20. Tytiuk, V. Analytical determination of the electromechanical system starting process efficiency index with regard to the distributed nature of input products consumption [Text] / V. Tytiuk // Eastern-European Journal of Enterprise Technologies. – 2016. – Vol. 6, Issue 2 (84). – P. 51–59. doi: 10.15587/1729-4061.2016.83203
21. Lutsenko, I. Definition of efficiency indicator and study of its main function as an optimization criterion [Text] / I. Lutsenko // Eastern-European Journal of Enterprise Technologies. – 2016. – Vol. 6, Issue 2 (84). – P. 24–32. doi: 10.15587/1729-4061.2016.85453
22. Lutsenko, I. Development of a verification method of estimated indicators for their use as an optimization criterion [Text] / I. Lutsenko, E. Fomovskaya, I. Oksanych, S. Koval, O. Serdiuk // Eastern-European Journal of Enterprise Technologies. – 2017. – Vol. 2, Issue 4 (86). – P. 17–23. doi: 10.15587/1729-4061.2017.95914
23. Lutsenko, I. Development of a method for the accelerated two-stage search for an optimal control trajectory in periodical processes [Text] / I. Lutsenko, E. Fomovskaya, I. Konokh, I. Oksanych // Eastern-European Journal of Enterprise Technologies. – 2017. – Vol. 3, Issue 2 (87). – P. 47–55. doi: 10.15587/1729-4061.2017.103731

UDC 656.08 (477)
DOI: 10.15587/1729-4061.2017.119237

EVALUATION OF THE RAILWAY TRAFFIC SAFETY LEVEL USING THE ADDITIVE RESULTANT INDICATOR

Запропоновано комплексний підхід щодо визначення рівня безпеки руху поїздів на об'єктах залізничної інфраструктури. Підхід передбачає урахування різних факторів впливу: технічні засоби, робота з персоналом, технологія роботи, грошові витрати у безпеку руху. Кожний фактор характеризується показниками з різними розмірностями. Дану задачу запропоновано вирішувати з використанням адитивного результуючого показника. Запропонований у роботі метод забезпечить більш якісний аналіз ситуації. Існує можливість виявити небезпечні об'єкти, що впливають загалом на рівень безпеки залізниці

Ключові слова: безпека руху, метод оцінки рівня безпеки руху, комплексний показник

Предложен комплексный подход к определению уровня безопасности движения поездов на объектах железнодорожной инфраструктуры. Подход предполагает учет разных факторов воздействия: технические средства, работа с персоналом, технология работы, денежные затраты в безопасность движения. Каждый фактор характеризуется показателями с различными размерностями. Данную задачу предложено решать с использованием аддитивного результирующего показателя. Предложенный в работе метод обеспечит более качественный анализ ситуации. Существует возможность выявить опасные объекты, влияющие в целом на уровень безопасности железной дороги

Ключевые слова: уровень безопасности движения, комплексный показатель, метод оценки уровня безопасности движения

O. Ohar
Doctor of Technical Sciences, Professor,
Head of Department*
E-mail: ogar.07.12@gmail.com

O. Rozsokha
PhD, Associate Professor*
E-mail: alexroz2010@gmail.com

M. Kutsenko
PhD, Associate Professor*
E-mail: maksimus84@meta.ua

Yu. Smachilo
Postgraduate student*
E-mail: lups92@rambler.ru

*Department of Railway Station and Junctions
Ukraine State University of Railway Transport
Feierbakha sq., 7, Kharkiv, Ukraine, 61050

1. Introduction

Ensuring traffic safety of Ukrainian railway transport is an important factor of joining the European trade zone [1]. However, the level of safety on Ukrainian railways does not meet present-day requirements and the accident rate is much worse compared to EU countries. The number of transport events tends to decrease from year to year but the losses caused by them remain almost at the same level.

Repetition of transport events from year to year and preconditions to their occurrence is the evidence of inadequacy of the existing system of transportation safety management. It does not ensure the interest of employees in the qualitative performance of technological processes, does not reveal violations, or prevent their consequences.

The existing railway traffic safety system in Ukraine is not able to cover all necessary production and operation processes on which guarantee of safety depends.

Safety management requires new approaches implementation of which should introduce essential adjustments to the current system of transportation safety management.

The priority lines of development of Ukrainian railway transport include rise of the railway traffic safety level and harmonization with EU transport legislation.

Only statistics data of transport events are used as quantitative indicators characterizing the level of traffic safety on the railways of Ukraine [2]. These indicators are defined for the entire railway network and concern various services.

In addition, the following indicators are indicated in annual reports:

– the amount of material losses from traffic accidents;

– the number of officials brought to responsibility on the issue of traffic safety;

– the number of comments made during inspections.

The use of above indicators is only suitable for collection of certain information. Forecast with the use of numerical values is problematic. Because of lack of an integrated approach to analysis of these data, it is impossible to unambiguously assess the level of safety in the railway transport of Ukraine.

Development of a new method for assessing the level of the railway safety will make it possible to justly approach to determination of its level on individual infrastructure objects. This will improve quality of assessment of the safety situation and ensure optimal allocation of resources to maintain its level within acceptable limits.

2. Literature review and problem statement

The railway transport operation is always risky. To control safety of railway transportation, any risk requires a quantitative assessment. However, even with a quantitative estimate at hand, further operation with risks is impossible because of absence of principles of ensuring safety.

On the EU railways, the undermentioned principles of accepting permissible risks are used.

The most known of them is the ALARP (As Low As Reasonably Practicable) principle which is spread in the UK and currently used on the railway routes of Russian Federation. This principle divides the risk into three levels. The first level, below which the risk is insignificant, should be monitored only to maintain low risk. The second level is where the risk should be kept as low as possible. The third level is where negative risk above it is inadmissible and should not be accepted, except in extraordinary circumstances. A rigorous analysis of costs can be applied to the lowest level of risk. However, if the risk significance is close to zero, the ALARP principle implies the need for risk management provided that processing costs do not significantly outweigh benefits [3].

At German railways, the MEM (Minimum Endogenous Mortality) principle has found practical application. The risk after introduction of a new system should not exceed the minimum endogenous mortality rate for an individual. The probability of human death during interactions with the railway transport should not exceed the probability of death of a person (in the age of 5 to 15 years) by natural causes. In Germany, this value is now fixed at a level 10^{-5} [4].

The French GAMAB (Globalement Au Moins Aussi Bon) principle requires that new controlled transport systems had a level of risk no worse than the system it substitutes or another existing analogous system. However, this principle does not motivate the new system to improve [4].

If ALARP, MEM and GAMAB principles are followed, a set of the risk assessment methods will be individually selected and implemented for each dangerous situation on the railway. Each of the above-mentioned principles does not form a standard algorithm of action in the event of a dangerous situation on the railway transport. These principles are inextricably linked to the definition of risk. The risk is the combination of the probability of causing damage and severity of the consequences of this damage.

The International Electrotechnical Commission has developed standard ISO/IEC 31010:2009 Risk Management – Risk Assessment Methods [3]. The standard contains 31 risk assessment methods that are currently used in EU countries. The main criterion in choosing a method of risk assessment is the possibility of obtaining quantitative data at the output. From these positions, the entire list of the risk assessment methods that provide this opportunity can be reduced to 13 [5].

The European Commission and the European Railway Agency are conducting a program for harmonization of risk assessment processes among EU member states (EU Regulation 402/2013 on the General Method of Security for the Risk Detection and Assessment). Risk management in EU countries does not define approved methods to be used. The concept of Common Safety Methods (CSM RA) is used in the technical, organizational and operational changes of the railway system. If the changes that take place relate to safety issues, then the author of this proposal guided by the relevant criteria finds out whether these changes are significant or not. If these changes are significant, further action should involve the CSM RA risk management process.

The CSM RA risk management process includes hazard identification and analysis and assessment of risks. In doing so, codes of practice are always applied, comparison with similar systems is made and a quantitative risk assessment is performed.

Regardless of the method used, the main factor is the combination of experience and competence, objectivity and impartiality. Only correct identification of all hazards will make it possible to manage risks.

Harmonizing of the risk assessment processes among EU member states does not foresee creation of specific criteria for risk analysis.

A system for reasonable assessment of railway risks using fuzzy-reasoning approach is presented in [6]. The system provides a structured method of combining qualitative and quantitative information from all available sources to facilitate railway risk analysis. The system simulates ability of the human mind to effectively use methods of reasoning. However, its disadvantage is that the methods of reasoning are approximate rather than accurate.

The authors of paper [7] offer a new method of useful analysis: time analysis of the tree of faults. This method expands conventional analysis of the tree of faults with temporary events and fault characteristics. The method of time analysis of the tree of faults can ascertain the errors to be fixed urgently. It allows one to predict how much time left to eliminate the root fault to prevent accidents. However, the method does not solve the problem of eliminating the root cause of faults and is most convenient only at the hazard identification stage.

A quantitative risk assessment model based on accident scenarios is proposed in [8]. Accident scenarios were formed based on the collected accident reports and conducted workshops with railway safety experts. The developed model will provide a general model for assessing the level of risk on Slovak railways. It will identify the railroad areas that require additional control of the level of risks. The presented model needs improvement of the level of simulation of human factors and the use of more complex statistical analysis methods with ability of processing limited input data.

Work [9] studies the use of Bayes' nets for the railway sector to improve simulation and analysis of risks, safety and reliability of railways. The method emphasizes suitability of Bayesian nets for quantitative assessment of risks and decision-making support systems. The proposed method was developed for a specific study of the system of automatic sliding doors on one of Sao Paulo (Brazil) subway platforms. Before its use, the method should be adapted to the specific operating environment of similar objects of railways and therefore further study is required.

The author of [10] puts forward safety criteria and software development methodology for improving safety system on a critical railway section. The methodology presented by the author misses an important step in assessing the level of traffic safety, namely identification of dangerous factors.

The method proposed in [11] improves the previously registered system-theoretical method of risk analysis. But the new method is used in practice solely to assess safety level of high-speed trains.

A methodology for distribution of levels of safety integrity is presented in [12]. The safety integrity levels can be applied to any safety-related function, a system or subsystem and their components. The developed methodology includes just identification of dangerous factors without their further processing.

The presented methods of assessing the level of traffic safety do not fully characterize actual situation with transportation safety. This is reflected in absence of a universal method for assessing the level of safety of the transportation process at railway infrastructure objects. Most of the analyzed methods characterize just separate stages of assessing the level of traffic safety and do not give attention to the all-round nature of the factors affecting this level.

3. The aim and objectives of the study

This study objective was to develop a method for assessing safety level of train traffic at a railway infrastructure object.

In order to achieve this objective, the following tasks had to be solved:

– determine factors and indicators that provide an objective assessment of the state of ensuring safety of the transportation process at railway ranges of the transportation sector;

– substantiate selection of the mathematical apparatus to achieve the set objective;

– form a resultant additive indicator for assessing the traffic safety level at a railway object.

4. Factors and method of assessing the level of traffic safety

4. 1. Factors characterizing the level of traffic safety

Any railway range assessed for its traffic safety is a complex technical system in which such factors as technical means, staffing, operation technology and investments in the traffic safety are proposed for consideration.

The following indicators provide an objective estimate of the state of ensuring safety of the transportation process in the corresponding sectors of the railway ranges of Ukraine (Fig. 1):

1. Quality of technical means:

1. 1. The level of provision with necessary technical devices according to the scope of the works being performed, %.

1. 2. Coefficient of operational readiness of technical means.

1. 3. Duration of unplanned breaks in the work of technical means, h.

1. 4. The level of execution of the schedule of technical means repair, %.

2. Quality of the production practice:

2. 1. Risk of occurrence of a transport event, UAH.

2. 2. Level of execution of the train schedule, %.

2. 3. Duration of train delays at the incoming signals, h.

2. 4. The level of adherence to the rules of communication between the train making and shunting workers, %.

3. Quality of personnel work:

3. 1. The level of workers' knowledge of the normative documents directly related to the work performed by them, point.

3. 2. The number of violations in the personnel work revealed during inspections.

4. Quality of investments in the traffic safety:

4. 1. The level of compliance of planned investments in development and maintenance of traffic safety with the required amount, %.

4. 2. The level of fulfillment of the plan of investing in development and maintenance of the traffic safety, %.

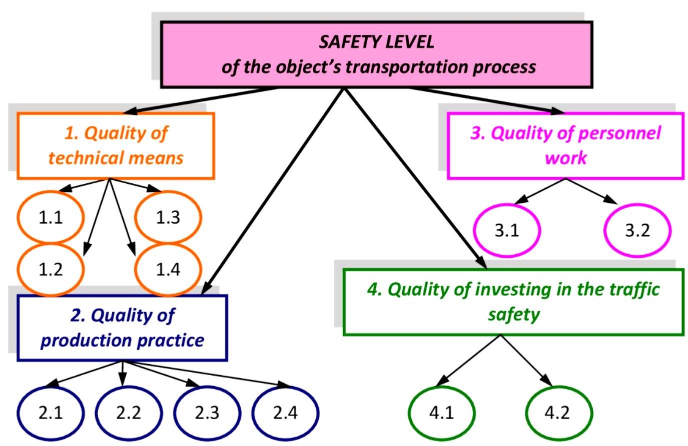

Fig. 1. Indicators determining the level of safety of the transportation process of the transport sector

In January 2016, the project of technical assistance of the European Union, Support for Implementation of the Association Agreement and the National Transport Strategy, was launched. The purpose of this project is to promote integration and modernization of the Ukrainian transport sector and some of its sub-sectors in accordance with the obligations under the Association Agreement between Ukraine and the EU as well as updating of the National Transport Strategy of Ukraine in accordance with EU legislation, standards and requirements and assistance in its further implementation. Promotion of harmonization of legislation in the field of transport in accordance with the priorities of the Association Agreement is one of the main components of the project.

Following the restructuring of Ukrzaliznytsya State Enterprise, the issues of standardization, certification, licensing and supervision of the railway transport were remained within the competence of the state. The issues of economic activity with observance of the established norms are within the competence of Ukrzaliznytsya PJSC. This procedure of interaction has not been worked out yet and requires solution of a number of technical and organizational problems. Therefore, there is an urgent necessity of creation of a corporate quality management system based on IS0-9000:2000 standards as well as a traffic safety management system.

"Quality management" is understood in the context of two systems: the Total Quality Management (TQM) and the ISO-9000 Quality System Standards administratively secured in a form of national standards in many countries. Observance of these standards should be the basis of the quality management system for railway transport.

Taking into account the aforementioned, in order to standardize the factors (criteria) of a comprehensive assessment of the level of traffic safety state, there is a need to develop a classifier of typical violations in the system of ensuring traffic safety in corresponding railway sectors. This classifier should be used for data input and further processing in an automated traffic safety management system.

4. 2. Formation of a scientific approach to assessing the level of traffic safety

The task is reduced to assessment of the state of safety of a particular transport infrastructure object. The results of this assessment can be used for further analysis and choice of a better option of this object development strategy. The essence of the task is to make a certain decision.

In most cases, human decision-making process consists of generating possible alternatives to decisions, evaluating and choosing the best alternative. To adopt the "right" decision means to choose such an alternative from the number of possible options which will maximally contribute to achievement of the goal [13–15].

The basic features of making a rational decision are:

– multicriteria problem of choice;

– quantitative and qualitative (fuzzy) description of indicators of the solution quality;

– expert information at a fuzzy statement of the task.

The general statement of the problem of multicriteria optimization has a certain form. Let $\overline{X}=|x_1,\ldots,x_i,\ldots,x_n|$ is the vector of optimized parameters of some system *S*. Some *j*-th feature of the system *S* is characterized by the magnitude of the *j*-th indicator $q_i(\overline{X})$; $j=\overline{1,m}$. Then the system as a whole is characterized by the vector of parameters $\overline{Q}=|q_1,\ldots,q_j,\ldots,q_m|$. The task of multicriteria optimization is reduced to the choice of such a variant from the set *Ms* of variants of the system *S* (system S_0) which has the most attractive value of vector $\overline{Q}$. It is assumed that the concept of the "best vector $\overline{Q}$" is preliminarily formulated mathematically, i. e. the appropriate criterion of advantage is chosen (substantiated).

After analyzing the sources, it can be noted that all methods for solving multicriteria problems can be reduced to three groups using:

– main indicator;

– resultant indicator;

– successive concessions.

The use of the main indicator is based on the transfer of all quality indicators, except any one (the main) into the category of limitations of an equality and inequality type.

Disadvantages are as follows:

– there are no reasons for considering one indicator as the main one and all others as minor;

– it is difficult to establish their permissible values for the quality indicators $q_2(S)$,..., $q_m(S)$ transferred into the category of restrictions.

The use of the resultant indicator is based on the influence of estimates of indicators q_1,..., q_m on the overall result.

Estimates of such influence are provided by a group of experts with an experience of development of similar systems. The additive, multiplicative and maximin resultant quality indicators have found the largest use [13].

When using successive concessions, a set of alternatives with the best estimate for the most important indicator is initially chosen. If this alternative is single, then it is considered the best. If there are several alternatives, then those that have a better estimate for other indicator are chosen from the subset and so on.

To expand the set of alternatives under consideration and improve quality of the solution based on a set of indicators, a concession can be assigned within which alternatives are considered equivalent.

The fundamental feature of the problem of solution choice is mainly the qualitative nature of the criteria. In this regard, the methods of multicriteria optimization under consideration should be formulated in a fuzzy statement. In this case, the quality criteria are the function of belonging to a given quality level.

In both classical and fuzzy statements, the choice of how to solve a multicriteria task is determined by the kind of expert information provided on the significance of indicators.

Taking into account that there is a possibility of involving experts for determining the weight factors of the target function, an additive resultant indicator can be applied to determine the level of safety.

4. 3. Formalization of the set task

It is proposed to introduce a term that determines quality of safe operation of the sector dealing with transportation of goods and passengers. The level of safety of the transportation process of the infrastructure object (RBO) is a set of certain properties of the object which determines its suitability for preservation of human and productive resources. These properties include quality of technical means, operation technique, personnel performance and funding the measures of traffic safety.

Thus, in this case, with regard to assessing the level of an object safety, there is a task of making decision with several criteria.

As it is stated in [16–18], the number of criteria should cover all features of the task. It is considered complete and sufficient when addition of a new criterion does not change the result of the decision and any rejection changes it. The criteria chosen for comparison should not have a high degree of mutual correlation.

To determine the degree of correlation between a pair of criteria (indicators), the correlation coefficient is used in [16–18].

There is no need to reject one of the criteria when choosing the best project decision if the value of correlation coefficients in pairs between the criteria significantly differs from 1(–1). The value of the indicators for determining correlation dependence is given in Table 1 where indicators are conventionally marked with numbers and values are indicated with no dimensionality specified. Decoding of these indicators is shown above. Stations were selected in one railway range. The statistics was determined in the mean values over a one-year period of observations with involvement of experts.

Table 1

Indicators for determining the correlation dependence

Indicator group	Indicator	Infrastructure object (railway station)									
		St. 1	St. 2	St. 3	St. 4	St. 5	St. 6	St. 7	St. 8	St. 9	St. 10
1	1.1	100	100	98.8	99.5	100	97.5	100	100	97	97.8
	1.2	0.85	0.99	0.98	0.97	0.95	0.94	0.98	0.99	0.94	0.96
	1.3	11	6	7	12	5	10	12	14	4	8
	1.4	99	98	100	97	99	100	94	92	96	100
2	2.1	3	5	9	12.5	14	8.6	11	11.2	15.2	9.8
	2.2	98.5	99.8	95.8	95.8	90.5	93.8	99.8	97.8	96.2	99.5
	2.3	1	0.8	0.9	0.8	0.8	1	1.4	0.9	0.7	1.1
	2.4	99.8	100	98.5	100	98.6	99.5	88	100	91.5	98.7
3	3.1	4.5	5	3	5	4.8	4.3	3.8	4.8	5	4.7
	3.2	5	2	4	10	6	4	8	2	2	11
4	4.1	100	99.5	100	98	100	99.5	98.5	100	100	100
	4.2	90	65	86	85	65	89	94	91	92	95

The correlation coefficient between all indicators at the corresponding results was determined and shown in Table 2.

Table 2 shows that there is no significant correlation between all pairs of indicators. Therefore, these indicators were accepted for further calculations.

It is proposed to consider an infrastructure object as a technical system. This system is characterized by a set of parameters. From among the sets of parameters, some of them were selected {P=Infrastructure Object}:

– quality of technical means, P_1;

– quality of production practice, P_2;

– quality of personnel work, P_3;

– quality of investments in the traffic safety, P_4.

Each of these parameters has relevant indicators that characterize it. Thus, for each parameter on each of the indicators, a positive additive function can be assigned.

On the set of quality parameters of technical means, P_1, the following values are proposed to be taken as such functions:

– N_{tm}: the level of provision with necessary technical means according to the volume of work performed, %;

– C_{or}: the coefficient of operational readiness of the technical means;

– D_{ub}: duration of unexpected breaks in operation of the technical means, h;

– T_{mr}: the level of execution of the technical means repair schedule, %.

On the set of parameters of the production practice quality, P_2, the following values are proposed to be taken as such functions:

– R_r: the risk of occurrence of transport events, UAH thousand.;

– T_{sc}: the level of execution of the train schedule, %;

– D_{td}: duration of train delays at the incoming signals, h;

– L_{ad}: the level of adherence to the rules of communication between the workers in train making and shunting yards, %.

On the set of the parameters of quality of personnel work, P_3, it is proposed to take the following values as such functions:

– L_{en}: the level of employees' knowledge of the normative documents directly related to the work performed by them;

– N_{pw}: the number of violations in the personnel work detected during inspections.

On the set of the parameters of investments in the traffic safety, P_4, the following values are offered to be chosen as such functions:

– L_{ci}: the level of compliance of the investments in development and maintenance of traffic safety with the required amount, %;

– L_{rp}: the level of realization of the plan of investments in development and maintenance of traffic safety, %.

Also, it is necessary to write: $N_{tm}=N_{tm}(P_1)$; $C_{or}=C_{or}(P_1)$; $D_{ub}=D_{ub}(P_1)$; $T_{mr}=T_{mr}(P_1)$; $R_r=R_r(P_2)$; $T_{sc}=T_{sc}(P_2)$; $D_{td}=D_{td}(P_2)$; $L_{ad}=L_{ad}(P_2)$; $L_{en}=L_{en}(P_3)$; $N_{pw}=N_{pw}(P_3)$; $L_{ci}=L_{ci}(P_4)$; $L_{rp}=L_{rp}(P_4)$.

A comprehensive safety indicator is proposed for estimating RBO which is an additive function for each of its arguments:

Table 2

Results of determination of the correlation dependence

Indicator No.	Coefficient of correlation between the indicators in pairs											
	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4	3.1	3.2	4.1	4.2
1.1	0	0.08	0.40	–0.33	–0.30	0.14	0.15	0.17	0.00	0.02	–0.25	–0.44
1.2	0	0	0.00	–0.36	0.40	0.09	0.00	–0.12	–0.10	0.00	–0.29	–0.19
1.3	0	0	0	–0.49	–0.21	0.33	0.50	0.10	–0.09	0.24	–0.45	0.49
1.4	0	0	0	0	–0.35	–0.31	–0.14	0.42	–0.20	0.22	0.26	–0.25
2.1	0	0	0	0	0	–0.48	–0.23	–0.42	0.18	0.15	–0.15	0.08
2.2	0	0	0	0	0	0	0.46	–0.22	–0.02	0.09	–0.14	0.39
2.3	0	0	0	0	0	0	0	–0.46	–0.48	0.46	–0.28	0.49
2.4	0	0	0	0	0	0	0	0	0.23	–0.06	0.25	–0.36
3.1	0	0	0	0	0	0	0	0	0	–0.01	–0.03	–0.27
3.2	0	0	0	0	0	0	0	0	0	0	–0.50	0.25
4.1	0	0	0	0	0	0	0	0	0	0	0	–0.06
4.2	0	0	0	0	0	0	0	0	0	0	0	0

$$RBO = f(N_{tm}, C_{or}, D_{ub}, T_{mr}, R_r, T_{sc}, D_{td}, L_{ad}, L_{en}, N_{pw}, L_{ci}, L_{rp}) = \\ = f(N_{tm}(P_1), C_{or}(P_1), D_{ub}(P_1), T_{mr}(P_1), R_r(P_2), T_{sc}(P_2), D_{td}(P_2), \\ L_{ad}(P_2), L_{en}(P_3), N_{pw}(P_3), L_{ci}(P_4), L_{rp}(P_4)) = f(P_1, P_2, P_3, P_4). \quad (1)$$

Thus, the RBO is a numeric function and one that is specified for the direct product of the sets of the corresponding parameters: $P_1 \times P_2 \times P_3 \times P_4$, positive and additive for each of the parameters.

Next, assign the following notations: G_1 for the value of the function $N_{tm}=N_{tm}(P_1)$, G_2 for the value of the function $C_{or}=C_{or}(P_1)$, G_3 for the value of the function $D_{ub}=D_{ub}(P_1)$, G_4 for the value of the function $T_{mr}=T_{mr}(P_1)$, G_5 for the value the function $R_r=R_r(P_2)$, G_6 for the value of the function $T_{sc}=T_{sc}(P_2)$, G_7 for the value of the function $D_{td}=D_{td}(P_2)$, G_8 for the value of the function $L_{ad}=L_{ad}(P_2)$, G_9 for the value of the function $L_{en}=L_{en}(P_3)$, G_{10} for the value of the function $N_{pw}=N_{pw}(P_3)$, G_{11} for the value of the function $L_{ci}=L_{ci}(P_4)$, G_{12} for the value of the function $L_{rp}=L_{rp}(P_4)$. For the convenience of working with the RBO function, each set of indicators was normalized. For each of the twelve indicators G_i (i=1, 12), the exact upper (supremum) and lower (infimum) boundaries of the indicators were determined. Further, G_i^* was taken as a notation for the exact upper boundary of the i-th index, so it should be written $G_i^* = \sup G_i$ and G_i^0 was taken as a notation for the exact lower boundary of the i-th indicator with the corresponding notation $G_i^0 = \inf G_i$ (i=1, 12). Next, a positive direction was determined for each of the indicators in order that the larger value of RBO corresponded to the better object. For indicators G_3, G_5, G_7, G_{10}, it will be from greater to smaller and for indicators G_1, G_2, G_4, G_6, G_8, G_9, G_{11}, G_{12} from smaller to larger.

Taking the above into account, the complex additive RBO function takes the form:

$$RBO = \sum_{i=1}^{12} a_i \cdot G_i^{/}, \quad (2)$$

where a_i is the weight factor taking into account significance (weight) of the relevant indicator in determining the RBO. Weight factors a_i>0 and their sum is 1; $G_i^{/}$ is a monotonically growing positive additive function that takes values from 0 to 1.

Depending on the chosen positive direction, for each of the G_i indicators, a monotonically growing function $G_i^{/}$ is formed:

$$G_1^{/} = \frac{N_{tm}}{\sup N_{tm} - \inf N_{tm}}; \; G_2^{/} = \frac{C_{or}}{\sup C_{or} - \inf C_{or}};$$

$$G_3^{/} = \frac{\sup D_{ub} - D_{ub}}{\sup D_{ub} - \inf D_{ub}}; \quad (3)$$

$$G_4^{/} = \frac{T_{mr}}{\sup T_{mr} - \inf T_{mr}}; \; G_5^{/} = \frac{\sup R_r - R_r}{\sup R_r - \inf R_r};$$

$$G_6^{/} = \frac{T_{sc}}{\sup T_{sc} - \inf T_{sc}};$$

$$G_7^{/} = \frac{\sup D_{td} - D_{td}}{\sup D_{td} - \inf D_{td}}; \; G_8^{/} = \frac{L_{ad}}{\sup L_{ad} - \inf L_{ad}};$$

$$G_9^{/} = \frac{L_{en}}{\sup L_{en} - \inf L_{en}};$$

$$G_{10}^{/} = \frac{\sup N_{pw} - N_{pw}}{\sup N_{pw} - \inf N_{pw}}; \; G_{11}^{/} = \frac{L_{ci}}{\sup L_{ci} - \inf L_{ci}};$$

$$G_{12}^{/} = \frac{L_{rp}}{\sup L_{rp} - \inf L_{rp}}.$$

Thus, the object safety level is an additive function for each of its parameters, P_i.

In determining the weight factors a_i, the expert judgement method [16, 17, 19] was used. This method takes into account experience of the relevant specialists in given issues. Before assessment, 20 highly qualified specialists on the subject under study were selected. They introduced a linear order for a set of parameters: each parameter was given an estimate of its significance from the most significant to the least significant by the 12-point scale, from 1 to 12.

The results of determining weight factors a_i are given in Table 3.

To determine the estimate consistency (W) between the experts, Kendall's concordance coefficient was used for the case when there are no related ranks (the same rank values in the estimates of one expert).

To check the Kendall's concordation coefficient (W=0.427) for its significance, Pearson's concordance criterion has been determined for a case where there are no related ranks.

With twelve parameters, twenty experts and the sum of squares of deviations of the sum of estimates S=24432.67, the above criterion was 93.97.

The calculated criterion was compared with the table value at the number of degrees of freedom K=n 1=11 and the set level of significance 0.01. Since the calculated value of the Pearson's concordance criterion is greater than the table value of 24.7, the calculated concordance coefficient is not random. Therefore, there is concordance between the experts' estimates in determining the weight factors.

Thus, the formula for determining the level of safety of the object acquires the following form:

$$RBO = 0.124 \cdot G_1^{/} + 0.115 \cdot G_2^{/} + 0.118 \cdot G_3^{/} + \\ +0.110 \cdot G_4^{/} + 0.053 \cdot G_5^{/} + 0.041 \cdot G_6^{/} + \\ +0.049 \cdot G_7^{/} + 0.050 \cdot G_8^{/} + 0.072 \cdot G_9^{/} + \\ +0.067 \cdot G_{10}^{/} + 0.099 \cdot G_{11}^{/} + 0.102 \cdot G_{12}^{/}. \quad (4)$$

Obtaining of numerical values of RBO gives only quantitative values taking into account the qualitative properties of the object. RBO is a dimensionless indicator. Its value will not exceed 1. The object which will have a greater value of RBO will be the best among others in terms of traffic safety. An object may be the best amongst others while not meeting the acceptable levels of safety. Defining of these levels is a separate task of this study. But in any case, without obtaining corresponding values from the experts possessing knowledge of the given issue, it is impossible to set one level or another. That is, we need to know gradation of safety levels. At present, there are no established levels of gradation of train traffic safety in the railway transport of Ukraine

Therefore, it is advisable to use relevant European standards when determining gradation of these levels. The standard [3] on the bases of which traffic safety levels were established (Fig. 2) was used in this work. There are four levels: 1) inadmissible (red); 2) undesirable (orange); 3) admissible (yellow); 4) high (green). The highest level of safety is 0.91 to 1, and the lowest is 0 to 0.6, respectively.

Table 3

The results of expert judgement on the weight factors of the object safety level

Expert	Parameter												Sum
	P_1				P_2				P_3		P_4		
	Indicator characterizing the parameter												
	1. 1	1. 2	1. 3	1. 4	2. 1	2. 2	2. 3	2. 4	3. 1	3. 2	4. 1	4. 2	
1	9	12	10	11	4	1	3	2	5	6	7	8	78
2	12	10	11	9	4	3	2	1	6	5	7	8	78
3	12	9	11	10	3	2	1	4	6	5	8	7	78
4	5	6	4	3	9	10	11	12	2	1	7	8	78
5	12	10	11	9	8	7	6	5	2	1	3	4	78
6	12	10	11	9	8	7	6	5	1	2	3	4	78
7	10	11	9	12	1	2	3	4	6	5	8	7	78
8	12	10	11	9	3	2	1	4	5	6	7	8	78
9	9	12	10	11	3	2	4	1	6	5	8	7	78
10	12	10	11	9	1	2	4	3	5	6	7	8	78
11	11	10	9	12	4	1	2	3	6	5	8	7	78
12	7	8	9	10	1	2	3	4	5	6	11	12	78
13	5	7	6	8	1	2	3	4	9	10	11	12	78
14	8	6	7	5	3	1	2	4	10	9	12	11	78
15	8	7	6	5	4	1	2	3	6	5	8	7	62
16	8	6	7	5	1	4	3	2	6	5	8	7	62
17	9	10	12	11	3	2	4	1	6	5	7	8	78
18	12	9	11	10	8	5	6	7	2	1	4	3	78
19	12	10	11	9	4	2	3	1	6	5	7	8	78
20	4	2	3	1	8	5	6	7	10	9	11	12	78
Sum of estimates	189	175	180	168	81	63	75	77	110	102	152	156	1528
Total rank	12	10	11	9	4	1	2	3	6	5	7	8	
Deviation from: – sum;	61.6	47.6	52.6	40.6	–46.3	–64.3	–52.3	–50.3	–17.3	–25.3	24,6	28,6	7,1×10^{-4}
– mean	3802.8	2272.1	2773.8	1654	2146.8	4139	2739	2533.4	300.4	641.8	608.4	821.78	24432.67
Weight factor a_i	0.124	0.115	0.118	0.11	0.053	0.041	0.049	0.05	0.072	0.067	0.099	0.102	1.000

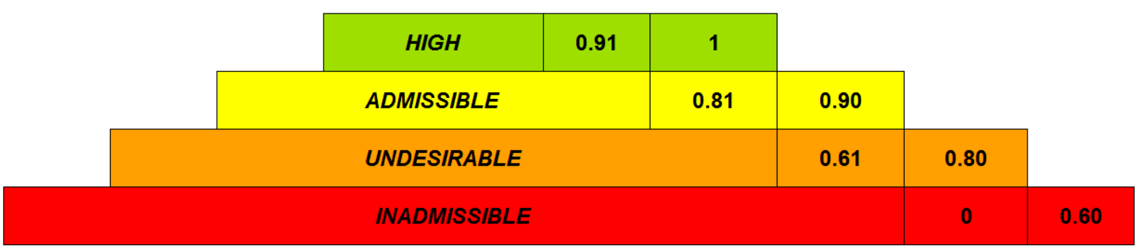

Fig. 2. Gradation of the object safety levels

Having the above gradation and numerical values of the RBC, one can analyze the actual state of traffic safety on the railway objects and work out appropriate measures.

5. Results of assessing the level of traffic safety in the railway infrastructure

The results of RBO assessment for the railway range infrastructure are shown in Table 4. When filling in this table, Tables 1–3 were used. Table 4 presents the numbers of indicator groups and indicators that are part of the additive resultant object safety indicator. The values of weight factors as the part of this indicator are obtained on the basis of Table 3 and formula (4). The basic information in Table 4 is the value of monotonically growing positive additive functions $G_i^{/}$ and RBO values. In determining these values, formulas (3), (4) were used. In the lower rows of the Table, exact upper ($G_i^{*} = \sup G_i$) and lower ($G_i^{0} = \inf G_i$) boundaries are given for each i-th indicator.

Table 4

Results of determining the level of safety of the railway range infrastructure

Infrastructure object (railway station)	Indicator group												Level of the object safety
	1				2				3		4		
	Monotonically growing positive additive function $G_i^/$ for indicator												
	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4	3.1	3.2	4.1	4.2	
	Weight factor												
	0.124	0.115	0.118	0.110	0.053	0.041	0.049	0.050	0.072	0.067	0.099	0.102	
St. 1	1.00	0.85	0.54	0.99	0.99	0.98	0.95	0.99	0.90	0.95	1.00	0.90	0.90 admissible
St. 2	1.00	0.99	0.75	0.98	0.99	0.99	0.96	1.00	1.00	0.98	0.99	0,65	0.93 high
St. 3	0.99	0.98	0.70	1.00	0.99	0.95	0.96	0.98	0.60	0.96	1.00	0.86	0,91 високий
St. 4	0.99	0.97	0.50	0.97	0.99	0.95	0.96	1.00	1.00	0.90	0.98	0.85	0.90 admissible
St. 5	1.00	0.95	0.79	0.99	0.99	0.90	0.96	0.98	0.96	0.94	1.00	0.65	0.92 high
St. 6	0.98	0.94	0.58	1.00	0.99	0.93	0.96	0.99	0.86	0.96	0.99	0.89	0.91 high
St. 7	1.00	0.98	0.50	0.94	0.99	0.99	0.95	0.88	0.76	0.92	0.98	0.94	0.89 admissible
St. 8	1.00	0.99	0.41	0.92	0.99	0.97	0.96	1.00	0.96	0.98	1.00	0.91	0.90 admissible
St. 9	0.97	0.94	0.83	0.96	0.99	0.96	0.97	0.91	1.00	0.98	1.00	0.92	0.95 high
St. 10	0.98	0.96	0.66	1.00	0.99	0.99	0.95	0.98	0.94	0.89	1.00	0.95	0.93 high
Sup_i	100	1	24	100	100000	100	24	100	5	100	100	100	
Inf_i	0	0	0	0	0	0	0	0	0	0	0	0	

Graphic interpretation of the results of assessment of safety level at the infrastructure objects (selective stations 1, 2 and 7) is given in Fig. 3–5.

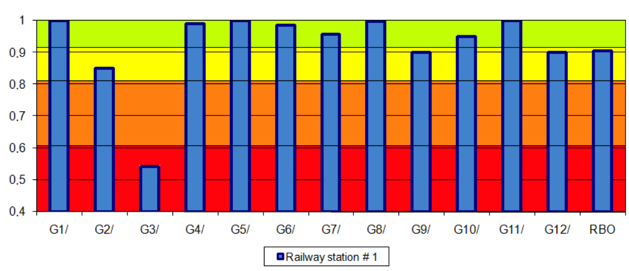

Fig. 3. Graphic interpretation of the results of assessing the level of traffic safety of the infrastructure object (railway station 1)

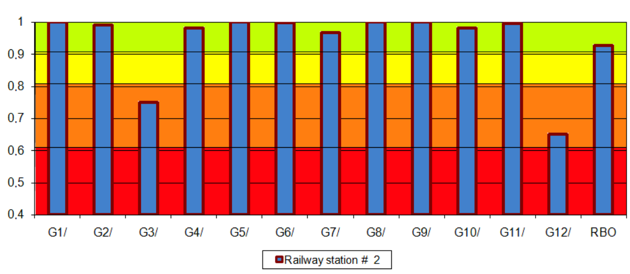

Fig. 4. Graphic interpretation of the results of assessing the level of traffic safety of the infrastructure object (railway station 2)

The use of the European standard of grading facility safety levels made it possible to demonstrate clearly which indicators of railway traffic safety are at inadmissible and undesired levels of safety. Accordingly, measures should be worked out to prevent occurrence of transport events and corrective measures for maintaining level of safety within the acceptable limits taken.

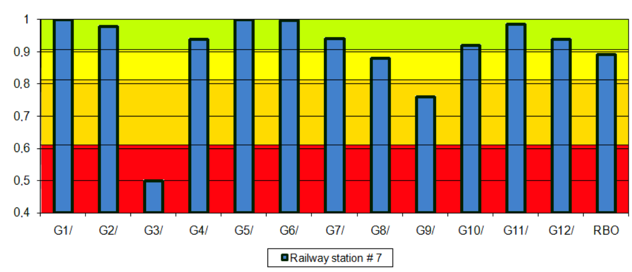

Fig. 5. Graphic interpretation of the results of assessing the level of traffic safety of the infrastructure object (railway station 7)

6. Discussion of the results of application of the developed method for assessing safety level of train traffic

According to the results of calculations, it should be noted that the RBO at some stations is in a zone of high admissible level. However, according to the components of the complex indicator, there are values that are in the inadmissible (red) and unwanted (orange) zones. For example, the value of RBO at station 1 is 0.90 (corresponds to the admissible level of safety) but the value of monotonically growing positive additive function by the parameter of duration of unexpected breaks in the work of technical means is 0.54. At station 2, the RBO value is 0.93 (corresponding to the high level of safety). The value of a monotonically growing positive additive function according to the parameter "duration of unexpected breaks in the work of technical means" is 0.75. By the parameter "the level of realization of the plan of investments in development and maintenance of traffic safety", the value of the monotonically growing positive additive function is, respectively, 0.65. Taking into account the above, it is necessary to implement safety measures on the indicated items more quickly for these stations. Instead, at station 9, the value of RBM is 0.95 (corresponding to a high level of safety) and the values of monotonically growing positive additive functions in all parameters are within acceptable limits. Therefore, for this station, at the time of conducting assessment, measures to improve traffic safety are not needed.

This is explained by the fact that the weigh factors and the monotonically growing positive additive functions of each indicator (formula (4)) influence the overall result. The values of these functions are influenced by the exact upper and lower boundaries of the indicators for which security level is evaluated (formula (3)). Therefore, experience of experts should be taken into account both in determining the coefficients and in establishing the above-mentioned boundaries.

The proposed method will provide a higher quality of analysis of the situation at the railway range. It is possible to identify more dangerous infrastructure objects that affect the overall level of safety of the railway net. Application of this method will optimize allocation of resources to ensure traffic safety while adhering to its permissible level. The method can be used in the design of infrastructure projects to determine their level of safety in the process of transportation of goods and passengers. In transition to new forms of management of Ukrainian railways, the method can be used by insurance companies for determining charges in the insurance rates for transportation.

The main advantage of the proposed method in comparison with the alternative ones analyzed above is its integrated approach. The infrastructure object is considered according to various factors characterized by certain indicators. Assessment can be performed in a concrete time period.

However, the proposed method has its own drawbacks. The level of expert experience and initial relevant information significantly affect the overall result in determining correlation between indicators when calculating weight factors and setting the limit values of indicators. It is necessary to constantly collect statistical data. To this effect, it is necessary to use appropriate software. When applying the additive indicator, there may be a mutual compensation of indicators. This means that reduction of one of the indicators, even to zero, can be compensated by an increase in another indicator. In order to alleviate this disadvantage, special limitations should be introduced on the minimum values of indicators and the value of the weight factors.

In the future, there is a possibility of working out studies and improvements in the issue of determining safety level of the railway traffic. In particular, a mathematical model of managing risks of transport events at the railway infrastructure objects should be developed. This will enable transition to development of a new system for managing safety of trains on the railways of Ukraine. In development of this system, there may be difficulties of objective and subjective nature. In particular, when collecting information about the status of the system elements at a concrete time period, there may be certain errors. Without relevant information, the forecast values for the system state will be doubtful. Therefore, in the future, attention should be paid to development of subsystems for collecting and recording primary information on the technical condition of the railway infrastructure.

7. Conclusions

1. It was established that in present-day conditions of functioning of the world railways, elucidation of the level of traffic safety is mainly performed with the help of a group of indicators that do not take into account the complex all-round nature. A comprehensive approach to determining the level of safety of train traffic at railway stations was offered. This approach involves determination of safety level taking into account a wide range of factors. These include factors such as technical means, staffing, production practice and investments in traffic safety. Each factor is characterized by its indicators. Quality of technical means is characterized by four indicators which show the level of provision with necessary technical devices and reliability of their operation. The quality of work technology is proposed to be described by four indicators which include the risk of traffic events, the level of execution of the train schedule and the rules of communication between employees in the process of work. It is offered to assess quality of the personnel work by the level of their knowledge of the normative documents and by the number of violations detected in inspection of their work (two indicators). Quality of provided investments will be characterized by two indicators for the level of investments in the improvement and maintenance of traffic safety.

2. It was proposed to evaluate the level of traffic safety in a complex of twelve indicators with diverse dimensionalities. In this case, the problem of complex evaluation relates to the tasks of multicriteria optimization. That is, in its idea, the problem is reduced to making a certain decision from among the set of possible ones. This problem is proposed to be solved using the resultant indicator. Its use is based on the impact of estimates for the indicators that characterize safety of the object on the overall result. These estimates are provided by a group of experts having corresponding experience and knowledge of such systems. Peculiarity of solution of this problem is the qualitative nature of the criteria. Consequently, the method of multicriteria optimization should be formulated in a fuzzy statement. In this case, the quality criterion is a function of belonging to the specified quality level. In this task, the choice of the method for solving the problem is determined by the type of expert information provided on significance of the indicators. In determining the weight factor of the target function, there is the possibility of involving experts, so it is advisable to use an additive resultant indicator to estimate the level of safety.

3. As a criterion for estimating traffic safety, a resultant additive indicator was formed. It determines the level of train traffic safety of the infrastructure object. This indicator represents sum of monotonically growing positive additive functions each of which has its weight (weight factor). The resultant indicator is dimensionless and does not exceed 1. In determining the weight factors, the method of expert estimates is used. To find consistency of estimates between experts, Kendall's concordance coefficient is used for the case when there are no associated ranks (the same rank values in the estimates of one expert). The value of the resultant indicator has only a numerical value. An object may be the best among others but will not be within the acceptable level

of security. In determining gradation of these levels, European standards were used.

The results of calculations indicate that the level of safety of the object at individual railway stations is in the zone of high and admissible level. At the same time, components of a complex indicator have values that are in inadmissible safety zones. This is because of the mutual compensation of indicators when using the additive function. That is, reduction of one of the indicators can be compensated by an increase in another indicator. In order to alleviate this disadvantage, special limitations should be introduced on the minimum values of indicators and the value of the weight factors. All these measures are difficult to implement without experienced experts. But despite this, the proposed method provides a more qualitative analysis of the situation at the railway range. In this case, there are dangerous infrastructure objects that affect the overall level of safety of the entire railway net.

References

1. Transportna stratehiya Ukrainy na period do 2020 roku [Text]. – Kabinet Ministriv Ukrainy, 2010. – No. 2174-r. – Available at: http://zakon3.rada.gov.ua/laws/show/2174-2010-p
2. Pro zatverdzhennia Polozhennia pro klasyfikatsiyu transportnykh podiy na zaliznytsiakh Ukrainy [Text]. – Ministerstvo Infrastruktury Ukrainy, 2017. – No. 235. – Available at: http://zakon3.rada.gov.ua/laws/show/z0904-17
3. ISO/IEC 31010:2009. Risk management – Risk assessment techniques (IDT) [Text]. – International Organization for Standardization, 2009. – 176 p. – Available at: https://www.iso.org/standard/51073.html
4. Schabe, H. Different principles used for determination of tolerable hazard rates [Text] / H. Schabe // Conference Proceeding. – 2001. – Vol. 1. – P. 435–442. – Available at: https://uic.org/cdrom/2001/wcrr2001/pdf/poster/3_5/041.pdf
5. Rozsokha, O. V. Analiz i osoblyvosti isnuiuchykh naukovykh pidkhodiv shchodo vyznachennia rivnia bezpeky rukhu [Text] / O. V. Rozsokha, Yu. V. Smachylo // Zbirnyk naukovykh prats DETUT. – 2016. – Issue 28. – P. 202–214.
6. An, M. An Intelligent Railway Safety Risk Assessment Support System for Railway Operation and Maintenance Analysis [Text] / M. An // The Open Transportation Journal. – 2013. – Vol. 7, Issue 1. – P. 27–42. doi: 10.2174/1874447801307010027
7. Peng, Z. Risk Assessment of Railway Transportation Systems using Timed Fault Trees [Text] / Z. Peng, Y. Lu, A. Miller, C. Johnson, T. Zhao // Quality and Reliability Engineering International. – 2014. – Vol. 32, Issue 1. – P. 181–194. doi: 10.1002/qre.1738
8. Leitner, B. A General Model for Railway Systems Risk Assessment with the Use of Railway Accident Scenarios Analysis [Text] / B. Leitner // Procedia Engineering. – 2017. – Vol. 187. – P. 150–159. doi: 10.1016/j.proeng.2017.04.361
9. Mahboob, Q. A Bayesian network methodology for railway risk, safety and decision support [Text] / Q. Mahboob // Dresden. – 2014. – 153 p. – Available at: https://pdfs.semanticscholar.org/2825/f8432dec94c4af485b4c4b98516a298fbc8f.pdf
10. Joung, E. Safety criteria and development methodology for the safety critical railway software [Text] / E. Joung, S. Oh, S. Park, G. Kim // INTELEC 2009 – 31st International Telecommunications Energy Conference. – 2009. doi: 10.1109/intlec.2009.5351957
11. Liu, J. T. An extended system-theoretic hazard analysis method for the safety of high-speed railway train control systems [Text] / J. T. Liu, T. Tang, J. B. Zhu, L. Zhao // Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit. – 2016. – Vol. 231, Issue 8. – P. 821–834. doi: 10.1177/0954409716664931
12. Wigger, P. Experience with Safety Integrity Level (SIL) allocation in railway applications [Text] / P. Wigger // WCRR. – 2007. – P. 25–29. – Available at: http://www.railway-research.org/IMG/pdf/043.pdf
13. Tarasov, V. A. Intellektual'nye sistemy podderzhki prinyatiya resheniy: Teoriya, sintez, effektivnost' [Text] / V. A. Tarasov, B. M. Gerasimov, I. A. Levin, V. A. Korneychuk. – Kyiv: MAKSN, 2007. – 336 p.
14. Gutkin, L. S. Optimizatsiya radioelektronnyh ustroystv po sovokupnosti pokazateley kachestva [Text] / L. S. Gutkin. – Moscow: Radio i svyaz', 1975. – 367 p.
15. Brahman, T. R. Mnogokriterial'nost' i vybor al'ternativy v tekhnike [Text] / T. R. Brahman. – Moscow: Radio i svyaz', 1984. – 287 p.
16. Hamhanova, D. N. Teoreticheskie osnovy obespecheniya edinstva ekspertnyh izmereniy [Text] / D. N. Hamhanova. – Ulan-Ude: VSGTU, 2006. – 170 p.
17. Popov, G. V. Vybor resheniy i bezopasnost' [Text] / G. V. Popov. – Ivanovo: IGEU, 2003. – 92 p.
18. Sistemniy analiz i prinyatie resheniy [Text]: slovar'-spravochnik / V. N. Volkova (Ed.). – Moscow: Vysshaya shkola, 2004. – 200 p.
19. Bol'shev, L. N. Tablitsy matematicheskoy statistiki [Text] / L. N. Bol'shev, N. V. Smirnov. – Moscow: Nauka, 1983. – 416 p.