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ЭЛЕКТР ЭНЕРГЕТИКАСЫ ЖӘНЕ КӨЛІКТІ АВТОМАТТАНДЫРУ

ЕСЕПТЕУ ТЕХНИКАСЫ ЖӘНЕ АҚПАРАТТЫҚ ЖҮЙЕЛЕР

СОДЕРЖАНИЕ

ЭЛЕКТРОЭНЕРГЕТИКА И АВТОМАТИЗАЦИЯ ТРАНСПОРТА

ВЫЧИСЛИТЕЛЬНАЯ ТЕХНИКА И ИНФОРМАЦИОННЫЕ СИСТЕМЫ

CONTENTS

ELECTRICAL POWER ENGINEERING AND TRANSPORT AUTOMATION

COMPUTER ENGINEERING AND INFORMATION SYSTEMS

Industrial Transport of Kazakhstan
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COMPUTER SUPPORT FOR RESPONDING TO RAILWAY EMERGENCIES

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Abstract. This study focuses on the automation of decision-making in analyzing emergency situations on railway transport involving the carriage of dangerous goods (DG). The relevance of the research is determined by the growing volume of DG transportation and the high likelihood of accidents, which can have serious consequences for the environment, economy, and public safety. The main objective of the study is to develop mathematical models that provide the basis for an intelligent decision support system (DSS) for the localization of accidents and minimizing their consequences. The tasks of the study include analyzing existing models and software for predicting pollutant dispersion, formalizing the DG transportation system as a directed graph of states, developing mathematical models for the probability of safe railway operation and estimating the duration of accident elimination, and studying the impact of organizational and technological measures on the efficiency of emergency response units. As a result, models were developed that allow forecasting the development of emergency situations, assessing the required resources for accident response, determining optimal deployment and concentration times for response units, and considering the influence of DG properties and external conditions on the incident dynamics. Statistical analysis of railway accidents involving DG in EU countries over the past decade revealed a dependency of accident numbers on cargo traffic. The mathematical models were implemented in a software prototype to evaluate the duration of liquidation operations and potential environmental and economic consequences. The study concludes that the application of the developed models and DSS increases the objectivity of decision-making, reduces delays in emergency response, and contributes to minimizing environmental damage. Future work includes expanding DSS functionality, integrating data from unmanned aerial vehicles and other sensors, and applying models for real-time planning of emergency operations.

Keywords: dangerous goods, railway transport, emergency situations, decision support system, environmental safety, mathematical modeling, accident mitigation.

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ТЕМІРЖОЛ КӨЛІГІНДЕГІ ТӨТЕНШЕ ЖАҒДАЙЛАРҒА ДЕН ҚОЮДЫ КОМПЬЮТЕРЛІК ҚОЛДАУ

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Аннотация. Бұл жұмыста қауіпті жүк тасымалы кезінде теміржол көлігінде туындайтын төтенше жағдайларды талдау кезінде шешім қабылдауды автоматтандыру мәселелері қарастырылады. Зерттеудің өзектілігі – қауіпті жүк тасымалы көлемінің артуы және апаттардың жоғары ықтималдығы, олардың қоршаған ортаға, экономикаға және халық қауіпсіздігіне елеулі әсер етуі мүмкіндігімен анықталады. Зерттеудің негізгі мақсаты – төтенше жағдайларды локализациялау және салдарын азайту үшін шешім қабылдауды қолдайтын интеллектуалды жүйені (ШҚҚЖ) құру негізін қамтамасыз ететін математикалық модельдерді әзірлеу. Зерттеу барысында қойылған міндеттер: ластануды болжауға арналған қолданыстағы модельдер мен бағдарламалық қамтамасыз етуді талдау; қауіпті жүк тасымалы жүйесін бағытталған граф түрінде формализациялау; теміржол инфрақұрылымының қауіпсіз жұмыс істеу ықтималдығын және апат салдарын жою ұзақтығын бағалауға арналған математикалық модельдер әзірлеу; ұйымдастырушылық және технологиялық шаралардың авариялық қызметтердің тиімділігіне әсерін зерттеу. Нәтижесінде төтенше жағдайлардың дамуын болжауға, апаттарды жоюға қажетті күш-құралдарды бағалауға, қызметтерді оңтайлы орналастыру және шоғырландыру уақытын анықтауға, сондай-ақ қауіпті жүктің қасиеттері мен сыртқы жағдайлардың оқиға дамуына әсерін ескеруге мүмкіндік беретін модельдер әзірленді. Соңғы онжылдықтағы ЕО елдеріндегі қауіпті жүк тасымалы кезінде болған теміржол апаттарының статистикалық талдауы апаттар санын жүк ағынымен байланыстыруға мүмкіндік берді. Математикалық модельдер апатты жою жұмыстарының ұзақтығын және экологиялық және экономикалық салдарын бағалау үшін бағдарламалық прототипке енгізілді. Зерттеу қорытындысы әзірленген модельдер мен ШҚҚЖ қолданылуы шешім қабылдаудың объективтілігін арттыратынын, апатты жоюдағы уақыт шығынын азайтатынын және қоршаған ортаға келетін зиянды азайтатынын көрсетеді. Болашақтағы жұмыстарға ШҚҚЖ функционалын кеңейту, ұшпайтын аппараттар мен басқа сенсорлық жүйелерден алынған деректерді біріктіру және модельдерді нақты уақыт режимінде авариялық іс-қимылды жоспарлауға қолдану кіреді.

Түйін сөздер: қауіпті жүк, теміржол көлігі, төтенше жағдайлар, шешім қабылдауды қолдау жүйесі, экологиялық қауіпсіздік, математикалық модельдеу, апат салдарын жою

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КОМПЬЮТЕРНАЯ ПОДДЕРЖКА РЕАГИРОВАНИЯ НА ЧРЕЗВЫЧАЙНЫЕ СИТУАЦИИ НА ЖЕЛЕЗНОДОРОЖНОМ ТРАНСПОРТЕ

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Аннотация. В данной работе рассматриваются вопросы автоматизации принятия решений при анализе чрезвычайных ситуаций на железнодорожном транспорте, сопровождающихся перевозкой опасных грузов (ОГ). Актуальность исследования обусловлена увеличением объёмов перевозки ОГ и высокой вероятностью аварий, которые могут иметь серьёзные последствия для окружающей среды, экономики и безопасности населения. Основная цель работы заключается в разработке математических моделей, обеспечивающих создание интеллектуальной системы поддержки принятия решений (СППР) для локализации аварий и минимизации их последствий. В рамках исследования поставлены следующие задачи: анализ существующих моделей и программного обеспечения для прогнозирования распространения загрязняющих веществ; формализация системы перевозки ОГ в виде ориентированного графа состояний; разработка математических моделей вероятности безопасного функционирования железнодорожной инфраструктуры и оценки времени ликвидации последствий аварий; исследование влияния организационных и технологических мер на эффективность действий аварийных служб. В результате работы разработаны модели, позволяющие прогнозировать развитие чрезвычайной ситуации, оценивать потребности в силах и средствах для ликвидации аварий, определять оптимальное время их концентрации и действия, а также учитывать влияние свойств опасных грузов и внешних условий на скорость развития инцидента. Проведён анализ статистики железнодорожных аварий с участием ОГ в странах ЕС за последние десять лет, что позволило определить зависимость числа аварий от грузопотока. Математические модели были внедрены в прототип программного обеспечения, позволяющего оценивать продолжительность ликвидационных работ и возможные экологические и экономические последствия. Заключение исследования подтверждает, что применение разработанных моделей и СППР повышает объективность принятия решений, снижает временные потери при ликвидации аварий и способствует минимизации ущерба окружающей среде. Перспективы дальнейшей работы включают расширение функционала СППР, интеграцию данных с беспилотных летательных аппаратов и других сенсорных систем, а также использование моделей для планирования аварийных действий в режиме реального времени.

Ключевые слова: опасные грузы, железнодорожный транспорт, чрезвычайные ситуации, система поддержки принятия решений, экологическая безопасность, математическое моделирование, ликвидация последствий.

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Introduction.

The study of railway emergencies (RWE) involving dangerous goods (DG) has become increasingly important due to the growing volume and complexity of freight transportation worldwide. Accidents during the transportation of DG can lead to catastrophic consequences, including loss of human life, environmental contamination, destruction of cargo and railway infrastructure, and significant economic losses (Batarlienė, 2014: 395–400). Despite previous research on railway safety and environmental protection (Abuova, 2019: 234–249; Hooghiemstra, 1999: 15–32), there remain unresolved challenges in providing timely, informed, and coordinated decision-making under conditions of incomplete or rapidly changing information. This gap highlights the need for advanced decision support systems (DSS) integrated with predictive mathematical models to enhance emergency response efficiency.

The rationale for this study is based on the increasing threat posed by RWE with DG and the complexity of managing their consequences. Traditional emergency management approaches often fail to account for the dynamic interplay between technological, organizational, and environmental factors. The relevance of this research is further emphasized by the absence of comprehensive methods that integrate real-time environmental data, predictive modeling, and operational planning for railway networks transporting DG (Katsman, 2015: 28–39; Kornaszewski, 2017: 282–292). The study addresses both theoretical and practical aspects of emergency management, aiming to improve the safety and reliability of railway transport systems while minimizing environmental risks.

The object of this research is the system of railway transportation of dangerous goods and its operational reliability during emergencies. The subject of the study is the process of managing railway emergencies involving DG, including the assessment, localization, and elimination of consequences, with a particular focus on environmental protection, cargo safety, and operational recovery.

The aim of this study is to develop mathematical models and decision support tools to enhance the efficiency of emergency response in railway transport systems during DG transportation. To achieve this aim, the following objectives are set:

- To formalize the DG railway transportation system as an oriented graph of safe functioning states (Shalabayeva, 2024: 1–2), incorporating emergency occurrence, assessment, localization, and elimination;
- To develop predictive models for the duration and scope of liquidation works necessary to mitigate RWE consequences;
- To integrate environmental, technological, and organizational factors into DSS to optimize the allocation of resources and improve operational efficiency;
- To provide a framework for practical implementation of software tools that support situational analysis, risk assessment, and informed decision-making at RWE sites.

This study employs a combination of mathematical modeling, simulation, and system analysis. Predictive models for RWE development and environmental impact are incorporated into the computational core of DSS. The research also uses statistical analysis of historical RWE data, GIS-based environmental monitoring, and scenario-based simulation to optimize decision-making processes.

The central hypothesis of this study is that the integration of predictive mathematical models into a DSS will significantly enhance the effectiveness of emergency response operations in railway transport systems transporting DG. Specifically, timely, informed decision-making supported by automated analysis of environmental and operational data can reduce the duration and severity of RWE consequences, minimize environmental damage, and improve system reliability.

The significance of this research lies in its potential to advance both theoretical knowledge and practical applications in the fields of railway safety, environmental protection, and emergency management. The proposed models and DSS framework provide a scientific basis for improving operational planning, resource allocation, and risk mitigation in railway networks transporting hazardous cargo. Ultimately, this research contributes to safer and more sustainable railway transport operations, supporting the broader goals of environmental safety and public health protection.

Materials and methods.

In works (Abuova, 2019: 234–249; Batarlienė, 2014: 395–400; Hooghiemstra, 1999: 15–32; Dindar, 2019: 203–216), it is shown that the use of intelligent decision support systems (DSS) will allow the head of the emergency operations center to carry out informational, technological, analytical, and organizational support of the iterative process of analyzing the situation that has developed on the site of RWE, preparing and evaluating decision options, and the choice of the final decision on the localization of the RWE and the elimination of their consequences, which is impossible without the appropriate mathematical models (Akhmetov, 2021: 80–90).

In works (Katsman, 2011: 86–93; Katsman, 2013: 72–85; Katsman, 2015: 28–39), it is shown that the reliability of railway transport (RWT) when transporting passengers and goods should be understood as its ability to ensure the timely and safe delivery of passengers and goods to their destination without deterioration of the health of passengers and the commercial quality of goods due to RWT (Akhmetov, 2021: 80–90).

An essential component of reliability is the safety of the railway transport system (RTS), which is focused on reducing the impact of hazardous factors of the RWE on human health, transport work, and Env. The solution to this problem is achieved through coordinated actions of liquidation units, designed to localize the RWE and eliminate their consequences (Akhmetov, 2021: 80–90; Katsman, 2015: 28–39; Abuova, 2019: 234–249; Kornaszewski, 2017: 282–292).

Particular attention should be paid to the transportation of DG, including those that pose a threat to the pollution of Env. This category includes cargoes with various physical, chemical, and fire-explosive properties. Emergencies with such cargoes are accompanied by the impact of hazardous factors harmful to people, Env., cargo and RWT facilities, and other ministries and departments of the country (Torretta, 2017: 1–9; Gheorghe, 2005: 247–272; Khanmohamadi, 2018: 230–241). Such situations include explosions, fires, scattering of solid cargo, spreading of liquid cargo, and emissions into the atmosphere of hazardous gaseous substances transported by RWT.

In other words, the reliability of RWT during the transportation of DG can be interpreted as its ability to restore its safe functioning during specific periods with a given probability after the RWE, accompanied by the action of hazardous factors harmful to people, Env., cargo and RWT (Nowacki, 2016: 21–29; Schröder, 2016: 322–334).

Many scientific works are devoted to studying the problems of safety and reliability of such transportation (Zelenko, 2019: 03011; Dvorak, 2020: 5494; Huang, 2020: 1–33).

However, many problematic issues related to computer support for decision-making on assessing the situation at the site of RWE and the development of control actions for eliminating the consequences of the accident have not been fully disclosed. It is this fact that determines the relevance of our study.

Practical software implementation of mathematical models in predicting environmental consequences is a complex technical problem that is designed for a specific area (transport, industry, etc.) and takes into account various factors. For example, it is rather challenging to consider changes in the dynamics of turbulent flows or factors of heat transfer, dust-containing fractions. Even more sophisticated models describe the scenarios of the response of various components of Env. to gaseous pollution, taking into account the transfer of solar and diffuse radiation (Knapcikova, 2018: 71–77).

Figure 1 shows the software implementation (Software, hereinafter referred to as SW) AERMOD (Canada, USA). This SW is intended for calculations and modeling of the atmosphere near large stationary industrial sources of pollution. Data within a radius of up to 50 km from the source are taken into account.

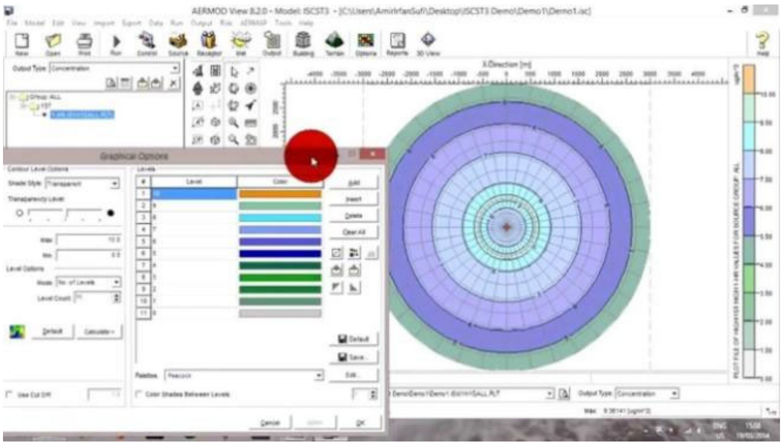


Fig. 1. General view of the AERMOD software package for automated assessment of atmospheric dispersion

The models embedded in the AERMOD SW make it possible to build predictive estimates for continuous emissions floating at different levels from the earth's surface, taking into account the dispersion of emissions (Knapcikova, 2018: 71–77). In the model, the concentration of pollutants does not affect the discharged flow. When simulated, turbulent flows are linear. However, there are limitations under which it is assumed that the average lateral speed and vertical wind speed are equal to zero. The model receives meteorological data from probes located at different altitudes. AERMOD SW allows us to create profiles of temperatures, winds, turbulences and considers factors associated with dry and wet deposition of pollutants (Abuova, 2019: 234–249).

Results and discussions.

The model and the corresponding ADMS-5 SW are modern means for calculating the concentrations of pollutants that can enter Env. from both point sources and mobile air pollutants see Fig. 2 (Zelenko, 2019: 03011).

The model and ADMS-5 SW contain algorithms that allow for many factors, including the complexity of the terrain; wet deposition of pollutants; short-term fluctuations in pollutant concentrations; chemical reactions inherent to various pollutants when external temperatures and humidity change; factors of radioactive decay and gamma doses, etc.

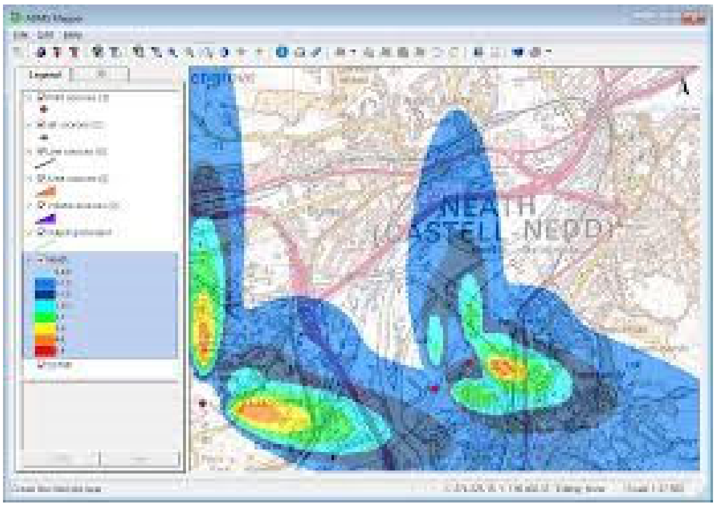


Fig. 2. General view of the software interfaces of the ADMS-5 complex

Techniques and corresponding SW "TOXI", "TOXI +", "TOXI + Risk" (Huang, 2020: 1–33), and ALOHA allow us to calculate the characteristics of hazardous substances cloud that moves in the atmosphere. The SW algorithms are based on the integral laws of conservation of mass and energy of pollutants (Torretta, 2017: 1–9).

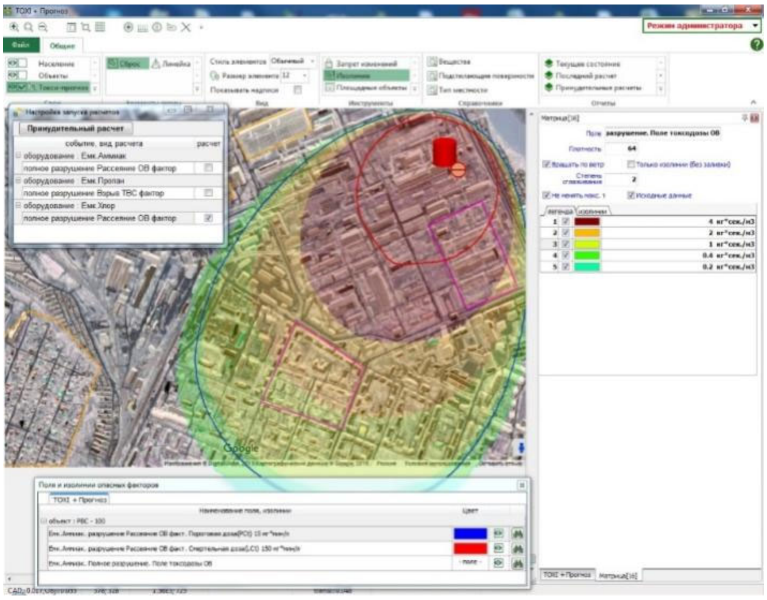


Fig. 3. General view of the software interfaces of the "TOXI" complex

Based on the above analysis and a brief overview of SW for modeling environmental emergencies, it can be concluded that there are many diverse models for calculating the dispersion of hazardous emissions. This list includes both simple Gaussian models and models that have become the basis for algorithms and SW for detailed calculations of complex gas-dynamic parameters of the movement of pollutants in Env (Dvorak, 2020: 5494).

The paper aims to develop mathematical models for the decision support system's computing core in response to accidents on railway transport, accompanied by a threat to environmental pollution (Batarlienė, 2014: 395–400).

Elimination of the consequences of railway emergencies with DG consists of interrelated processes that require a set of measures aimed at preventing threats to people, protecting the natural environment, ensuring the safety of cargo, RS, railway infrastructure facilities, restoring train traffic and shunting operations as soon as possible (Khanmohamadi, 2018: 230–241). At the same time, the rational use of a variety of resources required to carry out these activities is also important. So, the balanced timing of the restoration of train traffic (the operability of the transport system) and the resources required for this are the criteria for the effectiveness of the system for eliminating the consequences of railway emergency situations during the transportation of DG (Shalabayeva, 2020: 226–231; Gheorghe, 2005: 247–272).

To automate many works at the site of railway accidents and assess the operational situation, several researchers, including domestic ones, propose using the potential of automated information systems and DSS (Hooghiemstra, 1999: 15–32; Dindar, 2019: 203–216). It is necessary to have tools for processing a large amount of information about the nature of the accident and the ecological situation at the worksite in the area of elimination of the consequences of major accidents at RWT, which can potentially be accompanied by the emergence of threats and risks for Env. Moreover, the amount of such information may tend to grow exponentially as the situation develops, as, for example, happened during the catastrophe in Canada. It is necessary to minimize the consequences of environmental accidents on RWT in conditions when information flows are rapidly growing and liquidators are faced with a lack of time (Shalabayeva, 2020: 226–231).

The question arises about the need to create well-built computerized systems for automated operational information support for analyzing the situation at the RWT accident scene (Katsman, 2015: 28–39). Such systems are multifunctional and should, among other things, include the following functional modules (Shalabayeva, 2020: 226–231):

- a module for automated assessment of environmental safety in the elimination of the consequences of accidents at RWT;
- a module for the development and decision-making on responding to the threats to Env.;
- a module for assessing the risks for Env. They may arise as a result of the unfavorable development of scenarios of the accident consequences during the transportation of DS by RWT (Schröder, 2016: 322–334);
- other modules.

Using the data obtained from the tools for measuring contamination of Env. components directly at the accident site (data on the state of air, soil, water sources, etc.), it is possible, through DSS or information systems, not only to simulate different scenarios for the development of the situation at the accident site but also to obtain preliminary assessments of risks and consequences, if the development of the scenario of Env. pollution moves according to the pessimistic scenario ((Shalabayeva, 2020: 226–231; Nowacki, 2016: 21–29).

Studies by many authors in the field of environmental safety in transport show that the development of automated and intellectualized systems for assessing ecological safety in eliminating accident consequences at RWT can give a new impetus to the implementation of such systems in practice (Kornaszewski, 2017: 282–292). This is, in particular, necessary to increase the objectivity of assessments and reduce the time deficit in the process of liquidation work at the scene of accidents at RWT transporting DG (Shalabayeva, 2020: 226–231), which can lead to damage for the Env.

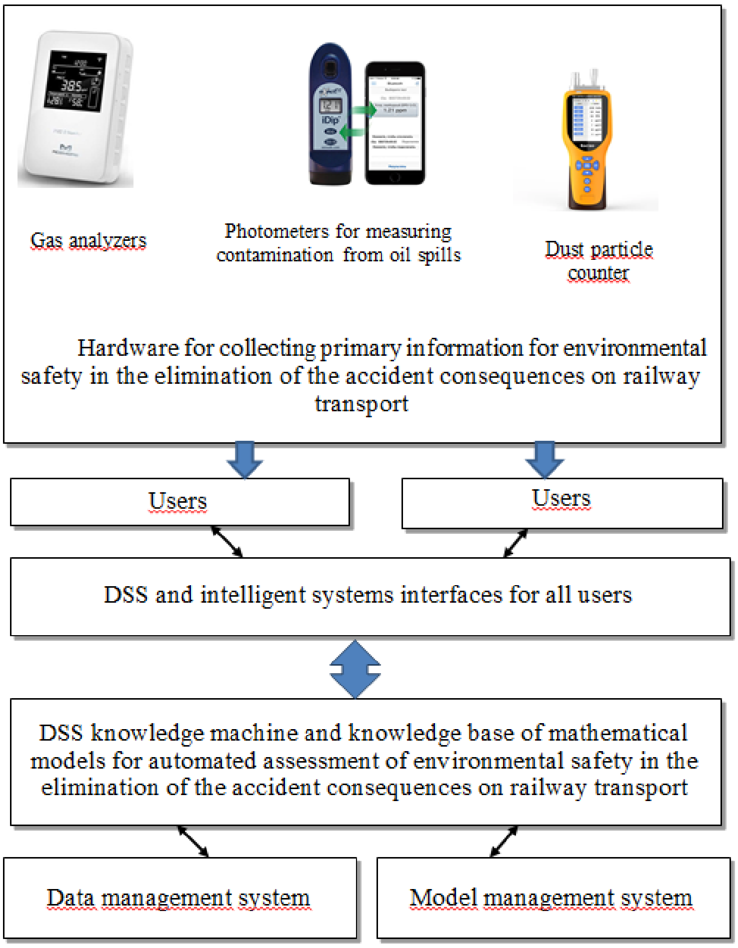


Fig. 4. Basic architecture of a computerized decision support system with modules for automated assessment of environmental safety in the elimination of the accidents consequences on railway transport (Akhmetov, 2022: 1287–1300)

In the structure of information and automated systems for managing the ecological state of Env., the main component is a database that provides the system with information and determines its structure, functions, and ability to solve management problems based on modeling the situation ((Akhmetov, 2022: 1287–1300; Knapcikova, 2018: 71–77).

Analysis of the current management scheme for the railway infrastructure's environmental safety indicates its imperfection and the absence in its structure of an organized system for obtaining and analyzing data for the timely adoption of managerial decisions on rational ecological management and minimizing the negative impact on the Env. (Akhmetov, 2022: 1287–1300).

At the output, the DSS will provide information containing the assessment of Env's state for the investigated territories at the accident site. Also, the computational core of the DSS includes models that allow making predictions about the health status of the population in the accident zone and assessing the situation from an economic point of view and the consequences for Env. The information obtained can be used by various management structures. For example, such information will be useful in the process of developing measures to eliminate the consequences of accidents and to allocate funds for restoring the Env. to its original state (Akhmetov, 2022: 1287–1300; Abuova, 2019: 234–249).

The models used in the computational core of such a DSS reflect an emergency situation associated with a DG leak (for example, a spill of contents from a railway tank car), and the response to such a situation by the units in charge of RWE localizing and eliminating the consequences, including for Env (Akhmetov, 2022: 1287–1300; Torretta, 2017: 1–9).

A refusal in the RIS safe operation should be understood as any transport accident due to which RWE with the participation of DG may occur (Dvorak , 2020: 5494). Analysis of the statistics of DG freight traffic on the railways of the EU countries over the past ten years made it possible to establish that the number of such RWE with DG participation depends on the total tonnage of all cargo transported by RWT, which is shown in Fig. 5.

The data shown in Fig. 5 correspond to the generalized statistics for six EU states for the specified period (Germany, France, Italy, Spain, Poland, Romania) (Huang, 2020: 1–33; Torretta, 2017: 1–9). The dependence of the number of traffic accidents with DG on the road's traffic load is undeniable, with an approximation coefficient of about 0.74. Obviously, it is general that it can be attributed not only to a specific EU state but also to any other RWT network.

The dependence $y = f(x)$ shown in Fig. 5 can be presented in a more straightforward form suitable for the calculations required in this model, for example,

$$y = \frac{1}{5}\exp\left\{\frac{1}{4}\cdot x\right\} \tag{1}$$

considering that $0{,}4822 \approx {}^{1}\!/_{2}$, a $0{,}2428 \approx {}^{1}\!/_{4}$.

Taking into account the technological parameters used in the model, the value $y = n_{SF}$, will then be given as:

$$n_{SF} = \frac{1}{2}\exp\left\{-\frac{365\cdot N\cdot G}{4\cdot 10^{6}}\right\}, \tag{2}$$

where $N-$ is the average daily number of trains that travel by rail in both directions;

$G-$ is average train gross weight, tons.

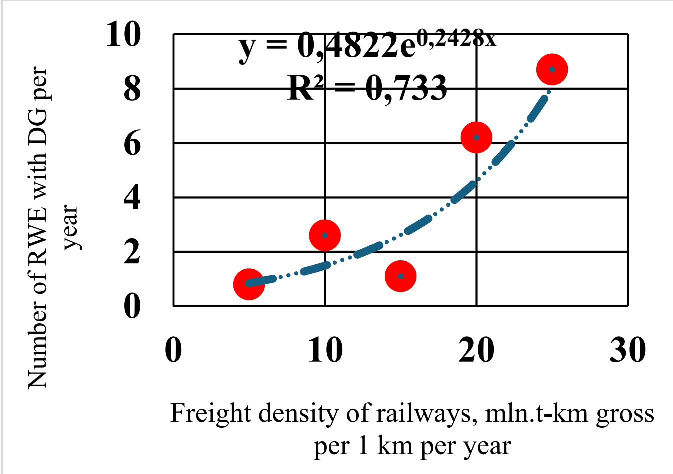


Fig. 5. Trend line for the number of RWE with DG in the EU countries over the past 10 years (data according to [16, 17 (Electronic edition)])

Given the formulas (2) and (3), taking the time $T = 356$ days, we obtain the value of the average duration of the RIS safe functioning state t_{SS} (in days):

$$t_{SS} = \frac{T}{n_{SF}} = 2 \cdot 365 \cdot \exp\left\{-\frac{365 \cdot N \cdot G}{4 \cdot 10^6}\right\}. \tag{3}$$

Now formula (9) can be modified, using in it, if necessary, time (formula (4)):

$$p_1 = \left\{1 + \frac{\left\{\dfrac{365 \cdot N \cdot G}{4 \cdot 10^6}\right\}}{2 \cdot 365} \cdot \left[\frac{t_{CR} + t_{CF}}{t_{CR} + 2 \cdot t_{CF}} \cdot (t_{CF} + t_{LF}) + t_{DR}\right]\right\}^{-1}, \tag{4}$$

here all parameters are defined above.

It is known from practice that the delay in the arrival of liquidation forces and means and their ineffective use always leads to more severe RWE consequences and more prolonged elimination. Moreover, the most rapidly the RWE develop in a dangerous direction of increasing losses from it just after the start of the process, which cannot be ignored in the corresponding mathematical model. Note that the rapid development of any process in time is well described by exponential dependence. It is this dependence that we will use, taking as a basis the formula (5):

$$t_{DR} = \frac{D_{DR}^{\max}}{\mu_{DR}}\left[1 - \exp\left\{-\frac{t_{CR} + t_{LE}}{t_{CR}}\right\}\right], \tag{5}$$

where $D_{DR}^{\max}$ – is the maximum possible amount of work that needs to be done to eliminate the RWE consequences (for example, removal of the top layer of soil saturated with a hazardous liquid, in tons, cubic meters, or other units of measurement), and μ_{DR} – is the productivity of the forces and means that are involved in eliminating the RWE consequences (in the same units of measurement per unit of time).

We can see from formula (5) that at $t_{CR} \to 0$,when the total loss of cargo occurs almost instantly (for example, an explosion), the volume of liquidation works tends to the maximum possible (since $\exp\{(t_{CR} + t_{LE})/t_{CR}\} \to 0$ then $D_{DR} \to D_{DR}^{\max}$)). It can also be seen from formula (5) that for any non-zero positive $t_{CR} > 0$, the longer the concentration time is for the liquidation forces and means involved in the RWE eliminating, accompanied by a threat to Env., $t_{CR}+t_{LE}$, the greater is the volume of liquidation work ($D_{DR}\to D_{DR}^{\max}$). Thus, the model adequately takes into account both the rate of undesirable RWE development, which depends on its nature and external conditions, the DG properties (through parameter t_{CR}), and the speed of response to this situation (through $t_{CR}+t_{LE}$) (Dindar, 2019: 203–216).

Regarding formula (4) and the previous formulas containing the value μ_{DR}, it should be noted that this value also depends on many factors, so we will focus on its analysis.

The value of the productivity of liquidation forces and means μ_{DR} is an "integral" value. This value can be represented as follows:

$$\mu_{DR}=\sum_{i=1}^{m}\mu_i\cdot n_i, \tag{6}$$

where μ_i – is the productivity of the liquidation forces and means of the i – type (for example, such as fire engines, cranes, or bulldozers), and n_i – is the number of units of the liquidation forces and means of the i – type (Abuova, 2019: 234–249). Moreover, the value t_{DR} is also "integral" in the sense that the indicated liquidation forces and means can be used simultaneously to perform various types of work, and these works, depending on the nature of the RWE and the plan for eliminating its consequences, can be completed at different times. Thus, the total duration of liquidation works t_{DR} is determined by the time from the beginning of the "first" (in order) work to the end of the "last" work, and its determination and minimization can be carried out using appropriate mathematical methods (for example, network planning or the PERT method (Knapcikova, 2018: 71–77).

Further attention will be focused on the fact that the earlier and more accurately the assessment of the RWE is made and the managerial decision on the choice of the parameters for the concentration and combat deployment of forces and means in the required quantity is made, the faster the RWE will be localized. And, accordingly, the less severe its consequences will be and the faster they will be eliminated (Hooghiemstra, 1999: 15–32). In terms of the model proposed in the thesis, this means that its mathematical parameters $t_{CF}=t_{SA}+t_{TT}+t_{RS}=t_{SA}+\left(L/V\right)+t_{RS}$, and also μ_{DR} can be optimized by applying appropriate organizational and technological measures (for example, the optimal deployment of liquidation forces and means, their appropriate equipment and rapid concentration) and technical means. For example, it is possible to use UAV and DSS for reconnaissance, assessing the situation and making decisions on the spot of the RWE. Thus, the most effective implementation of measures for the containment and elimination of the RWE can be ensured, and, therefore, the maximum possible reliability of the RTS is ensured when transporting DG that poses a threat to Env.

Let us return to our model, taking into account the previous reasoning. Now we can write such an analytical expression:

$$p_{SS}=p_1=\frac{1}{1+\dfrac{\exp\left\{\dfrac{365\cdot N\cdot G}{4\cdot 10^6}\right\}}{2\cdot 365\cdot 24}\left\{\dfrac{t_{CF}+3\cdot t_{LE}}{4}+\dfrac{D_{DR}^{\max}}{\mu_{DR}}\left[1-\exp\left\{-\dfrac{t_{CR}+t_{LE}}{t_{CR}}\right\}\right]\right\}}. \tag{7}$$

In order to reflect the logic of these considerations, we compose the following equation:

$$t_{CF} = t_{\min} + \frac{t_{CR} - t_{CF}}{t_{CR} - t_{\max}} \cdot (t_{CR} - t_{\max}). \quad (8)$$

Equation (6) reflects the fact that the actual time of concentration of liquidation forces and means is always within certain limits $t_{\min} \le t_{CF} \le t_{\max}$, and they try to reduce it in a certain way if $t_{CR} \to 0$. After transformations of equation (21), we obtain a quadratic equation regarding t_{CF}, the only root of which at $t_{\min} \le t_{CF} \le t_{\max}$ will be

$$t_{CF} = t_{CR} + \sqrt{t_{CR}^2 + \left(t_{SA} + \frac{L}{V}\right) \cdot \left(t_{CR} - \left(t_{SA} + \frac{L}{V} + t_{RC}\right)\right)}. \quad (9)$$

However, if $t_{CR} = 0$, then the minimum value of t_{CF} will be the geometric mean,

$$t_{CF} = \sqrt{\left(t_{SA} + \frac{L}{V}\right) \cdot \left(t_{SA} + \frac{L}{V} + t_{RC}\right)},$$

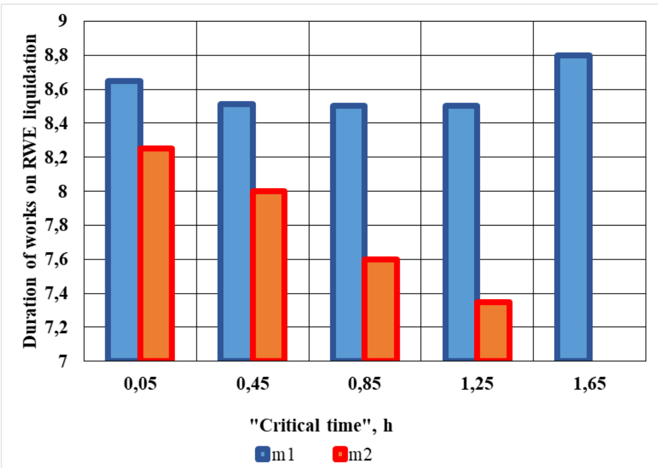
which is known to be close to the lower value.

This reflects that in practice, in hazardous situations, they try to reduce the concentration time in every possible way. If the "critical time" values are relatively large, that is $t_{CR} >> 0$, then there is a certain reserve of time for the concentration of forces.

Let us simulate possible scenarios for the development of the situation. In the first variant, the duration of time for assessing the situation and making a decision is taken $t_{SA} = 0{,}5$ h. In the second variant, this time is taken $t_{SA} = 0{,}25$ h.

The simulation results are shown in Fig. 6.

Fig. 6 shows that reducing the time for deciding to carry out liquidation works by only 15 minutes leads to a decrease in these works' total duration, on average, from one to almost four hours. Since every hour of delay in the start of response work is associated with a significant loss of cargo, a negative impact on Env., and direct and indirect economic losses, it is obvious the need for an early assessment of the current situation, and the adoption of a timely informed decision to eliminate RWE. This is possible due to the use of the latest technical means of monitoring the development of such a situation, such as the use of UAVs, security cameras, if available nearby, and the use of information technology and intelligent DSS (Abuova, 2019: 234–249).



(m1 – for $t_{SA} = 0{,}5$ *h*. and m2 – for $t_{SA} = 0{,}25$ *h*.)

Fig 6. Results of modeling the duration of liquidation works at the RWE site

Considering that a different level of economic indicators characterizes the presence of the DG transportation system (Fig.5) in each of the states (Huang, 2020: 1–33; Torretta, 2017: 1–9), it is advisable, using the proposed mathematical models, to assess the economic effects of maintaining an appropriate level of RIS reliability.

For the assessment and planning of the actions of the liquidation forces at the RWE site, a corresponding DSS was developed, the primary interfaces of which are shown in the article (Abuova, 2019: 234–249).

At the moment, work is underway to implement the models presented in this study in the form of an independent software product to assess the duration of the liquidation work at the RWE site, see Fig. 7 (Zelenko, 2019: 03011).

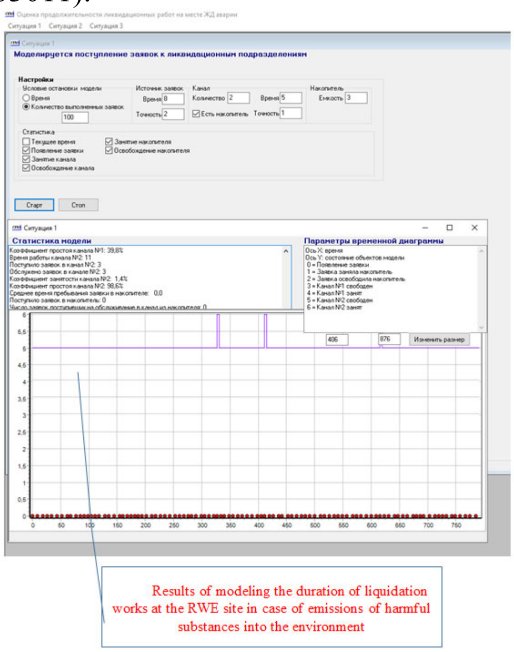


Fig. 7. General view of the program for assessing the duration of liquidation works at the RWE site with emissions of harmful substances into the Env.

Conclusion.

The objectives of this study have been fully realized through the development and application of mathematical models for the computational core of a decision support system (DSS) designed to respond to railway emergencies (RWE) involving dangerous goods (DG). The research methods included statistical analysis of railway accident data, modeling probabilistic and dynamic processes of emergency development, and constructing structural and logical schemes of actions for emergency response leaders. These methods allowed for an in-depth evaluation of the duration, volume, and efficiency of emergency mitigation activities, considering environmental impacts, technological parameters, organizational measures, and the speed of response of liquidation forces.

The main findings of this study can be summarized as follows:

1) Challenges of Decision-Making under Uncertainty: It was established that during an RWE, in conditions of incomplete or insufficient information regarding cause-and-effect relationships, the head of the emergency operations center must make numerous individual and collective decisions. These decisions, which include informational, organizational, and operational actions for coordinating subordinate control points and liquidation units, often exceed the capacity of a single manager and may affect the validity of the decisions made. This confirms the necessity of using DSS to ensure timely and informed decision-making.

2) Development of Predictive Mathematical Models: The study developed models capable of predicting emergency development, estimating the volume and duration of liquidation work, and assessing environmental risks. These models take into account the rate of emergency escalation, DG

properties, external environmental conditions, and the efficiency of liquidation forces. Integration of these models into DSS enables optimization of force concentration and deployment, significantly reducing emergency consequences and response times.

3) Formalization of the DG Railway Transport System: The system has been formalized as an oriented graph of the safe functioning states of the Railway Information System (RIS), considering emergency occurrence, assessment, localization, and elimination of consequences. This formalization allows for calculating the probability of RIS remaining in a safe state during DG transportation under varying technological and organizational measures. The models enable scenario-based simulation of accident consequences, providing predictive assessments of environmental and economic impacts.

4) Efficiency Enhancement through DSS and Modern Monitoring Tools: The use of UAVs, environmental sensors, surveillance cameras, and intelligent DSS allows for early situational assessment, rapid decision-making, and optimal allocation of resources. Simulation results indicate that even small reductions in decision-making time significantly decrease the total duration of liquidation work, thus minimizing cargo losses, environmental damage, and economic consequences.

5) Practical Implications and Prospects for Implementation: The proposed models and DSS can be implemented as practical software solutions capable of real-time assessment and management of RWE at DG transportation sites. The system can plan the deployment of liquidation forces, estimate environmental and economic risks, optimize resource use, and improve objectivity and efficiency in emergency management. Future development may include integration with railway traffic management systems, automated environmental monitoring, and predictive analytics, enhancing operational safety and ecological protection.

6) Scientific Contribution: The study confirms the validity of the hypotheses and contributes to advancing knowledge in modeling and managing railway emergencies with DG. The research emphasizes the importance of combining mathematical modeling, information technology, and automated decision-making to improve railway transport system reliability and safety. The approaches developed provide a foundation for further studies, including refinement of predictive models, expansion of DSS functionality, and development of comprehensive risk assessment frameworks for complex emergencies.

In conclusion, this research demonstrates that the implementation of intelligent DSS, supported by robust mathematical models, significantly enhances the operational efficiency of emergency response, ensures faster localization and elimination of RWE, reduces environmental and economic impacts, and strengthens the reliability of railway transport systems during the transportation of DG. The proposed solutions are practically applicable and open avenues for further research and real-world implementation in the fields of railway safety, environmental protection, and emergency management.

REFERENCES

Abuova, 2019 — Abuova A., et al. Conceptual model of the automated decision-making process in analysis of emergency situations on railway transport. — International Conference on Research and Practical Issues of Enterprise Information Systems. — Springer, Cham. — 2019. — Pp. 234–249. [Eng.]

Akhmetov, 2021 — Akhmetov, B. S., Shalabayeva, M. Kh. (2021). Matematicheskaya podderzhka reagirovaniya na zheleznodorozhnye avariynye situatsii [Mathematical support for responding to railway emergency situations]. // L.N. Gumilyov Eurasian National University Bulletin. Series: Technical Sciences and Technologies. — 2021. — 1(134). — Pp. 80–90. [Russ.]

Batarlienė, 2014 — Batarlienė N., Jarašūnienė A. Analysis of the accidents and incidents occurring during the transportation of dangerous goods by railway transport. — Transport. — 2014. — 29(4). — Pp. 395–400. [Eng.]

Dindar, 2019 — Dindar S., Kaewunruen S., An M. Rail accident analysis using large-scale investigations of train derailments on switches and crossings: Comparing the performances of a novel stochastic mathematical prediction and various assumptions. — Engineering Failure Analysis. — 2019. — 103. — Pp. 203–216. [Eng.]

Dvorak, 2020 — Dvorak Z., Rehak D., David A., Cekerevac Z. Qualitative Approach to Environmental Risk Assessment in Transport. — International Journal of Environmental Research and Public Health. — 2020. — 17(15). — P. 5494. [Eng.]

Gheorghe, 2005 — Gheorghe A. V., Birchmeier J., Vamanu D., Papazoglou I., Kröger W. Comprehensive risk assessment for rail transportation of dangerous goods: a validated platform for decision support. — Reliability Engineering & System Safety. — 2005. — 88(3). — Pp. 247–272. [Eng.]

Hooghiemstra, 1999 — Hooghiemstra J. S., Kroon L. G., Odijk M. A., Salomon M., Zwaneveld P. J. Decision support systems support the search for win-win solutions in railway network design. — Interfaces. — 1999. — 29(2). — Pp. 15–32. [Eng.]

Huang, 2020 — Huang W., Li Y., Kou X., Wang W., Xu Y. Using a FMEA–TIFIAD Approach to Identify the Risk of Railway Dangerous Goods Transportation System. — Group Decision and Negotiation. — 2020. — Pp. 1–33. [Eng.]

Khanmohamadi, 2018 — Khanmohamadi M., Bagheri M., Khademi N., Ghannadpour S. F. A security vulnerability analysis model for dangerous goods transportation by rail – Case study: Chlorine transportation in Texas-Illinois. — Safety Science. — 2018. — 110. — Pp. 230–241. [Eng.]

Katsman, 2011 — Katsman M., Kryvopishyn O., Lapin V. Mathematical models of decision support system for the head of the fire-fighting department on railways. — Reliability: Theory & Applications. — 2011. — 2(03). — Pp. 86–93. [Eng.]

Katsman, 2013 — Katsman M. D., Myronenko V. K., Adamenko M. I. Problematic model of ecological consequences of railroad accidents. — Reliability: Theory & Applications. — 2013. — 8(1). — Pp. 72–85. [Eng.]

Katsman, 2015 — Katsman M. D., Myronenko V. K., Matsiuk V. I. Mathematical models of ecologically hazardous rail traffic accidents. — Reliability: Theory & Applications. — 2015. — 10(1). — Pp. 28–39. [Eng.]

Knapcikova, 2018 — Knapcikova L., Konings R. European railway infrastructure: a review. — Acta Logistica. — 2018. — 5(3). — Pp. 71–77. [Eng.]

Kornaszewski, 2017 — Kornaszewski M., Chrzan M., Olczykowski Z. Implementation of new solutions of intelligent transport systems in railway transport in Poland. — International Conference on Transport Systems Telematics. — Springer, Cham. — 2017. — Pp. 282–292. [Eng.]

Nowacki, 2016 — Nowacki G., Krysiuk C., Kopczewski R. Dangerous goods transport problems in the European Union and Poland. — TransNav: International Journal on Marine Navigation and Safety of Sea Transportation. — 2016. — 10(1). — Pp. 21–29. [Eng.]

Schröder, 2016 — Schröder M., Prause G. Transportation of dangerous goods in green transport corridors – conclusions from Baltic Sea region. — Transport and Telecommunication Journal. — 2016. — 17(4). — Pp. 322–334. [Eng.]

Torretta, 2017 — Torretta V., Rada E. C., Schiavon M., Viotti P. Decision support systems for assessing risks involved in transporting hazardous materials: A review. — Safety Science. — 2017. — 92. — Pp. 1–9. [Eng.]

Zelenko, 2019 — Zelenko Y., Dzhus O., Dzhus V., Yanchenko D. Methodology of risk assessment and forms of environmental safety management for the transport of dangerous goods by railway transport. — MATEC Web of Conferences. — 2019. — 294. — 03011. [Eng.]

Shalabayeva, 2024 — Shalabayeva, M. Kh. Abstract of the dissertation "Methods and models of automated assessment of environmental safety during liquidation of consequences of railway transport accidents" for the degree of Doctor of Philosophy (PhD), educational program 8D07100 – Automation and Control. — 2024. — 10 p.

Shalabayeva, 2020 — Shalabayeva, M. Kh. Analiz metodov i modelei dlya avtomatizirovannoi otsenki ekologicheskoi bezopasnosti pri likvidatsii posledstvii avarii na zheleznodorozhnom transporte [Analysis of methods and models for automated assessment of environmental safety during the liquidation of consequences of railway accidents]. // Problemy informatiki v obrazovanii, upravlenii, ekonomike i tekhnike: Proceedings of the 20th International Scientific and Technical Conference. — Penza: Privolzhskii Dom Znanii. — 2020. — Pp. 226–231. [Russ.]

Akhmetov, 2022 — Akhmetov B., Lakhno V., Blozva A., Shalabayeva M., Abuova A. Skladannyi P., Sagyndykova Sh. Development of a mobile automated air quality monitoring system for use in places of technogenic accidents on railway transport. // Journal of Theoretical and Applied Information Technology. — Vol.100. — №5. — 2022. — Pp. 1287–1300.

ҚАЗАҚСТАН ӨНДІРІС КӨЛІГІ

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