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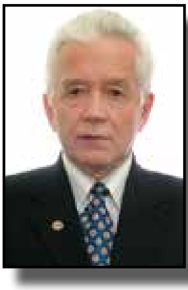
Development of Risk-Based Approaches to Determining the Damageability and Useful Life of Railway Transportation Assets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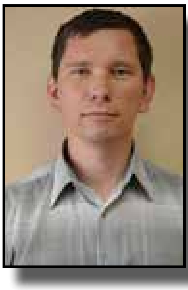
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ABSTRACT

Modern problems of railway transport in Russia, such as the general technical condition of transportation assets, and relevant issues of their safe operation, substitution of imported equipment and its components, implementation of the programs of technological development give rise to the need to create new equipment and technologies, constructing schemes for long-term development of transport based on new safety requirements and strategic planning. Current level of developments does not allow to completely eliminate damage, failures and accidents regarding railway transportation assets manufactured in accordance with the current regulatory framework. Solving these problems is possible by identifying the actual state of an object regarding cyclic, corrosion, wear and other damage accumulated during operation, which determines the onset of limit states of the basic elements of an asset, taking into account resource recovery technologies at various stages of the life cycle, both in standard (design) operating conditions and beyond them.

The article refers to the problems associated with ensuring safe operation of railway transport, with the aim of substantiating based on existing regulatory and technical documents of new approaches to the analysis of damageability, vulnerability of objects and assessment of the risks of accidents and disasters. The development of interaction through a system of new problem statements and regulatory and technical documents, as well as more active involvement in the use and development of the fundamental laws of physics, chemistry, and mechanics of real-life processes in the environment, make it possible to implement new concepts, strategies, and developments of advanced research for technical objects with the use of digital and intelligent technologies.

Keywords: railway transport, rolling stock, locomotive fleet, safety, useful life, service life, life cycle, reliability, accumulation of damage, diagnostics, dangerous state, risks, accidents, disasters.

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INTRODUCTION

Implementation of new technology, machinery and rolling stock, the current pace of the comprehensive improvements in railway transport highlights relevance of constructing patterns of its further development based on new requirements for safety and strategic planning.

It equally refers to all the interconnected aspects of railway transportation. For example, as for the locomotive fleet of railways, besides rolling stock itself, there is a need for a certain categorisation of the condition of railway facilities supporting its operation (railway bridges, tunnels, and other artificial structures), of their quantity and stages of operation. In this categorisation, it is important to identify a group of assets intended for long-term operation with damage accumulated in their structural elements.

Among most important factors, one can distinguish innovations, focus on new solutions, new equipment, new vehicles, new technologies that require equally new approaches to determining their reliability and useful life.

Another task is related to the fact that there are imported assets and equipment used at railway transport facilities, and it is necessary to provide for functioning of imported assets with domestic regulatory and technical documents.

It is also important to consider other factors as global change in the natural environment and climate.

The *objective* of the study is to substantiate new system approaches to the analysis of damageability, reliability of the assets and to the assessment of accidents and disasters.

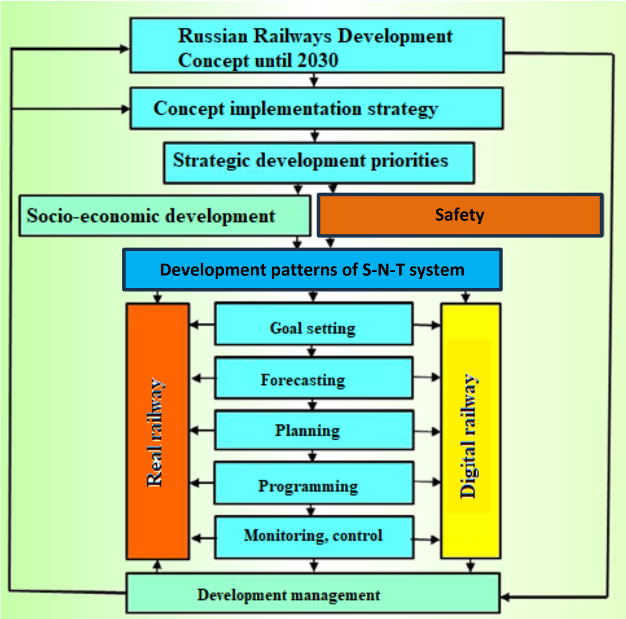
RESULTS

Relevance of Solving Useful Life and Safety Problems

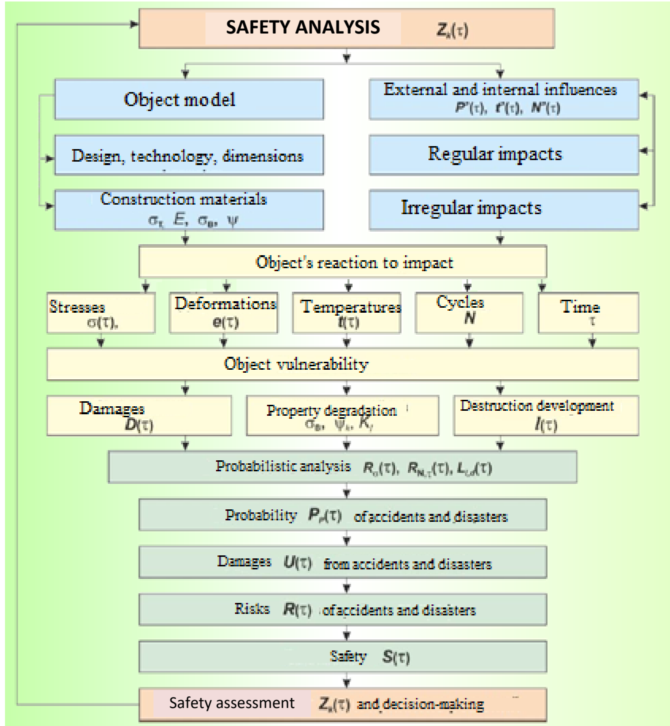
Railway transport should be considered as an integral part of social, state, natural, technogenic systems. Identification of a certain sequence in its development (goal setting, forecasting, planning, programming) is a component of planning to achieve the strategic goals of modern development of a state.

Based on this, we should dwell on the issue of constructing patterns for future development of transport based on new safety requirements and strategic planning (example of JSC Russian Railways, Pic. 1) [1–3]. Here it is important to determine availability of knowledge, real approaches and technologies, big database, hardware systems from the point of view of strategic planning.

In the diagram (Pic. 1) S-N-T is a combination of social, natural, technogenic spheres, determined by indicators of strength, useful life, safety, workload of assets. On the one hand, it is desirable to increase these indicators. On the other hand, it is imperative to consider the fact that neither failures, nor accidents, nor catastrophes occur instantly (suddenly) (Pic. 2). Then it becomes clear that the analysis of the real accumulated damage, of the degradation of the systems themselves during their operation [4]



Pic. 1. Structural diagram of the prospects for development of railway transport in aggregate [1–3].



Pic. 2. Basic model algorithm for computational and experimental determination of strength, useful life and safety according to risk criteria [4], where σ_B is the temporary resistance of the material; ψ_k – relative narrowing of the neck of a standard material sample; K_I – crack resistance; L ($L_{(r)}$, $l_{(r)}$) – survivability at various stages of life cycle; R_σ, R_N – and other letter combinations in this and subsequent figures functionally indicate the risks of destruction and resource exhaustion, respectively, according to damageability mechanisms (wear, corrosion, etc.), respectively, the list is not exhaustive and serves to demonstrate fundamental approaches.

constitutes the basis. These indicators are fundamental.

The problem of damageability itself comes first. Now the state legislation raises the issue that the stage of activity defined by a new requirement for the justification of the useful life and safety should be deemed among the most important ones. The word «justification» means that in some cases it is impossible to fully use the current regulatory and technical documentation. In case of deviations, when new circumstances and conditions arise, the current regulatory and technical documentation does not allow correct selection of solutions. Therefore, this requirement in legislation, which will be widespread in industrial safety to justify the useful life and safety, will become very important.

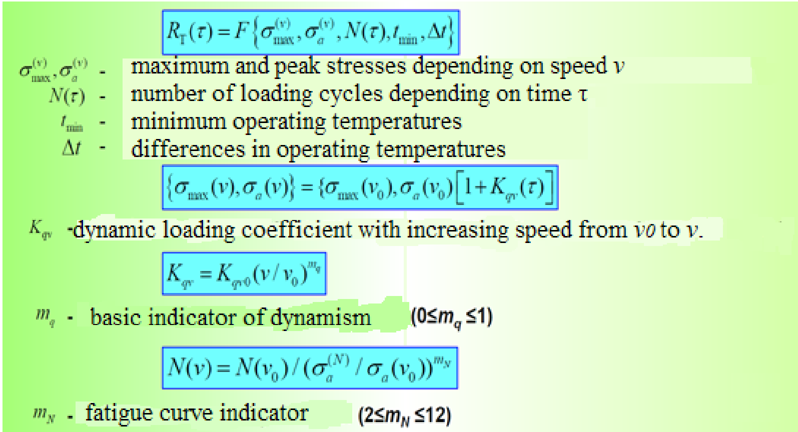
Methodology for Damage Analysis and Risk Assessment

A certain criterion-based ground for analysing damage under normal and abnormal operating conditions, damageability associated with time (τ) and the number of loading cycles (N), are the determining fundamental parameters on which further consideration of the risk of damage can be based (Pic. 3). This will include loading conditions, environmental conditions, and degradation of structures and materials. Considering all these factors will come down to the fact that the parameters that determine the state of systems are damageability and vulnerability [5]. The transition to these parameters referring to both rolling stock and infrastructure is extremely important.

The damageability itself as a function of time determines the risks (Pic. 4). Direct damage that turns into failures, destruction, accidents, disasters implies that specific methods of analysis, diagnostics, management, technology, and repair and restoration work must be inherent for each stage. The damage curve becomes key indicator in this case [6].

If damageability is taken as the main parameter, then other characteristics (strength, useful or service life, wear resistance, cold resistance, reliability, survivability, risks, safety) turn out to be functional from this key parameter (Pic. 5) [7].

If this approach is accepted, then for long-term objects, for imported, heavily damaged and new objects, a system of defining analytical



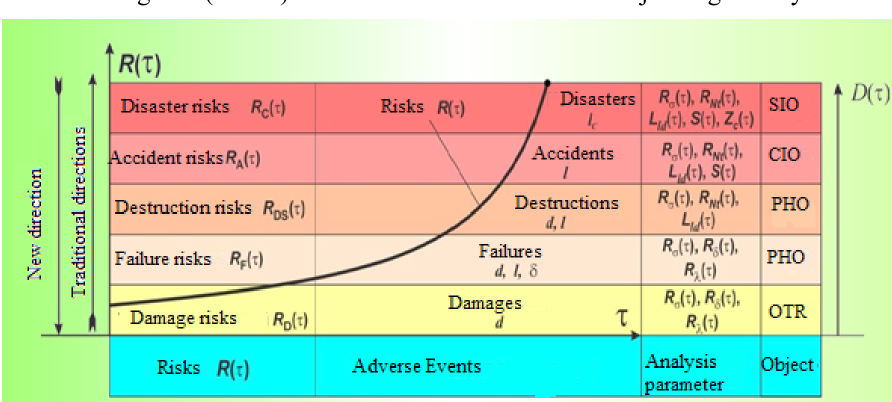
Pic. 3. Coherent analysis of technogenic and natural risks during normal operation [5].

expressions should be built, which will then be supported by digital and intelligent technologies. The necessary initial analytical base exists. Joint research by specialists from JSC VNIKTI and the Institute of Mechanical Engineering of the Russian Academy of Sciences, developments by JSC VNIIZhT related to safe traffic systems, have revealed that this kinetic structure of the work processes themselves, transformed into kinetics and levels, calculated and analytical damage curves, becomes the most important (examples of general foundations and criteria are shown in Pic. 6) [8].

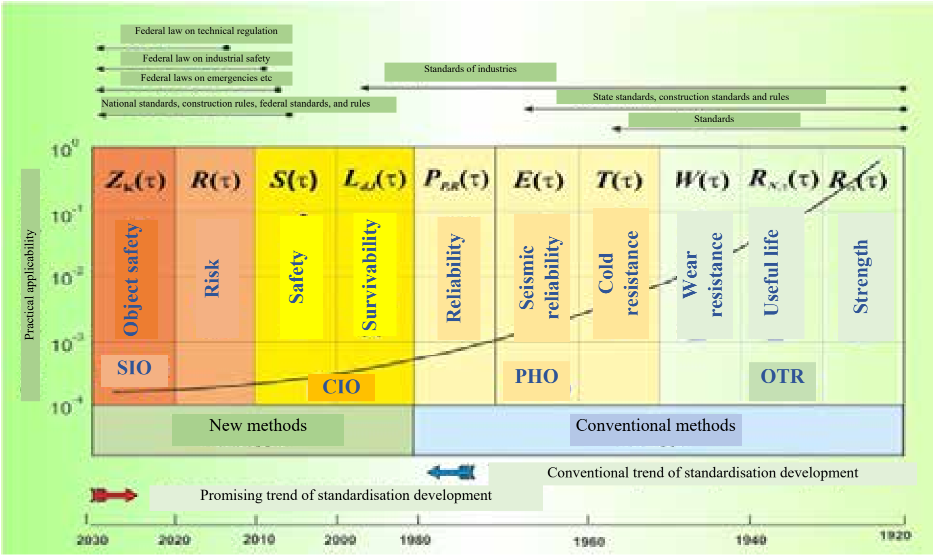
The problem of determining the service life of an object is solved by computational and experimental research methods including an assessment of physical and mechanical characteristics of the material, the stress-strain state of structural elements of the object, and the kinetics of damage accumulation in them. At the same time, determining safety and durability margins requires probabilistic approaches with construction of histograms (blocks) of distribution of current values of load amplitudes (stresses) under various operating modes of the object (for example, when changing the speed of rolling stock), calculating their equivalent values for the entire range of impacts, considering their shares in operation.

Consequently, it is relevant today to bring the existing methods for determining the actual useful life of railway facilities to the possibility of their incorporation into the regulatory framework. This will become a scientific and technical tool for justifying the safe operation period of an object with the required reliability.

Then, the decisions that will be made on any of the existing assets will be resumed to the statement that there are parameters such as time, number of cycles, years, ton-kilometres, initial and residual service life, accumulated and limit service life, which are subject to theoretical analysis. Therefore, the curve presented in Pic. 7 (the same picture shows also some key calculation formulas) can be implemented and used in all major regulatory and technical



Pic. 4. The sequence of analysis of hazardous conditions of assets and of corresponding risks: OTR – objects that are subject to technical regulation; PHO – potentially hazardous objects; CIO – critically important objects; SIO – strategically important objects [6].



Pic. 5. Model complex mechanisms for analysing and managing strength, useful life and safety [7].

Equations of initial long-term strength (over service time)

$$\{\sigma^э, e^э, \tau^э, N^э\} = f(P^э, \tau^э, N^э, t^э) \le \left\{\left(\frac{\sigma_{an}^t}{n_\sigma}, \frac{e_K^t}{n_e}, \frac{\tau_K}{n_\tau}\right), f(m_\tau)\right\}$$

Crack resistance taking into account local stresses and deformations, defect sizes, stress and deformation intensity factors, temperature conditions

$$\{\sigma^э, e^э, K_I^э, K_{Ie}^э\} = f(P^э, t^э, l^э) \le \left\{\frac{\sigma_K}{n_\sigma}, \frac{e_K}{n_e}, \frac{K_{Ic}}{n_K}, \frac{K_{Iec}}{n_{Ke}}\right\}$$

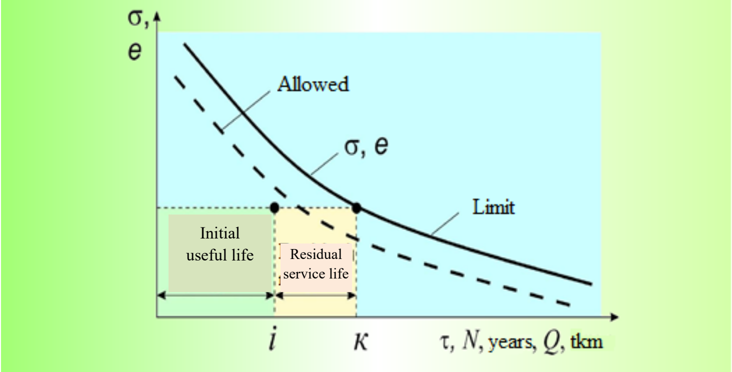
Relationships for estimating the initial and residual life, taking into account long-term and cyclic development of cracks

$$\{\sigma^э, e^э, K_{Ie}^э, N^э, \tau^э, t^э\} = f(P^э, t^э, l^э) \le \left\{\frac{\sigma_K}{n_\sigma}, \frac{e_K}{n_e}, \frac{N_K}{n_N}, \frac{\tau_K}{n_\tau}, \frac{t_K}{n_t}\right\}$$

Determination of design durability characteristics using kinetic fracture diagrams

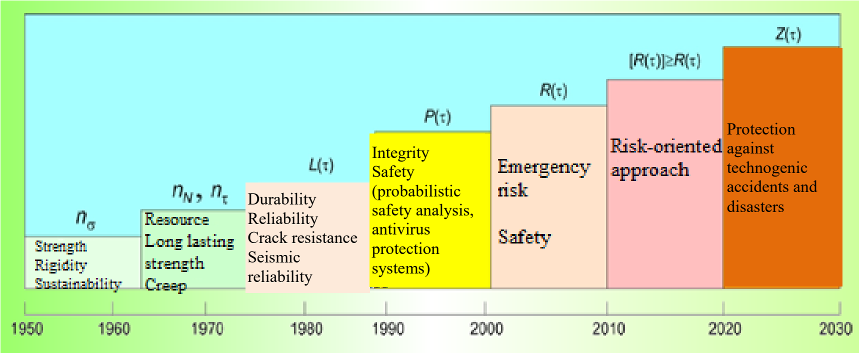
$$\{N_K, \tau_K\} = F\left\{(\Delta K_{Ie}^э)\left(\frac{dl^э}{dN}, \frac{dl^э}{d\tau}\right)\right\}$$

Pic. 6. Examples of general principles and criteria of strength, service life, risk, and safety [8].



$$d_i = f\left\{\frac{\tau_i}{\tau_K}, \frac{N_i}{N_K}, \frac{Q_i}{Q_K}\right\} \le 1 \qquad [d_{res}] = (d_K - d_i)/n_d \qquad n_d \text{ - margin of residual service life}$$

Pic. 7. Justification of residual service life [8].



Pic. 8. Sequence of formation and development of a risk-oriented approach to CIO and SIO [8].

METHODS OF DIAGNOSTICS OF THE CONDITION												
Methods	Defects			Temperature			Stresses			Mech.properties		
	Size l	Shape a/l	Place S	Value t	Cycle τ_c	Time τ	Value σ_a	Cycle N	Time τ	Strength σ_T, σ_v	Plast. δ, ψ	Crack. K_{Ic} KCV
Ultrasound	+ +	− +	− +	−	−	−	− +	−	−	−	−	−
MPT	+ −	−	−	−	−	−	−	−	−	−	−	−
Vis.control	+ −	−	−	−	−	−	−	−	−	−	−	−
X-ray	− +	− +	− +	−	−	−	− +	−	−	+ −	−	−
Vibrometry	+ −	−	+ −	−	−	−	+ −	−	−	−	−	−
Acous.control	+ −	−	+ −	−	−	−	+ −	−	−	−	−	−
Acous. emis.	+ +	+ −	+ +	−	−	−	+ +	−	−	− +	−	− +
Holography	−	− +	+ −	+ −	−	−	+ −	+ +	+ −	+ −	+ −	+ −
Thermal imaging	+ −	−	+ −	+ +	+ +	+ +	+ −	+ −	+ +	+ −	+ −	+ −
Tomography	+ +	+ +	+ +	−	−	−	−	−	−	−	−	−
F.-sc. str. gauge	+ −	+ −	+ −	+ +	+ +	+ +	+ +	+ +	+ +	+ −	+ −	+ −
DESIGN RATIOS												
$N_p = f(\sigma_a, t, \tau, l, \Phi)$	- Full-scale strain gauge											
$T = f(\sigma_a, N, \tau, l)$	- Thermal imaging											
$AЭ = f(\sigma_a, e_p, K_{Ie}, l)$	- Acoustic emissions											
$G = f(\sigma_a, t, N, \tau)$	- Holography											

Pic. 9. Possibilities of diagnostic methods for analysing parameters of an object state [9].

documents based on the level of damageability, useful life, safety, fault tolerance, resistance to accidents and disasters [8].

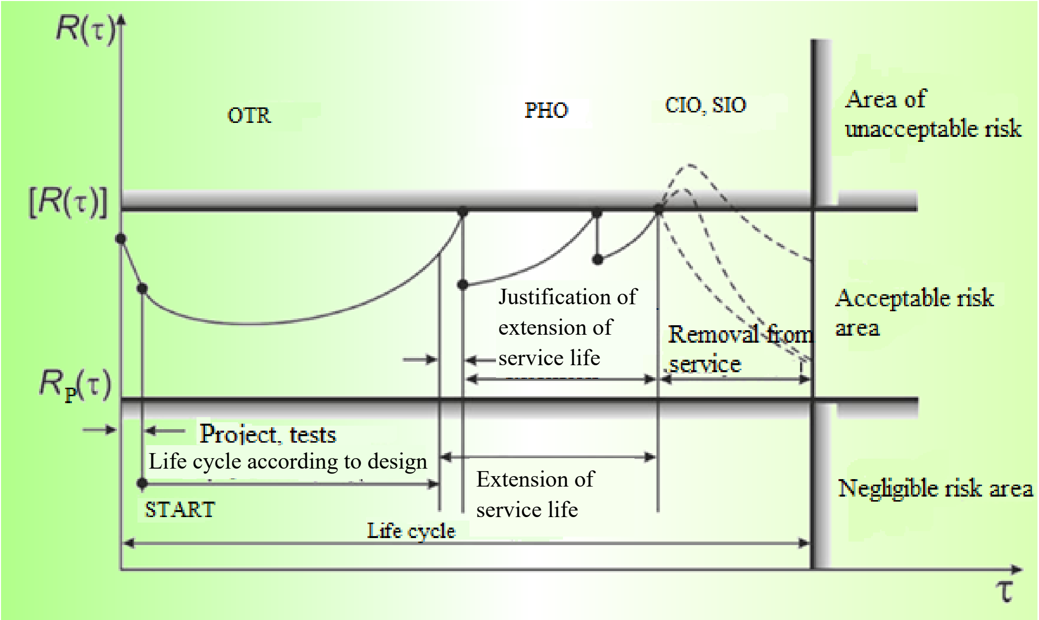
DISCUSSION AND CONCLUSIONS

Based on all the developments already made also in the regulatory and technical framework, adopting, and moving to risk-oriented approaches, which is now required by law, it is necessary not to fight all negative phenomena and risks not during operation, but to transfer this «struggle» to the design stage [8]. This ideology will be decisive for new assets and future development.

Diagnostic systems must be adjusted so that these real technical conditions, considering damageability, are determined by a large group of parameters that go beyond the traditional standards of diagnostics and control. Pic.9 shows which parameter and by what method can be obtained and illustrates examples of ratios and equations [9]. Once such approach is implemented, those parameters obtain decisive role. On-board recorders of service life, that will take into account the accumulated damage in elements, components, units, locomotives, wagons, will become models that will not only record the current state and create extensive Big Data statistics, but also predictive models based on physical, mechanical, chemical processes actually occurring in vehicles, structures and control systems.

Then management of the condition itself, management of risks, service life in terms of the level of damage and risks becomes not a periodically prescribed work and inspection to assess the need for maintenance and repair, but a scientifically based activity (Pic. 10) [10].

Within the context of comprehensive study of the problems stated in the research it is advisable to consider modern international

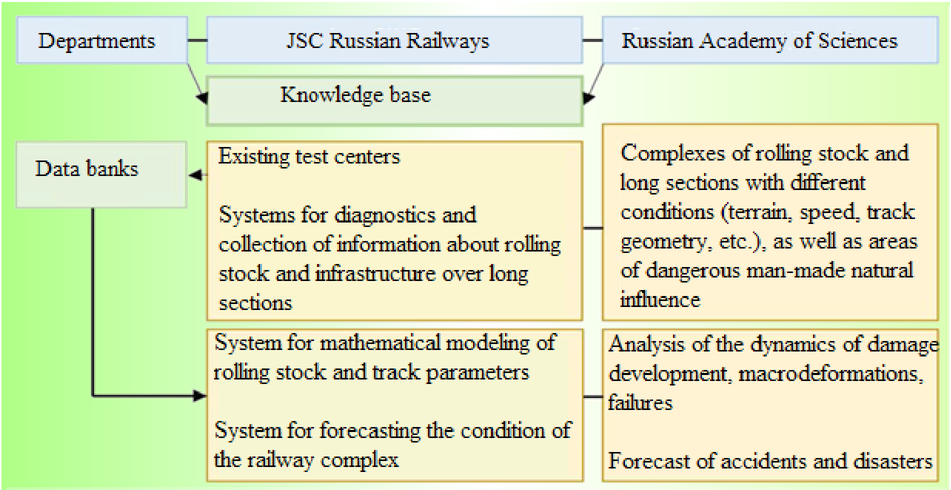


Pic. 10. Risk management for various stages of objects' life cycle [10].

research papers and expertise (the relevant analysis because of the vastness of the topic is beyond the purpose of the article and needs thorough particular consideration).

Considering the above and with respect to railway transport, the relevance of scientific follow-up of rail operational activity becomes quite evident. Particularly, the interaction that has developed between JSC Russian Railways and the Russian Academy of Sciences should obtain new development (Pic. 11). It must be implemented through a system of new problem statements and regulatory and technical documents, as well as concepts and strategies [11–15].

In this case, it is advisable for the Joint Scientific Council of JSC Russian Railways, research and scientific organisations and specialists of the railway transport industry to focus on the fact that the fundamental laws of physics, chemistry, mechanics of actually existing processes in the environment for technical objects should be more actively involved in use and development. The introduction of intelligent and digital technologies should ensure not just the recording of some actually developing situations, but also take into account the real patterns of deformation, damage, destruction and degradation. This direction becomes decisive.



Pic. 11. Concept of advanced research and development using digital and intelligent technologies [11–15].

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