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Economic Prerequisites for Assessing the Scope of Application of Transport Engineering Structures

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ABSTRACT

The objective of the study is to search for effective design solutions while expanding the passenger transportation network through high-speed rail development. Engineering structures, which occupy a significant part in the infrastructure of high-speed lines, require a revision of approaches to economic and feasibility evaluation of design solutions. The economic problems associated with the design process of HSR are considered, as due to different conditions and standards in divers countries, it became necessary to adapt design solutions through economic feasibility studies. The topicality of the problems of optimization of structures is due to the significant amount of work that can be initiated with the expected start of development of separate high-speed rail lines in Russia. The research significance consists in updating traditional approaches of the feasibility study in relation to the new tasks of railway construction.

The study was based on publications of domestic and foreign researchers in the field of railway infrastructure. For cost analysis, a standard costing methodology was used based on the estimated regulatory base. The cost comparison of options is presented in the sample cost structure, which methodically contributes to allocation of compared costs.

The main practical result of the work is deemed to be associated with formalization of the cost function of modern engineering structures for HSR. Choosing the embankment or overpass, the task which is traditional for railways, was solved on the basis of the analysis of the applied design solutions. For the roadbed, modern reinforcement methods necessary for track stability have been considered. When analyzing the estimated costs for construction of spans, significant disparities were revealed between promising technologies and resource-technological models traditionally used for standard quotations. This casts doubt on the possibility of using traditional approaches of application of engineering structures in HSR projects.

To justify the design and technological solutions for high-speed transport, a whole range of work is needed to jointly develop both technological schemes and cost standards. As far as Russian example is concerned, the current budget and regulatory framework does not allow for reliable economic feasibility justification of the scope of application of engineering structures.

Keywords: railways, railway transport, high-speed rail (HSR), engineering structures, embankment, overpass, soft soils, comparison, cost, economic analysis.

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Background. The traditional practicesы of using these or those design solutions in construction projects of new railways hasgot a significant evolutionary path. It is based on design standards, technological capabilities, as well as economic conditions that serve as the basis for project substantiation at the pre-design stage.

Now, Russian domestic rail transport is on the verge of a new era in creating a network of full-fledged high-speed railways (HSR). This defines a new goal in the field of feasibility analysis which is providing construction projects with scientifically sound tools for selecting design solutions. The peculiarity is that the current experience has been gained over a long period of development and operation of railways with speeds of up to 160–200 km/h, and its use in the pre-design analysis of HSR will lead to incompatible solutions that do not meet the requirements of cost-effective construction and ease of use. The primary task at the stage when construction is not started, but there are design solutions, is to study the practices of constructing HSR abroad and select the most effective structural and technological solutions for Russia with their subsequent adaptation to the peculiarities of domestic construction.

In the context of the problems of agglomeration development, HSR is quite widely considered by foreign researchers, e.g. [1; 2].

The experience of examination of design solutions within the framework of HSR Expert Council in Russian University of Transport has revealed several serious problems, requiring the exploration of corresponding research areas. A common difficulty in designation of certain structures, on which the authors [3] focus the attention, is the lack of practical experimental data on the behavior of infrastructure elements at speeds of more than 300 km/h. In any case, such speeds (300–350 km/h) are considered the most acceptable for the HSR network in France, Japan, and China [4]. Despite the highly developed modelling methods, a similar situation developed during the design of Moscow monorail transport system, when the choice of structures was made without calculating the indicators of comparative economic efficiency, only on the basis of boundary technical conditions, which finally turned to be overstated.

This experience is a warning before implementation of much more capital-intensive projects of construction of HSR urging at the stage of expert discussion to identify «weak points» in the economic sense and propose economically feasible solutions for their optimization. One of the similar problems considered by the author was the choice between embankment and overpass when designing the route. This choice in transport construction in the vast majority of cases was decided in favor of embankment even despite the fact that at the time an insufficient productivity of machinery for construction of the roadbed was felt quite sharply, increasing the road construction time. Domestic and foreign designers used viaducts only under the conditions of particularly difficult terrain (category IV) [5]. The use of the viaduct was justified by technical impossibility of the embankment arrangement. For more favorable tracing conditions, a comparison of estimated costs for construction of an overpass and embankment has always determined the latter as a cost-effective option [6]. Similar views exist among researchers in the field of non-rail high-speed transport [7].

Accepting this regularity as a rule is permissible for new broad gauge railways, albeit with a significant caveat as the ratio of technological, cost, environmental, and social factors is not constant when comparing the option; their quantitative proportions change over time and so the areas of rational use of designed constructions also naturally change. However, in relation to conventional railways, the relevance of this problem is limited by the small volumes of their construction [8]. The volume of construction provided by e.g. two-track HSR Moscow–Kazan project was of 760 km, while the route was supposed to be laid in fairly uniform conditions with the prospect of being extended to Yekaterinburg [9, p. 1].

The second reason for revision of previously identified patterns is a fundamental difference in design conditions. In this case, the construction divisions should initially be focused on the use of effective solutions, on mastering rational technologies as standard solutions, on purchase of appropriate equipment. Competing options when choosing engineering structures are European [10; 11] and Chinese [12] technological schemes of operation of transport systems.

Pic. 1. HSR overpass of low height in China (http://news.southcn.com).

Materials and methods

The above prerequisites determined the choice of *research topic* which is the search for economically feasible areas of application of embankments and overpasses for HSR. The main design solutions used for comparison were compiled according to the design documentation developed at the time for construction of the first Russian separate Moscow–Kazan HSR.

It is worth highlighting that issues of selection and justification of types of engineering structures are most relevant for promising roads that implement the principle of magnetic levitation. V. E. Kraskovsky in his works [7] noted that the share of overpass sections can reach 100 %, however, sections with embankments used as formation remain, and the technical possibility to arrange magnetic suspension systems is maintained even if the subgrade option is applied in a project. The factors reinforcing the role of overpasses are cited by the author in the form of a combination which is traditional for HSR, They include prevention of cross-cutting of lands used in the national economy by the railway, reduction of possible alienation of lands, and traffic safety at high speeds. Dynamic interactions of rolling stock and track infrastructure facilities are boundary conditions in the problems of economic comparison due to their impact on traffic safety [13; 14]. This allows us to make a judgment that the set of reasons for designing the entire route using overpasses is the same as compared to traditional rail transport.

The authors' study [15] on climatic features regarded as a factor affecting economic benefits is also similar to the traditional conclusions on the rational field of application of embankments for railways. Abroad, development of line bridge building technologies for construction of long overpasses led to a decrease in the practical border allowing use of that decision to 5–7 meters. This is confirmed by the experience of designing Chinese HSR, where overpasses are successfully used, starting from a height of 6–7 meters (Pic. 1).

When carrying out an economic analysis of the costs of construction of embankments, one should proceed from the fact that quality of the soil massif has a significant impact on both technical solutions and the cost of the embankment. The problem of strengthening embankments and of construction of HSR overpasses has been sufficiently resolved in international practices [16], however, the use of foreign economic comparison criteria is unacceptable due to the difference in the structure of construction costs in different countries. In design practice, the established term «soft soils» is adopted, and its meaning is not so much geomorphological as form-forming for linearly extended structures.

Here it will be appropriate to mention one of the principles formulated by V. M. Fridkin when solving the problem of optimal configuration of a complex of engineering structures: «The optimization problem must be solved taking into account the scenarios of the behavior of the structure during its operation. Such scenarios should reflect options for the economic, natural and social conditions of construction and its maintenance changing over time. In optimization algorithms, it is necessary to link the choice of values of design quality factors with achievement of a coordinated optimum of economic criteria under various (primarily normative) scenarios of operation of a structure» [17, p. 88]. This approach can, among other things, be applied in calculation of aggregated cost indicators, as mentioned earlier in the author's works [18]. The consolidation of normative indicators of estimated cost with reference to the mentioned «design factors» allows us to determine effective options by the criterion of minimum capital costs. The economic consequences of the operational phase have different properties: the structure of cost meters and their probabilistic characteristics do not allow them to be linked to design solutions. For this reason, to select an effective solution, it is advisable to aggregate indicators of capital investments and operating costs.

The most common method is the use of the reduced construction and maintenance costs as a comparative criterion. Its application in domestic practices preceded modern approaches to comparison based on discounted flows [19], however, at present, it remains possible to compare individual technical solutions based on the reduced costs. We are talking mainly about the structural elements of a facility, which do not have separate economic value, and do not affect the technological model of the structure. As example we can mention different options for supports, foundations, facing materials, provided that the dimensions, loads and reliability of the structure as of a whole are maintained. In a similar way, we can determine the effectiveness of replacing some types of culverting engineering structures with others, e.g. small bridges with pipes.

In accordance with the requirements of current methodological documents, cash flow discounting should be applied, including when introducing innovations. Since the issues of application of new solutions in the promising HSR projects are at the core of the problem of choosing the optimal infrastructure facilities, and if we consider Russian example, STO RZD [corporate standard] 08.005-2011 «Innovation in JSC Russian Railways. The procedure for evaluating the effectiveness of innovative projects» should be used. The main indicators for comparison are: net present value stream, profitability index and payback period. For the selection problem considered in the article, within the framework of a large investment project, the author proposes the criterion C_f, which is a discounted flow:

$$C_f = NPV = \sum_{t=1}^{T} CF_t \left(1+r\right)^{1-t} ,$$

where CF_t is annual cash flow determined by the innovative solution option;

E is discount rate;

T is settlement period.

In this case, it is assumed that there are definable financial flows that can be associated with each option of the technical solution, while there is no need to adjust the payback period of the entire project with each calculation. Nonlinearity with respect to time is specified through the standard factor $(1+E)^{1-t}$. This calculation procedure is very convenient and justified for the railway facilities when the revenue model from transportation or any other activity is within the same conceptual model. If we are talking about an element of the transport infrastructure, including expanding the scope of its application in the project, the profitable part of the flow cannot be determined directly. A situation arises of a methodical «crossroads» when there are several solutions to the problem, and the choice is determined by the degree of qualification, freedom, and interest of the actor.

Based on this, it becomes possible to carry out a cost comparison within an optional statement, avoiding full calculation of costs according to the traditional structure of estimated cost. The advantages of this method should also include the fact that there is no formal need for indexing costs. The content of indicators is determined by the current technology for creating products at the time of calculation. This is equivalent to the principles of considering the technological model in designing estimation standards, when the once considered technology exists in the regulatory framework, providing not only calculation of absolute cost indicators, but also accuracy in comparative economic analysis.

To resolve the issue of effective areas of application of described engineering structures, one should rely on the existing experience in construction of HSR. At present, the Chinese high-speed rail system should be considered the most suitable model for designing HSR network. There are several reasons for this:

• territorial layout of the network, its size, network density and location of gravity areas are more consistent with Russian conditions than similar indicators of European and, especially, Japanese HSR;

• prevailing geomorphological forms and climatic features of the northern part of China have sufficient tracing conditions in terms of complexity;

• climate in the northern provinces of China has similar requirements for construction and operation of both embankments and overpasses;

• land use system and relative indicators of the value of land alienation are similar to the Russian Nonblack Soil Zone [includes Central, North-Western, Northern and some other economic areas of the European part of the territory of the country – *ed. note*]. It should also be noted that the level of environmental requirements limiting some design solutions is comparable to Russia.

However, along with general features, there are serious differences associated mainly with different technological levels of the construction facilities in Russia and other states with a developed network of HSR. A feature of Russian railway construction is traditional development of machinery for earthworks. Thanks to this, at present, implementation of large volumes of earthwork has ceased to be a determining factor in choosing the route option. This aspect is most significant for railway lines with maximum gradient which is higher than the average ruling grade of the terrain.

This determines the rather high significance of practical height of the transition zone from the embankment to the overpass. In this case, the practical height should be understood as the average embankment height in the zone of transition to an overpass established in the practices of project activities. Such a transition has traditionally been used on approaches to bridges over certain obstacles. Hence the question of replacing the embankment with an overpass on long sections of the route without the presence of localized intersected obstacles until the beginning of the active growth of urban agglomerations in recent decades has not been massively considered in domestic practices. Elevated sections instead of embankments began to appear in design solutions in cities and under difficult engineering and geological conditions when designing non-high-speed railways. Yet at the beginning of 20^{th} century embankments with a height of more than 20 meters were competitive due to technological development of their construction [20, p. 262]. In many respects this was facilitated by maintainability of track ballast superstructure, which made it possible to compensate for the precipitation of the subgrade by adding a ballast prism.

The appearance of high-speed lines arranged along the ballastless track immediately determined a new level of requirements for permissible deformations of «bed/foundation – embankment» system. The inability to straighten the track in the traditional way involves necessity for small precipitation during operation, as small that it is almost impossible to provide them with traditional roadbed design. The design features of embankments of high-speed highways can be considered at the examples of the developed HSR network in China. As a measure to reduce the operational sediment, an integrated approach is used, which includes installation of a pile foundation of the embankment, reinforced soil structures (geogrids, laying of bentonite mats, increased compaction of the body of the embankment and, finally, replacement of the upper part of the embankment with protective layers). Such a saturation of the roadbed with engineering elements leads to a significant increase in estimated costs per kilometer of track. Also, when comparing with embankments, one should consider the wider main foundation site of 14,2 m for HSR.

The reinforcement of embankments is a synthesis of previously known technical solutions, but the mass practices of reinforcement in domestic railway construction are missing because of specific dynamic interactions [21]. For this reason, an analysis of the cost of reinforcement requires a comparison of the technologies used both in Russia and abroad. The main criterion for comparing an individual measure is the cost per 1 km of the route. Besides, the features of the reinforcement measures inherent in other types of construction are subject to accounting, the new types of works and structures to strengthen the earth masses being included in the projects.

The strength of the base of the embankment, insufficient to meet the requirements of the Special Specifications, necessitates construction of a continuous pile field with a flexible grill with geogrid [22]. A flexible geogrid grillage has cost of construction and installation works of 7,70 rubles per 1 m^2 in basic prices as of 01.01.2000. Given that under the HSR project 221 thousand m^3 of bored piles (BNS) account for

790 thousand m² of geogrid, 1 m³ BNS will require 3,57 m² of geogrid. The correlation of this indicator with the foreign counterpart (China) shows the identity in construction of the «pile–grillage» system, however, the proportion of sites with a similar type of reinforcement in the domestic HSR project is much lower, which reduces the capital intensity of the construction as a whole. It should be noted that in the practice of China's HSR, pile foundations with a rigid grillage at the level of the edge of the embankment are used, which resembles, rather, a simplified buried overpass.

The total cost of construction and installation works to strengthen the base of «BNS + flexible grillage» type is from 15 to 31 thousand rubles per 1 km of the track at basic prices. Moreover, the cost is primarily dependent on the average height of the embankment, as shown by the analysis of seven types of transverse profiles over 70 km of the route.

Research results

Evaluation of the project costs for construction of the embankment, composed of sand and rocky soil, is based on the hypothesis of sufficient strength of the base to exclude re-consideration of factors. The main differentiating feature here is also the height of the embankment. For comparison, the design data for HSR roadbed is accepted (type 1–17 on the section of ballastless track). This type is represented by an embankment composed of gravel and sand mixtures and drainage soils. For the section «km 97 + 580–Petushki», the average cost of construction and installation works for the roadbed taking into account design solutions is presented in Table 1.

Table 1

Estimated cost of construction and installation works on construction of the roadbed, million rubles per 1 km at basic prices

Embankment height, m	Sand	Rock
8	34,4	63,5
10	46,0	90,4
12	58,2	120,0

The cost of reinforcing the roadbed with geotextiles for the same heights of the embankment is as follows (Table 2).

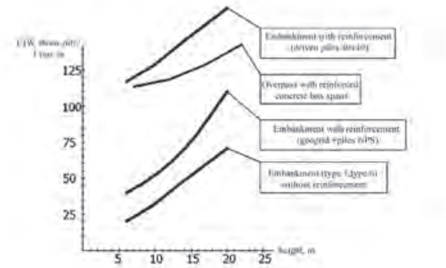
One of the possible options for strengthening the base of the roadbed is installation of a pile field from driven piles 40 x 40, which is provided for by the project on a 0,212 km long section with an individual I2 profile. The average height of the embankment in this section is 8,5 m. The estimated cost of construction and installation works for installation of piles with grillage is 110,7 million rubles per km of embankment at basic prices. Similar cost indicators (with a spread of -8/+13 %) were obtained when analyzing the market for commercial offers of works on pile reinforcement of road embankments.

All the facts cited point to the need to review the previously existing methods of economic justification of the areas of rational use of engineering structures. The «Special technical conditions for design of «Moscow–Kazan» section» of Moscow–Kazan–Yekaterinburg HSR with speeds of up to 400 km/h, developed in Russia (Coordination: Ministry of Construction of the Russian Federation, 08.03.16, No. 24651-ec03) say the same: «When designing the roadbed, the options for transition of the track from the roadbed to overpasses and tunnels should be considered. The decision on transition to overpasses and tunnels should be made based on a technical and economic comparison of design options». Technical purpose criteria can be determined similarly to those given in [23], considering domestic safety requirements. Comparison of options, including for the purpose of searching effective areas of application, should be subject to current methods for determining economic efficiency. The identification of discounted cash flows and the calculation of indicators of comparative economic efficiency are priority goals

Table 2

Estimated cost of construction and installation works to strengthen the roadbed with geotextiles

Embankment height, m	Cost per 1 km of embankment at basic prices, mln rub	
	Geotextile with density 300 g/m² (2 layers, standard solution of profile I4)	Geotextile with density 600 g/m² (2 layers, standard solution of profile I1)
8	2,7	6,0
10	6,4	14,2
12	13,8	24,3



Pic. 2. Comparison of the estimated cost of construction and installation works for embankment and overpass.

according to a number of currently used methodological recommendations on composition and contents of supporting materials for investment projects (approved by JSC Russian Railways on November 28, 2016 No. 2396r). However, feasibility of applying this approach is great only for projects that have the fullness of qualities both in the cost part and in return on investment. Moreover, the differences between the options should affect most of the financial and economic properties of the project. Such a comparison is of great importance in comparative calculations between different modes of transport, when choosing a route option with different areas of gravity. If the compared objects are parts of a large complex of structures and do not have differences in cash flows of return of funds (revenue), then the best way to compare is to calculate construction and maintenance costs. This allows in a fairly simple way to get a local optimum in a large system, improving its final economic indicators. Also, in this case, the significance of value standards increases, since a detailed analysis focuses on the cost norms during construction and operation of an object, excluding their ignoring in the numerically large cash flows of the project as a whole.

The issue under consideration is typical for the case of choosing between a roadbed and a bridge structure for high-speed traffic, and the costly comparison criteria in this situation are prevailing, since the structural parts of the route compete with each other, and the general economic effects obtained in operation are unchanged. The reduced construction and maintenance costs E_{pr} for time-variable values are determined by the formula:

$$E_{pr} = \sum_{t=0}^{T} \frac{K_t}{(1+E)^t} + (1-\gamma) \cdot \sum_{t=0}^{T} \frac{C_t}{(1+E)^t},$$

where K_t and C_t are capital investments and operating expenses (current expenses) at the *t*-th step (year), respectively;

γ is share of tax deductions from profits.

The costs of operating HSR infrastructure are currently the subject of a separate discussion, this allows us to consider the task of comparison in stages, starting with the capital costs of construction. Pic. 2 shows the capital costs of building competing construction options depending on embankment height.

As can be seen from the graph, in the range of rational differences in elevations of the route and the earth's surface (5–20 m), costs are «stratified» by options without intersection points, i.e. the subgrade design is competitive regardless of embankment height. At the same time, it should be noted that the cost of this or that variant of the roadbed is highly dependent on the degree of its strengthening. Some types of reinforcement (with the base of the embankment on driven prismatic piles) are comparable in cost to overpasses. In turn, the overpass option of the road can be made cheaper by industrialization of production and optimization of design solutions.

A feature of determining capital costs for construction of HSR infrastructure facilities is the novelty of structures and technologies for domestic construction. As a result of this, a reliability problem arose in determining the estimated cost of structures, in particular span structures of overpasses, ballastless track, embankments. The results of previous studies indicate that an analysis of the existing features of determining the estimated cost of spans and development of recommendations for improving accuracy are mandatory. To implement these tasks, it is necessary to consider not only construction of spans, but a complex of structural, technological and organizational solutions, taken into account in design of the bridge.

As a result of the analysis of project documentation, as well as comparison with available documents of the estimation regulatory base, controversial issues were identified in calculation of investment costs for the structures under consideration.

The use of some estimation norms and prices for bridge structures cannot be considered justified. So the price OERZh 30-02-005-05 for installation of reinforced concrete bridge spans for a single railway track up to 34,3 m in length by cantilever cranes was developed for typical prefabricated two-block spans. The resource-technological model, taken into account in this case, is very different from the expected technology when installing box-shaped beams under two tracks with a lock crane. The maximum possible solution in the existing regulatory framework is replacement of GEPK mounting crane, considered in the price, with Gottwald AMK-306-83 crane, though the latter by its features is unsuitable for installation of designed span structures. Since the spans for HSR are designed double-track, there is a need to link the prices (with a meter that can be formulated as «the «span for 1 track») to the project scope. In such a situation, objectivity of estimating the upcoming installation costs by applying the existing price with a coefficient equal to two can only be associated with random luck. The situation is similar with application of norms for transportation of spans (OSSPZh 01-01-01-050, 04-02-01-025, 04-02-01-026, 01-01-02-050), which consider much lighter products and other bogies. The cost of arrangement (concreting) of span structures can be considered at the rate of OERZh 30-02-024-01, which considers simple wooden-plywood formwork. When concreting box girders within the span, it is assumed to use a special rearranged set of scaffolds and formwork, the design and scope of work for which significantly differ from those considered by the rate.

The described situation during development of HSR project is not connected at all with a mistake or intent, but with a kind of hopelessness, since there are no corresponding norms and prices in the estimated regulatory base, including with regard to the required machines and mechanisms. For relatively small projects where new designs are measured in units, the method of artificially linking inappropriate prices is acceptable. The author has determined that, for example, reducing the cost of spans by one percent provides an economic effect of about 5 million rubles per kilometer of track. The project assumes almost 64 kilometers of overpasses of the mentioned construction, therefore the absolute value of the possible error is significant in the total amount of the estimated construction cost. In this regard, it should be considered economically feasible to consider the initiation of the process of developing the missing standards and prices, as well as the costs of operating the machines, followed by the inclusion in the register of federal estimation standards in accordance with the order of the Ministry of Construction No. 413 dated 02.06.2015.

The noted feature does not allow us to consider it possible to use the considered elements of direct costs in subsequent calculation of the project budget, in mutual settlements, etc. Specification of design decisions is required, turning them into standard ones for transport construction [24], including by filling in the gaps in the estimation regulatory base. This will not only solve the problems of choice within the framework of the project, but will also enrich the methodology for managing the development of quality of objects of complex nature, which include high-speed transport infrastructure [25].

Conclusion and discussion

Expert and analytical activities currently unfolding around the topic of building high-speed railways in Russia raise several scientific and practical problems of methodological novelty and based on a now different regulatory and technical model. The author has performed an analysis of the project costs in terms of engineering structures and roadbed, including its strengthening. To this end, a review of domestic and foreign approaches to criterial assessment of design decisions has been carried out, and the practical application of the concepts of rational areas of application of structures has been considered. The solution of applied problems of choice is made at the example of the most capital-intensive infrastructure elements which are embankments and overpasses. The result obtained is quite interesting from the point of view of choosing ways to improve the design works and estimation standards. Currently, all possible principal options for construction of the railway have monotonous differences in the total value of capital costs over the entire range of heights. This leads us to the conclusion that the search for a global result in the form of reduced investment in HSR project as a whole should be carried out in the plane of constructive and technological improvement of individual elements of the infrastructure. At the same time, the result of tracing the railway determines the cost of its construction mainly due to the track plan, i.e. length, the presence of curves, etc. The problems linked to the heights on the longitudinal profile are less significant, which distinguishes the HSR project from traditional railways. Traditional solutions based on structural optimization in design of HSR are constrained by the increased technical requirements for dynamics, safety, and ecology. A serious factor complicating the comparative valuation is the lack of estimation regulatory base in terms of norms and prices for fundamentally new works.

The problems raised represent a promising way for development of the economy of transport construction in the field of high-speed railways.

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