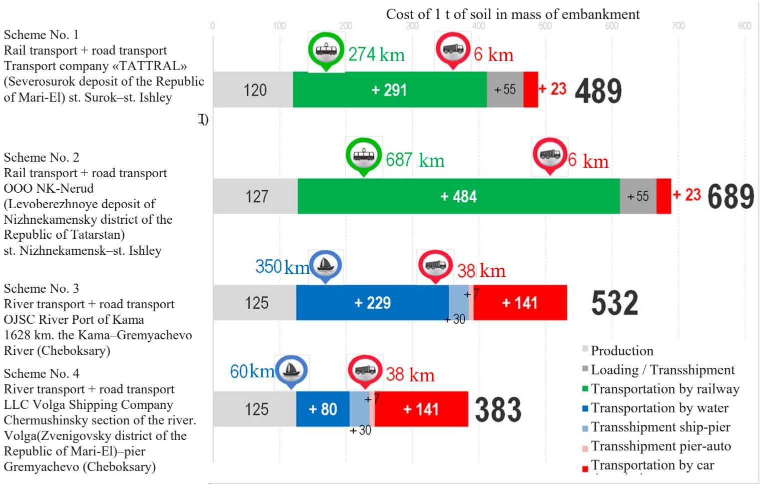
In the world practice for construction of high-speed railways both ballast and ballastless track superstructures are used. Ballast track superstructure is preferred in European countries with a relatively mild climate, a small amplitude of temperatures (France, Spain, Italy) and train speeds of up to 320 km/h. Ballastless track superstructure is mostly used for speeds of up to 350 km/h in Asian countries – Japan, Korea, China, as well as in Germany. Experience in design and construction of HSR in China shows that in climatic conditions similar to the main line Moscow–Kazan, only a ballastless design is reliable.

In accordance with STU-2 «Track superstructure» [7] for the main tracks of HSR-2 with a maximum speed of more than 200 km/h, the choice of the type of balastless track superstructure design in the design documentation is determined taking into account the following features:

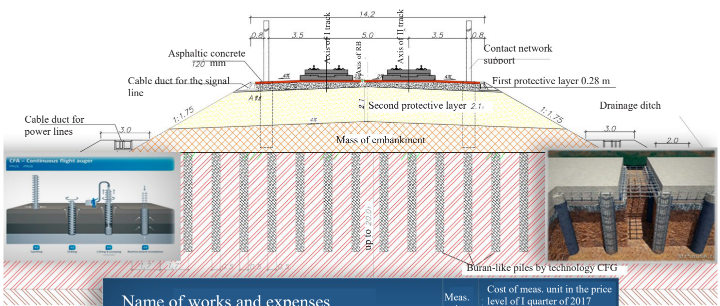
- *operating parameters of balastless track superstructure should be ensured in the temperature range of rails from minus –48˚C to +67˚C;*
- *for arrangement of the supporting structure, concrete should be used with a grade not lower than B 40, a mark for water permeability not lower than W8, for frost resistance – not lower than F300;*
- *it is necessary to maintain high rates of laying to reduce the construction time in compliance with the requirements for safety, durability, reliability and maintainability.*

The decision on the use of the constructive type of balastless track superstructure was made on the basis of the feasibility study, taking into account the optimization of the life-cycle cost of the structure (clause 4.1.2 of STU-2) [7]. Within the framework of such a rationale, the project documentation includes the calculation of the life cycle for various balastless track superstructure designs (Pic.7), namely:

- *two-section monolithic (RHEDA 2000, LVT, Zublin);*
- *on a slab track of continuous type (Bögl, CRTS II, PORR);*
- *on a slab track of block type (CRTS I, Shinkansen);*

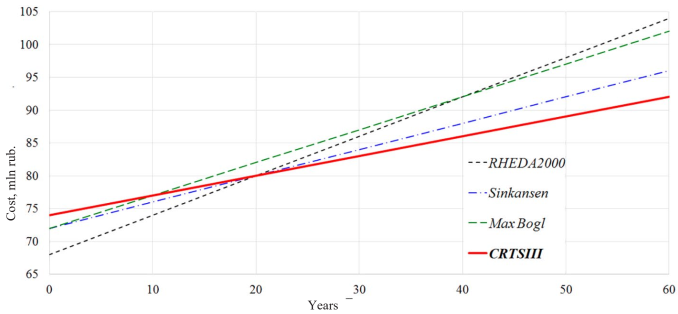


Pic. 5. Variant development of logistic schemes of soil delivery.



Name of works and expenses	Meas. unit	Cost of meas. unit in the price level of I quarter of 2017 thous. rub. without VAT
Immersion of prismatic piles 40x40 cm	m^3	18 544,00
The device of concrete piles by the SFG method, diameter 0.5 m	m^3	7 263,97
Strengthening the foundation of bored piles diam. 1.25 m	m^3	21 213,06
Cementation of cavities	t	11 501,23

Pic. 6. Anti-deformational measures in the zone of the basement of RB of HSR.



Pic. 7. Life cycle graph of various designs of ballastless track superstructure.

• on a slab track of block type (CRTS III, CRTS III RUS).

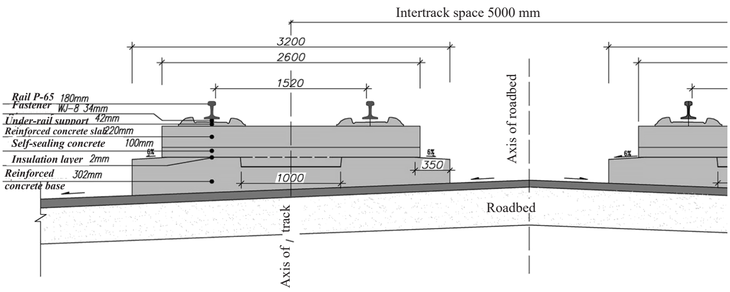
Thus, based on the conditions for movement of high-speed trains with a speed of up to 400 km/h, work in the cold zone, mixed traffic with different loads from the wheel set to the rails, and also taking into account optimization of the life cycle cost, the project documentation of the HSR-2 Moscow–Kazan provides for a modernized balastless track superstructure on a slab track of the type CRTS III RUS (Pic. 8).

The choice of available estimates in the Russian Federation to determine the estimated cost of a balastless track superstructure is very limited, but an analysis of the existing technology in the world of production, 3D models of ballastless track superstrucutre design and graphical modeling of the construction stages made it possible to calculate the cost of laying the ballastless track superstructure of HSR-2 and obtain positive conclusions from the departmental examination of JSC Russian Railways and FAI Glavgosexpertiza of Russia. The main cost

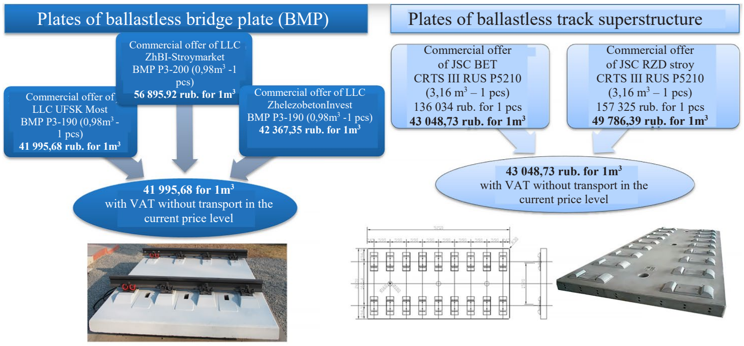
Table 2

The cost of the track superstructure on the hauls for the sections of HSR-2

Name of works and costs on the sections	Meas. unit	Length of the section	Estimated cost in the basis price level, thous. roubles	Estimated value of the unit cost, thous. roubles		
				In the basis price level of the year 2000	in the price level of I quarter of 2017	
					Total	including for one track
st. Zheleznodorozhnaya (excl.)–st. Noginsk (excl.) track superstructure on ballast for the speeds up to 250 km/h	1 km	29,01	175710	6057	48334	24167
st. Noginsk (excl.)–st. Orekhovo-Zuevo (excl.) Ballastless track superstructure	1 km	32	650023	20313	162100	81050
st. Orekhovo-Zuevo (excl.)–km 97+580 Ballastless track superstructure	1 km	7,88	158035	20055	160041	80020
km 97+580–st.Petushki (excl.) Ballastless track superstructure	1 km	28,02	559518	19969	146570	73285
st. Petushki (excl.)–st. Vladimir (excl.) Ballastless track superstructure	1 km	61,9	1269 060	20502	150483	75242



Pic. 8. The adopted design of ballastless track superstructure – CRTS III RUS.



Pic. 9. Analysis-comparison of the cost of plates of ballastless track superstructure and BBP.

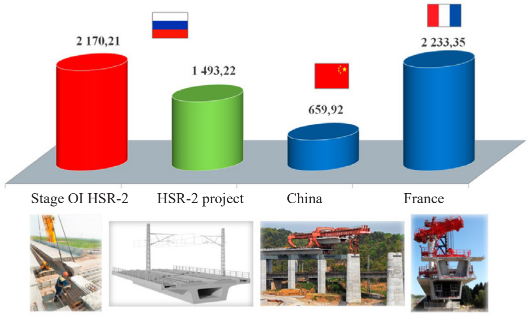
indicators are presented in Table 2 for both the section with ballast track superstructure for speeds up to 250 km/h and for the ballastless design.

The project documentation of HSR-2 Moscow–Kazan also received positive conclusions on the results of the mandatory technological and price audit (hereinafter – TPA) and scientific and methodological support (RUT (MIIT), PSTU).

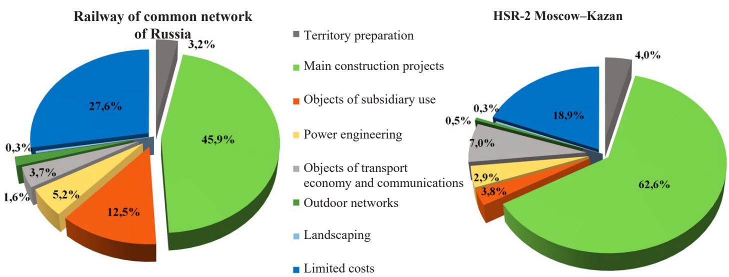
As part of the preparation of estimates, market analysis of the market was carried out, as well as a comparison of the cost of a slab of a ballastless track superstructure of the type CRTS III RUS with a ballastless bridge plate (BBP) widely used in bridge construction (Pic. 9). The difference in cost relative to the BBP slabs is an occasion for modernization of production for manufacture of ballastless plates of the track superstructure.

Section «Artificial structures»

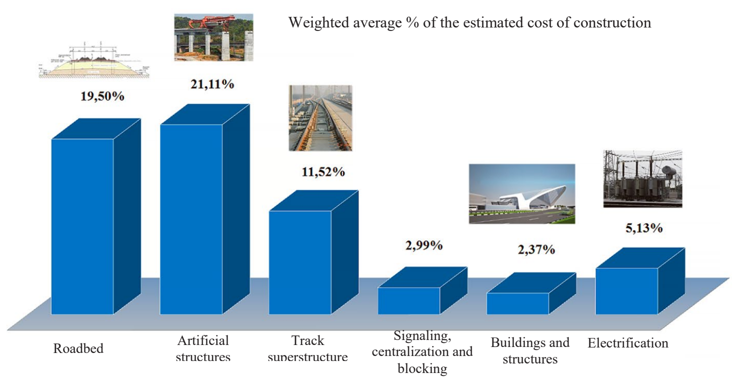
This is the main pricing forming section of the project HSR-2 – its share in the estimated cost of construction is more than 21 % (Pic. 12). Artificial structures, which are the most frequent on the route,



Pic. 10. The average cost of construction of 1 running meter of railway bridges of HSR.



Pic. 11. Structure of the cost of construction of railways of the common network and HSR-2 in the context of the consolidated estimate calculation.



Pic. 12. Cost of construction of the main objects of HSR-2.

are overpass bridges. They are used not only in places of watercourses, but also replace high embankments (above 8–10 m).

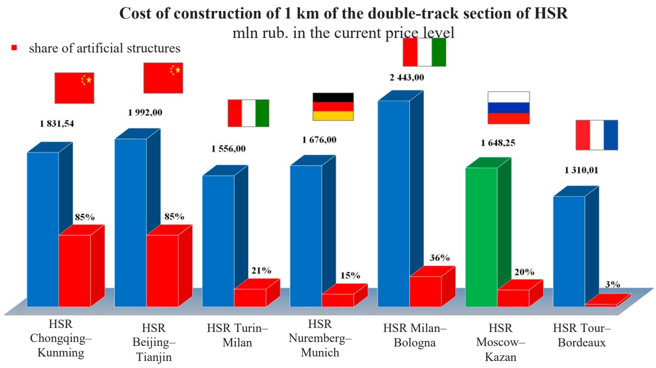
The project HSR-2 Moscow–Kazan uses non-trivial for Russia solutions for construction of artificial structures, which allowed to typify the technological processes and optimize the estimated cost:

- *unified constructions of beam spans of box-like type for two railway tracks (distance between them 5000 mm) from prestressed reinforced concrete with a total length of 23,6 and 34,2 m were developed;*
- *it is planned to create polygons for production of beams based on the presence of natural obstacles and the rational distance of transportation of structures along the prepared roadbed of HSR;*
- *in the design position, span structures are installed by special cantilever-sluice units on a pneumatic wheel with a carrying capacity of 900 tons.*

In the process of developing the project documentation, a comparative analysis of the unit cost of construction of one running meter of bridges/overpasses was carried out at the stage of investment justification, according to the design documentation for HSR-2, analogues in China and France (Pic. 10).

The organizational and technological schemes of production work proposed in the project documentation allow to shorten construction time and optimize the estimated cost of railway bridges/overpasses relative to the stage of investment justification. Further fine-tuning at the construction stage of the production technology can contribute to the transition to the innovative «overpass method» of construction of HSR.

Conclusion. *The high-speed railway line Moscow–Kazan is unique, technically complex, the first in Russia infrastructure project of this level. Compliance with the requirements of the terms of reference, regulatory documents and the application of best practices of foreign countries have a determining effect on the estimated cost of construction. In comparison with the railways of the common network with train speeds of up to 200 km/h,*



Pic. 13. Comparative analysis of the cost of 1 km of HSR.

the HSR-2 project significantly exceeds the share of the main construction sites (by more than 36 %) (Pic. 11, 12).

The specific construction cost of 1 km according to the design documentation of HSR-2 is commensurable and comparable with the world analogues (Pic. 13). At the same time, there is an objective and justified possibility to reduce the cost of construction of bridges and reduce the cost of arrangement of ballastless track superstructure (in particular, with respect to similar facilities in China).

To date, it is impossible to determine the final aggregate cost of project implementation (costs for rolling stock, operating costs are not determined), but now it is possible to reliably answer the question «why so much?». The presented data confirm that the cost of project solutions with the increase in the speed of trains by more than 200 km/h is interdependent from the increase in the requirements for safety and continuity of movement of high-speed railway transport.

The project HSR-2 project is definitely a «challenge» for the country's construction complex. The use of modern innovative technologies in construction is impossible without raising the level of mechanization and automation of production and, as a result, accelerated its development and expansion. International experience shows that the construction and operation of HSR «pulls» the progress of the entire industrial complex of the country and proves the commercial perspective of the movement of trains with speeds in excess of 250 km/h.

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