Science, Technology and Innovation
ISSN 2544-9125 ▪ 2025; 22 (3): 24-30
doi: 10.55225/sti.647

STI • 2025; 22 (3): 24-30

Safety management of transport systems

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Original article

Abstract

The importance of scientific research on the functioning and safety of transport systems cannot be overstated. Addressing scientific challenges in this field is essential for advancing a country's economic, technical, and technological development. Evolving operational conditions in transport systems present new and complex challenges for research, particularly as the transport sector increasingly contributes to critical state functions such as humanitarian support, defence, and social services. This study presents a methodology for managing transport system safety, with a particular focus on wartime conditions, where risk levels are significantly higher. The proposed methodology includes an assessment of the current state of transport system safety, risk forecasting, and the definition of a comprehensive risk indicator. This work contributes to the existing literature by expanding research on the management of transport system safety under high-risk conditions, characterized by a high probability of external interference and the presence of atypical operating environments.

Keywords

- safety management
- transport system
- rail transport
- transport accident risk
- risk analysis
- safety

Authors contributions

A – Preparation of the research project
B – Assembly of data for the research undertaken
C – Conducting of statistical analysis
D – Interpretation of results
E – Manuscript preparation
F – Literature review
G – Revising the manuscript

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Article info

Article history

- Received: 2025-07-11
- Accepted: 2025-09-19
- Published: 2026-02-06

Publisher

University of Applied Sciences in Tarnow
ul. Mickiewicza 8, 33-100 Tarnow, Poland

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Financing

This research did not receive any grants from public, commercial or non-profit organizations.

Conflict of interest

None declared.

Introduction

For any country, the construction, proper functioning, and continuous improvement of transport systems are among the priority tasks and form the foundation for successful economic, technical, and technological development. Well-developed transport systems are especially important during the introduction of martial law [1], as their role extends beyond economic functions to include population evacuation, military logistics, and the transportation of humanitarian aid. At the same time, with the transition of national infrastructure to special operating conditions, the issue of ensuring and managing transport system safety can be viewed from two perspectives [2]: internal and external. From the internal perspective, risks associated with alarms and failures in operation increase significantly due to human errors and technical reasons [3, 4]. As a result, the risk of traffic accidents may exceed acceptable levels and requires urgent implementation of safety management tools [5, 6]. From the external perspective, increased risks of interference in the functioning of transport systems—such as cyber-attacks or infrastructure damage caused by military operations—may make it impossible to implement timely actions to reduce accident risks.

Modern research in this field generally falls into two categories: the use of ergonomics methods for managing human-related safety factors [7–9], and the application of artificial intelligence tools for safety management [10, 11]. Considering current research trends focused on predictive approaches to safety management, as well as the limitations associated with artificial intelligence and the difficulties in adapting country-specific methods to other transport systems, the aim of this article is to develop a method for managing transport system safety. The proposed approach includes assessing the current safety status, predicting its future state, and ensuring adaptability to various elements of the transport system.

This paper presents the theoretical foundations for calculating and predicting the risks characteristic of rail transport in Ukraine, which makes it possible to forecast future trends for each type of transport event based on data on the actual state of transport safety.

Materials and methods

The study of possibilities for managing the safety of transport systems indicates the use of three generally accepted safety management methodologies: reactive, proactive, and predictive [12]. Taking into account the characteristics of safety management systems within each of these three methodologies, this work focuses primarily on the predictive approach, its advantages, and its potential applications [13].

Theoretical foundations for calculating the risk value

Taking into account the advantages of rail transport in passenger and freight transportation, the purpose of further research is to develop a methodology for managing transport system safety using the example of rail transport in Ukraine. Let us denote the set of transport system objects as $A = (A_1, A_2, ..., A_N)$ and the set of subsystems as $B = (B_1, B_2, ..., B_M)$, where N is the number of objects under consideration and M is the number of subsystems .

We introduce the a priori and a posteriori risk values for a particular object of the transport system of the studied railway A_i, denoted as $R(A_i)$ and $\hat{R}(A_i)$.

Similarly, for vehicles in the studied railway section B_i, we denote the a priori and a posteriori risks as $R(B_i)$ and $\hat{R}(B_i)$.

Past periods are characterized by the a posteriori risk values $\hat{R}(A_i)$ and $\hat{R}(B_i)$, while future periods are characterized by the a priori risk values $R(A_i)$ and $R(B_i)$.

$$R(X) = \hat{R}(X) \tag{1}$$

where X is the relevant transport process.

If the transport process on the railway changes linearly, then the following relationship applies:

$$R(X) = \gamma\hat{R}(X) \tag{2}$$

where γ is the linear coefficient describing changes in the corresponding transport process of the entire railway.

The total a priori and a posteriori risk values for a single object of the transport system of the studied railway A_i are determined by the following expressions:

$$R(A) = \sum_{i=1}^{N} R(A_i), \tag{3}$$

$$\hat{R}(A) = \sum_{i=1}^{N} \hat{R}(A_i), \tag{4}$$

and for vehicles of the respective investigated railway B_i:

$$R(B) = F_1[R(B_1), R(B_2), ..., R(B_M)] \tag{5}$$

$$\hat{R}(B) = F_2[\hat{R}(B_1), \hat{R}(B_2), ..., \hat{R}(B_M)] \tag{6}$$

where F_1, F_2 are functions determined by the design of vehicles.

For a specific case of a posteriori risk, if the probability value P_j is known, it can be written that:

$$\hat{R}(B) = \sum_{j=1}^{M} P_j \cdot \hat{R}(B_j). \tag{7}$$

Additionally, the a posteriori risk value for a train moving along a railway section bounded by specific points can be written as:

$$\hat{R}(X) = \sum_{i=1}^{N}\sum_{j=1}^{M} F\left(\hat{R}(A_i), \hat{R}(B_j)\right), \tag{8}$$

where F is a function that characterizes interaction dynamics between the track and rolling stock in the transport process.

To compare risk values, it is necessary to use appropriate indicators, which can be represented by the following vector:

$$R = [R{\downarrow}(X), R_0(X), R{\uparrow}(X)], \tag{9}$$

where $R{\downarrow}(X)$, $R_0(X)$, and $R{\uparrow}(X)$ are the values of a posteriori, current and a priori risks, respectively.

To determine the state of traffic safety when using the specified vector, the current state and the possible forecast of the traffic safety level are assessed in comparison with the previous or standard value.

For a factor indicator of traffic safety, a separate description with the following set of values can be provided:

$$R = (N_{min}, N, \bar{N}, \alpha), \tag{10}$$

where N_{min} is the minimum number of relevant transport events during the investigated time period; N is number of relevant transport events during the investigated time; $\bar{N}$ is the average number of transport events over the entire investigated period; α is indicator of changes in relevant transport events that characterizes a particular state of traffic safety.

Scalar traffic safety indicators can be constructed from this set of vector quantity parameters. The sequence for synthesizing these indicators is as follows. Let the number of transport events in the transport process over a time period (t, τ) for a specific cause i (failure, human factor, etc.) related to a particular railway service n be equal to:

$$K_{n_i}(t, \tau)$$

Then the total number of transport events in the transport process of a certain service n of the railway will be:

$$K_n(t,\tau) = \sum_i K_{n_i}(t,\tau), \tag{11}$$

and the value of the total number of transport events for all railway services will be determined as follows:

$$K(t,\tau) = \sum_n K_n(t,\tau) = \sum_n\sum_i K_{n_i}(t,\tau). \tag{12}$$

The following relative parameter is introduced:

$$R_{\,min} = \begin{cases} \dfrac{K_n(t,\tau)}{\max\limits_{\Theta} K_n(t,\tau)}, & \text{if } K_n(t,\tau) > 0 \\ \dfrac{1/K_n(t,\tau)}{\max\limits_{\Theta} K_n(t,\tau)}, & \text{if } K_n(t,\tau) < 0 \end{cases} \tag{13}$$

$$R_{\,max} = \begin{cases} \dfrac{K_n(t,\tau)}{\min\limits_{\Theta} K_n(t,\tau)}, & \text{if } K_n(t,\tau) > 0 \\ \dfrac{1/K_n(t,\tau)}{\min\limits_{\Theta} K_n(t,\tau)}, & \text{if } K_n(t,\tau) < 0 \end{cases} \tag{14}$$

where $\Theta \in (t, \tau)$

In expressions (13, 14), instead of using $\max\limits_{\Theta} K_n(t, \tau)$ the value $\min\limits_{\Theta} K_n(t, \tau)$ can also be applied, and certain normalized indicators of the traffic safety level can be expressed in terms of the acceptable number of traffic events that determine the overall traffic safety level.

The number of traffic events for a specific cause i (failure, human factor, etc.), related to a specific railway service n for the year (τ) is determined by the previous formulas, taking $t = \tau - 1$.

The following value can be used to indicate the change in the number of transport events:

$$\Delta K_{n_i}(\tau) = K_{n_i}(\tau - 1, \tau) - K_{n_i}(\tau - 1, \tau - 1), \tag{15}$$

$$\Delta K_n(\tau) = \sum_n \Delta K_{n_i}(t,\tau). \tag{16}$$

For an objective assessment of the traffic safety state, both its numerical evaluation for the past year and the trend of changes over recent years are important. This assessment of the traffic safety state for cause i (failures, human factors, etc.) over the years τ and $(\tau - k)$ can be expressed by:

$$V_{n_i}(\tau) = \sum_{j=\tau-k} \Delta K_n(j)\alpha_j, \tag{17}$$

where α_j is a coefficient that can be determined based on the exponential dependence of the species: $\alpha_j = e^{-k}$, where $k = 0, p, 2p, 3p, \ldots$, and p is anti-aliasing smoothing parameter.

The indicator of changes in the corresponding transport events that characterize traffic safety for certain services of a particular railway is expressed by:

$$\Delta R_{\,min}(t,\tau) = \frac{\Delta K_n(\tau)}{\max\limits_{\Theta} \Delta K_n(t,\tau)}; \tag{18}$$

$$\Delta R_{\,max}(t,\tau) = \frac{\Delta K_n(\tau)}{\min\limits_{\Theta} \Delta K_n(t,\tau)}. \tag{19}$$

Since the most severe consequence of a traffic accident is damage to human life and health, we determine the risk of serious consequences using the formula:

$$R = \frac{\sum N_{(F,\ I,\ D,\ A_{tc},\ A_{up})\ i}}{l \cdot \sum N_i}, \qquad (20)$$

where N_{Fi}, N_{Ii}, N_{Di}, N_{Atci}, N_{Aupi} are the numbers of fatalities, injuries, disasters, accidents due to technical causes, and accidents involving unauthorized persons during the investigated period; N_i is the total number of transport events during the investigated period; l is the duration of the period in hours.

The dynamics of indicators is analyzed using the value of the deviation characteristic of the final period (year) compared to the initial, i.e. annual growth R_i:

$$\Delta_{kp} = R_p - R_k \qquad (21)$$

The definition of a priori risks should involve the use of the weighted average risk increase. Therefore, the next step is to calculate these values using:

$$\bar{\Delta} = \frac{\sum_{i=1}^{n} \Delta_i}{n}, \qquad (22)$$

$$R\uparrow = \bar{R}\downarrow + \Delta \qquad (23)$$

To summarize the information obtained on the risks of a specific type of transport event and to enable analysis in two directions (from specific to general and from general to specific), it is appropriate to determine an integrated risk indicator.

The value of integrated risk

The integrated indicator is characterized by a linear combination of the corresponding established levels of traffic safety indicators, which can be written as follows:

$$I_p = \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n = \sum_{i=1}^{n} \beta_i x_i, \qquad (24)$$

where β_i is the weighting factors for the corresponding traffic safety indicator, and $\sum_{i=1}^{n} \beta_i = 1$; n is the number of investigated safety indicators.

Each indicator x_i characterized by an appropriate assessment of significance, which is determined by the descending ranking (for the accepted and considered indicators $x_1 > x_2 > x_3 > x_4 > x_5$), followed by the determination of the weighting factors β_i.

The weighting factors β_i can be determined using the Fishburne scale:

$$\beta_i = \frac{2(k - i + 1)}{k(k + 1)}. \qquad (25)$$

The use of expressions (24–25) makes it possible to determine the value of the integral risk of a transport accident with serious consequences and to build an appropriate forecast for the next period in order to take the necessary urgent measures to reduce the risk.

Results and discussion

To carry out an experimental verification of these provisions, we used data from the analysis of the state of traffic safety in Ukrainian rail transport, which are shown in Table 1.

Using expressions (15) and (16) makes it possible to determine the values of the relative parameters for each type of transport event. The calculation results for the total number of transport events are shown in Table 2.

Table 1. Data from the analysis of the state of traffic safety in Ukrainian rail transport 2017–2021

Type of transport event	Quantity transport events					Quantity fatality					Quantity injuries				
	2017	2018	2019	2020	2021	2017	2018	2019	2020	2021	2017	2018	2019	2020	2021
Diseasters (D)	2	2	0	0	1	0	0	0	0	0	18	0	0	0	0
Accidents (A)	203	684	705	479	716	104	293	354	212	266	61	245	232	140	191
Including accidents involving unauthorized persons (AIUP)	152	528	577	353	456	104	292	354	212	266	60	239	232	140	191
Including accidents due to technical causes (ADTC)	43	156	128	126	260	0	1	0	0	0	0	6	0	0	0
Incidents (I)	489	477	473	334	579	0	0	0	0	0	1	0	0	0	0
Total	**694**	**1163**	**1178**	**813**	**1296**	**104**	**293**	**354**	**212**	**266**	**80**	**245**	**232**	**140**	**191**

Table 2. Relative safety status parameters for the total number of transport events

Parameter	2017	2018	2019	2020	2021
R_{min}	0.54	0.90	0.91	0.63	1.00
R_{max}	1.00	1.68	1.70	1.17	1.87

The values indicating changes in the number of transport events are shown in Table 3.

The results of the calculation of the indicators of changes in the corresponding transport events that characterize traffic safety are presented in Table 4.

The calculation of the risk value specific to Ukrainian rail transport in 2017–2021 and the risk value forecasted using formula (23) for the next period are presented in the Table 5.

Table 3. Values that indicate changes in the number of transport events in Ukrainian rail transport in 2017–2021

Type of transport event	Quantity transport events					Quantity fatality					Quantity injuries				
	2017	2018	2019	2020	2021	2017	2018	2019	2020	2021	2017	2018	2019	2020	2021
Diseasters (D)	0	−2	0	1	0	0	0	0	−18	0	0	0	0	0	0
Accidents (A)	481	21	−226	237	189	61	−142	54	184	−13	−92	51	232	140	191
Including accidents involving unauthorized persons (AIUP)	376	49	−224	103	188	62	−142	54	179	−7	−92	51	232	140	191
Including accidents due to technical causes (ADTC)	113	−28	−2	134	1	−1	0	0	6	−6	0	0	0	0	0
Incidents (I)	−12	−4	−139	245	0	0	0	0	−1	0	0	0	0	0	0
Total	**469**	**15**	**−365**	**483**	**189**	**61**	**−142**	**54**	**165**	**−13**	**−92**	**51**	**232**	**140**	**191**

Table 4. Indicators of changes in relevant transport events that characterize traffic safety in Ukrainian rail transport in 2017–2021

Indicator name	2018	2019	2020	2021
$\Delta R_{max}(t, \tau)$	13.06	1.00	−9.51	9.33
$\Delta R_{min}(t, \tau)$	1.00	0.08	−0.73	0.71

Table 5. The calculation of the risk value specific to Ukrainian rail transport in 2017–2021 and the risk value forecasted for the next period, × 10⁻⁶

Risk	2017	2018	2019	2020	2021	2022
Fatality	1711	2876	3430	2977	2343	2825
Injuries	1316	2405	2248	1966	1682	2015
Disasters	33	20	0	0	9	6
ADTC	707	1531	1240	1769	2290	1903
AIUP	2500	5183	5591	4957	4017	4829

The weighting coefficients calculated using expression (25) are 0.33, 0.27, 0.20, 0.13, and 0.07.

To determine the ordinal number of each type of transport accident and assign the corresponding coefficient, the method of expert assessments with classification was applied. The values of integrated risk for Ukrainian rail transport in 2017–2022 are presented in Table 6.

Table 6. The value of integrated risk specific to Ukrainian rail transport in the period 2017–2022, × 10^{-6}

Indicator	2017	2018	2019	2020	2021	2022
$\beta_1 x_1$	564.5	949.1	1132.1	982.3	773.2	932.4
$\beta_2 x_2$	263.2	481.0	449.6	393.2	336.5	403.0
$\beta_3 x_3$	8.9	5.3	0.0	0.0	2.4	1.7
$\beta_4 x_4$	91.9	199.1	161.3	230.0	297.7	247.4
$\beta_5 x_5$	175.0	362.8	391.4	347.0	281.2	338.0
VIR*	1103.6	1997.2	2134.4	1952.4	1690.9	1922.5

*VIR – the value of integrated risk.

Taking into account the above provisions on calculating risk values, predicting, and generalizing them, the safety management methodology can be presented in the form of a flow chart (Figure 1).

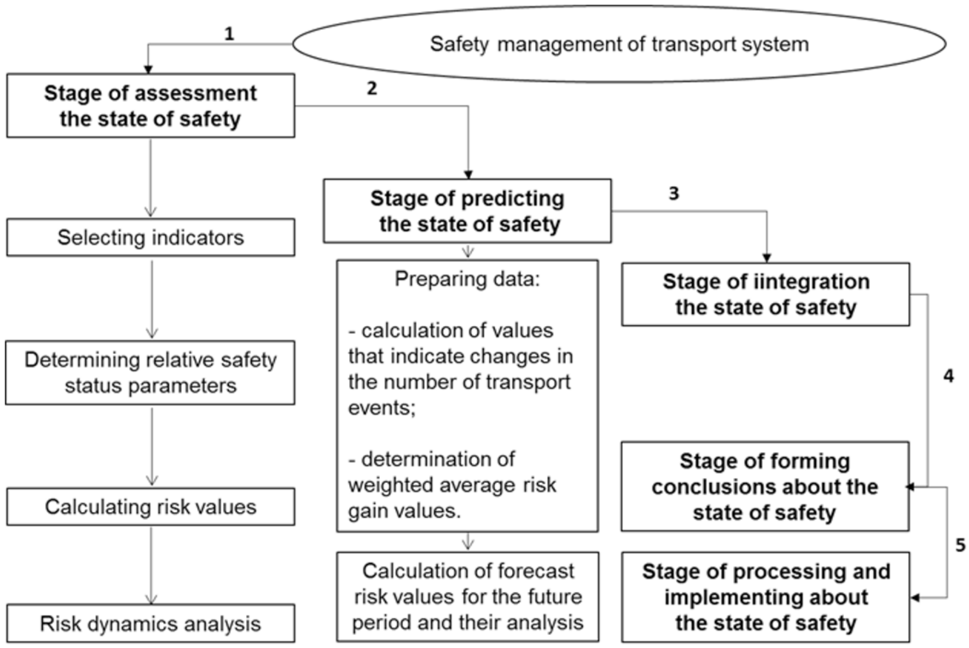

Figure 1. Methods of transport system safety management

Conclusion

Most methods for managing the safety of transport systems developed and implemented in peacetime are difficult to adapt during periods of martial law and combat operations.

This paper proposes a methodology for managing the safety of transport systems that consists of the step-by-step implementation of five stages, each supported by its own theoretical foundations. The first stage involves assessing the actual state of the transport system's safety by determining the values of safety-related indicators for past and current periods. In the second stage, risks for future periods are predicted and analyzed. To consolidate the information obtained on the risks associated with each type of transport event and to enable bidirectional analysis, the third stage introduces an integrated risk indicator and provides the corresponding calculation algorithm. The final two stages are interdependent and focus on formulating conclusions based on the processed results, developing measures to reduce risk levels, and implementing these measures.

Although the proposed safety management methodology has been implemented and experimentally verified in the context of Ukrainian rail transport, its structure is fundamentally universal. It is based on assessing a priori and a posteriori risk values by combining quantitative and qualitative indicators, which allows it to be adapted to the operational characteristics and safety requirements of different modes of transport. In the case of air transport—characterized by a high level of automation, complex technical infrastructure, and stringent safety standards—the methodology can be applied with appropriate modifications. Specific aviation-related risk factors such as human error, technical failures, meteorological influences, breaches of controlled airspace, and cyber threats can be incorporated into the model through adjustments to indicator functions and weighting coefficients.

The use of an integrated risk indicator, as outlined in the methodology, enables the synthesis of diverse safety-related parameters and supports the forecasting of safety levels within the air transport sector. This provides a scientifically grounded basis for preventive decision-making and for implementing targeted safety measures.

Consequently, the methodology constitutes a flexible and scalable tool that can support safety management not only in rail transport but also across other sectors, including aviation, road, maritime, and multimodal transport systems—particularly under conditions of heightened operational uncertainty and elevated external threats.

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