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Simulation Technologies as A Tool For Improving Railway Safety: International Practice And A Conceptual Model

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Abstract

Simulation technologies are becoming an increasingly important component of railway transport safety systems due to the growing complexity of operational processes and the continuing influence of the human factor on traffic safety. This study examines international approaches to the use of simulator technologies in locomotive crew training and analyses their role in improving railway safety. The research is based on a comparative analysis of centralized and decentralized training models used in the Russian Federation, the United States, and European countries. The study reviews modern simulator systems, including full-scale simulators, procedural simulators, scenario-based simulation technologies, and digital learning environments. Particular attention is paid to the integration of simulator technologies into safety management systems, personnel assessment, emergency preparedness, and human factor research. Based on the analysis conducted, a conceptual model for the integration of simulator technologies into railway safety systems is proposed. The results demonstrate that advanced simulation technologies not only improve professional training quality but also contribute to accident prevention, operational risk reduction, and the development of sustainable decision-making skills under complex operating conditions. The study concludes that the further development of simulation technologies is associated with the expansion of their analytical capabilities and deeper integration into comprehensive railway safety management systems.

Keywords: Railway safety, simulation technologies, locomotive crew training, human factor, full-scale simulators, digital learning environments, railway transport.

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1. Introduction

In modern rail transport, ensuring the safety of train operations remains one of the key areas of development for the industry. Increasing speeds, higher traffic volumes, and the introduction of automated control systems and modern safety measures significantly raise the bar for the quality of locomotive crew training. Despite the development of technical systems, the human factor continues to be a significant source of risk. Errors in assessing the situation, breaches of regulations, and the influence of fatigue and stress factors can lead to abnormal and emergency situations.

In these circumstances, simulation technologies play a key role, enabling the development of robust professional skills in a controlled environment. The use of digital modelling, scenario-based approaches and objective assessment systems makes simulation training a vital component of modern safety management systems.

This study aims to analyse international practices in the application of simulation technologies and to develop a conceptual model for their use in the railway transport safety system.

The novelty of this study lies in the development of a conceptual framework integrating simulator technologies with railway safety management systems and international training practices.

Research methodology

This study is based on a comparative analysis of training systems for locomotive crews using simulator technologies.

The following models are examined:

- a centralised training system (Russian Federation);
- decentralised systems (the USA and European Union countries).

The methodology includes:

- analysis of regulatory body materials (FRA, ERA);
- a review of manufacturers' solutions (CORYS, Transurb, FAAC);
- a review of scientific publications;
- analysis of practical experience in implementing training systems.

Methods of comparative analysis and a systematic approach were applied.

A limitation of the study is the use of open data and aggregated industry indicators.

3. Simulator training in rail transport: conceptual foundations

Simulator training is a structured pedagogical system that integrates digital modelling technologies with the analysis of the human factor in the process of railway transport management.

In the system of professional training for railway personnel, simulators perform several key functions.

Initial Training

At the basic training stage, simulators are used to develop basic skills in locomotive control and interaction with infrastructure elements.

Simulator systems enable:

- develop basic locomotive control skills;
- master algorithms for interacting with infrastructure;
- practise prescribed procedures without compromising traffic safety.

Thus, simulators act as a bridge between theoretical training and real-world operational practice.

Recurrent Training

As part of regular professional development, simulators are used to maintain professional skills and practise actions in emergency and critical situations.

The main objectives of this stage are:

- maintaining professional proficiency;
- updating knowledge in line with changes to the regulatory framework;
- practising procedures in complex and non-standard operating conditions.

Safety Assessment

Modern digital simulators are also used as a tool for the objective assessment of staff training.

They can be used to assess:

- compliance with technical regulations;
- reaction speed to signals and restrictions;
- stress resilience;
- the quality of decision-making under time pressure.

In this way, simulators become part of the Safety Management System.

Emergency Preparedness

One of the most important areas of application for simulator technology is the simulation of abnormal and emergency situations.

Simulators allow the reproduction of:

- equipment failure;
- adverse weather conditions;
- complex track conditions;
- emergency scenarios.

The use of scenario-based simulation enables the rehearsal of staff actions under conditions which, if replicated in real-world operations, would pose a risk to staff lives, threaten

damage to infrastructure and rolling stock, and in some cases would be technically impossible. This primarily concerns complex and rare combinations of factors, including simultaneous equipment failures, adverse weather conditions, and malfunctions in safety systems and the development of emergency situations.

Under real-world operating conditions, conducting such training exercises is either unacceptable for safety reasons or requires significant resources and is constrained by organisational limitations. In this context, simulation systems become the only tool capable of systematically modelling such scenarios, providing a controlled environment for analysing personnel actions and developing robust professional skills.

Thus, the development of scenario-based simulation marks the transition from practising individual operations to comprehensive training in conditions that are as close as possible to real-world operations.

4. Types of simulation technologies

The development of simulation technologies in the railway industry has led to the emergence of a wide range of solutions, varying in terms of realism, functional purpose and the degree of integration with actual operational processes. Modern simulation systems cover both basic training and the practice of individual operations, as well as the simulation of complex scenarios involving the interaction of various systems and factors.

The choice of simulator system is determined by the training objectives, the level of staff training and the required depth of simulation. Key parameters include the level of detail in the simulated processes, the ability to manage scenarios and the degree of realism in replicating actual operational conditions.

In this regard, the modern railway simulator industry distinguishes several main types of systems.

Full-Scale Simulators

This type of simulator consists of a full-scale model of the driver's cab, constructed using real control panels and equipment corresponding to a specific series of rolling stock.

The simulation environment includes mathematical models of the traction, braking, safety and train dynamics systems, as well as visualisation of the track layout, ensuring a high degree of realism in operating conditions.

Full-scale simulators are used to develop and practise rolling stock control skills, including actions in normal and abnormal situations, with the ability to analyse results and identify errors made.

They allow for the most accurate reproduction of real-world rolling stock operating conditions and are primarily used for:

- basic driver training;
- simulating complex emergency situations.

Procedural Simulators

This type of simulator is designed to practise specific procedures and action algorithms, developing basic professional skills until they become second nature.

As a rule, they are implemented as software models of control systems using touchscreen interfaces that replicate the locomotive's instruments and controls. At the same time, individual elements that critically affect traffic safety may be implemented in full-scale form.

Procedural simulators enable the modelling of various rolling stock series within a single complex and are used for:

- studying the operating principles of systems and equipment;
- rehearsing prescribed actions;
- refresher and maintenance training for personnel;
- assessing the level of knowledge and skills.

Scenario-Based Simulation

Scenario-based simulation is a methodological approach to training in which the training process is built on the basis of predefined and dynamically changing scenarios that adapt depending on the trainee's actions.

Within this approach, the training system creates a controlled environment that allows for the reproduction of various operational situations, including abnormal and emergency conditions, with the possibility of their variable development. The instructor can modify the scenario parameters during the training process, setting movement conditions, equipment failures, weather factors and other external influences.

A key feature is the integration of scenario-based simulation with analysis and assessment systems, which enables the recording of the trainee's actions, the identification of

errors, and the creation of personalised training pathways. The use of repeatable and controllable scenarios ensures that complex situations are practised repeatedly, leading to the development of consistent action sequences.

Thus, scenario-based modelling facilitates the development of decision-making skills under conditions of uncertainty, time constraints and changing circumstances, which corresponds to the real-world operating conditions of rail transport.

Digital Learning Environments

The current stage in the development of simulation technologies involves their integration into digital learning environments, which provide a comprehensive approach to staff training.

Such environments include distance learning modules, systems for collecting and analysing telemetry data, automated assessment tools, and integration with learning management systems (LMS).

Combining these components allows for the creation of a continuous training process, encompassing theoretical instruction, practical skills development, and subsequent analysis of the trainee's performance.

Thus, simulator training ceases to be an isolated element of training and becomes part of a unified digital ecosystem focused on competence management and improving safety levels.

5. International approaches to simulator-based training

In the developed railway systems of Europe and the USA, simulator technologies, in particular full-scale simulators, are an established element of locomotive crew training and are widely used at various stages of training. Their use covers both initial training and further training, as well as practising actions in emergency situations.

Full-scale simulators provide a high level of realism by replicating the driver's cab, the dynamics of train movement, and control and signalling systems, which allows practical skills to be developed in conditions as close as possible to real-world operations. At the same time, the practical application of simulators is primarily focused on addressing training objectives and enhancing safety culture, including the rehearsal of standard and emergency scenarios, as well as the development of decision-making skills in conditions of uncertainty.

Leading international developers of training systems, such as Transurb, CORYS, FAAC and SIM Factor, create high-tech solutions for train driver training, including full-scale simulators, procedural systems and digital platforms.

The modern training complexes developed by these companies enable the simulation of various types of rolling stock (passenger, freight, and metro), operational modes, and emergency scenarios. For example, Transurb's solutions cover the simulation of passenger and freight trains, metro systems and ERTMS systems, including real-world signalling systems and operating conditions.

CORYS develops simulators based on dynamic mathematical models and virtual environments, enabling the integration of training, certification and engineering analysis within a single platform. Moreover, modern solutions allow the modelling of entire railway networks within a single digital environment, encompassing different countries and signalling systems.

American developers, such as FAAC, emphasise a high degree of realism and the development of skills through immersive environments, whilst research shows that the use of simulators can ensure up to 90% retention of learning material.

From a regulatory perspective, the Federal Railroad Administration views simulator technology as a tool for improving the quality of training and reducing accident rates. FRA research confirms that simulators are used to analyse driver behaviour, transfer skills and assess training effectiveness; however, their implementation takes place at the level of individual companies and training programmes, without a single centralised system.

European studies also confirm the effectiveness of simulator-based training. In particular, as part of the roll-out of the ERTMS system, it has been established that the use of simulators enables train drivers to be trained safely in new technologies and reduces the number of errors during the transition to new traffic control standards.

Furthermore, in European practice, simulators are used not only for training, but also for designing and testing infrastructure solutions. For example, research centres (VTI, Sweden) use simulators to test signalling systems, analyse traffic profiles and evaluate control interfaces prior to their implementation in live operations.

Overall, the practice of using simulators demonstrates that simulation technologies fulfil several key functions:

- training and retraining of train drivers;

- rehearsing abnormal and emergency situations;
- staff certification;
- engineering testing and verification of solutions;
- research into the human factor.

However, despite the high level of technological development, simulation systems in most countries remain separate elements of training and research, rather than being integrated into a unified personnel training management system.

For example, the practice of using simulation technologies in the Russian Federation demonstrates their transition from a supplementary training tool to a comprehensive element of the training and safety management system.

One of the key advantages is the personalisation of training based on real operational data. As part of integration with the Comprehensive Personnel Assessment System, information on violations identified during train operation analysis is automatically used to generate personalised tasks. This makes it possible to organise targeted training focused on addressing specific skill gaps identified during actual operations.

An important area of development is the expansion of simulator functionality through the modelling of operational procedures. Unlike traditional solutions focused on traffic control, simulators for specialised self-propelled rolling stock enable the practice of operational tasks, including loading and unloading operations, crane control and infrastructure maintenance work. This develops comprehensive skills relevant to real-world working conditions.

An additional advantage is the opportunity for in-depth study of technical systems. The use of procedural simulators in educational institutions allows the operation of electrical, pneumatic and other rolling stock systems to be modelled, enabling the performance of calculation tasks and the analysis of equipment behaviour in various modes. The use of step-by-step analysis and ‘time-stop’ modes enables a detailed analysis of the trainee’s actions and the processes occurring within the system.

Specialised training on critical components, such as braking equipment, is of particular importance. Simulator complexes allow for the analysis of a train’s longitudinal dynamics, force distribution and the behaviour of the train in various modes, as well as the rehearsal of a wide range of abnormal situations, which directly impacts traffic safety.

Comparative analysis of international practices

A comparative analysis shows that international practices for train driver training largely coincide in their objectives.

The main objectives of simulator training are:

- reducing the risk of accidents;
- improving the consistency of professional skills;
- preparing staff for rare and complex situations.

Differences between national systems are evident in the degree to which simulator training is integrated with other elements of the safety management system.

The contribution of simulation technologies to safety

Simulation technologies enable research and training experiments that would be limited or impossible to carry out under real-world operating conditions. This is due to safety requirements, as well as technical and organisational constraints.

Such research includes:

Incident analysis

Furthermore, simulator systems are used as an engineering analysis tool in incident investigations. Modelling the parameters of emergency situations allows the conditions of incidents to be reproduced and the impact of personnel actions and technical factors to be assessed, which helps to improve the quality of investigations and prevent recurrence. Thus, in Russian practice, a simulator is not an isolated training tool, but a comprehensive system combining the functions of training, analysis, assessment and safety improvement, integrated into the professional cycle of a railway worker.

Psychophysiological studies

Simulator complexes allow for a detailed analysis of the human factor’s influence on a driver’s performance, including the effects of fatigue, stress, cab ergonomics and working conditions. In a controlled environment, it becomes possible to simulate various operating modes and external influences, including long journeys, temperature fluctuations and increased cognitive load, which allows for the assessment of sustained attention, reaction speed and the quality of decisions made.

The use of simulators for psychophysiological research significantly expands their functionality, taking them beyond the scope of a purely educational tool. The data

obtained can be used to optimise rolling stock design, improve control interfaces, and develop more effective staff training programmes that take into account the individual characteristics of trainees. Thus, simulator technologies become a tool for the comprehensive study of human behaviour within the 'driver–machine–environment' system, providing a deeper understanding of the human factor's influence on traffic safety and allowing it to be taken into account at both the design and operational stages.

Scientific research

An additional area of application for simulator technologies is the use of systems as tools for engineering and scientific research. The ability to integrate simulators with external systems and devices allows their functionality to be expanded and enables them to be used to analyse the interaction of various elements of the 'rolling stock – infrastructure – control systems' system. From a safety perspective, this opens up opportunities for modelling and evaluating the performance of new technical solutions, control algorithms and safety systems before their implementation in actual operation. Conducting such research in a simulator environment allows potential risks to be identified, the correct functioning of equipment to be verified, and the impact of changes on system behaviour to be assessed without posing a threat to train movements.

Furthermore, integration with external data sources and monitoring systems enables the reproduction of real-world operational conditions and the analysis of scenarios involving equipment failures, process disruptions and non-standard situations. This allows simulation systems to be used as a tool for the preliminary verification of solutions and for enhancing the reliability of the railway system's operation.

Thus, the use of simulators expands their role in ensuring safety, enabling a shift from training to predicting, analysing and preventing potential incidents at the design and implementation stages of technical solutions.

Discussion of results

The results obtained show that simulator technologies in all the countries under consideration are an important element of staff training; however, the extent to which they are integrated into the safety management system varies significantly.

In decentralised models (the US, EU countries), simulators are predominantly used as a tool for training and professional development, and their implementation depends on the policies of individual operators. This provides flexibility but leads to inconsistent approaches and differences in training standards.

In the centralised model, there is a higher level of systemic integration of simulator technologies, including the use of real-world operational data, standardisation of requirements, and the incorporation of simulators into a unified cycle of staff training and assessment.

Of particular interest is the expansion of simulator functionality beyond training – into the areas of analysis, research and verification of technical solutions. This allows simulator complexes to be viewed as a tool for predicting and preventing incidents. At the same time, the results obtained should be interpreted with due regard to the limitations associated with the availability of comparable quantitative data across different countries and companies.

A promising area for further research is the development of standardised approaches to assessing the effectiveness of simulator training and its impact on the safety of rail transport.

Conclusion

The analysis conducted shows that simulator technologies are becoming an important element of the railway transport safety system. International practice demonstrates the widespread use of simulators; however, their integration into staff training systems varies.

Centralised models exhibit a higher level of system integration, including the use of operational data and the standardisation of training processes. The development of scenario-based simulation and digital learning environments contributes to the development of sustainable professional skills and reduces the impact of human error.

The further development of simulation technologies is linked to the expansion of their analytical functions and their integration into safety management systems.

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