

Vol. 10, no. 3, 2026

eISSN 2541-9129

PEER-REVIEWED SCIENTIFIC AND PRACTICAL JOURNAL

Safety of Technogenic and Natural Systems

Technosphere Safety

Machine Building

Chemical Technologies,
Materials Sciences,
Metallurgy



www.bps-journal.ru
DOI 10.23947/2541-9129



Safety of Technogenic and Natural Systems Bezopasnost' Tekhnogennykh i Prirodnnykh Sistem

Peer-Reviewed Scientific and Practical Journal

eISSN 2541-9129

Published Since 2017

Periodicity – 4 issues per year

DOI: 10.23947/2541-9129

Founder and Publisher — Don State Technical University (DSTU), Rostov-on-Don, Russian Federation

The journal is created in order to highlight the results of research and real achievements on topical issues of Mechanical Engineering, Technosphere Safety, Modern Metallurgy and Materials Science. The journal highlights the problems of the development of fundamental research and engineering developments in a number of important areas of technical sciences. One of the main activities of the journal is integration into the international information space.

The journal is included in the List of the leading peer-reviewed scientific publications (Higher Attestation Commission under the Ministry of Science and Higher Education of the Russian Federation), where basic scientific results of dissertations for the degrees of Doctor and Candidate of Science in scientific specialties and their respective branches of science should be published.

The Journal Publishes Articles in the Following Fields of Science:

- Labor protection in construction (Engineering Sciences)
- Ground Transport and Technological Means and Complexes (Engineering Sciences)
- Machines, Aggregates and Technological Processes (Engineering Sciences)
- Metallurgical Science and Heat Treatment of Metals and Alloys (Engineering Sciences)
- Powder Metallurgy and Composite Materials (Engineering Sciences)
- Materials Science (Engineering Sciences)
- Fire Safety (Engineering Sciences)
- Environmental Safety (Engineering Sciences)
- Occupational Safety (Engineering Sciences)

Registration: Mass Media Registration Certificate ЭЛ № ФС 77 – 66531 Dated July, 21, 2016, Issued by the Federal Service for Supervision of Communications, Information Technology and Mass Media

Indexing and Archiving: RISC, CyberLeninka, CrossRef, DOAJ, Index Copernicus, Internet Archive

Website: <https://bps-journal.ru>

Address of the Editorial Office: 1, Gagarin Sq. Rostov-on-Don, 344003, Russian Federation

E-mail: vestnik@donstu.ru

Telephone: +7 (863) 2–738–372

Date of Publication No.3,2026: 30.08.2026





Безопасность техногенных и природных систем

Safety of Technogenic and Natural Systems

Рецензируемый научно-практический журнал

eISSN 2541-9129

Издается с 2017 года

Периодичность – 4 выпуска в год

DOI: 10.23947/2541-9129

Учредитель и издатель — Федеральное государственное бюджетное образовательное учреждение высшего образования «Донской государственный технический университет» (ДГТУ), г. Ростов-на-Дону

Создан в целях освещения результатов исследований и реальных достижений по актуальным вопросам машиностроения, техносферной безопасности, современной металлургии и материаловедения. В журнале освещаются проблемы развития фундаментальных исследований и инженерных разработок в ряде важнейших областей технических наук. Одним из главных направлений деятельности журнала является интеграция в международное информационное пространство.

Журнал включен в перечень рецензируемых научных изданий, в котором должны быть опубликованы основные научные результаты диссертаций на соискание ученой степени кандидата наук, на соискание ученой степени доктора наук (Перечень ВАК) по следующим научным специальностям:

- 2.1.16 – Охрана труда в строительстве (технические науки)
- 2.5.11 – Наземные транспортно-технологические средства и комплексы (технические науки)
- 2.5.21 – Машины, агрегаты и технологические процессы (технические науки)
- 2.6.1 – Металловедение и термическая обработка металлов и сплавов (технические науки)
- 2.6.5 – Порошковая металлургия и композиционные материалы (технические науки)
- 2.6.17 – Материаловедение (технические науки)
- 2.10.1 – Пожарная безопасность (технические науки)
- 2.10.2 – Экологическая безопасность (технические науки)
- 2.10.3 – Безопасность труда (технические науки)

Регистрация:

Свидетельство о регистрации средства массовой информации ЭЛ № ФС 77 – 66531 от 21 июля 2016 г., выдано Федеральной службой по надзору в сфере связи, информационных технологий и массовых коммуникаций

*Индексация
и архивация:*

РИНЦ, CyberLeninka, CrossRef, DOAJ, Index Copernicus, Internet Archive

Сайт:

<https://bps-journal.ru>

Адрес редакции:

344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1

E-mail:

vestnik@donstu.ru

Телефон:

+7 (863) 2–738–372

Дата выхода

№3, 2026 в свет:

30.08.2026



Editorial Board

Editor-in-Chief

Besarion Ch. Meskhi, Dr.Sci. (Eng.), Professor, Don State Technical University (Rostov-on-Don, Russian Federation)

Deputy Chief Editors

Anatoliy A. Korotkiy, Dr.Sci. (Eng.), Professor, Don State Technical University (Rostov-on-Don, Russian Federation)

Valery N. Azarov, Dr.Sci. (Eng.), Professor, Volgograd State Technical University (Volgograd, Russian Federation)

Executive Editor

Manana G. Komakhidze, Cand.Sci. (Chemistry), Don State Technical University (Rostov-on-Don, Russian Federation)

Executive Secretaries

Grigoriy Sh. Khazanovich, Dr.Sci. (Eng.), Professor, Don State Technical University (Rostov-on-Don, Russian Federation)

Nadezhda A. Shevchenko, Don State Technical University (Rostov-on-Don, Russian Federation)

Aleksandr A. Poroshin, Dr.Sci. (Eng.), All-Russian Research Institute for Fire Protection of the Ministry of the Russian Federation for Civil Defence, Emergencies and Elimination of Consequences of Natural Disasters (Balashikha, Russian Federation)

Aleksandr N. Chukarin, Dr.Sci. (Eng.), Professor, Rostov State Transport University (Rostov-on-Don, Russian Federation)

Aleksandr P. Amosov, Dr.Sci. (Phys.-Math.), Professor, Samara State Technical University (Samara, Russian Federation)

Aleksandr P. Tyurin, Dr.Sci. (Eng.), Associate Professor, Kalashnikov Izhevsk State Technical University (Izhevsk, Russian Federation)

Aleksandr V. Lagerev, Dr.Sci. (Eng.), Professor, Ivan Petrovsky Bryansk State University (Bryansk, Russian Federation)

Aleksey S. Nosenko, Dr.Sci. (Eng.), Professor, Shakhty Road Institute (branch) SRSPU (NPI) named after. M.I. Platova (Shakhty, Russian Federation)

Boris V. Sevastyanov, Dr.Sci. (Eng.), Cand. Sci. (Pedagog.), Professor, Kalashnikov Izhevsk State Technical University (Izhevsk, Russian Federation)

Ekaterina V. Ageeva, Dr.Sci. (Eng.), Associate Professor, Southwest State University (Kursk, Russian Federation)

Eleonora Yu. Voronova, Dr.Sci. (Eng.), Associate Professor, Shakhty Road Institute (branch) SRSPU (NPI) named after. M.I. Platov (Shakhty, Russian Federation)

Evgeniy V. Ageev, Dr.Sci. (Eng.), Professor, Southwest State University (Kursk, Russian Federation)

Fanil Sh. Hafizov, Dr.Sci. (Eng.) Professor, Ufa State Petroleum Technological University (Ufa, Russian Federation)

Grigoriy Sh. Khazanovich, Dr.Sci. (Eng.), professor, Don State Technical University (Rostov-on-Don, Russian Federation)

Igor A. Lagerev, Dr.Sci. (Eng.), Associate Professor, Ivan Petrovsky Bryansk State University (Bryansk, Russian Federation)

Ildar F. Hafizov, Dr.Sci. (Eng.), Associate Professor, Ufa State Petroleum Technological University (Ufa, Russian Federation)

Konstantin P. Manzhula, Dr.Sci. (Eng.), Professor, Peter the Great St. Petersburg Polytechnic University (Saint Petersburg, Russian Federation)

Mikhail S. Pleshko, Dr.Sci. (Eng.), Associate Professor, National University of Science and Technology (MISiS) (Moscow, Russian Federation)

Nadezhda V. Menzelintseva, Dr.Sci. (Eng.), Professor, Volgograd State Technical University (Volgograd, Russian Federation)

Nail Kh. Abdrakhmanov, Dr.Sci. (Eng.), Professor, Ufa State Petroleum Technological University (Ufa, Russian Federation)

Natalya I. Baurova, Dr.Sci. (Eng.), Professor, Moscow Automobile and Road Construction State Technical University (Moscow, Russian Federation)

Oksana S. Gurova, Dr.Sci. (Eng.), Associate Professor, Don State Technical University (Rostov-on-Don, Russian Federation)

Roman S. Fediuk, Dr.Sci. (Eng.), professor, Far Eastern Federal University (Vladivostok, Russian Federation)

Sergey L. Pushenko, Dr.Sci. (Eng.), Professor, Don State Technical University (Rostov-on-Don, Russian Federation)

Sergey N. Egorov, Dr.Sci. (Eng.), South-Russian State Polytechnic University (NPI) named after MI Platov (Novocherkassk, Russian Federation)

Vadim I. Bepalov, Dr.Sci. (Eng.), Professor, Don State Technical University (Rostov-on-Don, Russian Federation)

Viktor N. Pustovoit, Dr.Sci. (Eng.), Professor, Don State Technical University (Rostov-on-Don, Russian Federation)

Viktor O. Gutarevich, Dr.Sci. (Eng.), Associate Professor, Donetsk National Technical University (Donetsk, Donetsk People's Republic)

Vladimir L. Gaponov, Dr.Sci. (Eng.), Professor, Don State Technical University (Rostov-on-Don, Russian Federation)

Vladimir V. Moskvichev, Dr.Sci. (Eng.), Professor, Krasnoyarsk Branch of the Federal Research Center for Information and Computational Technologies (Krasnoyarsk, Russian Federation)

Vladimir Yu. Dorofeev, Dr.Sci. (Eng.), Professor, South-Russian State Polytechnic University (NPI) named after MI Platov (Novocherkassk, Russian Federation)

Vladislav B. Deev, Dr.Sci. (Eng.), Professor, National University of Science and Technology (MISiS) (Moscow, Russian Federation)

Vsevolod A. Minko, Dr.Sci. (Eng.), Professor, Belgorod State Technological University named after V.G. Shukhov (Belgorod, Russian Federation)

Vyacheslav G. Kopchenkov, Dr.Sci. (Eng.), Professor, North-Caucasus Federal University (Stavropol, Russian Federation)

Yuriy I. Bulygin, Dr.Sci. (Eng.), Professor, Don State Technical University (Rostov-on-Don, Russian Federation)

Zhanna V. Ereemeva, Dr.Sci. (Eng.), Professor, National University of Science and Technology (MISiS) (Moscow, Russian Federation)

Редакционная коллегия

Главный редактор

Месхи Бесарион Чохоевич, доктор технических наук, профессор, Донской государственный технический университет (Ростов-на-Дону, Российская Федерация)

Заместители главного редактора

Короткий Анатолий Аркадьевич, доктор технических наук, профессор, Донской государственный технический университет (Ростов-на-Дону, Российская Федерация)

Азаров Валерий Николаевич, доктор технических наук, профессор, Волгоградский государственный технический университет (Волгоград, Российская Федерация)

Выпускающий редактор

Комахидзе Манана Гивиевна, кандидат химических наук, Донской государственный технический университет (Ростов-на-Дону, Российская Федерация)

Ответственные секретари

Хазанович Григорий Шнеерович, доктор технических наук, профессор, Донской государственный технический университет (Ростов-на-Дону, Российская Федерация)

Шевченко Надежда Анатольевна, Донской государственный технический университет (Ростов-на-Дону, Российская Федерация)

Абдрахманов Наиль Хадитович, доктор технических наук, профессор, Уфимский государственный нефтяной технический университет (Уфа, Российская Федерация)

Агеева Екатерина Владимировна, доктор технических наук, доцент, Юго-Западный государственный университет (Курск, Российская Федерация)

Агеев Евгений Викторович, доктор технических наук, профессор, Юго-Западный государственный университет (Курск, Российская Федерация)

Амосов Александр Петрович, доктор физико-математических наук, профессор, Самарский государственный технический университет (Самара, Российская Федерация)

Баурова Наталья Ивановна, доктор технических наук, профессор, Московский автомобильно-дорожный государственный технический университет (Москва, Российская Федерация)

Беспалов Вадим Игоревич, доктор технических наук, профессор, Донской государственный технический университет (Ростов-на-Дону, Российская Федерация)

Булыгин Юрий Игоревич, доктор технических наук, профессор, Донской государственный технический университет (Ростов-на-Дону, Российская Федерация)

Воронова Элеонора Юрьевна, доктор технических наук, доцент, Шахтинский автодорожный институт (филиал) ЮРГПУ (НПИ) (Шахты, Российская Федерация)

Гапонов Владимир Лаврентьевич, доктор технических наук, профессор, Донской государственный технический университет (Ростов-на-Дону, Российская Федерация)

Гурова Оксана Сергеевна, доктор технических наук, доцент, Донской государственный технический университет (Ростов-на-Дону, Российская Федерация)

Гутаревич Виктор Олегович, доктор технических наук, доцент, Донецкий национальный технический университет (Донецк, Донецкая Народная Республика)

Деев Владислав Борисович, доктор технических наук, профессор, Национальный исследовательский технологический университет «МИСиС» (Москва, Российская Федерация)

Дорофеев Владимир Юрьевич, доктор технических наук, профессор, Южно-Российский государственный технический университет (НПИ) имени М. И. Платова (Новочеркасск, Российская Федерация)

Егоров Сергей Николаевич, доктор технических наук, профессор, Южно-Российский государственный технический университет (НПИ) имени М. И. Платова (Новочеркасск, Российская Федерация)

Еремеева Жанна Владимировна, доктор технических наук, профессор, Национальный исследовательский технологический университет «МИСиС» (Москва, Российская Федерация)

Копчиков Вячеслав Григорьевич, доктор технических наук, профессор, Северо-Кавказский федеральный университет (Ставрополь, Российская Федерация)

Лагерева Александр Валерьевич, доктор технических наук, профессор, Брянский государственный университет имени академика И.Г. Петровского (Брянск, Российская Федерация)

Лагерева Игорь Александрович, доктор технических наук, доцент, Брянский государственный университет имени академика И.Г. Петровского (Брянск, Российская Федерация)

Манжула Константин Павлович, доктор технических наук, профессор, Санкт-Петербургский политехнический университет Петра Великого (Санкт-Петербургский, Российская Федерация)

Мензелинцева Надежда Васильевна, доктор технических наук, профессор, Волгоградский государственный технический университет (Волгоград, Российская Федерация)

Минко Всеволод Афанасьевич, доктор технических наук, профессор, Белгородский государственный технологический университет имени В.Г. Шухова (Белгород, Российская Федерация)

Москвичев Владимир Викторович, доктор технических наук, профессор, Красноярский филиал Федерального исследовательского центра «Информационных и вычислительных технологий» (Красноярск, Российская Федерация)

Носенко Алексей Станиславович, доктор технических наук, профессор, Шахтинский автодорожный институт (филиал) ЮРГПУ (НПИ) (Шахты, Российская Федерация)

Плешко Михаил Степанович, доктор технических наук, доцент, Национальный исследовательский технологический университет МИСиС (Москва, Российская Федерация)

Пустовойт Виктор Николаевич, доктор технических наук, профессор, Донской государственный технический университет (Ростов-на-Дону, Российская Федерация)

Пушенко Сергей Леонардович, доктор технических наук, профессор, Донской государственный технический университет (Ростов-на-Дону, Российская Федерация)

Порошин Александр Алексеевич, доктор технических наук, Всероссийский ордена «Знак Почета» научно-исследовательский институт противопожарной обороны МЧС России (Балашиха, Российская Федерация)

Севастьянов Борис Владимирович, доктор технических наук, кандидат педагогических наук, профессор, Ижевский государственный технический университет имени М.Т. Калашникова (Ижевск, Российская Федерация)

Тюрин Александр Павлович, доктор технических наук, доцент, Ижевский государственный технический университет имени М.Т. Калашникова (Ижевск, Российская Федерация)

Федок Роман Сергеевич, доктор технических наук, профессор, Дальневосточный федеральный университет (Владивосток, Российская Федерация)

Хазанович Григорий Шнеерович, доктор технических наук, профессор, Донской государственный технический университет (Ростов-на-Дону, Российская Федерация)

Хафизов Ильдар Фанисевич, доктор технических наук, доцент, Уфимский государственный нефтяной технический университет (Уфа, Российская Федерация)

Хафизов Фаниль Шамильевич, доктор технических наук, профессор, Уфимский государственный нефтяной технический университет (Уфа, Российская Федерация)

Чукарин Александр Николаевич, доктор технических наук, профессор, Ростовский государственный университет путей сообщения (Ростов-на-Дону, Российская Федерация)

Contents

TECHNOSPHERE SAFETY

The Impact of Assessing the Vibrational Energy Loss Coefficients of Multi-Purpose Machines on Occupational Safety	193
<i>Maksim V. Grichishin, Besarion Ch. Meskhi</i>	
Clustering of Groups of Key Greenhouse Gas-Emitting Countries Based on Economic, Demographic, and Energy Indicators	206
<i>Oleg A. Loktionov, Daniil O. Maksimov, Mikhail A. Zabelin, Irina A. Beloshitskaya</i>	
System for Identifying the Condition of Hoisting Crane Runways	219
<i>Vladislav V. Egelsky, Nikolai N. Nikolaev, Elena V. Egelskaya, Anatoly A. Korotkiy, Leonid A. Ternovskoi</i>	
Gazebo-Type Small Architectural Form as a Noise Protection Structure for Residential Area Improvement Sites	232
<i>Artyem V. Artyemov, Evgenii S. Kurkin, Pavel S. Zakharov, Tat'yana V. Shteba</i>	
Integration of Computer Vision and Hydrodynamic Modeling Methods to Improve Environmental Safety by Identifying Sources of Negative Impact on Water Bodies	247
<i>Andrey V. Gusev</i>	
Assessment of Electromagnetic Radiation Intensity from Smartphones in Video Communication Mode	256
<i>Tatyana A. Budykina, Andrey A. Blokhin</i>	
A Mobile Technical Module for the Production of Composite Sorbents for Petroleum Products	266
<i>Vitaly V. Gaevskiy, Irina V. Odinkova, Irina Yu. Isaeva, Galina Yu. Ostaeva</i>	

CHEMICAL TECHNOLOGIES, MATERIALS SCIENCES, METALLURGY

Geometrical Parameters of 14G2 Steel Structure as a Material with High Ballistic Resistance	277
<i>Viktor N. Pustovoyt, Yuri V. Dolgachev, Ivan V. Ivanko</i>	

Содержание

ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ

- Влияние оценки коэффициентов потерь колебательной энергии многоцелевых станков на безопасность труда** 193
М.В. Гричишин, Б.Ч. Месхи
- Формирование кластерных групп ключевых стран-эмитентов парниковых газов в разрезе экономико-демографических и энергетических показателей** 206
О.А. Локтионов, Д.О. Максимов, М.А. Забелин, И.А. Белошицкая
- Система идентификации состояния рельсовых путей грузоподъемных кранов** 219
В.В. Егельский, Н.Н. Николаев, Е.В. Егельская, А.А. Короткий, Л.А. Терновской
- Применение малой архитектурной формы типа «Беседка» в качестве шумозащитной конструкции для площадок благоустройства жилых зон** 232
А.В. Артёмов, Е.С. Куркин, П.С. Захаров, Т.В. Штеба
- Интеграция методов компьютерного зрения и гидродинамического моделирования для повышения экологической безопасности за счет идентификации источников негативного воздействия на водные объекты** 247
А.В. Гусев
- Оценка интенсивности электромагнитных излучений от смартфонов в режиме видеосвязи** 256
Т.А. Будыкина, А.А. Блохин
- Мобильный технический модуль для производства композитного сорбента нефтепродуктов** 266
В.В. Гаевский, И.В. Одинокова, И.Ю. Исаева, Г.Ю. Остаева

ХИМИЧЕСКИЕ ТЕХНОЛОГИИ, НАУКИ О МАТЕРИАЛАХ, МЕТАЛЛУРГИЯ

- Геометрические параметры структуры стали 14Г2 как материала с высокой баллистической стойкостью** 277
В.Н. Пустовойт, Ю.В. Долгачев, И.В. Иванков

TECHNOSPHERE SAFETY

ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ



UDC 658.345 + 06

Original Empirical Research

<https://doi.org/10.23947/2541-9129-2026-10-3-193-205>

The Impact of Assessing the Vibrational Energy Loss Coefficients of Multi-Purpose Machines on Occupational Safety

Maksim V. Grichishin¹✉, Besarion Ch. Meskhi² ¹ Rostov State Transport University, Rostov-on-Don, Russian Federation² Don State Technical University, Rostov-on-Don, Russian Federation✉ grichishinmv@rostcsu.ru

EDN: TEIWAE

Abstract

Introduction. Vibration in multi-purpose drilling-milling-boring machines affects equipment reliability, production noise levels, and operator safety. Literature discusses sources of vibration, damping mechanisms, and methods for measuring vibration characteristics, while regulatory documents establish permissible levels of vibration acceleration and vibration velocity. However, the frequency dependencies of vibration energy loss factors for individual machine components, which are necessary for engineering vibration forecasting, remain insufficiently studied. The aim of this research is to evaluate vibration energy loss factors in the components of multi-purpose drilling-milling-boring machines and analyze their effect on the level of vibration affecting the operator, thereby substantiating measures to improve occupational safety. The objectives included conducting octave-band measurements, performing regression analysis of the data, and selecting relationships with the lowest standard deviation.

Materials and Methods. This study utilized an integrated approach combining experimental measurements and mathematical data processing methods. Experiments were conducted on a dedicated test bench and directly on the machine using a torque hammer to excite vibrations. Vibration acceleration was recorded in octave frequency bands using modern measuring equipment. Vibrational energy loss coefficients (η) were calculated using a modified formula that took into account vibration acceleration levels. To summarize the experimental data and construct predictive models, regression analysis was used, including approximation by nonlinear functions and polynomials of varying degrees. The quality of the approximation was assessed using the minimum standard deviation criterion.

Results. It was experimentally established that the loss coefficients for cast iron housing parts in the frequency range from 125 to 8000 Hz varied within the range of $(7.8\text{--}8.8) \cdot 10^{-3}$, demonstrating a weak frequency dependence. For engineering calculations, constant value of $\eta \approx 8 \cdot 10^{-3}$ could be adopted. Regression analysis revealed that the best approximating relationship for the gearbox housing was a sixth-order polynomial. Specific relationships were obtained for the cutting units: for boring and drilling, the best fit was provided by a seventh-order polynomial, and for the milling unit, by a fifth-order polynomial. The resulting mathematical models accurately described the behavior of loss coefficients within the studied frequency range.

Discussion. The analysis of the results confirmed that the dissipative properties of machine structural elements were not constant and depended significantly on the type of technological operation and frequency range. The identified analytical relationships allowed us to move from point estimates at fixed frequencies to continuous energy loss prediction, which was critical for analyzing the dynamic behavior of the machine at its natural frequencies. This opens up opportunities for targeted design. Knowing the frequency spectrum of the most hazardous vibration modes, we can optimize damping specifically in these areas. For example, we can select materials with increased internal friction, or use composite vibration-absorbing coatings in specific structural areas.

Conclusion. This study provides tools for quantitative assessment of vibrational energy loss coefficients for the main vibration sources in multi-purpose machine tools. The potential practical significance of this work lies in the possibility of using the derived regression relationships to develop active and passive vibration control algorithms, design damping systems, and select materials. Implementation of these findings will reduce noise and vibration levels in work areas, minimize the risk of occupational illnesses for operators, and improve overall occupational safety. Additionally, it will extend equipment life by reducing the vibration loads on components. The practical significance of this work lies in its potential for use in developing vibration control algorithms, which will significantly reduce noise levels in work areas.

Keywords: occupational safety, vibrational energy loss coefficient, cutting units during boring, drilling and milling, dissipative properties of distributed structures

For Citation. Grichishin MV, Meskhi BCh. The Impact of Assessing the Vibrational Energy Loss Coefficients of Multi-Purpose Machines on Occupational Safety. *Safety of Technogenic and Natural Systems*. 2026;10(3):193–205. <https://doi.org/10.23947/2541-9129-2026-10-3-193-205>

Оригинальное эмпирическое исследование

Влияние оценки коэффициентов потерь колебательной энергии многоцелевых станков на безопасность труда

М.В. Гричишин¹✉, Б.Ч. Месхи² 

¹ Ростовский государственный университет путей сообщения, г. Ростов-на-Дону, Российская Федерация

² Донской государственный технический университет, г. Ростов-на-Дону, Российская Федерация

✉ grichishinmv@rostcsm.ru

Аннотация

Введение. Вибрация сверлильно-фрезерно-расточных станков снижает надёжность оборудования, повышает уровень производственного шума и влияет на безопасность операторов. В литературе широко представлены источники колебаний, механизмы демпфирования и методы измерения вибрационных характеристик, а нормативными документами установлены допустимые уровни виброускорения и виброскорости. Вместе с тем недостаточно изучены частотные зависимости коэффициентов потерь колебательной энергии отдельных узлов станка, необходимые для инженерного прогнозирования вибрации. Цель настоящей работы — оценка коэффициентов потерь колебательной энергии в элементах многоцелевых сверлильно-фрезерно-расточных станков и анализ их влияния на уровень вибрации, воздействующей на оператора, для обоснования мероприятий по повышению безопасности труда. Для достижения этой цели были проведены измерения в октавных полосах, применен регрессионный анализ данных и выбраны зависимости с наименьшим среднеквадратическим отклонением.

Материалы и методы. В ходе работы был применен комплексный подход, сочетающий экспериментальные измерения и методы математической обработки данных. Эксперименты проводились на специальном стенде и непосредственно на станке с использованием динамометрического молоточка для возбуждения колебаний. Регистрация виброускорения осуществлялась в октавных полосах частот современной измерительной аппаратурой. Коэффициенты потерь колебательной энергии (η) рассчитывались по модифицированной формуле, учитывающей уровни виброускорения. Для обобщения экспериментальных данных и построения прогнозных моделей использовался регрессионный анализ на основе аппроксимации нелинейными функциями и полиномами разных степеней. Качество аппроксимации оценивалось по критерию минимального среднеквадратического отклонения.

Результаты исследования. Экспериментально установлено, что коэффициенты потерь для корпусных деталей из чугуна в диапазоне частот от 125 до 8000 Гц варьируются в пределах $(7,8–8,8) \cdot 10^{-3}$, демонстрируя слабую частотную зависимость. Для инженерных расчетов может быть принято постоянное значение $\eta \approx 8 \cdot 10^{-3}$. Регрессионный анализ показал, что наилучшей аппроксимирующей зависимостью для корпуса редуктора является полином шестого порядка. Для узлов резания получены частные зависимости: при растачивании и сверлении наилучшее соответствие обеспечивает полином седьмого порядка, а для узла фрезерования — полином пятого порядка. Разработанные математические модели с высокой точностью описывают поведение коэффициентов потерь в исследуемом частотном диапазоне.

Обсуждение. Анализ результатов подтверждает, что диссипативные свойства конструктивных элементов станка не являются постоянными и существенно зависят от типа технологической операции и частотного диапазона. Выявленные аналитические зависимости позволяют перейти от точечных оценок на фиксированных частотах к непрерывному прогнозированию потерь энергии, что критически важно для анализа динамического поведения станка на собственных частотах колебаний. Это открывает возможности для целенаправленного проектирования: зная частотный спектр наиболее опасных с точки зрения вибрации режимов, можно оптимизировать демпфирование именно в этих областях, например, за счет выбора материалов с повышенным внутренним трением или за счет применения композитных вибропоглощающих покрытий в определенных зонах конструкции.

Закключение. Проведенное исследование позволило получить инструментарий для количественной оценки коэффициентов потерь колебательной энергии основных источников вибрации многоцелевых станков. Практическая значимость работы заключается в возможности использования выведенных регрессионных зависимостей при разработке алгоритмов активного и пассивного контроля вибрации, проектировании демпфирующих систем и выборе материалов. Внедрение в практику данных наработок позволит снизить уровни шума и вибрации в рабочих зонах, минимизировать риск профессиональных заболеваний операторов и повысить общую безопасность труда, одновременно способствуя увеличению ресурса оборудования за счет снижения вибрационных нагрузок на его элементы. Результаты могут быть полезны при создании алгоритмов контроля вибрации, что позволит значительно снизить уровень шума и вибрации на рабочих местах.

Ключевые слова: безопасность труда, коэффициент потерь колебательной энергии, узлы резания при растачивании, сверлении и фрезеровании, диссипативные свойства распределенных конструкций

Для цитирования. Гричишин М.В., Месхи Б.Ч. Влияние оценки коэффициентов потерь колебательной энергии многоцелевых станков на безопасность труда. *Безопасность техногенных и природных систем*. 2026;10(3):193–205. <https://doi.org/10.23947/2541-9129-2026-10-3-193-205>

Introduction. The vibration of drilling-milling-boring machines has a significant impact on the reliability of equipment, the accuracy of machining, noise levels, and the safety of the operators' working conditions [1]. An analysis of failures in CNC metal-cutting equipment has shown that up to 30–40 % of unscheduled stops are due to the degradation of spindle units and bearing supports, which develop under increased vibration loads, and the costs of repairing a spindle unit account for a significant share of the equipment's cost [2]. An increase in oscillation amplitude in the cutting zone by tens of percent leads to an increase in surface roughness by one to two classes, and a reduction in tool life by 1.5–2 times. This directly affects production costs. In the structure of occupational diseases in mechanical engineering, vibration-related illness consistently ranks among the leading causes. Its share in the number of newly identified occupational diseases in the industry, according to various estimates, is between 15 and 25%.

A distinctive feature of multi-purpose machines is the wide range of operating rotation speeds, cutting modes, and types of operations. This determines the complex and varied nature of the generation and transmission of vibrational energy within the structure, making the use of general vibration protection systems more difficult.

Vibration intensity in a machine tool is determined by the energy transmission, transformation, and dissipation processes in the “machine tool — unit — instrument — workpiece” system. Some of the energy introduced into the system is used for the useful work of cutting, but the excess energy is converted into vibrational processes and is dissipated due to internal friction in materials, guides, bearings, joint damping, and bolted connections, as well as due to the interaction of structural elements with each other. The main sources of vibration excitation include dynamic forces and impact loads during cutting, imbalances in rotating parts, and operations of hydraulic and pneumatic systems. Aerodynamic processes in cooling and chip removal systems also contribute to vibration. The specified factors cause oscillations in the spindle unit, table, bed, and housing parts. The distribution of vibrational energy between these parts depends not only on their mass and stiffness, but also on their dissipative properties, which dynamically change with variations in excitation frequency and processing modes.

A quantitative characteristic of dissipative properties is vibrational energy loss coefficient η (eta), which is related to relative damping by equation $\eta = 2\xi$ and to resonance quality factor $Q = 1/\eta$. This allows us to determine the ability of different components to dissipate vibrational energy and identify weak points in a structure that are most likely to experience increased vibration and risk of failure [3].

Research into the vibration of metal-cutting machines is progressing in several different directions. One area of focus is related to cutting process stability. Based on the theory of regenerative self-oscillations, stability diagrams (radar charts) have been constructed that allow for the selection of optimal rotation speed and cutting depth to prevent self-oscillations. These models describe the conditions for emergence of oscillations, but they include the damping level as an integral part of the overall system, without considering the contributions of individual components. The second area of focus involves the work on experimental modal identification of machine tool systems, in which natural frequencies, vibration modes, and damping coefficients are determined using half-power method, logarithmic decrement of damping, or by measuring the rate of decay of oscillation levels. It has been shown that up to 80–90 % of energy dissipation in the machine tool beds and structural parts occurs at joints and moving interfaces, rather than due to internal friction in the material. The third direction of research includes studies on vibration diagnostics and the standardization of equipment technical condition, focusing on measuring vibration speed and vibration acceleration at control points and comparing them to permissible levels [4].

A common limitation of the research areas listed above is that the assessment results primarily consist of the resulting vibration parameters (amplitude, vibration speed, vibration acceleration, spectrum, and natural frequencies), while loss coefficient η remains either an averaged value across the system or is determined in narrow frequency intervals near individual resonances. This is due to methodological reasons: measuring η over a wide frequency range requires separate excitation and recording of oscillations of specific components under conditions close to the operating ones, while on a running machine the excitation spectrum is non-stationary and includes the superposition of several sources. As a result, the literature contains virtually no systematic data on frequency dependencies of η for structural parts and cutting units of multi-purpose machines in respect to various types of machining — boring, drilling, and milling. This, in turn, does not allow for the development of engineering models that predict the level of vibration in the operator's work area, taking into account the dissipative properties of individual structural elements. This circumstance constitutes a gap in scientific knowledge, which acquires practical significance when referring to the regulatory framework. The current requirements and regulations do not provide the dissipative characteristics of the structure, but rather the final consequence of their operation — the levels of vibration transmitted to the operator. The maximum permissible values of vibration speed and vibration acceleration are established by SanPiN 1.2.3685-21 "Hygienic Standards and Requirements for Ensuring the Safety and (or) Harmlessness of Environmental Factors for Humans"¹ and the relevant standards. Thus, the standards indirectly impose the requirements for the minimum necessary damping precisely in those frequency ranges that are most hazardous for the worker. However, it is impossible to move from the regulated vibration levels to the justified requirements for damping in components without knowledge of frequency dependencies of η — that is, without filling in the identified knowledge gap. It is precisely this logical link "dissipative properties of the component — vibration level at the workplace — occupational safety requirements" that defines the goal and objectives of this work. Thus, the aim of the presented research is to assess vibrational energy loss coefficients in the components of drilling-milling-boring machines and to analyze their impact on the vibration levels affecting the operator, in order to substantiate measures to reduce occupational risk and improve workplace safety.

To achieve this goal, we need to solve the following tasks:

1. Analyze the main sources of vibration excitation and the mechanisms of dissipating vibrational energy in multi-purpose drilling, milling, and boring machines, as well as the current requirements for limiting the vibration impact on the operator. Determine in which frequency ranges the regulatory limits are most stringent.
2. Conduct experimental assessments of the coefficients of vibrational energy loss η for the main components of machine tools — body parts and cutting units — during boring, drilling, and milling within a frequency range that covers the standardized octave bands.
3. Perform regression analysis of the collected data using a range of approximating functions (linear, power, logarithmic, exponential, and fractional rational), and select analytical dependencies $\eta(f)$ suitable for engineering calculations based on statistical adequacy criteria.
4. Based on the obtained dependencies, assess the contribution of the dissipative properties of individual components to the formation of vibration levels in the operator's work area, identify frequency ranges and components that are critical in terms of exceeding permissible levels, and determine measures to reduce vibration exposure, occupational risk, and increase damping of joints. Adjust processing modes and implement organizational measures.

Practical significance of this work lies in the fact that the identified frequency dependencies η will make it possible to move from the diagnostic assessment of vibration levels to predicting the vibrational environment at the workplace. This, in turn, will enable us to select vibration-suppression solutions that not only reduce the risk of vibration-related health problems for operators but also increase the service life of equipment.

Materials and Methods. The engineering calculations took into account the vibrational energy loss coefficients, based on the results of the thematic processing of experimental data obtained on a special test bench, which is described in detail in [5]. Vibrations were excited using a special dynamometric hammer [6]. The measurements recorded vibration acceleration levels in the third to ninth octaves at the moment of impact and after three seconds [7].

In the calculations for cast iron body parts, experimental studies were conducted on plates with a thickness of 10–25 mm. These studies showed that the difference in numerical values was not more than 10–12%, which, when converted to vibration levels, amounted to $10 \lg 1.2 = 0.8$ dB. The calculation of the vibrational energy loss coefficient was conducted using formula [8]:

$$\eta = \frac{\ln \frac{A_k}{A_i}}{f_i \pi t} \quad (1)$$

¹ SanPiN 1.2.3685-21. *Hygienic Standards and Requirements for Ensuring the Safety and (or) Harmlessness of Environmental Factors for Humans.* (In Russ.) URL: https://www.consultant.ru/document/cons_doc_LAW_375839/e66874e0ad1f04c3a48e95cd16355056937feded/ (accessed: 10.08.2026)

Since time (t) was two seconds, relationship (1) took the form:

$$\eta = 0,16 \frac{\ln \frac{L_{ak}}{L_{ai}}}{f_i}, \quad (2)$$

where A_k and A_i — oscillation amplitudes at the beginning and end of the measurements; f_i — oscillation frequencies, Hz; t — time from turning on to turning off the electromagnet, s; L_{ak} and L_{ai} — vibration acceleration levels (dB) at the end and the beginning of the measurement cycle [9].

In practice, it was not the oscillation amplitudes that were measured, but the vibration acceleration levels. Given the characteristics of modern measuring equipment (Ekopfizika, Assistant, and Oktava), it was advisable to measure the octave levels of vibration acceleration [10]. Vibration acceleration was recorded in octave frequency bands using modern measuring equipment, while vibration acceleration levels were determined by the formula:

$$L_a = 20 \lg \frac{\alpha}{3 \cdot 10^{-4}},$$

where acceleration amplitude was determined as $\alpha = 3 \cdot 10^{-4} \cdot 10^{0,05 L_a}$.

Accordingly, $\alpha = A \cdot f_i^2$, then relationship (2) took the form:

$$\eta = 0,1 \frac{\ln 10^{0,05(L_{ak}-L_{ai})}}{f_i} = 0,1 \cdot 2,3 \frac{\lg 10^{0,05 L_{ak}}}{f_i} = 10^{-2} \frac{L_{ak}}{f_i}. \quad (3)$$

Thus, vibrational energy loss coefficients (η) were calculated using a modified formula that took into account vibration acceleration levels. For octave bands, the loss coefficients were calculated as follows:

$$\eta_{31,5} = 3,17 \cdot 10^{-4} \cdot L_{a31,5}$$

$$\eta_{63} = 1,6 \cdot 10^{-4} \cdot L_{a63}$$

$$\eta_{125} = 8 \cdot 10^{-5} \cdot L_{a125}$$

$$\eta_{250} = 1 \cdot 10^{-5} \cdot L_{a250}$$

$$\eta_{500} = 2,1 \cdot 10^{-5} \cdot L_{a500}$$

$$\eta_{1000} = 1 \cdot 10^{-5} \cdot L_{a1000}$$

$$\eta_{2000} = 5 \cdot 10^{-6} \cdot L_{a2000}$$

$$\eta_{4000} = 2,5 \cdot 10^{-6} \cdot L_{a4000}$$

$$\eta_{8000} = 1,25 \cdot 10^{-6} \cdot L_{a8000}$$

To summarize the experimental data and build predictive models, regression analysis was used, which included approximation using nonlinear functions and polynomials of various degrees. Using algebraic techniques and variable substitution, these nonlinear functions could be transformed quite easily into a linear form, which allowed obtaining regression coefficients for nonlinear functions using the least squares method. However, for some functions, it was necessary to remember the inverse transformation in order to obtain accurate values for the regression coefficients [11].

Thus, it was possible to obtain a number of different analytical relationships for the same set of data. With the help of computing technology, we calculated the regression coefficients for all possible functions, analyzed their accuracy relative to the original data, and chose the most adequate one. As a measure of the accuracy of analytical dependencies, it was proposed to use a parameter such as the root-mean-square deviation:

$$\sigma = \sqrt{\frac{1}{(n-m)-1} \sum_{i=1}^n (y_{\vartheta_i} - y_i)^2}, \quad (4)$$

where n — amount of experimental data; m — polynomial degree; y_{ϑ_i} — function value in the experiment; y_i — calculated value based on the obtained dependence. This parameter took into account not only the total deviation but also the polynomial degree, that is, it refined the polynomial influence. By calculating the root-mean-square deviation for all analytical dependencies obtained, it was possible to determine the most adequate function based on the minimum value of the parameter. If the calculations of regression coefficients and the root-mean-square deviation were accompanied by graphing, the accuracy analysis could be verified visually [12].

Research Results. Table 1 and Figure 1 provide the measurement results for the conditions when the gearbox housing was installed on a bench and on a machine table. It should be noted that when installing the machine on a table, the numerical value of the loss coefficients was 7–8% higher than when installed on the bench, due to different reduced stiffness. Moreover, the difference in the numerical values of the above octaves did not exceed 6%. This circumstance made it possible to use a constant value of the vibrational energy loss coefficient for the convenience of engineering calculations of vibroacoustic characteristics $\eta = 8.5 \cdot 10^{-3}$.

Table 1

Experimental data on vibrational energy loss coefficients (η) of the gearbox housing

Measurement conditions	Numerical values of loss coefficients ($\eta \cdot 10^{-3}$) in octave frequency ranges (Hz)						
	125	250	500	1000	2000	4000	8000
On the special bench	7.8	7.8	8.1	7.9	7.8	8.0	8.0
On the machine table	8.1	8.2	8.8	8.6	8.4	8.7	8.6

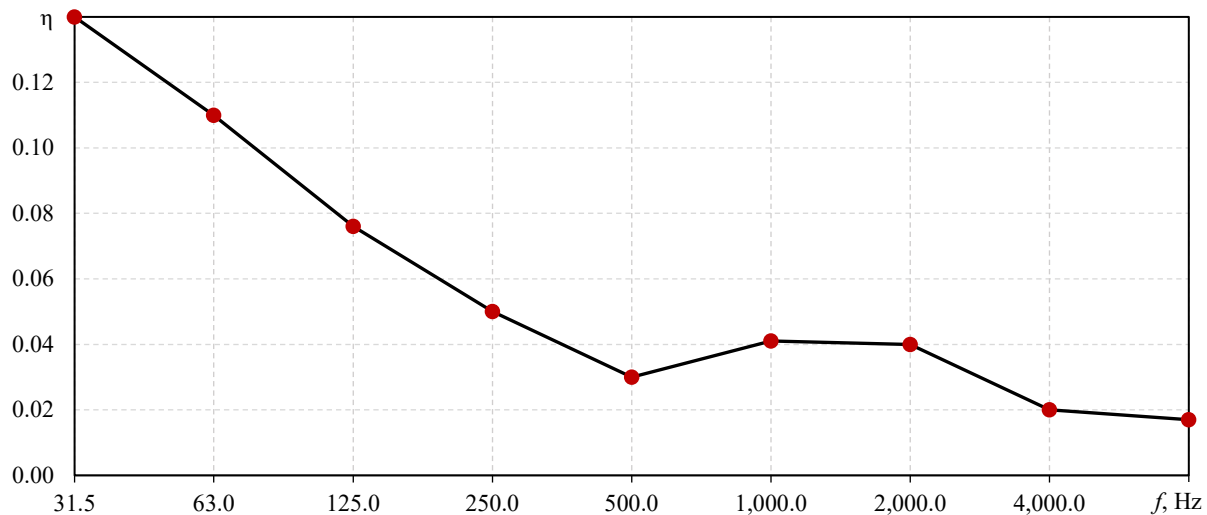


Fig. 1. Vibrational energy loss coefficients of the gearbox housing

Vibrational energy loss coefficients (η) were calculated using a modified formula that took into account vibration acceleration levels. Regression analysis was applied to generalize experimental data and create predictive models, including approximation by nonlinear functions and polynomials of varying degrees. Visual confirmation of the accuracy analysis was possible if the calculations of the regression coefficients and the standard deviation were accompanied by plotting [13].

The results of calculating the regression coefficients of the gearbox housing for various analytical dependencies presented in Tables 2 and 3, and also in Figures 2 and 3.

Table 2

Results of regression analysis by nonlinear functions

Name of the curve	Equation	Standard deviation (RMSD)
Exponential	$\eta = 0.068e^{2.2 \cdot 10^{-4} f}$	$2.11 \cdot 10^{-2}$
Power	$\eta = 0.504 f^{-0.41}$	$8.42 \cdot 10^{-3}$
Hyperbolic type I	$\eta = 0.034 + \frac{4.2}{1.1 f}$	$6.51 \cdot 10^{-3}$
Hyperbolic type II	$\eta = \frac{1}{40.22 + 0.022 f}$	$4.2 \cdot 10^{-2}$

Hyperbolic type III	$\eta = \frac{1}{-4722 + 90.316f}$	$0.14 \cdot 10^{-2}$
Logarithmic	$\eta = 0.21 - 0.024 \cdot \ln f$	$1.82 \cdot 10^{-2}$
S-shaped	$\eta = e^{\frac{-4.173 + 62.235}{f}}$	$2.04 \cdot 10^{-2}$
Inverse logarithmic	$\eta = \frac{1}{-6.0 + 18.19 \cdot \ln f}$	$7.5 \cdot 10^{-2}$

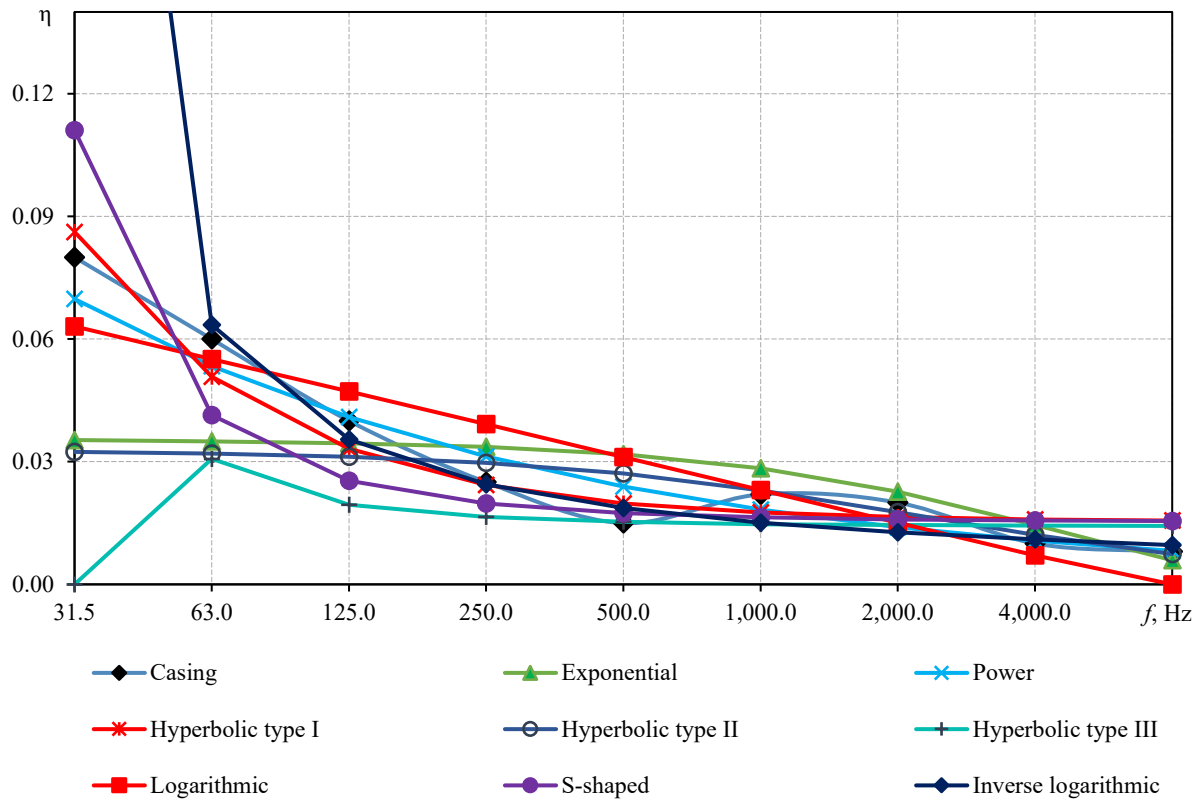


Fig. 2. Approximation by nonlinear functions

Table 3

Results of regression analysis by polynomials

Degree	Equation	RMSD
1	$\eta = 0.012 - 0.032(\lg f)$	$2.4 \cdot 10^{-2}$
2	$\eta = 0.4 - 0.12(\lg f) + 0.02(\lg f)^2$	$7.13 \cdot 10^{-3}$
3	$\eta = 0.4 - 0.4(\lg f) + 0.15(\lg f)^2 - 0.01(\lg f)^3$	$5.4 \cdot 10^{-3}$
4	$\eta = 0.1 - 0.21(\lg f) + 0.24(\lg f)^2 - 0.811(\lg f)^3 - 0.0078(\lg f)^4$	$5.6 \cdot 10^{-3}$
5	$\eta = -2.2 + 4.5(\lg f) - 4.1(\lg f)^2 + 1.8(\lg f)^3 - 0.285(\lg f)^4 - 0.0205(\lg f)^5$	$4.13 \cdot 10^{-3}$
6	$\eta = 6.2 - 15.4(\lg f) + 16.8(\lg f)^2 + 9.1(\lg f)^3 + 3.12(\lg f)^4 - 0.51(\lg f)^5 + 0.032(\lg f)^6$	$7.8 \cdot 10^{-3}$
7	$\eta = 9.11 - 125.1(\lg f) + 27.3(\lg f)^2 - 16.07(\lg f)^3 + 6.2(\lg f)^4 - 1.8(\lg f)^5 + 0.24(\lg f)^6 - 0.0051(\lg f)^7$	$3.3 \cdot 10^{-3}$

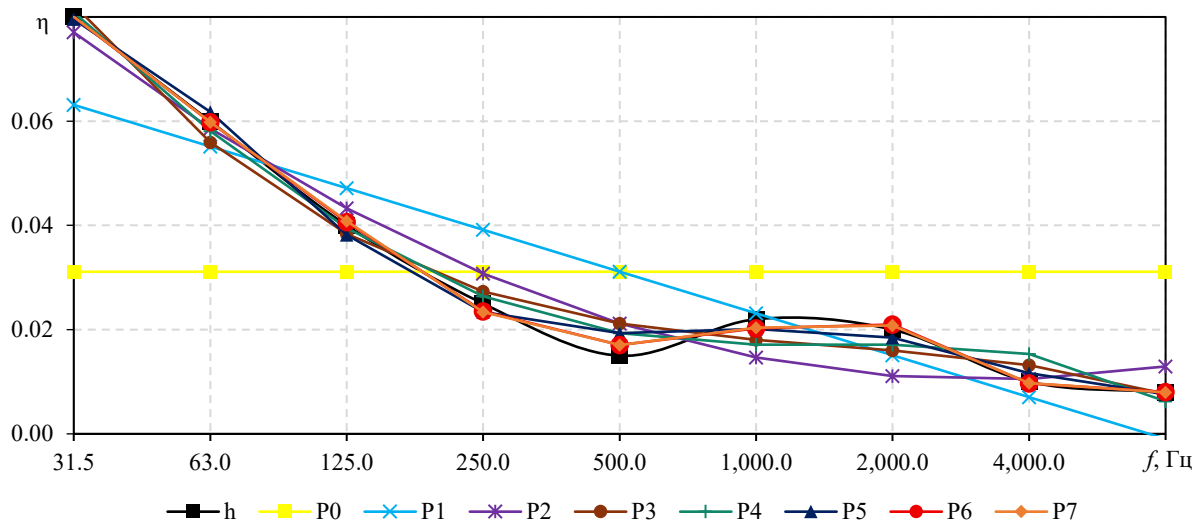


Fig. 3. Approximation by polynomials

It was experimentally found that the loss coefficients for cast iron body parts in the frequency range from 125 to 8000 Hz ranged within $(7.8\text{--}8.8) \cdot 10^{-3}$, indicating a weak frequency dependency. For engineering calculations, constant value $\eta \approx 8 \cdot 10^{-3}$ could be assumed. Regression analysis revealed that the best approximating dependence for the gearbox housing was a sixth-order polynomial.

Having analyzed the results, we could conclude that the best analytical relationship was a sixth-order polynomial:

$$\eta = 6.1 - 15.21(\lg f) + 16.1(\lg f)^2 + 9.33(\lg f)^3 + 3.25(\lg f)^4 - 0.54(\lg f)^5 + 0.036(\lg f)^6. \quad (5)$$

Cutting units during boring and drilling. The results of calculating the loss coefficients of cutting units during boring and drilling operations are presented in Figure 4.

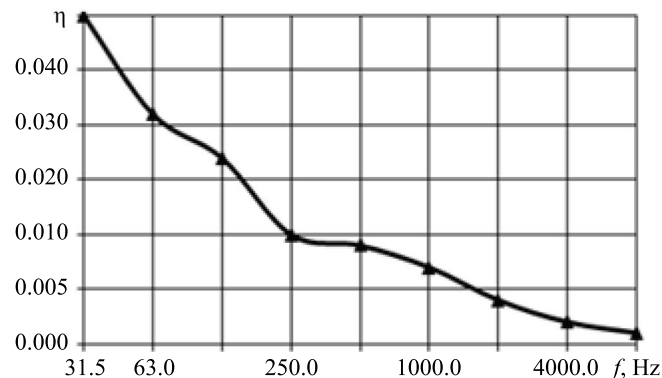


Fig. 4. Coefficients of loss of the cutting units during boring and drilling

The results of the regression coefficients calculation are presented in Tables 4 and 5, as well as in Figures 5 and 6.

Table 4

Results of regression analysis by nonlinear functions

Name of the curve	Equation	RMSD
Exponential	$\eta = 0.016e^{3.82 \cdot 10^{-4} f}$	$7.12 \cdot 10^{-3}$
Power	$\eta = 0.34 f^{-0.676}$	$3.14 \cdot 10^{-3}$
Hyperbolic type I	$\eta = 0.062 + \frac{0.866}{f}$	$3.57 \cdot 10^{-3}$
Hyperbolic type II	$\eta = \frac{1}{41 + 0.14 f}$	$3.34 \cdot 10^{-3}$
Hyperbolic type III	$\eta = \frac{1}{-14.5 + 350.7 f}$	$1.97 \cdot 10^{-2}$

Logarithmic	$\eta = 0.052 - 0.00057 \cdot \ln f$	$3.42 \cdot 10^{-3}$
S-shaped	$\eta = e^{-5.478 + \frac{77.777}{f}}$	$9.12 \cdot 10^{-3}$
Inverse logarithmic	$\eta = \frac{1}{-602.7 + 133.1 \cdot \ln f}$	$2.87 \cdot 10^{-2}$

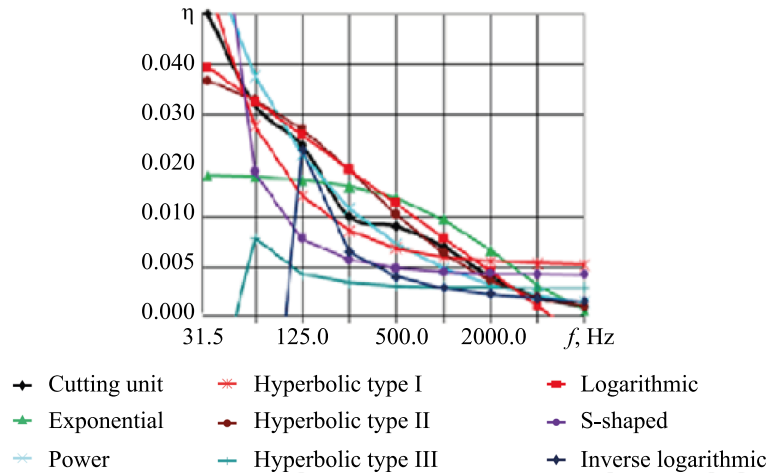


Fig. 5. Approximation by nonlinear functions

Table 5

Results of regression analysis by polynomials

Degree	Equation	RMSD
1	$\eta = 0.041 - 0.015(\lg f)$	$4.55 \cdot 10^{-2}$
2	$\eta = 0.11 - 0.061(\lg f) + 0.0072(\lg f)^2$	$2.52 \cdot 10^{-3}$
3	$\eta = 0.419 - 0.158(\lg f) + 0.571(\lg f)^2 - 0.0051(\lg f)^3$	$1.71 \cdot 10^{-3}$
4	$\eta = 0.44 - 0.59(\lg f) + 0.37(\lg f)^2 - 0.091(\lg f)^3 - 0.0064(\lg f)^4$	$1.02 \cdot 10^{-3}$
5	$\eta = 0.88 - 1.41(\lg f) + 1.1(\lg f)^2 - 0.41(\lg f)^3 + 0.062(\lg f)^4 - 0.0036(\lg f)^5$	$9.06 \cdot 10^{-4}$
6	$\eta = -1.57 + 4.91(\lg f) - 5.12(\lg f)^2 + 3.21(\lg f)^3 - 0.98(\lg f)^4 - 0.16(\lg f)^5 + 0.0091(\lg f)^6$	$4.94 \cdot 10^{-4}$
7	$\eta = -8.2 + 23.5(\lg f) - 27.8(\lg f)^2 + 17.9(\lg f)^3 - 6.96(\lg f)^4 + 1.51(\lg f)^5 + 0.198(\lg f)^6 + 0.0092(\lg f)^7$	$2.12 \cdot 10^{-4}$

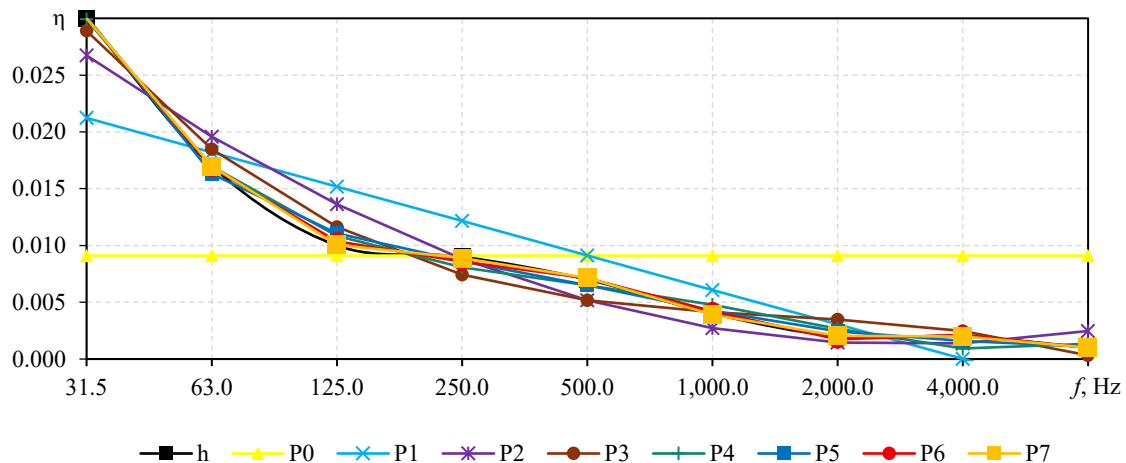


Fig. 6. Approximation by polynomials

After analyzing the results for the cutting units, it became obvious that the best analytical dependence would be a seventh-order polynomial

$$\eta = -8.21 + 23.2(\lg f) - 27.8(\lg f)^2 + 18.12(\lg f)^3 - 7.07(\lg f)^4 + 1.54(\lg f)^5 - 0.19(\lg f)^6 + 0.0079(\lg f)^7. \quad (6)$$

Cutting unit during milling. The results of calculating the loss coefficients of the milling unit are shown in Figure 7.

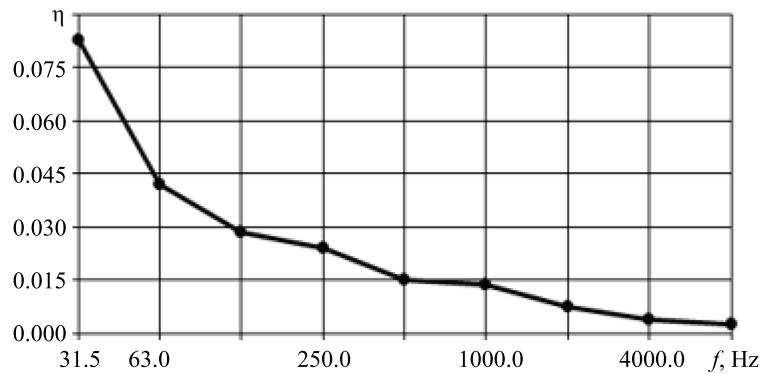


Fig. 7. Loss coefficients of the milling unit

The results of calculating the regression coefficients of the milling unit are presented in Tables 6 and 7, as well as in Figures 8 and 9.

Table 6

Results of regression analysis by nonlinear functions

Name of the curve	Equation	RMSD
Exponential	$\eta = 0.03e^{-3.153f}$	$1.98 \cdot 10^{-2}$
Power	$\eta = 0.62f^{-0.6}$	$3.05 \cdot 10^{-3}$
Hyperbolic type II	$\eta = 0.007 + \frac{1.57}{f}$	$3.01 \cdot 10^{-3}$
Hyperbolic type I	$\eta = \frac{1}{41.2 + 0.11f}$	$1.24 \cdot 10^{-2}$
Hyperbolic type III	$\eta = \frac{1}{-10400 + 261f}$	$2.98 \cdot 10^{-2}$
Logarithmic	$\eta = 0.088 - 0.0091 \cdot \ln f$	$8.5 \cdot 10^{-3}$
S-shaped	$\eta = e^{-6.01 + \frac{90.2}{f}}$	$1.22 \cdot 10^{-2}$
Inverse logarithmic	$\eta = \frac{1}{-420.5 + 97.08 \cdot \ln f}$	$4.07 \cdot 10^{-2}$

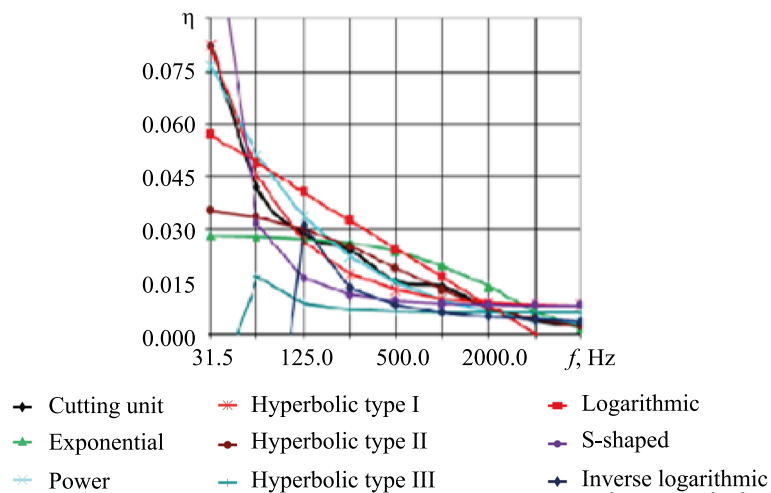


Fig. 8. Approximation by nonlinear functions

Table 7

Results of regression analysis by polynomials

Degree	Equation	RMSD
1	$\eta = 0.089 - 0.022(\lg f)$	$9.1 \cdot 10^{-3}$
2	$\eta = 0.16 - 0.1(\lg f) + 0.03(\lg f)^2$	$5.78 \cdot 10^{-3}$
3	$\eta = 0.52 - 0.34(\lg f) + 0.11(\lg f)^2 - 0.016(\lg f)^3$	$3.68 \cdot 10^{-3}$
4	$\eta = 1.01 - 1.08(\lg f) + 0.64(\lg f)^2 - 0.15(\lg f)^3 + 0.018(\lg f)^4$	$1.97 \cdot 10^{-3}$
5	$\eta = 1.72 - 2.91(\lg f) + 1.98(\lg f)^2 - 0.81(\lg f)^3 + 0.18(\lg f)^4 - 0.0087(\lg f)^5$	$1.65 \cdot 10^{-3}$
6	$\eta = 3.94 - 8.07(\lg f) + 7.61(\lg f)^2 + 3.85(\lg f)^3 + 1.1(\lg f)^4 - 0.17(\lg f)^5 + 0.0075(\lg f)^6$	$1.71 \cdot 10^{-4}$
7	$\eta = 0.74 - 7.12(\lg f) + 5.88(\lg f)^2 - 2.35(\lg f)^3 + 0.41(\lg f)^4 - 0.021(\lg f)^5 - 0.011(\lg f)^6 + 0.001(\lg f)^7$	$2.15 \cdot 10^{-4}$

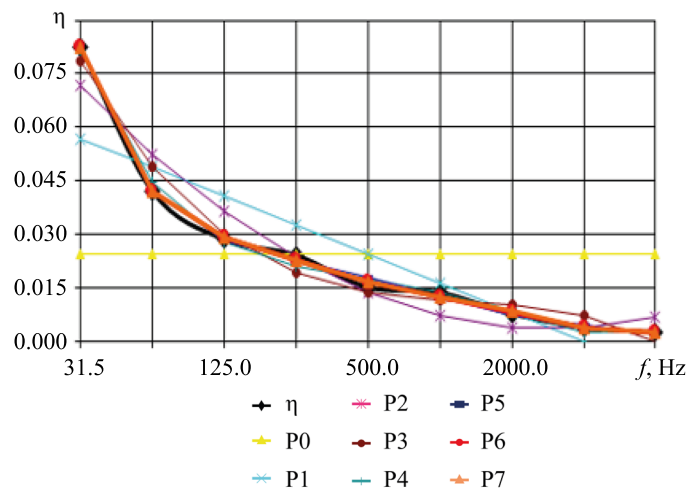


Fig. 9. Approximation by polynomials

For the milling unit, the best matching was provided by a fifth-order polynomial

$$\eta = 1.81 - 2.95(\lg f) + 1.98(\lg f)^2 - 0.71(\lg f)^3 + 0.18(\lg f)^4 - 0.0081(\lg f)^5. \quad (6)$$

Discussion. The analysis of the research results confirms that the dissipative properties of structural elements of the machine are not constant and significantly depend on the type of technological operation and frequency range. The revealed analytical dependencies make it possible to move from point estimates at fixed frequencies to continuous prediction of energy losses, which is critically important for analyzing the dynamic behavior of the machine at natural oscillation frequencies. This opens up opportunities for targeted design. Knowing the frequency spectrum of the most hazardous vibration modes, it is possible to optimize damping in these areas. For example, we can choose materials with increased internal friction or use composite vibration-absorbing coatings in specific areas of the structure.

Conclusion. The regression analysis allowed us to determine analytical dependencies of the vibrational energy loss coefficients of noise and vibration sources during the operation of drilling-milling-boring machines. These dependencies make it possible to determine the value of the loss coefficient not only at geometric mean frequencies of the octave spectrum, but also at natural oscillation frequencies. Using the equations presented in this paper, we can accurately estimate the amount of vibrational energy losses at various frequencies, which will make it possible to purposefully apply vibration isolation and vibration damping methods. In particular, a more efficient design of damping elements and the choice of optimal materials for the manufacture of mills and other load-bearing structures of machine tools is possible [11]. The results can be useful in creating vibration control algorithms, which will significantly reduce noise and vibration levels in the workplace.

References

1. Alekseev MV, Smychok IA, Chukarin AN, Finochenko TA. Analysis of Working Conditions of Employees at Transport Engineering Enterprises. *Trudy Rostovskogo Gosudarstvennogo Universiteta Putey Soobseniya*. 2024;3(68):6–12. (In Russ.) https://doi.org/10.46973/1818-5509_2024_3_6
2. Mekhi BCh. *Improving the Working Conditions of Operators of Metal-Cutting and Woodworking Machines by Reducing Noise in the Working Area (Theory and Practice)*. Rostov-on-Don: DSTU Publishing center; 2003. 131 p. (In Russ.)
3. Grichishin MV, Chukarin AN. Experimental Studies of the Spectral Composition of Noise during Boring of Drilling-Milling-Boring Machine. *Trudy Rostovskogo Gosudarstvennogo Universiteta Putey Soobseniya*. 2025;(3):24–32. (In Russ.) https://doi.org/10.46973/1818-5509_2025_3_24
4. Razakov ZhP, Grichishin MV, Finochenko TA, Chukarin AN. Vibroacoustic Dynamics of Gearboxes of Drilling-Milling Boring Machines with Multi-Speed Electric Motors. *Noise Theory and Practice*. 2022;8,2(29):56–62. (In Russ.) URL: <https://clck.ru/3VL4HH> (accessed 10.08.2026)
5. Ryzhov SP, Novikov VV, Khozyaev IA, Chukarin AN. Regressive Dependencies of the Coefficient of Loss of Vibrational Energy of the Main Sources of Goothing Machines. *News of the Tula State University. Technical Sciences*. 2023;(8):398–401. (In Russ.)
6. Chukarina NA, Ruslanov DV, Shamshur SA. Regression Dependences of Vibrational Energy Loss Coefficients of Multilayer Wood Materials. *News of the Tula State University. Technical Sciences*. 2020;(3):65–71. (In Russ.)
7. Chukarina NA, Motrenko DV. Loss Factor of Vibrational Energy for Different Wood Species. *Monitoring. Science and Technologies*. 2019;2(40):66–71. (In Russ.) <https://doi.org/10.25714/MNT.2019.40.010>
8. Shonia DP, Beskopylny AN, Chukarin AN. Determination of Loss Ratio Vibrational Energy for Planing Machine. *News of the Tula State University. Technical Sciences*. 2024;8:263–268. (In Russ.)
9. Chukarin AN, Fedenko AA, Shashurin AE, Vasilyeva V. Regression Analysis of the Coefficients of Vibration Energy Losses in Gas-Discharge Systems of Power Plants. *Akustika*. 2021;(41):115–118. <https://doi.org/10.36336/akustika202141115>
10. Klyuchev VI, Kostin AV, Smirnov AA. *Practical Training in Vibration Diagnostics of Machines*. Moscow: Mashinostroenie; 2018. 240 p. (In Russ.)
11. Korobov SM, Lukashonok VB, Sazonova SA, Finochenko TA. Regression Dependencies of the Dissipative Function of the “Table — Workpiece” System of Metal-Cutting Machines of Various Functional Purpose. *News of the Tula State University. Technical Sciences*. 2026;(2):202–208. (In Russ.)
12. Stuzhenko NI, Sazonova SA, Chukarin AN, Finochenko VA. Assessment of Oscillatory Energy Losses of Spindle Headstocks of Diamond Boring and Grinding Machines. *News of the Tula State University. Technical Sciences*. 2026;2:244–251. (In Russ.)
13. Ryzhov SP, Soldatov AG, Kharlamov OG, Finochenko TA. Experimental Studies of the Spectral Composition of Vibrations of Goothing Machines. *Trudy Rostovskogo Gosudarstvennogo Universiteta Putey Soobseniya*. 2024;(4):31–36. (In Russ.) https://doi.org/10.46973/1818-5509_2024_4_31

About the Authors:

Maksim V. Grichishin, Postgraduate Student, Rostov State Transport University, Senior Lecturer of the Department of Standardization, Certification and Quality Management, Rostov Branch of the Academy for Standardization, Metrology and Certification (58/173, Sokolova Ave., Rostov-on-Don, 344003, Russian Federation), [SPIN-code, grichishinmv@rostcsm.ru](mailto:grichishinmv@rostcsm.ru)

Besarion Ch. Meskhi, Dr. Sci. (Eng.), Professor, Rector, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation), [SPIN-code](#), [ORCID](#), [ScopusID](#), [ResearcherID](#), reception@donstu.ru

Claimed Contributorship:

BCh Meskhi: supervision, writing – review & editing.

MV Grichishin: conceptualization, calculations, writing – original draft preparation.

Conflict of Interest Statement: the authors declare no conflict of interest.

All authors have read and approved the final version of manuscript.

Об авторах:

Максим Владимирович Гричишин, аспирант Ростовского государственного университета путей сообщения, старший преподаватель кафедры «Стандартизация, сертификация и управление качеством» Ростовского филиала Академии стандартизации, метрологии и сертификации (344003, Российская Федерация, г. Ростов-на-Дону, просп. Соколова, 58/173), [SPIN-код, grichishinmv@rostcsm.ru](mailto:grichishinmv@rostcsm.ru)

Бесарион Чохоевич Месхи, доктор технических наук, профессор, ректор Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), [SPIN-код](#), [ORCID](#), [ScopusID](#), [ResearcherID](#), reception@donstu.ru

Заявленный вклад авторов:

Б.Ч. Месхи: научное руководство, анализ результатов исследований, корректировка выводов.

М.В. Гричишин: формирование основной концепции, цели и задачи исследования, проведение расчетов, подготовка текста, формирование выводов.

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 10.06.2026

Reviewed / Поступила после рецензирования 11.07.2026

Accepted / Принята к публикации 23.07.2026

TECHNOSPHERE SAFETY

ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ



UDC 504.3:620.9

Original Empirical Research

<https://doi.org/10.23947/2541-9129-2026-10-3-206-218>

Clustering of Groups of Key Greenhouse Gas-Emitting Countries Based on Economic, Demographic, and Energy Indicators

Oleg A. Loktionov[✉]^{ID}, Daniil O. Maksimov^{ID}, Mikhail A. Zabelin^{ID},Irina A. Beloshitskaya^{ID}National Research University "MPEI"¹, Moscow, Russian Federation✉ maximovdo@mpei.ru

EDN: IRNGWU

Abstract

Introduction. The relevance of this work stems from the need to move away from general decarbonization plans and towards differentiated climate strategies, since countries that emit greenhouse gases (GHGs) differ in terms of their energy balance, level of industrialization, population size, carbon intensity of their economy, and the export of fuel and energy resources. The same emission reduction goals may require different technological, investment, and regulatory solutions. Unification approaches are not effective in this context. The literature mainly focuses on analyzing carbon intensity, low-carbon development scenarios, and individual energy indicators. The fragmentary nature of the known approaches prevents the creation of a typology of GHG-emitting countries based on a combination of economic, demographic, energy, and climatic characteristics. The presented scientific work fills this gap. The aim of this study was to form and interpret the typology of key GHG-emitting countries based on a comprehensive analysis of economic, demographic, energy, and climatic indicators. According to this typology, decarbonization conditions and transitional climate risks within clusters were identified.

Materials and Methods. The research was based on a statistical database for more than 40 GHG-emitting countries. To ensure comparability, data preprocessing, z -score normalization of features, clustering by Ward's hierarchical method, and the combined t -SNE² + k -means³ approach were used. The optimal number of clusters was determined using the elbow method and the silhouette coefficient, and the clustering quality was determined by the Davies–Bouldin index.

Results. Significant cross-country differences in specific greenhouse gas emissions per capita, the carbon intensity of GDP at PPP⁴, the structure of generation capacity, and specific emissions per unit of electricity produced have been identified. Based on the results of hierarchical clustering and t -SNE + k -means, four groups of states were identified:

- two largest emitters with large-scale and diversified energy production;
- four exporters of fuel and energy resources;
- eight carbon-intensive industrial and developing countries;
- 31 relatively energy-efficient and low-carbon economies.

Discussion. Cluster analysis suggested that the absolute amount of GHGs emissions was not the only factor to consider when choosing a climate strategy. Countries with similar carbon footprints could differ significantly in terms of economic scale, the proportion of coal generation, export orientation of the energy complex, industrialization level, energy efficiency, and final energy consumption structure. Each formed cluster required different priorities and approaches for adapting decarbonization strategies, namely: reduction of coal generation and modernization of networks for the largest emitters; reduction of emissions in mining and processing; CCUS⁵ and export diversification for resource economies; improvement of industrial energy efficiency and modernization of generation for industrial countries; elimination of residual emissions and accounting for imported carbon footprint for low-carbon economies. The limitations of the study were related to differences in national statistical reporting, incompleteness of some indicators, and sensitivity of clustering to the choice of variables.

¹ Previously — Moscow Power Engineering Institute.

² Distributed stochastic neighbor embedding. This is a machine learning algorithm for dimensionality reduction and visualization of multidimensional data.

³ k -means method.

⁴ Gross domestic product at purchasing power parity.

⁵ Carbon capture, utilization, and storage.

© Loktionov OA, Maksimov DO, Zabelin MA, Beloshitskaya IA, 2026

Conclusion. The proposed cluster approach makes it possible to move from ranking countries based on emissions to identifying groups with similar profiles of economic, demographic, energy, and climate indicators. The results of clustering can be used in further analysis of key emitting countries to identify the most suitable technologies and legislative measures for reducing greenhouse gas emissions. Additionally, the results can be used to assess the effectiveness of implementing and adapting decarbonization strategies.

Keywords: decarbonization scenario, adaptation of decarbonization strategy, carbon load structure, carbon intensity of the economy, carbon pollution of the country

Funding Information. The research was conducted as part of the project “Development of a Digital Tool for Assessing Transitional Climate Risks and the Potential for Decarbonization of the Energy Industry”, which was supported by a grant from the National Research University “MPEI” for the scientific research program “Priority 2030: Technologies of the Future” in 2024–2026.

For Citation. Loktionov OA, Maksimov DO, Zabelin MA, Beloshitskaya IA. Clustering of Groups of Key Greenhouse Gas-Emitting Countries Based on Economic, Demographic, and Energy Indicators. *Safety of Technogenic and Natural Systems*. 2026;10(3):206–218. <https://doi.org/10.23947/2541-9129-2026-10-3-206-218>

Оригинальное эмпирическое исследование

Формирование кластерных групп ключевых стран-эмитентов парниковых газов в разрезе экономико-демографических и энергетических показателей

О.А. Локтионов[✉]^{ID}, Д.О. Максимов^{ID}, М.А. Забелин^{ID}, И.А. Белошицкая^{ID}

Национальный исследовательский университет «МЭИ», г. Москва, Российская Федерация

✉ maximovdo@mpei.ru

Аннотация

Введение. Актуальность работы связана с необходимостью перехода от общих схем декарбонизации к дифференцированным климатическим стратегиям, поскольку страны-эмитенты парниковых газов (ПГ) различаются по энергобалансу, индустриализации, демографии, углеродоемкости экономики, экспорту топливно-энергетических ресурсов. Одинаковые цели по снижению выбросов могут требовать разных технологических, инвестиционных и регуляторных решений, поэтому унификация неэффективна. В литературе преимущественно анализируются углеродоемкость, сценарии низкоуглеродного развития, отдельные энергетические индикаторы. Фрагментарность известных подходов препятствует созданию типологизации эмитентов по совокупности экономико-демографических, энергетических и климатических признаков. Представленная научная работа восполняет этот пробел. Цель исследования — формирование и интерпретация типологии ключевых страны-эмитентов ПГ на основе комплексного анализа экономико-демографических, энергетических и климатических показателей. По этой типологии определяются условия декарбонизации и переходные климатические риски в рамках кластеров.

Материалы и методы. Исследование основано на статистической базе по более чем 40 странам-эмитентам ПГ. Для обеспечения сопоставимости выполнены предобработка данных, нормализация признаков методом z -преобразования, кластеризация иерархическим методом Уорда и комбинированным подходом t -SNE + k -means. Оптимальное число кластеров определено по методу локтя и коэффициенту силуэта, а качество кластеризации — по индексу Дэвиса-Болдина.

Результаты исследования. Определены существенные межстрановые различия по удельным выбросам парниковых газов на душу населения, углеродоемкости ВВП по ППС, структуре установленной мощности генерации, удельным выбросам на единицу произведенной электроэнергии. По итогам иерархической кластеризации и t -SNE + k -means выделены четыре группы государств:

- два крупнейших эмитента с масштабной и диверсифицированной энергетикой;
- четыре экспортера топливно-энергетических ресурсов;
- восемь углеродоемких индустриальных и развивающихся стран;
- 31 относительно энергоэффективная и низкоуглеродная экономика.

Обсуждение. Анализ кластеров позволяет утверждать, что абсолютный объем выбросов ПГ не является достаточным основанием для выбора климатической стратегии. Страны с близкой углеродной нагрузкой могут существенно различаться по масштабу экономики, доле угольной генерации, экспортной ориентации энергетического комплекса, уровню индустриализации, энергоэффективности и структуре конечного энергопотребления. Для каждого сформированного кластера требуются разные приоритеты и направления адаптации стратегий декарбонизации, а именно: сокращение угольной генерации и модернизация сетей для крупнейших эмитентов; снижение выбросов в добыче и переработке; CCUS и диверсификация экспорта для ресурсных экономик; повышение промышленной энергоэффективности и модернизация генерации для индустриальных стран; устранение остаточных выбросов и учет импортированного углеродного следа для низкоуглеродных экономик. Ограничения исследования связаны с различиями национальной статистической отчетности, неполнотой некоторых показателей и чувствительностью кластеризации к выбору переменных.

Заключение. Предложенный кластерный подход позволяет перейти от ранжирования стран по объему выбросов к выделению групп со схожим профилем экономико-демографических, энергетических и климатических показателей. Результаты кластеризации можно применить в дальнейшем анализе ключевых стран-эмитентов для выявления наиболее подходящих технологий и законодательных мер снижения выбросов парниковых газов. Кроме того, итоги работы подходят для оценки эффективности реализации и адаптации климатических стратегий декарбонизации.

Ключевые слова: сценарий декарбонизации, адаптация стратегии декарбонизации, структура углеродной нагрузки, углеродоемкость экономики, углеродозагрязненность страны

Финансирование. Исследование проводилось в рамках проекта «Разработка цифрового инструмента оценки переходных климатических рисков и потенциала декарбонизации энергетической отрасли» при поддержке гранта НИУ «МЭИ» на реализацию программы научных исследований «Приоритет 2030: Технологии будущего» в 2024–2026 гг.»

Для цитирования. Локтионов О.А., Максимов Д.О., Забелин М.А., Белошицкая И.А. Формирование кластерных групп ключевых стран-эмитентов парниковых газов в разрезе экономико-демографических и энергетических показателей. *Безопасность техногенных и природных систем.* 2026;10(3):206–218. <https://doi.org/10.23947/2541-9129-2026-10-3-206-218>

Introduction. The central issue of this study is that while the global goals for decarbonization have been formulated as general and universal, the actual conditions for achieving them vary significantly between countries. For some countries, the carbon footprint is determined by factors such as the size of their economy and population, while for others it is influenced by a high reliance on coal generation, export-oriented fuel and energy complexes, energy-intensive industries, or insufficient technological modernization. As a result, simply ranking countries based on their GHG emissions does not provide a reliable basis for determining the priorities for climate policy or the direction of decarbonization strategies. The focus of the global discussion on reducing greenhouse gas emissions is shifting from setting common goals to choosing decarbonization trajectories for countries with fundamentally different energy structures. In the long term, the goal of the Paris Agreement is to limit the growth of the global average temperature. The starting point in this case is the pre-industrial level. The goal is formulated as follows: “well below 2°C.” Solution to this problem requires a serious transformation of the global energy system [1].

More than 130 countries have expressed their intention to achieve full carbon neutrality by 2050. These countries have either already committed to ensuring a zero balance of greenhouse gas emissions or are considering achieving zero emissions by the middle of this century [2].

The practical implementation of the adopted strategies depends not only on political commitments, but also on factors such as the energy balance, level of industrialization, structure of final energy consumption, export role of the fuel and energy complex, demographics, and initial carbon intensity of the economy [3].

Modern research shows that the energy sector remains the main source of anthropogenic GHG emissions, and decarbonization scenarios vary significantly in terms of the depth of technological transformation, the cost of transition, and the degree of involvement of low-carbon energy sources [4]. Materials about the problem were published by REA^{6, 7}, RANEPa⁸, IEF RAS⁹, CENEF¹⁰, Energy Institute^{11, 12}, IEA^{13, 14}.

Scenarios for achieving carbon neutrality, macroeconomic consequences of energy transition, potential of hydrogen energy, the role of nuclear generation, renewable energy sources (RES), energy efficiency, and carbon capture technologies have all been thoroughly discussed in Russian and international literature. Through a comparative analysis of these scenarios based on macroeconomic modelling, we have identified three key pathways.

The first category includes inertial approaches. Experts from the REA, RANEPa and CENEF pointed to unjustified adherence to established models and factors hindering development in the field of decarbonization. The authors noted that infrastructure modernization focuses on fossil fuels. This leads to a moderate change in the structure of primary energy resources, as well as stagnation or an increase in GHG emissions (up to 6.5 gigatons of carbon dioxide equivalent by 2050).

The second one combines moderately optimistic scenarios. The authors of IEF RAS refer to these as a “reasonable” choice [5], and REA as a “rational technological” option. CENEF believes that reaching the so-called “carbon plateau” would be a significant achievement. This refers to the gradual implementation of low-carbon technologies. The potential for a gradual increase in energy efficiency and a partial diversification of the energy mix formed the basis for the goal: by 2050, emissions should be reduced to 1.5–3.5 gigatons of carbon dioxide equivalent, or stabilized at that level.

Finally, the third group proposes radical approaches to solving the problem. They aim to achieve low [6] or zero carbon footprints, acting actively or even aggressively in this direction [5]. The implementation of these solutions requires a deep structural restructuring of the economy, large-scale introduction of renewable energy sources, nuclear generation, hydrogen technologies, and carbon capture and storage systems. By 2050, emissions are expected to be reduced to 0.54–2 gigatons of carbon dioxide equivalent. The total consumption of primary energy resources is forecast to decrease to 12.4 billion tons of oil equivalent. These indicators are included in the “Net Zero” scenario of the REA of the Ministry of Energy of Russia.

In all the scenarios considered, the peak demand for coal, oil, and natural gas is projected to occur in 2030, after which it is expected to decline, especially for coal. Factors critical to the implementation of these scenarios include balanced modernization of energy-intensive industries, the development of regulatory mechanisms, including carbon pricing, and ensuring the economic affordability of low-carbon solutions [7].

The published studies can be broadly divided into three groups. The first group includes work on modeling scenarios for low-carbon development, with estimates of potential trajectories for changes in energy balances, emissions, and consumption patterns for primary energy resources. The second category compares countries and regions based on individual indicators, such as absolute GHG emissions, per capita emissions, the carbon intensity of GDP, the share of fossil fuels, energy intensity of the economy or the pace of renewable energy introduction. The authors of the third group use methods of multidimensional analysis and clustering. However, this work is often limited to specific groups of countries, narrow sets of energy or emissions characteristics, or fails to relate the results to transition risks related to climate change and practical trends towards decarbonization.

The solution in this case is to classify countries according to a set of features reflecting structural changes in the carbon load [8]. Cluster analysis will help overcome the disadvantages of the standard ranking and identify groups of countries that are similar in their carbon footprint, as well as in their economic, demographic, energy, and climate characteristics.

The analysis of scientific literature has shown that the comprehensive classification of GHG-emitting countries is insufficiently developed, and the presented scientific work is intended to fill this gap. The proposed approach will make it possible to determine which decarbonization measures can be replicated within a group of countries, and which require targeted adaptation, taking into account the national structure of the energy balance and transitional climate risks. This is the difference between this concept and others, which are limited to the analysis of individual energy or emission indicators.

⁶ Russian Energy Agency.

⁷ REA of the Ministry of Energy of Russia. Scenarios of global energy development up to 2050. 2024. 130 p.

⁸ Russian Presidential Academy of National Economy and Public Administration.

⁹ Institute of Economic Forecasting of the Russian Academy of Sciences.

¹⁰ Center for Efficient Energy Use.

¹¹ Energy Institute

¹² Energy Institute. Statistical Review of World Energy (73rd edition). 2024. 76 p. ISSN 2976-7857.

¹³ International Energy Agency.

¹⁴ IEA. World Energy Outlook 2024. Paris: IEA. 2024. 398 p.

Thus, this research aims to form and interpret the typology of key greenhouse gas-emitting countries based on a comprehensive analysis of economic, demographic, energy, and climatic indicators. The resulting classification can be used to identify differences in the prerequisites for decarbonization and transitional climate risks for countries with similar profiles.

To achieve the goal, the following tasks were set:

- formation, preprocessing, and normalization of economic, demographic, energy, and climate indicators for key GHG-emitting countries to ensure cross-country comparability;
- establishing the most informative feature groups and performing clusterization of countries with an assessment of the sustainability of the groups;
- interpretation of the profiles of the formed clusters and identification of priority areas for decarbonization strategies adaptation.

Materials and Methods. The research project consisted of 10 stages.

1. Collection of statistical data for more than 40 key greenhouse gas emitting countries between 2010 and 2022 [9].
2. Selection of countries based on their contribution to global emissions and representativeness of the energy model.
3. Creation of a system of economic, demographic, energy, resource, and climate characteristics.
4. Unification of country names, measurement units, and data time periods.
5. Clearing the data set and excluding indicators that do not provide cross-country comparability.
6. Standardization of quantitative features using z -transformation method.
7. Preliminary visual verification of the data structure with dimensionality reduction using the principal component analysis (PCA) method.
8. Clustering of data using Ward's method and the combined t -SNE + k -means approach.
9. Selection of the optimal number of clusters using the elbow method and the silhouette coefficient. Evaluation of the clustering quality using the Davies-Bouldin index.
10. Interpretation of clusters taking into account the energy profile, carbon load and transitional climate risks.

The study group included countries that meet one of two or two criteria. The first was the value for global GHG emissions. The second was representativeness in terms of the energy model. In other words, not only large absolute emissions were taken into account, but also a high proportion of fossil fuels, the export orientation of the fuel and energy complex, advanced low-carbon generation, or a significant transformation of the energy balance.

The figures for 2022 were used to ensure comparability. This approach provided the most complete cross-section by country. The time series for 2010–2022 was used to interpret the dynamics and verify the stability of the identified differences.

The assessment was based on a system of indicators for two groups, or blocks, of data.

The first (economic and demographic) group included GDP, population, and the share of urban and rural populations.

The second (energy and resources) group included:

- installed generation capacity by type of sources;
- production and import of primary energy;
- production of heat and electricity by type of generation;
- energy consumption by economic sectors;
- recoverable coal, natural gas and oil;
- total reserves of energy resources.

The third (climate) block combined GHG emissions — general and across sectors of the economy (energy, industrial processes, agriculture, waste).

The final matrix was created based only on the quantitative indicators that ensured comparability between countries. For each feature, units of measurement, ranges of values, and omissions were verified. Indicators for which there was no comparable data for a significant number of countries were only used in the descriptive analysis phase and were not included in the final clustering matrix. Standardization was performed using the z -transformation formula: the average value of a set of countries was subtracted from each attribute value, after which the result was divided by the standard deviation. This allowed us to eliminate the influence of features with large absolute scales, such as GDP, population, and installed generation capacity.

In order to analyze the production and consumption of energy resources, assess the effectiveness of their use and the impact of the emitters on the environment, the formation of cluster groups of key emitting countries by economic, demographic and energy indicators was considered. More than 10 methods of statistical data processing for cluster formation were considered [10]. Table 1 provides information on the most suitable methods.

Table 1

Comparative analysis of methods for processing statistical data to form cluster groups

Method	Input data	Output data	Advantages	Disadvantages
Hierarchical clustering	– an array with the characteristics of data points, – a proximity matrix	– dendrogram – a hierarchy of nested clusters	– does not require specifying the number of clusters, unlike the <i>k</i>-means method, – easy to interpret, – good visualization of the results	– computational complexity, – sensitivity to outliers, – inability to separate overlapping clusters
<i>k</i> -means	– an array with the characteristics of data points, – estimated number of clusters (<i>k</i>)	– a set of clusters with the distribution of objects, – set of clusters with the distribution of objects	– does not require specifying the number of clusters, unlike the <i>k</i>-means method, – easy to interpret, – good visualization of the results	– dependence of the result on the choice of initial cluster centers and their number, – sensitivity to outliers, – inconsistency of results
<i>t</i> -SNE	– an array of data with features (high-dimensional data)	– visualization with preservation of local clusters,	– effective for visualizing complex nonlinear structures, – preserves local relationships between points well	– high computational complexity, – the result depends on the parameters and the number of iterations
<i>DBSCAN</i> ¹⁵	– an array with the characteristics of data points, – the minimum number of points in a cluster	– a set of clusters with the distribution of objects across clusters, – noise points	– does not require specifying the number of clusters, – insensitive to the order of points, – can find clusters of arbitrary shape, – takes noise into account and is robust to outliers	– computational complexity, – poor clustering when the data is uniformly distributed

Cluster analysis involved classifying observational objects (cases) into groups (clusters) based on similarities of their characteristics across a variety of variables [11]. Hierarchical clustering was performed using Ward's method on a standardized feature matrix using the Euclidean distance. Ward's method was chosen because it minimized intracluster variance and allowed obtaining an interpretable dendrogram of country similarity. Additionally, the combined *t*-SNE + *k*-means approach was used. For the nonlinear mapping of a high-dimensional data structure into a two-dimensional space, *t*-SNE was used, followed by clustering using the *k*-means method on the resulting representation.

To ensure the reproducibility of the calculations, the parameters of the algorithms were fixed in the software implementation. The number of clusters was checked in the range $k = 2-10$ using the elbow method and the silhouette coefficient. Additionally, we assessed the quality of the final solutions using the Davies-Bouldin index. The initial state of the random number generator (*random_state* = 42) was recorded in the *k*-means procedures. When selecting the number of clusters, initialization of *k*-means++ centroids was used. The *n_init* and *max_iter* parameters were not set separately and were assumed to be equal to the default values of the used version of the *scikit-learn* library. For *t*-SNE, *n_components* = 2, *perplexity* = 30, *random_state* = 42 were set. The parameters *learning_rate*, *max_iter* / *n_iter*, *init* and *metric* were not set separately. After constructing the two-dimensional *t*-SNE representation, clustering was performed using the *k*-means method at $k = 4$.

¹⁵ Density-based spatial clustering of applications with noise.

Research Results. An analysis of statistics on the main GHG-emitting countries made it possible to obtain cross-distributions of emissions per capita and per unit of GDP at PPP (Fig. 1). The first indicator characterized the specific demographic carbon burden and allowed comparing countries based on their population size. The second indicator was the carbon intensity of the economy, which was the amount of emissions produced per unit of economic output. A joint analysis of these indicators made it possible to distinguish between countries with high absolute emissions, countries with a high carbon intensity of production, and countries where a significant carbon burden was primarily related to the scale of the economy and consumption. The size of the circles is related to the population in 2022 (in millions of people).

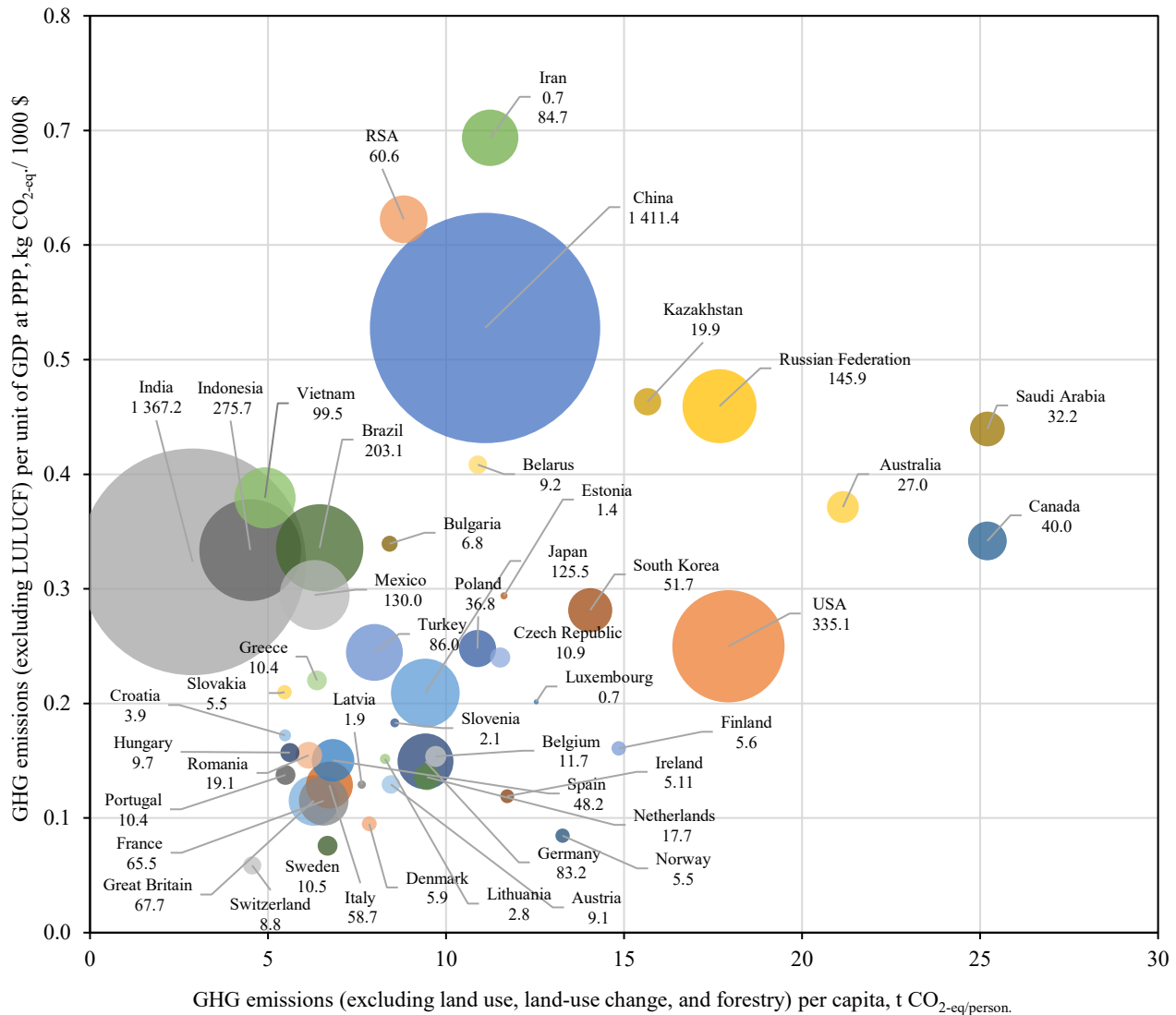


Fig. 1. Cross-distribution of greenhouse gas emissions¹⁶ per unit of GDP and per capita, 2022

Within the framework of the study, a comprehensive set of economic, demographic, energy, resource, and climatic characteristics was clearly the most meaningful to interpret, as individual blocks of indicators only reflected specific aspects of differences between countries. The economic and demographic blocks mainly divided countries according to their economic scale and population size, while the climate block divided them according to the level of absolute and specific emissions. The energy block divided countries based on the structure of energy generation and the role of fossil fuels. Only by combining these groups of characteristics did we identify clusters that differed both in the amount of emissions and the reasons for their formation.

¹⁶ In this case, the impact of the “Land use, land-use change and forestry” (LULUCF) sector was excluded from the total volume of anthropogenic emissions of heat-trapping gases.

Figure 2 shows the structure of electricity generation by installed capacity for the 15 largest emitters. The map illustrates the total generation capacity in terawatts. The data on the shares of thermal, hydropower, nuclear power plants, and renewable sources in the overall energy balance were visualized for each country. It was evident that traditional energy with fossil fuels accounted for the largest share in all countries. However, there were exceptions, such as Canada and Brazil, where hydroelectric power plants played a significant role in electricity production.

It was determined that approximately one in four tons of CO₂ emitted into the atmosphere was generated at thermal power plants during the combustion of natural gas, coal, and fuel oil. This amounted to 12.5 billion tons of CO₂ per year.

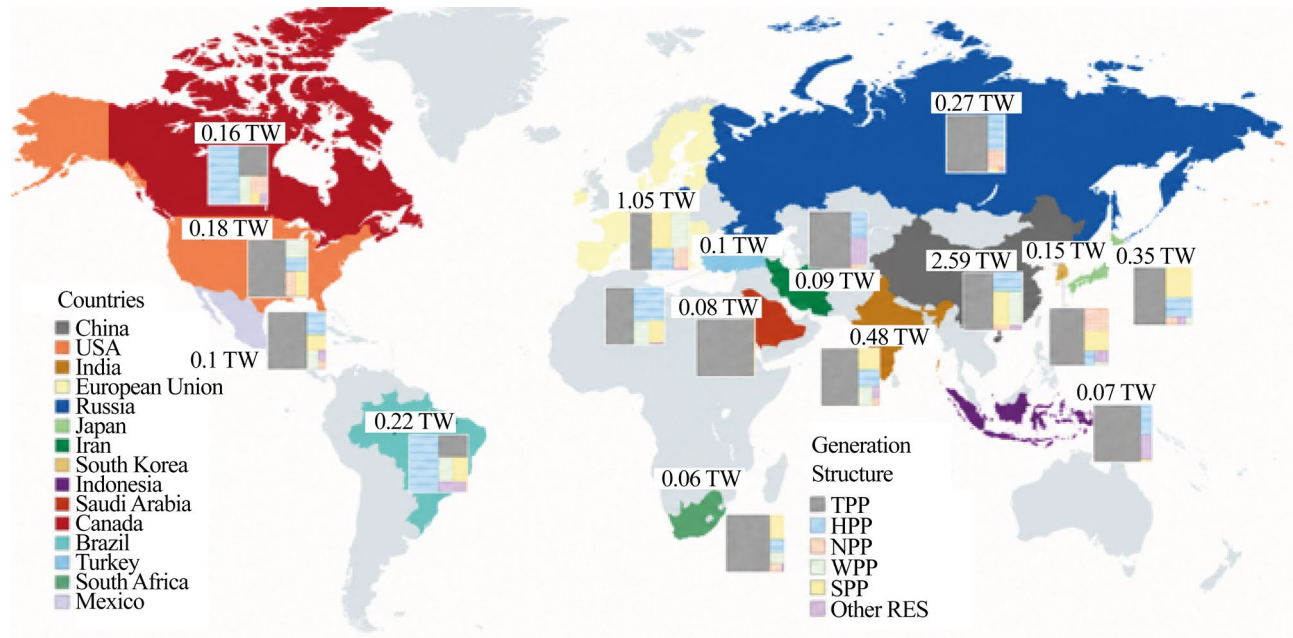


Fig. 2. Generation structure for the top 15 GHG-emitting countries by type and installed capacity, 2022

The dendrogram in Figure 3 was the result of a hierarchical clustering analysis using Ward's method. After normalizing the data, we took into account their variance and determined the distances between the closest similar elements. This approach provided a detailed analysis of the production, consumption, and efficiency of energy resources, as well as the impact of GHG-emitting countries on the environment based on all analyzed indicators.

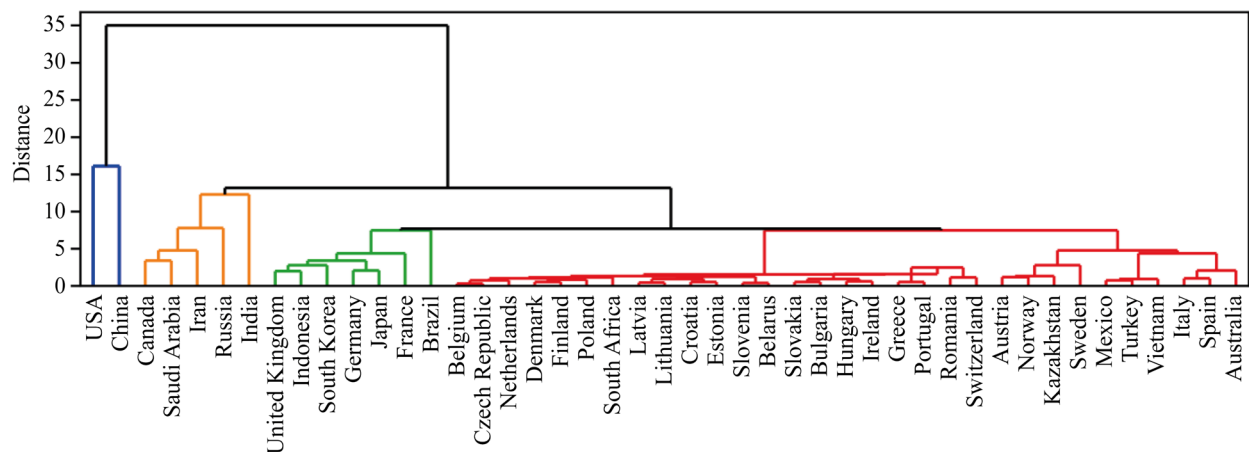


Fig. 3. Dendrogram of hierarchical clusterization of GHG-emitting countries by economic, demographic and energy indicators

The dimensionality reduction algorithm (*t-SNE*, Fig. 4) was used as a tool for nonlinear dimensionality reduction and visualization of the local data structure. The clusters were then interpreted based on the results of the hierarchical clustering and quality metrics. The clusters are indicated by the same colors as in Figure 3.

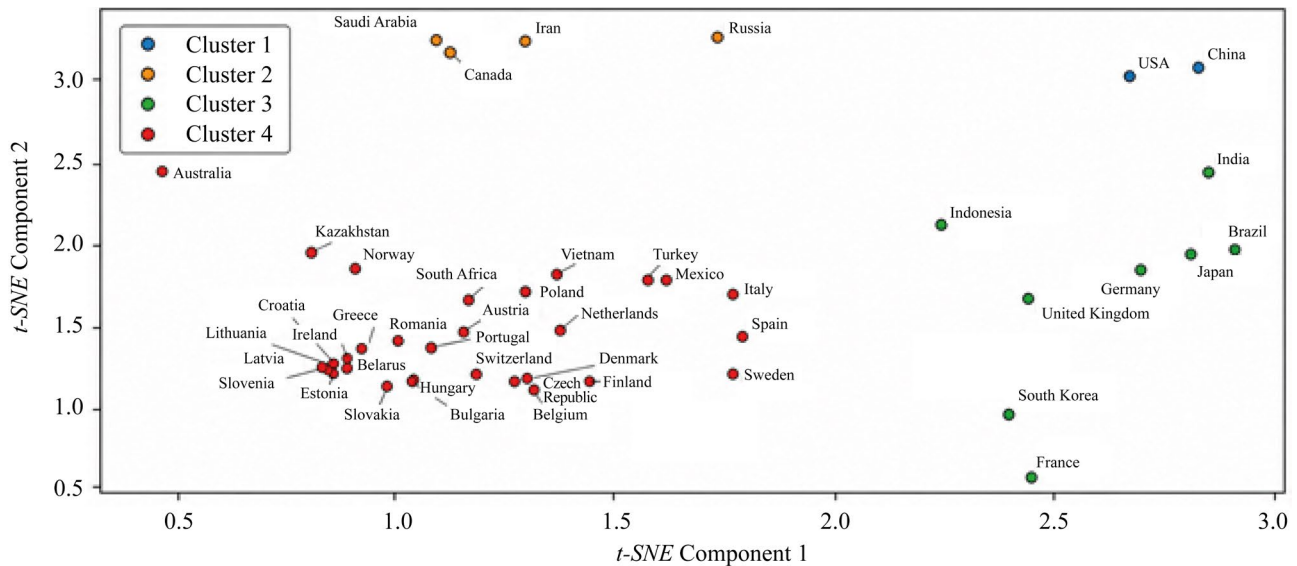


Fig. 4. Clustering of GHG-emitting countries based on *t-SNE* algorithm according to economic, demographic and energy indicators

The stability of the resulting groups was assessed by comparing the results of the hierarchical clustering and *t-SNE* + *k-means* approach. The clusters were considered stable in a meaningful sense if countries with similar energy and emission profiles remained in the same group when using different algorithms, or if they formed associations that were comparable in interpretation. The consistency of the main cluster profiles between the two methods allowed us to conclude that the result with four clusters was the most reasonable.

As you can see, the countries were divided into four clusters. This result was obtained using two approaches:

- the elbow method (optimum at $k = 4$, where k — number of clusters);
- the silhouette coefficient (maximum 0.62 at $k = 4$).

From the point of view of assessing the quality of clustering results, the Davies–Bouldin index (DBI) took the maximum values for k equal to 4 and 3, 0.92 and 0.89, respectively. This indicated a comparable quality of separation. Since a lower DBI value corresponded to more compact and better separated clusters, this indicator alone did not provide a clear advantage for the $k = 4$ option. However, the decision to use four clusters was based on a combination of factors, including the maximum silhouette coefficient, the results of the elbow method, and the improved interpretability of the clusters (Fig. 3, 4).

Figure 4 shows a two-dimensional *t-SNE* representation of a multidimensional space of features characterizing GHG-emitting countries in terms of economic, demographic, energy, and climate parameters. The *t-SNE* 1 and *t-SNE* 2 components were conditional coordinates of a nonlinear mapping and did not have a direct independent economic or energy interpretation. They served to visualize the local proximity of countries. The proximity of points indicated the similarity of countries based on a set of normalized features, while the distance indicated their differences in profiles. The distribution obtained confirmed the existence of four clusters, which was consistent with the clustering results and the estimated optimal number of clusters.

The first cluster was represented by the largest GHG-emitting countries — China and the USA. They were united by an exceptional scale of economy, energy consumption, and absolute emissions, as well as diversified generation.

The second cluster included fuel and energy exporters — Russia, Canada, Iran, and Saudi Arabia. Their common features were the high role of extraction, production and (or) export of primary energy resources, a significant share of fossil fuels in the energy mix, and increased sensitivity to climate transition risks.

The third cluster was a group of carbon-intensive industrial and developing economies. They were characterized by a growing demand for energy, a significant share of industry, and the infrastructural inertia of the energy system.

The fourth cluster included countries with higher energy efficiency, a greater share of low-carbon generation, and/or progressive climate policies.

Discussion. Thus, GHG emissions cannot be the sole factor in determining a country's climate strategy. Instead, it is a complex combination of factors that determine a country's cluster affiliation. These factors include the size of the economy, population, generation structure, share of fossil fuels, role of exported energy resources, level of energy efficiency, and specific carbon load [12]. Therefore, countries with similar absolute emissions can belong to different categories based on the types of decarbonization tasks. Examples include reducing coal dependence, decarbonization of mining and processing, improving energy efficiency, and eliminating residual emissions from end-use sectors.

The interpretation of clusters in this study was based not on a normative assumption about the “correct” decarbonization strategy, but on the identified structural features of each group. If the cluster was characterized by a high proportion of coal generation, the priority of reducing coal dependence was clear from the energy profile. Conversely, if the cluster included countries with a significant role in the production and export of hydrocarbons, the key risks included reduced external demand, carbon regulations on imports, and technological decarbonization of the extractive sector. If a group of countries had a lower carbon intensity of generation, the focus shifted to residual emissions, final energy consumption, and the imported carbon footprint.

The separation of China and the United States into a separate cluster can be explained by their significant role in global energy and climate policies. These two countries account for a large portion of global energy demand and possess the resources to implement low-carbon technologies. However, it is important to note that the two economies differ in terms of their energy use [13]. Industrial coal emissions in China are higher than in the United States. The United States, on the other hand, has a high energy intensity of the economy and high emissions per capita. Therefore, even within a cluster, it is crucial to consider the differences in technological and behavioral sources of carbon emissions.

Table 2 summarizes the clusters and lists the most significant transitional climate risks, that is, the economic and financial threats associated with the global transition to a low-carbon economy. Here are the directions of adaptation of decarbonization strategies.

Table 2

Cluster profiles and directions for adapting decarbonization strategies

Cluster	Countries	Key indicators	Transition climate risks	Priority decarbonization solutions
1. Largest emitters	China, USA	– the maximum scale of the economy, energy consumption, and absolute emissions; – diversified energy sector	– high inertia in the energy sector; – socio-economic costs of an accelerated energy transition	– reduction of coal-fired generation; – electrification and modernization of grids; – CCUS for hard-to-decarbonize industries
2. Resource-exporting	Russia, Canada, Iran, Saudi Arabia	– high role of extraction and energy exports; – significant share of fossil fuels; – dependence on external demand for hydrocarbons	– carbon regulation of importers; – declining demand for primary energy resources	– reduction of methane leaks; – decarbonization of production; – diversification of exports
3. Carbon-intensive industrial and developing	Japan, Germany, United Kingdom, South Korea, France, India, Brazil, Indonesia	– growth in energy consumption; – significant share of industry	– entrenchment of a high-carbon development trajectory; – investment shortfall; – technological dependence	– phasing out of inefficient coal-fired generation; – energy efficiency in industry; – financing of climate programs
4. Energy-efficient and relatively low-carbon	EU (except France, Germany), Australia, Norway, Switzerland, South Africa, Turkey, etc.	– low carbon intensity of GDP; – well-developed institutional climate policy; – significant share of low-carbon generation	– residual emissions from transport, buildings, and industry; – high carbon footprint associated with imports	– deep electrification of final consumption; – accounting for the consumer carbon footprint; – reduction of imported emissions

For Russia, Canada, Iran, and Saudi Arabia (a cluster of resource-exporting economies), decarbonization goes beyond domestic emissions reduction. It impacts the structure of international trade, the stability of export revenue, and the ability to comply with carbon regulations of trading partners [14]. Therefore, technologies that reduce emissions from mining and processing, CCUS, and the formation of new export directions for low-carbon products are crucial for these countries. All this is of particular importance in terms of transitional climate risks.

For industrial and developing economies (the third cluster), decarbonization should be consistent with energy demand growth and the expansion of industrial capacity. Transferring the approaches of developed countries to this cluster could result in socio-economic costs and slow down development. Therefore, it is essential to continuously modernize power generation, enhance industrial energy efficiency, and develop network infrastructure [15].

For developed and relatively low-carbon economies, the main challenge is to reduce residual and difficult-to-eliminate emissions. Although these countries have an initially more advanced regulatory framework and rely heavily on low-carbon energy sources, they still face the challenge of emissions from transportation, buildings, and consumer products. In these countries, the importance of solutions such as end-use electrification, flexibility in the energy system, and reduction of the carbon footprint of imported products is increasing [16].

The comparison of the results with available research on low-carbon development scenarios, global energy statistics, and the assessment of the carbon intensity of the economy demonstrates that the cluster approach described in this article does not replace, but complements scenario modeling.

Scenario studies are used to evaluate potential ways of achieving energy balance changes and reducing emissions. Clustering allows us to identify countries with similar initial conditions, and therefore, similar or overlapping climate risks during the transition. Unlike indicator rankings based on a single metric, multidimensional classification takes into account the size of the economy, energy generation structure, resource base, and carbon intensity simultaneously.

The limitations of the study stemmed from several factors. Firstly, national statistical systems varied in their completeness and methods for recording energy and climate indicators. Secondly, clustering results were influenced by the composition of features included and how they were normalized. Thirdly, *t-SNE* was primarily used as a visualization tool for non-linear data structures and should not be taken as an independent indicator of cluster stability. Therefore, to interpret the results, we compared several clustering methods and conducted a meaningful analysis of the energy and emissions profiles of countries.

From a practical perspective, the results made it possible to group countries in advance according to the similarities of the prerequisites for decarbonization. So, for the largest emitters, the key factors were the scale of the energy system and absolute emissions. For resource-exporting economies, it was dependence on the extraction, processing and export of fossil energy resources. For industrial and developing countries, this was a combination of rising energy demand and the high role of carbon-intensive generation. For relatively low-carbon economies, the main problems were related to residual emissions and the carbon footprint of final consumption. Thus, the directions of decarbonization should be considered not as general recommendations, but as measures determined by the profile of the relevant cluster.

Conclusion. A database of economic, demographic, energy, and climate indicators for key greenhouse gas-emitting countries has been created. Hierarchical clustering using Ward's method and a combined *t-SNE* + *k-means* approach was used to standardize the features and classify the countries. The four-cluster option was the most significant. In this case, the differences between countries were reflected:

- the largest greenhouse gas-emitting countries;
- resource-export countries;
- carbon-intensive industrial and developing countries;
- relatively energy efficient and low carbon countries.

The scientific significance of the research lies in the transition from a one-dimensional ranking of countries based on emissions to a multidimensional typology of emitters that takes into account economic, demographic, energy, and climatic characteristics. In addition, the proposed clustering could be the basis for the preliminary selection of directions for decarbonisation, assessment of transition climate risks, and this is the practical value of the study.

Clustering results should not be considered as a universal set of recommendations. Nevertheless, they can be used to further analyze the similarities and differences between key emitting countries, identify optimal technologies and legislative measures needed to reduce GHG emissions, and evaluate the effectiveness of climate decarbonization strategies.

References

1. Klimenko VV, Klimenko AV, Tereshin AG. Prospects for Achieving Carbon Neutrality by Economically Developed Countries. *Doklady Physics*. 2024;517(1):71–80. (In Russ.) <https://doi.org/10.31857/S2686740024040116>
2. Sukhareva MA, Lenkov IN, Puyu Zh. Carbon Neutrality: Prospects for Development and Impact on the Global Economy. *Lomonosov Public Administration Journal. Series 21*. 2022;3:101–121. (In Russ.) URL: <http://vestnik21msu.ru/articles/article/7050/> (accessed 11.06.2026).

3. Lotnikova DYU. Russia's "Green Transformation" as Part of the Global Decarbonisation Trend. *Scientific Works of KubSTU*. 2021;3:62–71. (In Russ.) URL: <https://ntk.kubstu.ru/data/mc/0080/3961.pdf> (accessed 11.06.2026).
4. Potashnikov V, Golub A, Brody M, Lugovoy O. Decarbonizing Russia: Leapfrogging from Fossil Fuel to Hydrogen. *Energies*. 2022;15(3):683. <https://doi.org/10.3390/en15030683>
5. Porfir'ev BN, Shirov AA, Kolpakov AYU. Low-Carbon Strategy Development: Prospects for the Russian Economy. *World Economy and International Relations*. 2020;64(9):15–25. (In Russ.) <https://doi.org/10.20542/0131-2227-2020-64-9-15-25>
6. Bashmakov IA. Russian Low Carbon Development Strategy. *Voprosy Ekonomiki*. 2020;7:51–74. (In Russ.) <https://doi.org/10.32609/0042-8736-2020-7-51-74>
7. Ilyasov RKh, Plotnikov VA. Macro-Regional Analysis of the Carbon Intensity of the Economy. *Administrative Consulting*. 2023;175(7):42–52. (In Russ.) <https://doi.org/10.22394/1726-1139-2023-7-42-52>
8. Strielkowski W, Chygryn O, Drozd S, Koibichuk V. Sustainable Transformation of Energy Sector: Cluster Analysis for the Sustainable Development Strategies of Selected European Countries. *Heliyon*. 2024;19(10):e38930. <https://doi.org/10.1016/j.heliyon.2024.e38930>
9. Loktionov OA, Maksimov DO. *Database of Economic, Demographic, Energy and Climatic Indicators of Greenhouse Gas Emitting Countries*. RU2024624471. 2024. Federal Service for Intellectual Property. Bul. No. 10. (In Russ.)
10. Panferova EV, Matushin RA. Comparative Evaluation of Clustering Methods in Working with Big Data. *Bulletin of Perm University. Series: Mathematics. Mechanics. Computer Science*. 2024;65(2):61–67. (In Russ.) URL: <https://press.psu.ru/index.php/Math/article/view/9054> (accessed 11.06.2026).
11. Sangwon Jung, Dagobert T, Morel J-M, Facciolo G. A Review of t-SNE. *Image Processing On Line*. 2024;14:250–270. <https://doi.org/10.5201/ipol.2024.528>
12. Lamb WF, Grubb M, Diluiso F, Minx JC. Countries with Sustained Greenhouse Gas Emissions Reductions: An Analysis of Trends and Progress by Sector. *Climate Policy*. 2022;22(1):1–17. <https://doi.org/10.1080/14693062.2021.1990831>
13. Hou MZ, Luo Jiashun, Huang Liangchao, Beck H-P, Mehmood Faisal, Wang Qichen, et al. Strategies toward Carbon Neutrality: Comparative Analysis of China, USA, and Germany. *Carbon Neutral Systems*. 2025;1:3. <https://doi.org/10.1007/s44438-025-00003-1>
14. Salimi Mohsen, Amidpour Majid. The Impact of Energy Transition on the Geopolitical Importance of Oil-Exporting Countries. *World*. 2022;3(3):607–618. <https://doi.org/10.3390/world3030033>
15. Doğan Ebru. Electricity Capacity Convergence in G20 Countries: New Findings from New Tests. *Sustainability*. 2024;16(19):8411. <https://doi.org/10.3390/su16198411>
16. Zhen Wang, Haoben Yan, Xue Gao, Qiaomei Liang, Zhifu Mi, Lancui Liu. Have Consumption-Based CO₂ Emissions in Developed Countries Peaked? *Energy Policy*. 2024;184(3):113894. <https://doi.org/10.1016/j.enpol.2023.113894>

About the Authors:

Oleg A. Loktionov, Cand. Sci. (Eng.), Associate Professor of the Department of Environmental Engineering and Occupational Safety, National Research University "MPEI" (14, Krasnokazarmennaya Str., Moscow, 111250, Russian Federation), [SPIN-code](#), [ORCID](#), [ResearcherID](#), [ScopusID](#), loktionovoa@mpei.ru

Daniil O. Maksimov, Student of the Department of Environmental Engineering and Occupational Safety, National Research University "MPEI" (14, Krasnokazarmennaya Str., Moscow, 111250, Russian Federation), [SPIN-code](#), [ORCID](#), [ScopusID](#), maximovdo@mpei.ru

Mikhail A. Zabelin, Post-Graduate Student, Assistant Professor of the Department of Environmental Engineering and Occupational Safety, National Research University "MPEI" (14, Krasnokazarmennaya Str., Moscow, 111250, Russian Federation), [SPIN-code](#), [ORCID](#), [ScopusID](#), zabelinma@mpei.ru

Irina A. Beloshitskaya, Student of the Department of Engineering Ecology and Occupational Safety, NRU "MPEI" (14, Krasnokazarmennaya Str., Moscow, 111250, Russian Federation), [SPIN-code](#), [ORCID](#), beloshitskayaia@mpei.ru

Claimed Contributorship:

OA Loktionov: conceptualization, supervision.

DO Maksimov: assessment of economic and demographic indicators of greenhouse gas-emitting countries, review of studies and forecasts on primary energy consumption for the short and medium term.

MA Zabelin: formation of cluster groups of key emitting countries in terms of economic, demographic, and energy indicators.

IA Beloshitskaya: assessment of the actual structure of energy consumption and production in Russia and the world, as well as the energy indicators of the issuing countries.

Conflict of Interest Statement: the authors declare no conflict of interest.

All authors have read and approved the final version of manuscript.

Об авторах:

Олег Александрович Локтионов, кандидат технических наук, доцент кафедры инженерной экологии и охраны труда Национального исследовательского университета «МЭИ» (111250, Российская Федерация, г. Москва, ул. Красноказарменная, 14, стр. 1), [SPIN-код](#), [ORCID](#), [ResearcherID](#), [ScopusID](#), loktionovoa@mpei.ru

Даниил Олегович Максимов, студент кафедры инженерной экологии и охраны труда Национального исследовательского университета «МЭИ» (111250, Российская Федерация, г. Москва, ул. Красноказарменная, 14, стр. 1), [SPIN-код](#), [ORCID](#), [ScopusID](#), maximovdo@mpei.ru

Михаил Андреевич Забелин, аспирант, ассистент кафедры инженерной экологии и охраны труда Национального исследовательского университета «МЭИ» (111250, Российская Федерация, г. Москва, ул. Красноказарменная, 14, стр. 1), [SPIN-код](#), [ORCID](#), [ScopusID](#), zabelinma@mpei.ru

Ирина Андреевна Белошицкая, студент кафедры инженерной экологии и охраны труда Национального исследовательского университета «МЭИ» (111250, Российская Федерация, г. Москва, ул. Красноказарменная, 14, стр. 1) [SPIN-код](#), [ORCID](#), beloshitskayaia@mpei.ru

Заявленный вклад авторов:

О.А. Локтионов: разработка концепции, научное руководство.

Д.О. Максимов: оценка экономико-демографических показателей стран-эмитентов парниковых газов, обзор исследований и прогнозов по потреблению первичных энергоресурсов на кратко- и среднесрочную перспективу.

М.А. Забелин: формирование кластерных групп ключевых стран-эмитентов в разрезе экономико-демографических и энергетических показателей.

И.А. Белошицкая: оценка фактической структуры потребления и производства энергоресурсов в России и мире, энергетических показателей стран-эмитентов.

Received / Поступила в редакцию 01.06.2026

Reviewed / Поступила после рецензирования 22.06.2026

Accepted / Принята к публикации 06.07.2026

TECHNOSPHERE SAFETY

ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ



UDC 62.78

Original Empirical Research

<https://doi.org/10.23947/2541-9129-2026-10-3-219-231>

System for Identifying the Condition of Hoisting Crane Runways

Vladislav V. Egelsky , Nikolai N. Nikolaev , Elena V. Egelskaya ✉,

Anatoly A. Korotkiy , Leonid A. Ternovskoi

Don State Technical University, Rostov-on-Don, Russian Federation

✉ egelskaya72@mail.ru

EDN: JOZTEV

Abstract

Introduction. Inspecting the overhead crane runways in production workshops and warehouses is a challenging and dangerous task. The risks for specialists are associated with the high altitude at which the runways are located and the lack of walkways along them. At the same time, standard visual and dimensional inspection is characterized by a low inspection speed. The scientific literature contains numerous studies on the potential of artificial intelligence (AI) to ensure occupational safety: methods for monitoring occupational risks and preventing accidents, the relationship between accident rates and the competencies of crane operators, the detection of defects in removable load-handling devices using computer vision tools, as well as remote monitoring of crane safety based on video data from IP cameras. However, these solutions do not address the inspection of crane runways, which have specific features, primarily their considerable length (often up to 200 meters or more). The application of AI requires video-analytical monitoring along the entire length of the runway and training a neural network to recognize local defects and geometric deviations, which existing methods do not provide. Today, crane runway inspection is conducted through visual and dimensional control methods, including direct inspection and surveying using total stations and theodolites. While these methods are accurate, they are labor-intensive and time-consuming. Therefore, there is a need for the use of AI to improve safety and speed while maintaining accuracy in identifying faults in crane runways. The aim of this research is to develop a method for remote inspection of the overhead crane runways located at height in industrial facilities. This will help minimize the exposure of workers to hazardous and harmful working conditions while maintaining accuracy, speed, and reliability of the inspection results.

Materials and Methods. Data on crane runway defects collected during inspections at industrial facilities was used as the basis for the study. The methodology for identifying defects in crane runways was based on GOST R 56944–2016¹. Computer vision neural networks were trained using open libraries for Python language. A modernized pre-trained YOLOv8 neural network was used to detect defects.

Results. A method for remote detection of defects on overhead crane runways was developed using an unmanned aerial vehicle designed by the authors (a quadcopter with a protective frame, equipped with a Livox MID-40 lidar, an Orbbec Gemini 2 depth camera, a 4K RGB camera, and a DWM1000 positioning system supporting TWR and TDOA). Based on survey data collected in 2024 from 352 overhead cranes with a total runway length of approximately 14 kilometers, a modernized YOLOv8 neural network for computer vision was trained. This resulted in the creation of a complete three-dimensional point cloud that covered the runways, crane beams and supports, as well as reference to column lines and

¹ GOST R 56944–2016 “Lifting Cranes. Overhead Crane Rail Tracks. General Technical Requirements” (approved and put into effect by Order No. 463-st of the Federal Agency for Technical Regulation and Metrology dated 1 June 2016). URL: <https://ohranatruda.ru/upload/iblock/8fe/4293754222.pdf?ysclid=mnsm94qrk671517049> (accessed: 10.04.2026).

centers. The three-dimensional model allowed for the automatic identification and classification of local defects, as well as the estimation of their sizes with accuracy of one millimeter. Automated geometry assessment showed that the deviations in the runway markings in the model in question did not exceed the permitted values according to GOST R 56944–2016 (40 millimeters in one section and 10 millimeters on adjacent columns), which confirmed the effectiveness of the method.

Discussion. The results obtained indicate that the authors' goal has been achieved — the development of a method for remote inspection of overhead crane runways. This was made possible by conducting a significant number of surveys, which provided a diverse range of defects for training neural networks. A comparison with previous studies has shown the uniqueness of the proposed approach to inspecting overhead crane runways. Methods based on artificial intelligence and unmanned aerial vehicles (UAVs) have previously been used to monitor personnel, assess removable lifting attachments, and inspect tower cranes outdoors. However, these methods were not suitable for detecting local defects in overhead crane runways inside production facilities. The main limitation of the developed method was the flight time of the UAV (no more than 20 minutes), which was due to the low battery capacity. This capacity could not be increased without increasing the maximum size of the device (0.5 meters) in the confined conditions of enclosed spaces. The new method's results were positive, as it enabled inspection of tracks along their entire length from a close distance. By building a 3D model using photogrammetry, it was possible to assess the size of defects and reduce labor intensity and duration of the survey by at least half. These benefits made its further development and practical implementation worthwhile.

Conclusion. The main outcome of the study was the development of a method for remote inspection of overhead crane runways located at height in industrial facilities. During the research, neural networks were trained to detect defects, and an algorithm was created for inspection. This involved creating a three-dimensional model that allowed for automated assessment of geometric deviations in the runways in both longitudinal and transverse planes, as well as the identification of local defects. The key benefit of this method was that it eliminated the need for experts to climb to heights, ensuring their safety. Additionally, it allowed for the inspection of hard-to-reach areas and the detection of previously invisible defects, reducing the likelihood of future emergency situations. Further research in this field will focus on improving the system's ability to automatically identify the condition of load-bearing metal structures and possible defects in cranes.

Keywords: overhead travelling crane, runway, neural network, safety monitoring, unmanned aerial vehicle

For Citation. Egelsky VV, Nikolaev NN, Egelskaya EV, Korotkiy AA, Ternovskoi LA. System for Identifying the Condition of Hoisting Crane Runways. *Safety of Technogenic and Natural Systems*. 2026;10(3):219–231. <https://doi.org/10.23947/2541-9129-2026-10-3-219-231>

Оригинальное эмпирическое исследование

Система идентификации состояния рельсовых путей грузоподъемных кранов

В.В. Егельский , Н.Н. Николаев , Е.В. Егельская ✉, А.А. Короткий , Л.А. Терновской 

Донской государственный технический университет, г. Ростов-на-Дону, Российская Федерация

✉ egelskaya72@mail.ru

Аннотация

Введение. Обследование крановых путей мостовых кранов в производственных цехах и на складах — сложная и небезопасная задача. Риск для специалистов связан с большой высотой, на которой расположены пути, а также с тем, что проходные галереи вдоль них часто отсутствуют. При этом стандартный визуально-измерительный контроль отличается низкой скоростью обследования. В научной литературе широко представлены исследования, в которых рассматриваются возможности искусственного интеллекта (ИИ) для обеспечения производственной безопасности: методы контроля производственных рисков и предотвращения аварий, взаимосвязь аварийности с компетенциями машинистов кранов, распознавание дефектов съемных грузозахватных приспособлений средствами компьютерного зрения, а также дистанционный мониторинг безопасности кранов по данным видео с IP-камер. Однако эти решения не касаются обследования самих крановых путей,

которые обладают рядом специфических особенностей — прежде всего значительной протяженностью (нередко до 200 метров и более). Применение ИИ здесь требует видеоаналитического контроля по всей длине пути и обучения нейросети распознаванию специфических местных дефектов и отклонений геометрии, чего существующие методы не обеспечивают. Сегодня такое обследование выполняется в форме визуально-измерительного контроля с непосредственным осмотром и планово-высотной съемкой тахеометрами и теодолитами. Эти методы точны, но трудоемки и медленны. Таким образом, существует запрос на применение ИИ для идентификации неисправностей крановых путей с сохранением точности при повышении безопасности и скорости. Цель данного исследования — разработка метода дистанционного обследования крановых путей мостовых кранов, расположенных на высоте в производственных помещениях, позволяющего минимизировать воздействие опасных и вредных производственных факторов на персонал при сохранении точности, скорости и достоверности получаемых результатов.

Материалы и методы. В качестве базовой информации были использованы данные о дефектах крановых путей, полученные в ходе обследования их на промышленных предприятиях. Методическая часть по выявлению дефектов крановых путей основана на ГОСТ Р 56944–2016. Нейронные сети компьютерного зрения обучали на основе открытых библиотек для языка Python. Для распознавания дефектов использовалась модернизированная предобученная нейронная сеть YOLOv8.

Результаты исследования. Разработан метод дистанционной дефектации надземных крановых путей мостовых кранов с применением беспилотного летательного аппарата авторской конструкции (квадрокоптер с защитным каркасом, оснащённый лидаром Livox MID-40, камерой глубины Orbbec Gemini 2, RGB-камерой 4K и системой позиционирования DWM1000 с поддержкой TWR и TDOA). На основе данных обследования 352 надземных крановых путей общей протяжённостью около 14 километров, полученных в 2024 году, была обучена модернизированная нейронная сеть компьютерного зрения YOLOv8. В результате было создано целостное трёхмерное облако точек, охватывающее рельсы, подкрановые балки и опоры с привязкой к створам и осям колонн. Построенная трёхмерная модель позволила в автоматизированном режиме выявить и классифицировать локальные дефекты и оценить их размеры с точностью до одного миллиметра. Автоматизированная оценка геометрии показала, что отклонения отметок рельсов в рассматриваемой модели не превышают допустимые по ГОСТ Р 56944–2016 значения (40 миллиметров в одном сечении и 10 миллиметров на соседних колоннах), что подтвердило работоспособность метода.

Обсуждение. Полученные результаты свидетельствуют о достижении поставленной авторами цели — о разработке метода дистанционного обследования крановых путей мостовых кранов. Этому способствовал значительный объём проведённых обследований, обеспечивший разнообразную выборку дефектов для обучения нейронных сетей. Сравнение с ранее проведенными исследованиями показало уникальность предложенного подхода к обследованию путей мостовых кранов: уже описанные методы на основе искусственного интеллекта и БПЛА применялись для контроля персонала, оценки съёмных грузозахватных приспособлений, стальных канатов или для обследования башенных кранов на открытом воздухе, однако ни один из них не был пригоден для выявления локальных дефектов надземных крановых путей внутри производственных помещений. Основным ограничением разработанного метода является время полёта БПЛА (не более 20 минут), обусловленное малой ёмкостью аккумуляторов, которую без повышения предельного размера аппарата (0,5 метра) невозможно увеличить в стеснённых условиях закрытых помещений. Результаты разработки нового метода интерпретируются как положительные: он обеспечивает осмотр путей по всей длине с близкого расстояния, построение 3D-модели методом фотограмметрии позволяет оценить размеры дефектов и снизить трудоёмкость и продолжительность обследования не менее чем в два раза. Все это делает целесообразным его дальнейшее развитие и внедрение в практику.

Заключение. Основным итогом исследования стал разработанный метод дистанционного обследования крановых путей мостовых кранов, расположенных на высоте в производственных помещениях. В ходе проделанной работы были обучены нейронные сети поиска дефектов и создан алгоритм обследования с построением трёхмерной модели, обеспечивающей автоматизированную оценку геометрических отклонений рельсов в продольной и поперечной плоскостях и выявление локальных дефектов. Ключевое достоинство метода — обеспечение безопасности экспертов за счёт исключения подъёма на высоту, а также возможность обследования труднодо-

ступных участков и обнаружения ранее незаметных дефектов, что снижает вероятность возникновения впоследствии аварийных ситуаций. Дальнейшие исследования в этом плане будут направлены на дополнение системы функцией автоматической идентификации состояния металлоконструкций самих грузоподъемных кранов и их возможных дефектов.

Ключевые слова: мостовой кран, рельсовый путь, нейронная сеть, мониторинг безопасности, беспилотный летательный аппарат

Для цитирования. Егельский В.В., Николаев Н.Н., Егельская Е.В., Короткий А.А., Терновской Л.А. Система идентификации состояния рельсовых путей грузоподъемных кранов. *Безопасность техногенных и природных систем*. 2026;10(3):219–231. <https://doi.org/10.23947/2541-9129-2026-10-3-219-231>

Introduction. The inspection of overhead crane runways in production facilities and warehouses is a complex and risky task for experts and professionals in the field of lifting equipment. Currently, the inspection of overhead crane runways is conducted in accordance with Rostekhnadzor Order No. 461 dated November 26, 2020 “On the Approval of Federal Standards and Regulations in the Field of Industrial Safety “Safety Rules for Hazardous Production Facilities with Lifting Facilities”². The inspection involves visual and measuring control along the entire length of the crane runway, as well as geometric parameter control during the planned compilation survey using special devices such as total stations and theodolites. The danger during this inspection arises from the fact that crane runways are located at a considerable height, usually ranging from 3–5 meters, but in some cases exceeding 20 meters. Overhead cranes come in two types, depending on how they are supported on the crane tracks. There are supported cranes and suspended cranes. In the supported type, the runways are attached to the crane beam, which is most often an I-beam, by welding or bolting, and these joints are prone to wear. When heavy-lift cranes are installed, connecting passages may be arranged to allow for inspection of the supporting crane runways. However, if the lifting capacity is less than 10 tons, connecting passages may not be provided. With suspended cranes (where the crane runways are in the form of I-beams), connecting passages are also typically not provided. In such cases, inspection is conducted from repair sites and using scaffold towers, which greatly increases the difficulty and duration of the inspection, as well as the risk of falling from height. Therefore, it is necessary to develop examination methods that do not require specialists and experts to be lifted to a height, while ensuring the accuracy of detecting and evaluating defects. Additionally, there is a challenge in developing faster and more efficient control methods than direct visual inspection.

The scientific literature has already discussed the potential of artificial intelligence for industrial safety. One well-known platform is a digital video monitoring system [1], which provides round-the-clock monitoring of crane operations, loading and unloading activities. It also monitors the use of special clothing and personal protective equipment by workers, the presence of workers in a dangerous area when moving goods, areas of rail tracks (absence or presence of unauthorized persons, equipment), the condition of load-handling devices (LHDs), as well as the positioning of transported cargo, and compliance with warehousing regulations. The system uses video analytics from IP cameras, processed by artificial intelligence, to provide this information to specialists and managers. The advantage of this approach is that it allows for comprehensive control over crane operations and personnel actions and equipment. This method is based on video data from permanently installed IP cameras. Each camera covers a fairly large area, although the exact size is not specified [1]. This allows the method to perform its intended functions. However, it is not suitable for overhead crane runways. To identify local defects, the video must cover the entire length of the runways and have high resolution. Shooting must be done in stereo format, with data on the depth of the structure and defects.

A method for LHD assessment based on computer vision algorithms trained using the Roboflow platform has been developed and applied [2]. The method allows for assessing the condition of LHDs located on a storage stand by processing photo and video materials captured by a webcam. However, the limitation of this method is that it can only be applied to LHDs as the webcam is permanently installed on a special stand for storing them, and it cannot receive data from a significant distance. Additionally, the neural network used for training was focused on defects specific to LHDs and therefore cannot be used for overhead crane runways.

² Rostekhnadzor Order No. 461 dated November 26, 2020 “On the Approval of Federal Standards and Regulations in the Field of Industrial Safety “Safety Rules for Hazardous Production Facilities with Lifting Facilities”. (In Russ.) URL: https://www.consultant.ru/document/cons_doc_LAW_373321/ (accessed: 14.07.2026).

In foreign studies [3], computer vision neural networks based on the pre-trained YOLOv8 model [4] and complex data analysis of the large GPT-3.5 Turbo language model [5] were used to ensure the safe operation of tower cranes. The authors developed a specialized safety knowledge base, which was compared with GPT-3.5 to discuss safety in context. The model proposed in [6] provides practical recommendations for improving safety during the operation of tower cranes in high-risk construction. The authors of [7] claim that computer vision can provide real-time spatial awareness, dynamically determining worker positions, equipment movement, and proximity to hazardous areas. A positive aspect of this study is its emphasis on staff safety and the recommendation of AI tools to further improve it. However, computer vision is unable to cover the entire working area of a crane, leaving out possible local structural defects. This makes it impossible to use computer vision methods to identify defects in the tracks of overhead cranes.

It is known that unmanned aerial vehicles (UAVs) are used for visual inspection of hard-to-reach areas of tower crane structures [8]. This allows for the identification of defects and damages, as well as the prevention of accidents. While this survey method has many advantages, it should be noted that the UAVs used for this purpose are only intended for outdoor use, as their positioning is based on GPS navigation protocols. Overhead crane runways are typically located inside buildings (workshops), so this method cannot be used to examine them.

The authors of [9] use computer vision methods to determine the degree of wear of parts, corrosion, and residual life of machines.

There are studies on the integral assessment of the risk of operating steel ropes using computer vision technologies [10]. Based on the analysis of possible defects in steel ropes [11], a neural network computer vision model [12] was trained and an intelligent decision support system (IDSS [13]) with artificial intelligence methods was developed. This development has several advantages, and its principles can be applied to develop methods for inspecting overhead crane runways. During this development, a database of rope defects was created by artificially applying them to 1,500 lengths of rope, followed by stretching them under the cameras on a horizontal milling machine. The result of this work is a stationary device that includes elevator ropes (or one cable car rope) with three webcams and a light source inside the device. The ropes move inside the device under the continuous all-round surveillance of the cameras. This principle of operation is not suitable for the inspection of overhead crane runways.

There are several UAVs that are designed specifically for use indoors and in enclosed spaces [14]. These UAVs can be equipped with cameras of various types and spectral ranges of operation, as well as lidars to create a point cloud of the surveyed objects [15]. A positive feature of UAV data is its independence from GPS navigation. At the moment, UAV-based methods are used to survey difficult-to-access enclosed spaces, such as blocked sections of mines or rubble of destroyed buildings, to adjust rescue operations. While these studies do not involve the use of artificial intelligence for the automated detection of defects in overhead crane runways, some ideas from these studies could be applied to the development of a method for examining overhead crane runways.

An analysis of the published results of such studies has revealed a gap in scientific knowledge regarding the lack of an effective survey method for crane runways located at a height inside industrial premises. This method should identify defects in crane tracks with sufficiently high accuracy and inspection speed, while ensuring the safety of personnel. This method could be developed by integrating the scientific knowledge presented in previous research, adding unique and essential components.

This research aims to develop a method for remote inspection of overhead crane tracks located at a height in industrial premises, which will minimize the impact of hazardous and harmful production factors on technical personnel and ensure the accuracy, speed and reliability of the results.

To achieve this goal, it is necessary to solve the following tasks:

1. Create a three-dimensional point cloud for the rails, crane beams, supports, with reference to the locations of crane beam supports along the axes of both rails (hereinafter referred to as the A-axis rail and the B-axis rail). The model should provide a complete picture of the relative positions of rail elements along these axes.
2. Add a three-dimensional cloud of high-density points for A-axis and B-axis rails to identify deviations of crane runway elements from their design positions in plan and profile (planned high-altitude survey), as well as detect defects in crane tracks.
3. Develop a three-dimensional model of the above-ground crane runways with automatic assessment (measurement) of deviations in the geometry of crane runways, wear and local defects, and link them to column lines and sections.

Materials and Methods. Data on defects on overhead crane runways was used as initial information. This data was obtained during the inspection of overhead cranes as part of expert control of lifting cranes at machine-building enterprises in 2024. A survey was conducted during which 352 overhead crane runways with a total length of 14 kilometers were examined. The methodological part of the study was based on GOST R 56944–2016³. Computer vision neural networks were trained using open libraries for the Python language. An upgraded YOLOv8 pre-trained neural network was used to detect defects. Its architecture was a three-part system consisting of a feature extractor (CSPDarknet53 software module), a feature combinator (C2f module) and an output predictive block (decoupled head module). YOLOv8 was developed by Ultralytics and had open source code available for further modernization to meet the needs of a specific project.

The hardware basis of the platform was a flying mobile system with a modular architecture (Fig. 1)



Fig. 1. Industrial inspection FPV drone (quadcopter) with protective frame

The authors proposed their own design of an unmanned aerial vehicle (quadcopter), assembled from the components manufactured in China and available for purchase from the distributors of such equipment.

To position UAVs relative to base stations and so-called anchors, the DWM1000 sensor was used — TWR positioning support (Two-Way Ranging, a method used to determine the distance between two devices using signal exchange) and the TDOA sensor (Time Difference of Arrival, a positioning method that determines the location of an object by measuring the difference in the time of arrival of its signal by several receiving stations (anchors) with known coordinates).

The sensor complex included three key types of sensors:

- spatial sensing equipment (Livox MID-40 multi-lens lidar, Orbbec Gemini 2 depth camera);
- visual perception equipment (DJI O3 Air Unit— a digital FPV system that included a compact 4K RGB camera and a transmitter);
- positioning and stabilization systems (DWM1000 sensors, NAV40 inertial modules, short-range detection systems based on ArduPilot firmware, backup navigation methods — visual odometry and optical navigation based on lidar and cameras).

The computing subsystem was based on the Aocoda-RC F765 V2 processor module with graphics acceleration, which supported the computer vision algorithms, neural network processing and data fusion.

The survey procedure for the above-ground crane runway of the supporting structure using an unmanned aerial vehicle was conducted in accordance with the following algorithm (Fig. 2):

1. Checking the condition and installing the charged battery of the UAV.
2. Calibration of the means of spatial and visual perception.
3. Performing a test flight to verify the operation of the navigation systems and the systems for capturing and transmitting point clouds of the 3d model.

³ GOST R 56944–2016 “Lifting Cranes. Overhead Crane Rail Tracks. General Technical Requirements” (approved and put into effect by Order No. 463-st of the Federal Agency for Technical Regulation and Metrology dated 1 June 2016). URL: <https://ohranatruda.ru/upload/iblock/8fe/4293754222.pdf?ysclid=mnsrm94qrk671517049> (accessed: 10.04.2026).

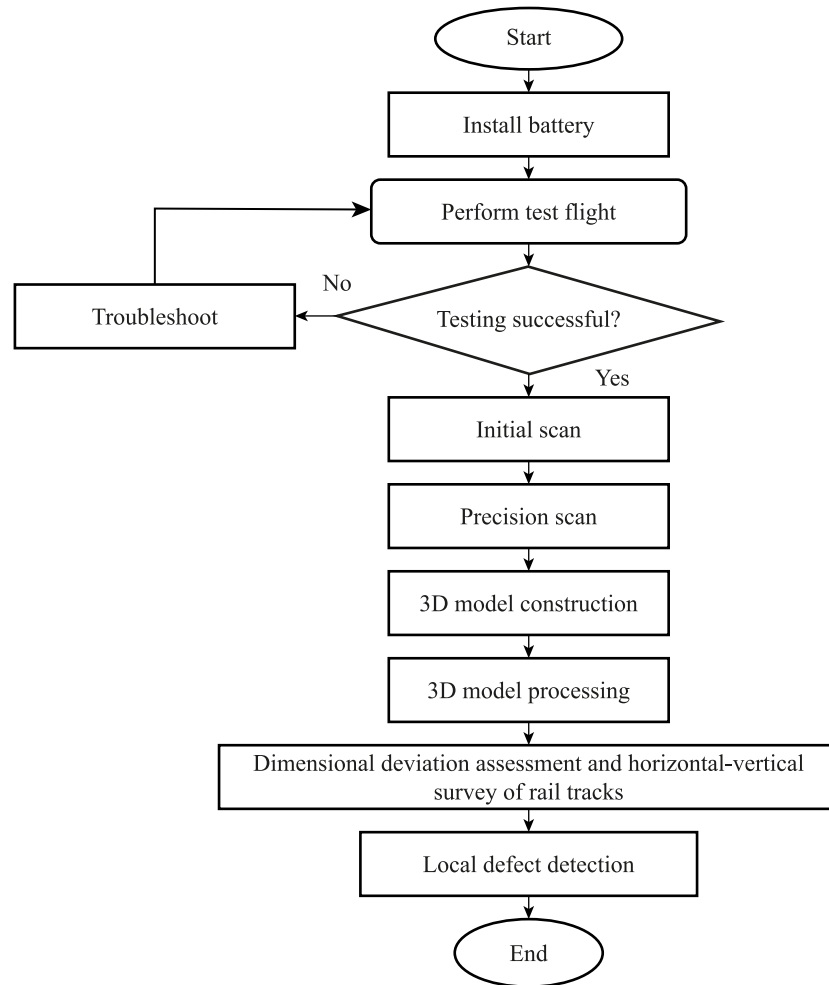


Fig. 2. Algorithm for using UAVs to inspect overhead crane runways

4. Performing the initial scan (Fig. 3, pos. 1) to create a complete three-dimensional point cloud covering runways, crane beams, supports, with reference to the locations of the crane beam supports along the axes of both rails. At the same time, to ensure the integrity of the model, the scan could cover the floor of the room or the structural element connecting the crane beams of the A and B axes. The span distance was about one meter from the scanned elements. The speed was 5 m/s. The density of scan points was 2,000 pcs/m².

5. Performing an accurate scan of the runways of A and B axes to add a three-dimensional cloud of high-density points (Fig. 3, pos. 2). In this case, the flight was made at a distance of approximately 0.2 meters from the scanned elements. The speed was 1 m/s. The density of scanning points was 40,000 pcs/m².

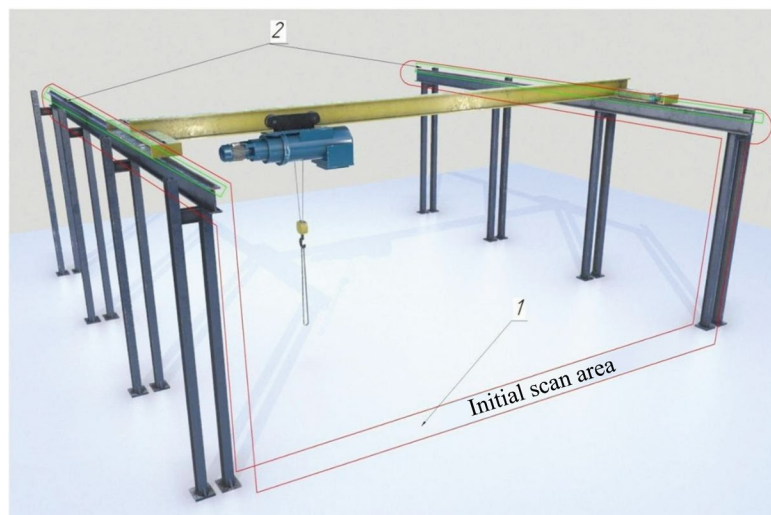


Fig. 3. Primary (1) and close scanning area (2)

6. Creation of a 3D model from the captured point cloud in the Geomagic Wrap application.

7. 3D model processing using artificial intelligence. At the same time, the following elements of the model were determined: rails, crane beams, supports, and lines locations. The processing was performed using a proprietary application based on the upgraded YOLOv8 model.

8. Model determination of deviations in the size and planned height position of runways from the limit values of GOST R 56944-2016 “Cranes. Overhead Crane Railways. General Specifications”⁴.

9. Identification of local defects of crane runways on the model.

In paragraphs 8 and 9 of the algorithm, the accuracy of the detected deviations and defects at the test stage of the method was verified by comparison with the results of visual and measuring control. After completing the tests of the method, the parameters of its accuracy would be indicated in the regulatory and technical documentation.

Research Results. A method of flaw detection of overhead crane runways using unmanned aerial vehicles has been developed. Local defects of crane runways have been identified. The data were obtained during the survey of overhead cranes as part of an expert survey of lifting cranes at machine-building enterprises.

In particular, the following tasks set by the authors were solved:

1. A three-dimensional point cloud was created (Fig. 4), which included rails, crane beams, supports, with reference to the locations of the crane beam supports along the axes of both rails (A-axis rail and B-axis rail). At the same time, the model provided a comprehensive view of the relative position of the path components along the A and B axes.



Fig. 4. Model of a beam crane with crane runways

Figure 4 demonstrates a model of an overhead beam crane with crane runways obtained from a three-dimensional point cloud, the axes of A and B rails are indicated, as well as the line numbers — columns with a median line between them.

2. A three-dimensional cloud of high-density points was obtained for the rails of axis A and axis B in order to identify deviations of crane runway elements from the design position in plan and profile (compilation survey), as well as to detect defects in the crane runways (Fig. 5–10).

The photographs of the defects shown in Figures 5–10 were taken in the workshops of an industrial company during a real-life survey, using the available lighting and optical clarity of the air.

The defects were assessed using a trained computer vision neural network.

Figure 5 shows a defect in the joint of an I-beam with poor-quality welding of the fixing plate.

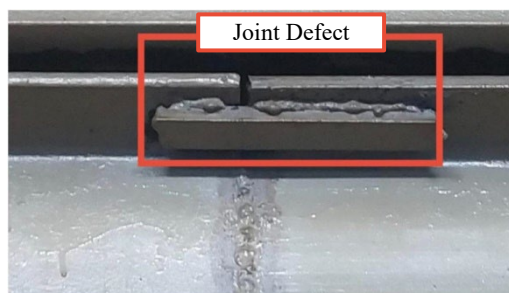


Fig. 5. Joint defect

⁴ GOST R 56944-2016 “Lifting Cranes. Overhead Crane Rail Tracks. General Technical Requirements” (approved and put into effect by Order No. 463-st of the Federal Agency for Technical Regulation and Metrology dated 1 June 2016). URL: <https://ohranatruda.ru/upload/iblock/8fe/4293754222.pdf?ysclid=mnsrm94qrk671517049> (accessed: 10.04.2026).

Figure 6 demonstrates a defect in the perforation of the I-beam of a suspended overhead crane (in the weld area).

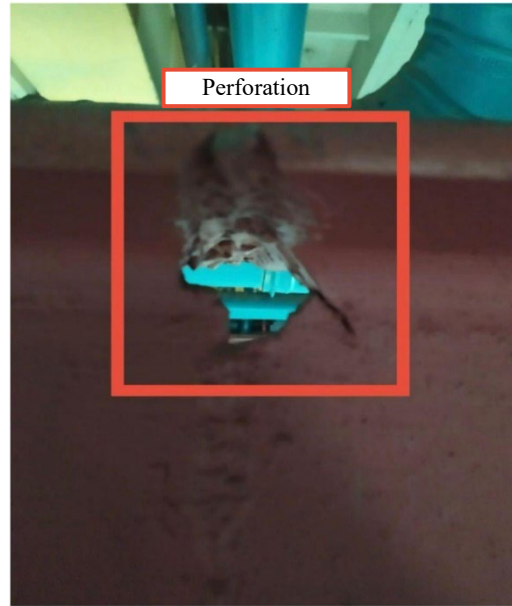


Fig. 6. I-beam perforation

Figure 7 shows an example of rail wear with chipping of the side edges and holes on the work surface.

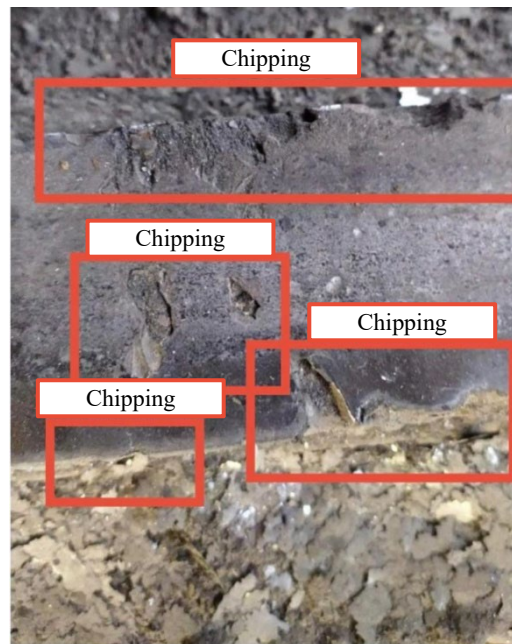


Fig. 7. Wear of the rail with chipping and holes

Figure 8 provides the result of abrasion of the I-beam by the wheel of an overhead crane. The defect could occur as a result of bending of the beam or malfunction of the crane structures.

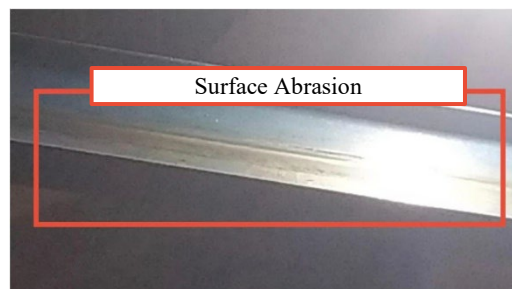


Fig. 8. Abrasion of the side surface of the I-beam

Figure 9 shows the wear of the rail as a result of wheel slipping of the support crane.



Fig. 9. Wear of the rail as a result of the crane wheel slipping

Figure 10 shows a defect in the thermic cut of the I-beam without a bottom plate.

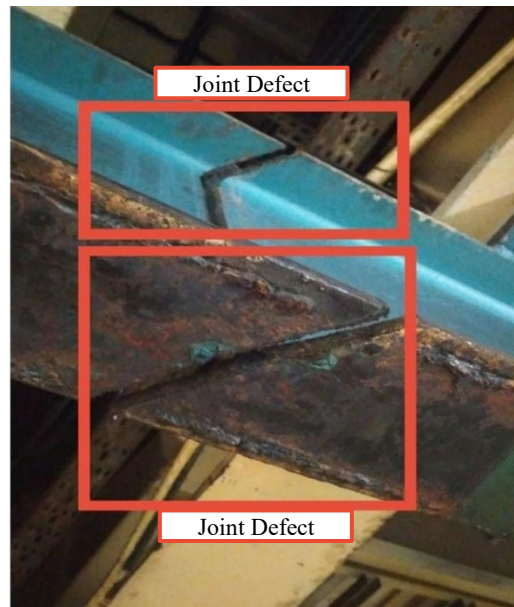


Fig. 10. Defect in the thermic cut area of the I-beam

3. The created three-dimensional model of crane runways allows for an automated assessment of deviations in the geometry of crane runways, wear and local defects with reference to the column sections and axes (Fig. 4).

Evaluation of the geometry of crane runways, presented as a model in Figure 4, gave the following results, which are shown on Figure 11.

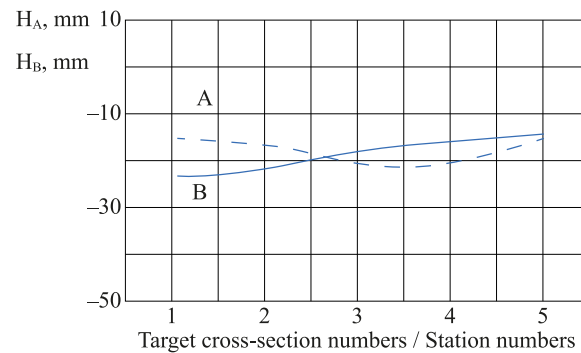


Fig. 11. Evaluation of the geometry of rails in the vertical plane

The permissible difference in rail elevation within one cross-section along the axis of symmetry [P1] was 40 mm, and the permissible difference between adjacent columns [P2] was 10 mm (according to GOST R 56944–2016⁵). By comparing the data in Figure 11 to the allowable values, we could conclude that the geometry deviations in the crane track under consideration were within tolerance.

This method of flaw detection allowed us to obtain photo and video data, which could be used to estimate the size of defects with accuracy of one millimeter.

Discussion. The results obtained during the application of the method developed by the authors fully meet both the research goals and the objectives of its implementation. Achieving accurate and precise indicators was made possible by the large number of above-ground crane runway surveys, which allowed us to collect a variety of samples of defects in the geometry of crane runways and local defects. Data processing made it possible to train neural networks for computer vision and create fully functional three-dimensional models that can automatically identify and evaluate defects.

Comparison of the results obtained with literature data, theories, and other developments allows us to conclude that this study is unique. No such method has been developed before for overhead crane runways.

At the moment, the main disadvantage of the developed method is the limited operation time of an unmanned aerial vehicle due to a lack of battery power. It is not possible to install larger batteries, as this would require increasing the size of the unmanned aerial vehicle. Therefore, the maximum size of a drone can be no more than 0.5 meters, due to the limited space in enclosed areas, and the flight time can be no longer than 20 minutes (depending on the weight of the equipment).

The results of the study should be interpreted as positive. The method should be developed and implemented to improve the efficiency of inspection of overhead crane runways. In practice, the method allows you to:

- inspect crane runways from a close distance along their entire length;
- estimate the size of local defects using photo and video recordings and specialized software;
- create a 3D model of the crane runway using photogrammetry and assessing deviations from straightness in both the longitudinal and transverse planes;
- reduce labor intensity and duration of inspections by at least two times.

Conclusion. In conclusion, it should be noted that the work done by the authors has produced significant results, the most important of which is the development of a method for remote inspection of overhead crane runways. During the study, neural networks were trained to detect defects and an algorithm was created for examining crane runways by creating a three-dimensional model that allows for estimating geometric deviations in the rails in the longitudinal and transverse planes. The main advantage of this method is that it ensures the safety of experts and specialists who inspect lifting facilities. Additionally, the method enables the inspection of hard-to-access areas of crane runways and the identification of defects that may have gone unnoticed, reducing the likelihood of accidents.

Future research plans for lifting cranes involve the development of additional features to the system that will help identify their condition. The system will automatically inspect the crane runways and analyze the condition of the metal structures, identifying any defects.

References

1. Junlin Wang, Songbo Hu, Yihai Fang, Hongling Guo. Knowledge-Augmented Multi-Modal Data Fusion and Reasoning for Automated Crane Lift Monitoring. *Automation in Construction*. 2026;183:106822. <https://doi.org/10.1016/j.autcon.2026.106822>
2. Egelsky VV, Nikolaev NN, Egelskaya EV, Korotkiy AA. Use of Artificial Intelligence to Monitor the Reliability of Removable Load-Handling Devices. *Safety of Technogenic and Natural Systems*. 2024;(2):57–67. <https://doi.org/10.23947/2541-9129-2024-8-2-57-67>
3. Lingxiao Wang, Jingfeng Yuan, Shu Su, Hongxing Ding, Yu Bai, Skibniewski MJ. Fusing Enhanced YOLO and knowledge graph-Based Large Language Models for Automatic Risk Perception in Tower Crane Operations. *Automation in Construction*. 2026;183:106823. <https://doi.org/10.1016/j.autcon.2026.106823>
4. Shi Qiu, Benxin Cai, Weidong Wang, Jin Wang, Qasim Zaheer, Xianhua Liu, et al. Automated Detection of Railway Defective Fasteners Based on YOLOv8-FAM and Synthetic Data Using Style Transfer. *Automation in Construction*. 2024;162:105363. <https://doi.org/10.1016/j.autcon.2024.105363>
5. Yiheng Wang, Hanbin Luo, Weili Fang. An Integrated Approach for Automatic Safety Inspection in Construction: Domain Knowledge with Multimodal Large Language Model. *Advanced Engineering Informatics*. 2025;65(B):103246. <https://doi.org/10.1016/j.aei.2025.103246>

⁵ GOST R 56944–2016 “Lifting Cranes. Overhead Crane Rail Tracks. General Technical Requirements” (approved and put into effect by Order No. 463-st of the Federal Agency for Technical Regulation and Metrology dated 1 June 2016). URL: <https://ohranatruda.ru/upload/iblock/8fe/4293754222.pdf?ysclid=mnsrm94qrk671517049> (accessed: 10.04.2026).

6. Yiheng Wang, Bo Xiao, Ahmed Bouferguene, Mohamed Al-Hussein. Proactive Safety Hazard Identification Using Visual–Text Semantic Similarity for Construction Safety Management. *Automation in Construction*. 2024;166:105602. <https://doi.org/10.1016/j.autcon.2024.105602>
7. Yuexiong Ding, Ming Zhang, Jia Pan, Jinxing Hu, Xiaowei Luo. Robust Object Detection in Extreme Construction Conditions. *Automation in Construction*. 2024;165:105487. <https://doi.org/10.1016/j.autcon.2024.105487>
8. Xiaohui Li, Hailong Huang, Savkin AV, Jian Zhang. Robotic Herding of Farm Animals Using a Network of Barking Aerial Drones. *Drones*. 2022;6(2):29. <https://doi.org/10.3390/drones6020029>
9. Na Zhang, Gang Yang, Dawei Wang, Fan Hu, Hua Yu, Jingjing Fan. A Defect Detection Method for Substation Equipment Based on Image Data Generation and Deep Learning. *IEEE Access*. 2024;12:105042–105054. <https://doi.org/10.1109/ACCESS.2024.3436000>
10. Panfilov AV, Nikolaev NN, Yusupov AR, Korotkiy AA. Integral Risk Assessment in Steel Ropes Diagnostics Using Computer Vision. *Safety of Technogenic and Natural Systems*. 2023;(1):56–69. <https://doi.org/10.23947/2541-9129-2023-1-56-69>
11. Peterka P, Krešák J, Vojtko M, Mantič M. Failure Analysis of the Journal Bearing Pulley of the Cargo Cable Way. *Engineering Failure Analysis*. 2020;111:104329. <https://doi.org/10.1016/j.engfailanal.2019.104329>
12. Korotkiy AA, Panfilov AV, Yusupov AR. Detection and Classification of Defects in Steel Ropes of Elevators Using Computer Vision. *News of the Tula State University. Technical Sciences*. 2023;4:643–648. (In Russ.) URL: https://tidings.tsu.tula.ru/tidings/pdf/web/preview_therest_ru.php?x=tsu_izv_technical_sciences_2023_04_e&year=2023 (accessed: 25.03.2026)
13. Kruchkov MS. Analysis of Methods of Intelligent Decision Support Systems. *Vestnik Nauki*. 2025;7(88):303–314. (In Russ.) URL: <https://www.вестник-науки.рф/article/25033> (accessed: 25.03.2026)
14. Yasser E El-Alfy, Uthman Baroudi. Monocular Based 3D Depth Estimation and SLAM Integration. *Drone Systems and Applications*. 2025;13:1–14. <https://doi.org/10.1139/dsa-2024-0025>
15. Yangzi Cong, Chi Chen, Bisheng Yang, Ruofei Zhong, Shangzhe Sun, Yuhang Xu, et al. OR-LIM: Observability-Aware Robust Lidar-Inertial-Mapping under High Dynamic Sensor Motion. *ISPRS Journal of Photogrammetry and Remote Sensing*, 2024;218(A):610–627. <https://doi.org/10.1016/j.isprsjprs.2024.09.036>

About the Authors:

Vladislav V. Egelsky, Postgraduate Student of the Department of Operation of Transport Systems and Logistics, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation), [ORCID](https://orcid.org/0000-0001-9714-1414), sp_5sp_6pb_97n14@mail.ru

Nikolai N. Nikolaev, Cand. Sci. (Eng.), Associate Professor of the Department of Operation of Transport Systems and Logistics, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation), [SPIN-code](https://orcid.org/0000-0001-9714-1414), [ORCID](https://orcid.org/0000-0001-9714-1414), ScopusID, nnneks@yandex.ru

Elena V. Egelskaya, Cand. Sci. (Eng.), Associate Professor of the Department of Operation of Transport Systems and Logistics, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation), [SPIN-code](https://orcid.org/0000-0001-9714-1414), [ORCID](https://orcid.org/0000-0001-9714-1414), egelskaya72@mail.ru

Anatoly A. Korotkiy, Dr. Sci. (Eng.), Professor, Head of the Transport Systems Operation and Logistics Department, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation), [SPIN-code](https://orcid.org/0000-0001-9714-1414), [ORCID](https://orcid.org/0000-0001-9714-1414), ScopusID, korot@novoch.ru

Leonid A. Ternovskoi, Postgraduate Student of the Department of Transport Systems and Logistics, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation), [ORCID](https://orcid.org/0000-0001-9714-1414), leonidternovskoi@yandex.ru

Claimed Contributorship:

VV Egelsky: conceptualization, software.

NN Nikolaev: methodology, visualization.

EV Egelskaya: writing – review & editing.

AA Korotkiy: supervision, project administration.

LA Ternovskoi: writing – original draft preparation.

Conflict of Interest Statement: the authors declare no conflict of interest.

All authors have read and approved the final version of manuscript.

Об авторах:

Владислав Витальевич Егельский, аспирант кафедры «Эксплуатация транспортных систем и логистика» Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), [ORCID](https://orcid.org/0000-0001-9714-1414), sp_5sp_6pb_97n14@mail.ru

Николай Николаевич Николаев, кандидат технических наук, доцент кафедры «Эксплуатация транспортных систем и логистика» Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), [SPIN-код](#), [ORCID](#), [ScopusID](#), nnneks@yandex.ru

Елена Владимировна Егельская, кандидат технических наук, доцент кафедры «Эксплуатация транспортных систем и логистика» Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), [SPIN-код](#), [ORCID](#), egelskaya72@mail.ru

Анатолий Аркадьевич Короткий, доктор технических наук, профессор, заведующий кафедрой «Эксплуатация транспортных систем и логистика» Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), [SPIN-код](#), [ORCID](#), [ScopusID](#), korot@novoch.ru

Леонид Александрович Терновской, аспирант кафедры «Эксплуатация транспортных систем и логистика» Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), [ORCID](#), leonidternovskoi@yandex.ru

Заявленный вклад авторов:

В.В. Егельский: формулирование идеи, гипотезы, цели исследования, создание программного обеспечения, скриптов, алгоритмов.

Н.Н. Николаев: разработка методов и процедур исследования, создание графиков, схем, иллюстраций.

Е.В. Егельская: редактирование, доработка текста.

А.А. Короткий: научное руководство проектом, организационное управление проектом.

Л.А. Терновской: написание первоначального текста статьи.

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 30.05.2026

Reviewed / Поступила после рецензирования 20.06.2026

Accepted / Принята к публикации 30.06.2026

TECHNOSPHERE SAFETY

ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ



UDC 613.644

Original Empirical Research

<https://doi.org/10.23947/2541-9129-2026-10-3-232-246>

Gazebo-Type Small Architectural Form as a Noise Protection Structure for Residential Area Improvement Sites

Artyem V. Artyemov¹, Evgenii S. Kurkin², Pavel S. Zakharov¹,
Tat'yana V. Shteba³

¹ Ural State Forest Engineering University, Yekaterinburg, Russian Federation

² Federal State Institution “Uralupravitodor”, Yekaterinburg, Russian Federation

³ Ural Institute of the State Fire Service of EMERCOM of Russia, Yekaterinburg, Russian Federation

✉ artemovav@m.usfeu.ru



EDN: GGZPEL

Abstract

Introduction. The new “Infrastructure for Life” project aims to renovate housing, public spaces, and develop convenient public transportation routes. Along with chemical air pollution, motor vehicle traffic is becoming a significant source of noise pollution that threatens public health. Special acoustic barriers and green spaces are used to control noise. However, existing methods of noise protection for courtyard spaces are not always effective and/or require significant material costs. To overcome these limitations, the use of small architectural forms (SAFs) has been proposed. These forms can serve as noise reduction measures and also be elements of landscaping. The aim of this research is to provide a calculated justification for the possibility of using engineering and technical landscaping elements, namely SAFs, to reduce the noise from adjacent residential infrastructure, particularly motor vehicles, on recreational and leisure areas in residential districts.

Materials and Methods. The empirical basis of the study consisted of data from regulatory documents, scientific publications, and field observations. The research object was a small architectural form, a semi-enclosed gazebo with a solid rear wall, which could be used for noise protection of adjacent courtyard spaces and landscaped areas. For comparison, we also considered the following design solutions: no barrier, a standard noise barrier, a strip of green space, and a small railway barrier. Acoustic calculations were performed in accordance with current standards using specialized software, including Ecolog-Noise, Calculation of Sound Insulation, and Calculation of Traffic Flow Noise.

Results. Calculations of noise impact and airborne sound insulation were performed for various design options, and the results were presented in tables and graphical materials. The frequency characteristic of airborne sound insulation for a solid SAF wall was determined graphically in the form of a broken line. The airborne sound insulation index for the rear wall of the SAF was 29 dB, which indicated its potential use as a local noise protection element under the considered calculation conditions. Calculations of traffic noise characteristics showed that the equivalent sound level of the motor traffic flow was 59.7 dBA, while the maximum permissible level for a residential recreation area was 45 dBA. The graphical representation of the noise propagation calculation results was presented as isolines of acoustic discomfort zones at the normalization height of 1.5 m. Additionally, a 3D graphical distribution of noise was prepared for visualization purposes.

Discussion. The results showed that the calculated noise reduction was primarily determined by the presence of a solid enclosing surface between the acoustic impact source and the protected area. In the conditions considered, a standard noise-proof screen and a gazebo-type SAF proved to be the most effective, while green spaces, a small acoustic screen and the absence of any protective measures did not provide the required level of noise protection.

Conclusions. The use of enclosing structures, including acoustic barriers and SAFs, can significantly reduce the noise level and decrease the acoustic discomfort zone. The need to develop affordable and effective solutions for reducing noise levels in residential areas is determined by sanitary and hygienic legislation. The calculated data demonstrate the prospects of using semi-enclosed SAFs with solid enclosing elements as an additional means of local noise protection. However, the final assessment of their effectiveness requires further verification for other structural solutions, planning conditions, and noise load scenarios.

Keywords: physical impact, noise, residential area, small architectural forms, sound insulation

Acknowledgements. The authors would like to thank the Editorial board and the reviewers for their attentive attitude to the article and for the specified comments that improved the quality of the article.

For Citation. Artyemov AV, Kurkin ES, Zakharov PS, Shteba TV. Gazebo-Type Small Architectural Form as a Noise Protection Structure for Residential Area Improvement Sites. *Safety of Technogenic and Natural Systems*. 2026;10(3):232–246. <https://doi.org/10.23947/2541-9129-2026-10-3-232-246>

Оригинальное эмпирическое исследование

Применение малой архитектурной формы типа «Беседка» в качестве шумозащитной конструкции для площадок благоустройства жилых зон

А.В. Артёмов¹, Е.С. Куркин², П.С. Захаров¹, Т.В. Штеба³

¹ Уральский государственный лесотехнический университет, г. Екатеринбург, Российская Федерация

² ФКУ «Уралуправдор», г. Екатеринбург, Российская Федерация

³ Уральский институт ГПС МЧС России, г. Екатеринбург, Российская Федерация

✉ artemovav@m.usfeu.ru

Аннотация

Введение. Новый проект «Инфраструктура для жизни» предусматривает обновление жилищного фонда, развитие общественных пространств и формирование удобных маршрутов общественного транспорта. Наряду с химическим загрязнением атмосферного воздуха автотранспорт является значимым источником шумового воздействия, представляющего угрозу для здоровья населения. Для снижения уровня шума применяются специальные акустические экраны и зеленые насаждения. Однако существующие способы шумозащиты внутридворовых пространств не всегда обладают достаточной эффективностью и/или требуют существенных материальных затрат. С целью устранения указанных недостатков предлагается использовать малые архитектурные формы (МАФ), которые могут выступать как эффективное средство снижения шума и одновременно служить элементом благоустройства территории. Цель настоящего исследования — расчетное обоснование возможности применения инженерно-технических элементов благоустройства (МАФ) для снижения шумового воздействия придомовой инфраструктуры, в первую очередь автотранспорта, на площадки отдыха и досуговые зоны жилых районов.

Материалы и методы. Эмпирическую основу исследования составили данные нормативных документов и научных публикаций, дополненные результатами натурных наблюдений. Объектом изучения являлась МАФ в виде полужакрытой беседки с глухой задней стенкой. Для сопоставления были рассмотрены расчетные варианты без ограждения, со стандартным шумозащитным экраном, с полосой зеленых насаждений, с малым акустическим экраном и с МАФ типа «Беседка». Расчеты выполнены с применением программ «Эколог-Шум», «Расчет звукоизоляции» и «Расчет шума от транспортных потоков» в соответствии с действующими нормативными методиками.

Результаты исследования. Проведены расчеты шумового воздействия и изоляции воздушного шума для различных вариантов, результаты которых представлены в таблицах и отражены в графических материалах. Частотная характеристика изоляции воздушного шума для сплошной стенки МАФ, изображенная в виде ломаной линии, была определена графическим способом. Индекс изоляции воздушного шума для задней стенки МАФ составил 29 дБ, что указывает на потенциальную возможность ее применения в качестве локального шумозащитного элемента при рассматриваемых расчетных условиях. Расчеты шумовой характеристики транспортного потока показали, что эквивалентный уровень звука составляет 59,7 дБА при предельно допустимом уровне воздействия на зону отдыха жилой территории 45 дБА. Графическое отображение результатов расчета распространения шума представлено в виде изолиний зон акустического дискомфорта на высоте нормирования 1,5 м. Для дополнительной визуализации также выполнено графическое распределение шума в перспективе (3D).

Обсуждение. Полученные результаты показывают, что расчетное снижение уровня шума определяется прежде всего наличием сплошной ограждающей поверхности между источником акустического воздействия и защищаемой площадкой. В рассматриваемых условиях наиболее результативными оказались стандартный шумозащитный экран и МАФ типа «Беседка», тогда как зеленые насаждения, малый акустический экран и отсутствие защитных мероприятий не обеспечили требуемый уровень шумозащиты.

Заключение. Использование ограждающих конструкций, включая экраны и МАФ, значительно снижает уровень шума и уменьшает зону акустического дискомфорта. Необходимость разработки доступных и эффективных решений, направленных на снижение шумового воздействия в жилых зонах, обусловлена требованиями санитарно-гигиенического законодательства. Полученные расчетные данные свидетельствуют о перспективности применения полужакрытых МАФ с глухими ограждающими элементами в качестве дополнительного средства локальной шумозащиты. Окончательная оценка их эффективности требует дальнейшей проверки для иных конструктивных решений, планировочных условий и сценариев шумовой нагрузки.

Ключевые слова: физическое воздействие, шум, жилая зона, малые архитектурные формы, звукоизоляция

Благодарности. Авторы выражают благодарность редакции и рецензентам за внимательное отношение к статье и указанные замечания, которые позволили повысить ее качество.

Для цитирования. Артёмов А.В., Куркин Е.С., Захаров П.С., Штеба Т.В. Применение малой архитектурной формы типа «Беседка» в качестве шумозащитной конструкции для площадок благоустройства жилых зон. *Безопасность техногенных и природных систем*. 2026;10(3):232–246. <https://doi.org/10.23947/2541-9129-2026-10-3-232-246>

Introduction. The implementation of national projects aimed at the development of transport and housing infrastructure increases the requirements for the quality of urban environment, as well as for the safety and comfort of courtyard spaces [1, 2]. In these circumstances, the noise generated by vehicles is considered not only as an engineering challenge in road design, but also as sanitary and hygienic risk for the population.

It has been established in scientific literature that traffic noise is a significant component of physical pollution in urban areas and has an adverse effect on the quality of life and health of residents [3]. Generalized studies have linked prolonged exposure to noise to neurological disorders, cardiovascular diseases, anxiety, and other negative health effects [4–6]. Consequently, reducing the acoustic load in residential areas has a pronounced sanitary and hygienic, and urban planning significance.

Existing approaches to noise pollution control in urban areas can be divided into several categories. The first category includes engineering solutions, such as acoustic screens, enclosure structures, and sound insulation elements in buildings [8–10]. The effectiveness of these measures depends on factors such as height, position in relation to the noise source, geometric characteristics, material used, and the presence of sound-absorbing materials [11–13].

At the same time, engineering screens are not always the best solution for courtyard spaces. In reality, their use can be limited by various factors such as architectural, operational, sanitary, and economic considerations. Additionally, the actual condition of acoustic screens and the way they are placed can reduce their expected noise reduction effectiveness [14].

The second group of solutions involves the use of small and specialized acoustic screens [15, 16]. These structures can reduce local noise, but their effectiveness depends on several factors, such as height, position relative to the noise source and receiver, and the type of traffic. Therefore, the results obtained for railway or mainline noise cannot be automatically transferred to courtyards and landscaping sites. Figure 1 provides a generalization of these screen solutions.

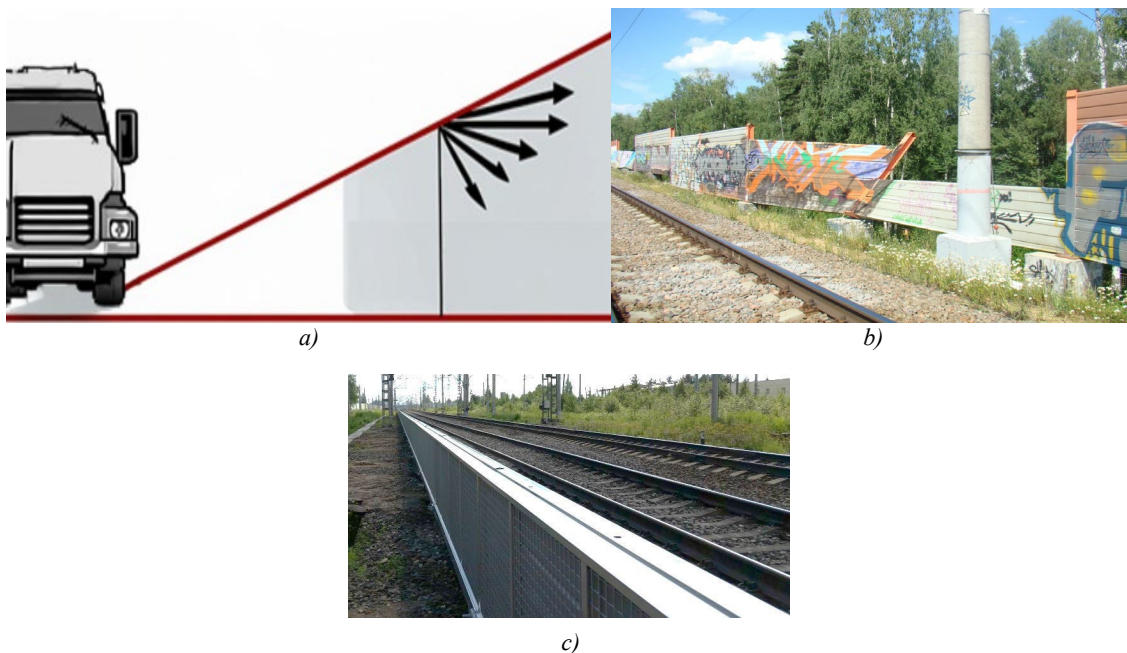


Fig. 1. The use of noise fencing (acoustic) screens: *a* — attenuation during sound propagation; *b* — loss of effectiveness of artificial noise-proof structures [14]; *c* — small acoustic screens [16]

The third group of solutions involves using green spaces to provide noise protection. These spaces can have a sufficient width, density, and number of plants to perform this function [17, 18]. The most effective form of this is an array of tall trees, complemented by shrubs. Vertical structure and density of the trees' crowns determine their ability to attenuate noise.

Existing or specially designed green spaces can serve as natural noise barriers. Studies have shown that their effectiveness depends not on the mere presence of landscaping, but on the structural parameters of the plants: height, density, strip width, number of levels, and presence of a shrub layer [17, 18].

Consequently, green spaces have a significant ecological and urban planning potential. However, under conditions of limited courtyard space, their noise reduction effectiveness may be insufficient. The main challenges are related to the requirement for additional land, insufficient planting density, and the preservation of open canopy areas.

In practice, this can lead to a situation where landscaping enhances the appearance of a territory, but it does not always guarantee the achievement of noise levels required by regulations at the borders of recreational and leisure areas.

When placing guest parking spaces and local driveways near children's and sports areas, additional local safety measures are needed that are compatible with the architectural and planning design of the courtyard (Fig. 2).

This formulation of the problem allows us to consider SAFs as a potential element of the first line of defense against noise in regulated residential areas.

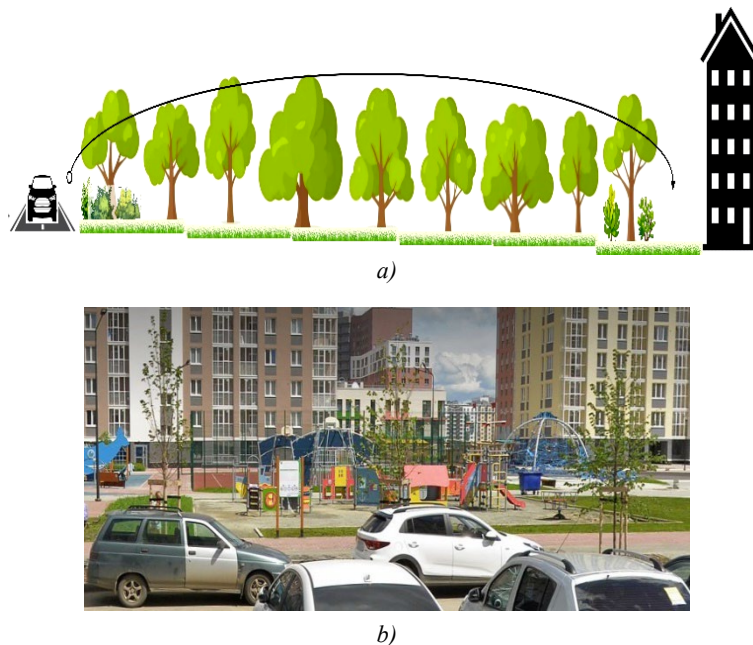


Fig. 2. The use of green spaces as protective strips: *a* — attenuation during sound propagation; *b* — landscaping sites with landscaping on the side of the object with negative impact (Yandex-maps open Internet source)

The analysis of these approaches shows that each of them has its limitations when used in high-density residential development. Traditional screens can worsen the visual appeal of the courtyard area and require additional design and construction costs. Green spaces require a significant amount of space and may not always provide adequate protection, even with an open canopy. Small acoustic screens can be effective in certain geometric situations, but their applicability is limited.

This issue is particularly significant for recreational and leisure areas that are located near local roads and parking lots. Under these circumstances, a local noise reduction solution is needed, which not only decreases the acoustic impact but also maintains the functionality and aesthetic appeal of the landscape area [7].

When it is difficult to install traditional screens or create full-fledged green or protective strips, design and maintenance companies can utilize continuous landscaping features such as retaining walls, enclosing structures or small architectural forms (SAFs) (Fig. 3). Their advantage lies in their ability to combine the protective function with landscape design.



Fig. 3. Gazebo-type small architectural form for residential landscaping areas

From these perspectives, the use of landscaping elements as part of a noise protection system is a promising approach. Unlike special engineering screens, small architectural forms can simultaneously perform recreational, urban planning, and protective functions, which is particularly significant for small courtyard spaces.

However, existing research focuses on traditional acoustic screens, green spaces, and engineering noise-proof structures. The possibility of using small architectural forms with blind enclosing surfaces as local structures to protect landscaping areas from noise has not been sufficiently studied.

Despite the availability of research on traditional acoustic screens, green spaces, and small noise-proof structures, the potential of using functional landscaping elements combining recreational and protective functions as a means of local noise reduction in courtyard areas has not been fully explored. The scientific novelty of this work consists in the calculated assessment of a small architectural form with blind enclosing surfaces as a local noise protection element for recreational areas in residential areas and in comparing its effectiveness with traditional noise protection options.

This work aimed to estimate the potential of using small architectural forms with blind enclosing surfaces as local noise protection elements of landscaping (SAF) to reduce the noise impact of around the house infrastructure, primarily vehicles, on recreation areas and leisure areas of residential areas.

To achieve this goal, we have solved the following tasks:

1. We have analyzed possible noise protection solutions for residential landscaping sites.
2. We have prepared calculated noise protection options, including the absence of fencing, a typical noise barrier, green spaces, a small acoustic screen, and a gazebo-type SAF.
3. We have determined the initial parameters of traffic noise and the sound insulation characteristics of the SAF enclosing structure.
4. We have simulated noise propagation in the landscaping area and compared the calculated levels with the maximum permissible values.
5. We have conducted a comparative assessment of the options based on sanitary, ecological, urban planning, and economic criteria.

Materials and Methods. Empirical Base and Data Sources. The research was based on the data from regulatory documents, scientific publications, technical specifications of noise-resistant structures, as well as field route observations conducted on the territory of residential buildings. This information was used to develop design scenarios, define initial parameters of traffic flow, and establish criteria for assessing noise levels.

Specialized software, ecological Geographic Information System (GIS) “Ecolog-Shum” was used to conduct computational and analytical work to assess the acoustic load. The software package is included in the Unified Register of Russian Computer Programs and Databases, having been approved by the Ministry of Digital Development, Communications and Mass Media of the Russian Federation.

There were also additional modules of the software package:

- “Noise from Highways” module. It was used to calculate the equivalent (LA_{eq}) and maximum (LA_{Fmax}) sound levels of the traffic flow. The methodological basis was provided by the relevant documents of the transport industry;
- “Sound Insulation Calculator” module. It was used to determine the air noise insulation index (R_w) of enclosing structures. The calculation was performed in the one-third octave frequency bands of 100–3150 Hz, followed by extrapolation to standard octave values. Additionally, when selecting criteria for evaluating the characteristics of materials, reference information from the electronic catalog of the Research Institute of Building Physics (1988) was used.

The rationale for the adopted acoustic models was based on current regulatory and technical documents of the Russian Federation and reference materials (see notes throughout the text and references).

The parameters of planned residential development facilities were taken from the previously developed design documentation.

Noise characteristics of vehicles were determined based on the traffic density recorded during field work in July 2025 on the territory of the projected residential neighborhood in Yekaterinburg. These works were conducted as part of engineering and environmental surveys for the pre-design study of project documentation and were aimed at assessing the actual noise level at the boundary of the planned landscaping site.

When developing recommendations for noise reduction, we used the maximum permissible levels (MPLs) set by the sanitary and hygienic standards for residential area facilities as a basis. We selected the characteristics of the proposed noise shielding, including the panel material, sound absorption coefficient α_w , surface density, and other parameters based on the manufacturers' technical specifications, or taking into account proposed design solutions and background information.

GIS graphical interface allowed simultaneous editing of the parameters of sources and obstacles, including specified sound absorption coefficients and calculated points, both in tabular form and on a digital map. To create the noise map, a substrate from the design documentation was used and adapted using open geodata, which was imported through the GIS-Standard module in *.SHP format. The effectiveness of the measures was assessed by comparing “basic” and “design” scenarios: the “basic” scenario was before the introduction of protection measures, and the “design” scenario included the implementation of noise protection options that were considered.

Object of Research. A small architectural gazebo-type form with a solid back wall was chosen an object of research to protect landscaping sites from noise from local traffic (Fig. 3, 4). This design was analyzed as a local enclosing element that could partially perform the function of an acoustic screen.



a)



b)

Fig. 4. Gazebo-type SAF location in the landscaping of a residential area:
a — without SAF; b — with SAF from the side of the roadway

Limits of Applicability of the Design Scheme. In this paper, we considered a special computational case involving the use of a small architectural form (SAF) in the form of a semi-enclosed gazebo with a blank back wall. The results were obtained based on the accepted planning diagram, the specified traffic flow parameters, and the selected configuration of the enclosing structure. To extend these conclusions to other types of SAFs, building options, and noise load scenarios, additional computational and field studies were required.

Calculation scenarios. To compare the effectiveness of noise protection solutions, five design options were set, differing in the type of enclosing or protective structure:

- option 0 — absence of any enclosing structure;
- option 1 — the use of a typical combined noise-proof screen: a noise-reflecting panel + a noise-absorbing panel + a noise-reflecting translucent panel, without a structural canopy; the sound insulation index of air noise was taken from technical data;
- option 2 — the use of double-row deciduous tree and shrub plantings; the attenuation of sound in octave bands when passing through dense foliage was determined by the length of the sound propagation path;
- option 3 — the use of a small noise shield; the effectiveness of a small acoustic shield, depending on the frequency, was accepted according to [16];
- option 4 — the use of a gazebo-type SAF with a solid back wall made of wood laths; the air noise insulation index was determined by calculation.

Table 1 presents brief initial data on the accepted options for enclosing structures.

Table 1

Accepted options for performing acoustic assessment

Option	Type of noise-protection structure	Characteristic	Note
0	None	–	–
1	Noise screen	Standard design, height 3 m	Manufacturer's technical data
2	Green spaces	Height 8 m, strip width 5 m	Attenuation in foliage according to GOST 31295.2-2005 ¹
3	Small acoustic screen	Height 0.85 m	[16]
4	SAF (gazebo-type)	Wood, height 2.5 m, thickness 20 mm	Sound insulation calculation

Initial Sound Insulation Parameters of the Enclosing Structure. The calculation of airborne noise insulation for a single-layer flat thin screen was performed according to the algorithm given in clause 9.2 of SP 275.1325800.2016². The calculation was done using the “Sound Insulation Calculator” software (developed by Integral), which followed this method.

The frequency response of the air noise insulation of the SAF solid wall, considered as a single-layer flat thin enclosing structure, determined graphically and represented as a broken line, is shown in Figure 5.

Table 5 presents the calculation results of air noise insulation index RwR_w for the SAF back wall.

The data on the enclosing structure given in Table 2 was used as the initial data for the calculation.

¹ GOST 31295.2-2005 “Noise. Attenuation of sound during propagation outdoors. Part 2. General method of calculation”. (In Russ.) URL: <https://docs.cntd.ru/document/1200046351> (accessed 14.04.2026)

² SP 275.1325800.2016. “Construction fencing of residential and public buildings. Rules of sound insulation design”. (In Russ.) URL: <https://docs.cntd.ru/document/456050583> (accessed 14.04.2026).

Table 2

Initial data for calculating the sound protection of an enclosing structure

Parameter	MU	Value	Note
Type of structure	–	a single-layer flat thin enclosing structure made of metal, glass, asbestos-cement sheet, gypsum plasterboard (dry gypsum plaster) and similar materials	SP 275.1325800.2016 ³
Type of material	–	chip board	similar material*
Density of the material	kg/m ³	650	SP 275.1325800.2016 ⁴
Thickness of the structure	mm	20	minimum recommended thickness

Note to Table 2: * Clause 9.2 of SP 275.1325800.2016⁵ lists materials for calculating single-layer thin screens, including metal, glass, and plasterboard. This clause indicates that the methodology can be applied to materials with similar behavior. However, there is no direct reference to wood construction (board, rail, etc.) in clause 9.2 of SP 275.13258.2016⁶, so the tabular values for chipboard as a material with similar acoustic properties (density, structure) were used to calculate sound insulation of the single-layer part of the structure (wood laths). The wording “etc.” normatively allows for the use of this calculation methodology for other materials as long as they have similar acoustic properties to those listed.

Initial parameters of the traffic flow. To determine noise characteristics of the traffic flow, the calculation algorithm described in clauses 6.2.8–6.12.8 of SP 276.1325800.2016⁷ was used. The initial parameters included the estimated time of day, traffic density, share of freight traffic, speed, roadway slope, pavement type, and the presence of other road factors.

Software tools for calculating traffic noise. The calculation of traffic noise was performed in the “Noise from Highways 1.1” module (developed by Integral). This module allowed us to determine the equivalent sound level when traffic flowed under specified road conditions, considering the individual characteristics of the flow.

The initial data for calculating noise characteristics of automobile traffic flows are presented in Table 3.

Table 3

Initial data for calculating noise from automobile traffic flow

Parameter	MU	Value	Note	Regulatory document
Estimated time of day	–	day	Use of landscaping areas primarily during daytime hours (from 7:00 to 23:00)	SanPiN 1.2.3685-21 ⁸
Average annual traffic density	unit/day	750	Local street – a street in a residential area	SP 396.1325800.2018 ⁹
Share of trucks in the flow	%	0	Freight transport is not permitted in accordance with the assigned category	SP 396.1325800.2018 ¹⁰

³ SP 275.1325800.2016. “Construction fencing of residential and public buildings. Rules of sound insulation design”. (In Russ.) URL: <https://docs.cntd.ru/document/456050583> (accessed 14.04.2026).

⁴ Ibid.

⁵ Ibid.

⁶ Ibid.

⁷ Ibid.

⁸ SanPiN 1.2.3685-21 Hygienic Standards and Requirements for Ensuring the Safety and (or) Harmlessness of Environmental Factors for Humans. (In Russ.) URL: https://www.consultant.ru/document/cons_doc_LAW_375839/fa69e15a74de57cbe09d347462434c11fcfeaca/ (accessed 14.04.2026).

⁹ SP 396.1325800.2018 Streets and Roads of Settlements. Regulation of Urban Planning. (In Russ.) URL: <https://docs.cntd.ru/document/552304870> (accessed 14.04.2026).

¹⁰ Ibid.

Driving speed	km/h	20	In residential areas, bicycle zones, and courtyard areas	Decree of the Government of the Russian Federation No. 1090 dated October 23, 1993 ¹¹
Slope of the roadway	%	3	To ensure consistent speed and traffic safety, as well as taking into account the possibility of future road reconstruction	SP 34.13330.2021 ¹²
Type of roadway surface	–	Asphalt concrete	Taking into account the traffic density on this section and the road category	SP 42.13330.2016 ¹³
Width of the central median strip	–	no	Not considered in the work	–
Presence of an intersection	–	no	Not considered in the work	–

Assessment Criteria. Software tools for noise propagation simulation. The simulation of noise propagation was performed using “Ecolog-Shum 2.4” (developed by Integral), which had the recommendations of the Research Institute of Building Physics (Certificate of Conformity ROSS RU.SP04. N00084 dated 05.03.2007). The complex allowed calculating noise pressure levels at individual points and at sites, taking into account the diffraction and reflection of sound from obstacles.

Calculated Assumptions. The assessment was based on the equivalent noise level (dBA), which took into account temporary unevenness of the noise exposure. However, when performing the calculations, we did not take into account the effects of sound absorption or shielding from reflected signals from nearby buildings, structures, and green spaces, which allowed us to consider the values obtained as the result of the accepted calculation scheme.

Computing Chain. The research algorithm included: 1) setting the research object and design scenarios; 2) determining the sound insulation characteristics of the enclosing structure; 3) calculating the noise characteristics of the traffic flow; 4) modeling noise propagation for each option; 5) comparing the obtained levels with the maximum permissible values; 6) comparative evaluation of the options according to the specified criteria.

Evaluation Criteria. Noise parameters characterizing the acoustic impact on the environment, the location of noise sources and enclosing structures were used as initial data for the calculation. Sound pressure levels were calculated in octave bands with geometric mean frequencies of 31.5–8000 Hz, as well as for equivalent LA sound levels.

The modeling took into account the following:

- Calculations were performed in a local coordinate system, with the OX axis oriented to the east and the OY axis oriented to the north, assuming ground level as 0.0 and without considering terrain. The minimum dimensions of the calculated rectangle were 70 × 70 m.

- The calculation considered the diffraction and reflection of sound waves by enclosing structures, taking into account meteorological parameters such as temperature and humidity.

- Equivalent sound pressure levels L_{eq} during exposure time T were calculated based on octave levels and considering the duration of the time interval: daytime — from 7 to 23 hours, night — from 23 to 7 hours.

- The selected points were located directly on the territory of the adjacent residential area, in accordance with the requirements of SP 51.13330.2011 ¹⁴. For recreation areas of residential districts, groups of residential buildings, sections of preschool institutions, schools, hospitals, and sanatoriums, the points were chosen at the boundaries of the closest sites to the noise source, at a height of 1.5 meters above the ground.

¹¹ Decree of the Government of the Russian Federation No. 1090 dated October 23, 1993 “On the Rules of Road Traffic”. (In Russ.) URL: https://www.consultant.ru/document/cons_doc_LAW_2709/ (accessed 14.04.2026).

¹² SP 34.13330.2021 SNiP 2.05.02-85* *Automobile Roads*. (In Russ.) URL: <https://docs.cntd.ru/document/573818172> (accessed 14.04.2026).

¹³ SP 42.13330.2016 *Urban Development. Urban and Rural Planning and Development. Updated Version of SNiP 2.07.01-89**. (In Russ.) URL: <https://docs.cntd.ru/document/456050583> (accessed 14.04.2026).

¹⁴ SP 51.13330.2011. “Noise protection. Updated version of SNiP 23-03-2003 (with Amendment No. 1)”. URL: <https://clck.ru/3VQEPA> (accessed 14.04.2026).

The results were presented in tables and in the form of colored noise maps — isolines.

The normalized noise parameters for the considered territory — recreation areas and leisure areas of residential areas — were adopted according to SanPiN 1.2.3685-21¹⁵ (Table 4). The main criterion was the compliance with the maximum permissible equivalent sound level of 45 dBA.

Table 4

Specified noise indicators

Purpose of rooms or premises	Time of day	For sources of fluctuating noise	
		Equivalent noise levels $L(A_{eq.})$, dBA	Maximum noise levels $L(A_{max})$, dBA
Recreation areas allocated on the territory of residential districts and groups of residential buildings ...	—	45	60

Research Results. According to the accepted assessment procedure, the required calculations were conducted, the results of which are shown in the relevant tables and figures.

The frequency response of air noise isolation for the SAF solid wall as a single-layer, flat, thin enclosing structure is shown graphically in Figure 5 as a broken line.

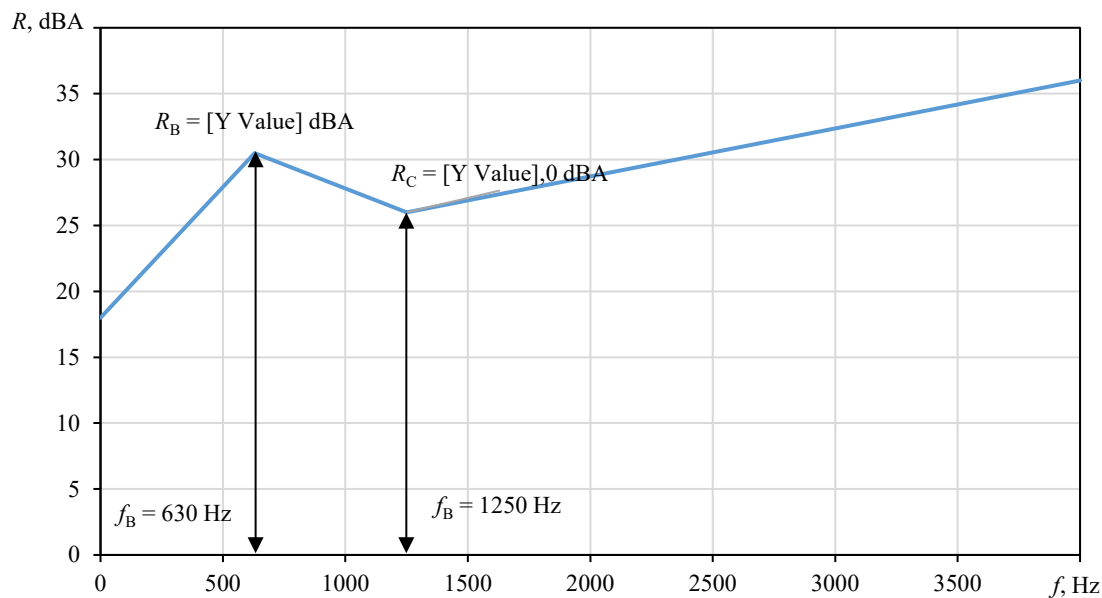


Fig. 5. Broken line frequency characteristic of air noise isolation
(diagram made by “Sound Insulation Calculation”)

The calculation results of air noise insulation index (R_w) for the SAF back wall are presented in Table 5.

Table 5

Calculation of the air noise insulation index of a solid SAF wall

Indicator	Octave bands with geometric mean frequencies, Hz								
	31.5	63	125	250	500	1,000	2,000	4,000	8,000
Sound insulation, dB	11.1	15.6	20	24.5	29	27.5	31	38.5	46
Airborne noise insulation index, R_w : dB					29				

¹⁵ SanPiN 1.2.3685-21. “Hygienic standards and requirements for ensuring safety and (or) harmlessness to humans of environmental factors”. URL: https://www.consultant.ru/document/cons_doc_LAW_375839/fa69e15a74de57cbe09d347462434c11fcfeeaca/ (accessed 14.04.2026).

Table 6 provides the calculations results of transport noise characteristics.

Table 6

Calculation of noise from traffic flows

Indicator	Result, dBA
Correction for the change in the number of trucks and buses in the traffic flow compared to the estimated composition ($L_{\text{труз}}$)	–3
Correction for the change in the average speed compared to the calculated value ($L_{\text{ск}}$)	–6.5
Correction for the longitudinal slope ($L_{\text{ук}}$)	0.75
Correction for the type of road surface ($L_{\text{пок}}$)	3
Correction for the presence of a median strip ($L_{\text{пн}}$)	0
Correction for the presence of an intersection ($L_{\text{перес}}$)	0
Equivalent sound level of automobile traffic flow ($L_{\text{авт. экв.}}$)	59.7

Table 7 provides the results of the noise propagation calculations.

Table 7

Calculation results of noise levels on the territory of the considered landscaping area

No.	Option	Noise level at the border of the specified area (maximum value), dBA
0	None	53
1	Noise protection screen	45
2	Green spaces	53
3	Small acoustic screen	53
4	Gazebo-type SAF	45
	MPL	45

The areas of negative impact from noise are represented by the isolines of the acoustic discomfort zones at a height of 1.5 meters (Fig. 6).

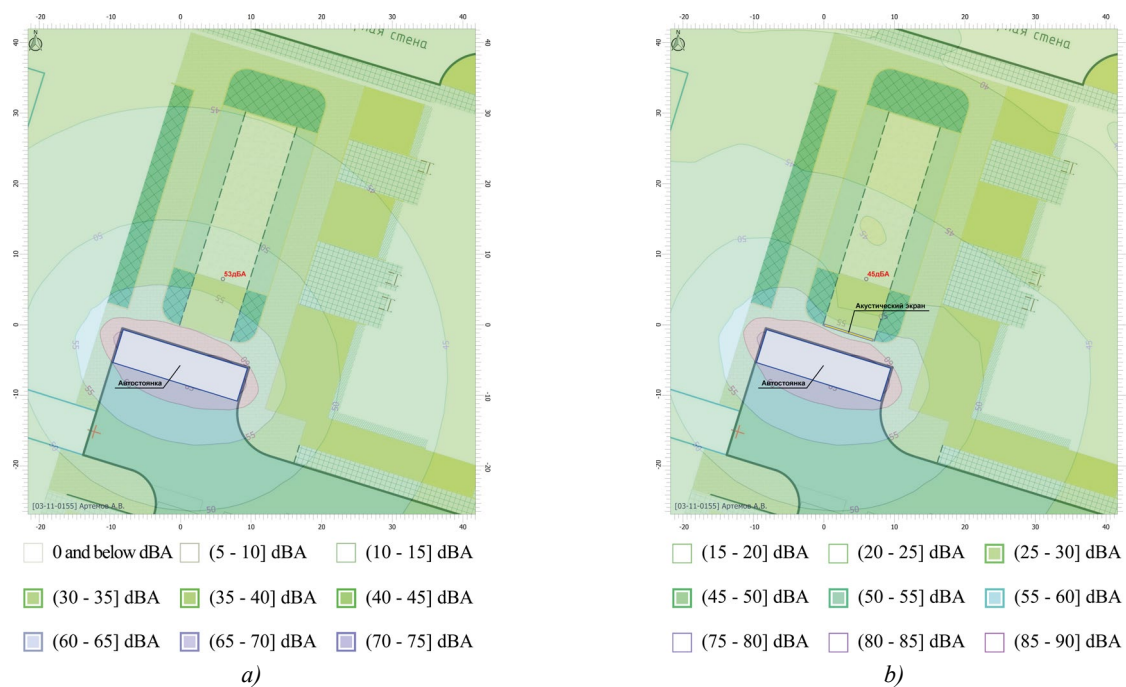


Fig. 6. Calculated noise level distribution in the landscaping area at a height of 1.5 m: *a* — option No. 0 — no enclosing structure; *b* — option No. 1 — typical noise screen (noise maps generated by the “Ecolog-Shum”)

For visualization, a graphical distribution of noise in perspective (3D) was performed at a specified height of 1.5 m (Fig. 7).

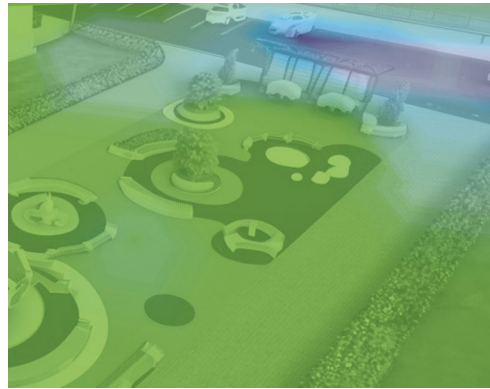


Fig. 7. Calculated noise level distribution in 3D for option No. 4 — Gazebo-type SAF with a blind back wall. The calculation was performed for a height of 1.5 m

Discussion. The calculated results indicated that the key factor in reducing noise levels at the border of the specified area was the presence of a solid enclosing surface between the noise source and the protected area. In this regard, options with a typical noise-proof screen and a gazebo-type SAF ensured that the maximum permissible level was achieved. However, without any enclosing structure, only green spaces and a small acoustic screen, in the current design scheme, did not lead to a comparable reduction in noise levels.

This interpretation was consistent with the literature data, which suggested that the effectiveness of acoustic screens was determined by their height, geometric parameters, position relative to the noise source and receiver, and the presence of a continuous shielding surface [11–14]. For gazebo-type SAFs, the noise protection effect was not due to landscaping itself, but rather to the presence of a blind back wall, which acted as a local barrier to sound wave propagation.

It should be emphasized that the results were calculated. While the software tools and regulatory techniques used allowed for a preliminary assessment of the acoustic effectiveness of the solutions analyzed, they could not replace instrumental verification under field conditions. Therefore, the noise reduction achieved for the SAF option should be regarded as a calculated and predicted value valid for the assumed geometry of the structure, the characteristics of the traffic flow, and the conditions of sound propagation.

To interpret the practical applicability of the considered solutions, a comparative assessment was conducted according to criteria reflecting not only the acoustic result, but also the possibility of using the appropriate measure in residential conditions:

- “Ensuring sanitary and hygienic standards” — compliance of the calculated noise level with the maximum permissible value for the normalized area;
- “Urban planning integration” — the possibility of including solutions in the architectural and planning structure of the courtyard area without compromising its functionality and visual perception;
- “Ecological effect” — the potential reduction of the negative impact of noise on the environment and living conditions of the population;
- “Material costs” — the estimated need for additional financial investments beyond the usual landscaping work.

This ranking indicates that the choice of noise protection measures should not be solely based on the magnitude of estimated noise reduction. Urban compatibility, operational feasibility, and the possibility of implementing a solution without creating a separate engineering structure are also important factors to consider for landscape sites.

Table 8 presents the comparative assessment results for the considered noise protection options.

Table 8

Comparative assessment results of noise protection options according to priority criteria

Option	Provision of sanitary and hygienic standards	Urban planning integration	Environmental effect	Material costs
0	–	–	–	–
1	+	–	+	+
2	–	+	+	–*
3	–	–	+	+
4	+	+	+	–*

Notes: * material costs only within the framework of the landscaping project

The interpretation of the considered options demonstrated that a standard noise shield was the most obvious engineering solution, with the highest priority for achieving sanitary and hygiene goals. However, its use in the outdoor area could be constrained by aesthetic and planning considerations, as such a barrier would be perceived as a separate technical structure.

The low efficiency of the green space solution was explained by the fact that a strip 5–10 meters wide and an ordinary planting without a dense understory did not create a continuous acoustic barrier. This finding was consistent with data suggesting that sufficient width, density, and layers of plantings were needed to achieve a significant noise reduction effect [17, 18].

The low efficiency of a small acoustic screen was due to its limited height. At 0.85 meters, this design did not block a significant portion of the sound path between the traffic flow and the design point at a height of 1.5 meters. Therefore, in the planning scheme under consideration, it did not guarantee the achievement of MPL.

The gazebo-type SAF option differed from the standard screen in that it combined the noise protection function with recreational and urban planning. This allowed us to consider such a structure not as a separate environmental protection facility, but rather as an element of landscaping that simultaneously created a protected space while preserving the functional purpose of the site.

The practical significance of the results obtained lies in the possibility of using a SAF with a blind back wall as a local noise protection structure, where traditional screens are undesirable or difficult due to architectural and planning constraints. However, further research is needed to fully assess the effectiveness of this solution for other geometric configurations and noise loading conditions.

The limitations of this study include the computational nature of the results, the consideration of only one type of SAF, one planning configuration, and one scenario for transport load. Additionally, the calculation method did not take into account certain factors of the urban environment, such as reflections from neighboring buildings and variations in actual traffic intensity.

Thus, the results should be interpreted as a calculated justification for the potential use of a gazebo-type SAF with a blind back wall for local noise protection. To verify the practical effectiveness, it would be necessary to conduct full-scale noise measurements before and after installing the structure, as well as perform a series of calculations at different distances from the source, considering traffic intensity and various building options.

Conclusion. The paper provides a calculated assessment of the possibility of using a gazebo-type SAF with a blind back wall as a local noise-proof structure for residential landscaping sites.

Based on the simulation results, it was found that with the specified parameters of the traffic flow, the option without protective measures did not ensure compliance with the maximum permissible noise level at the border of the specified territory. A typical noise shield and a gazebo-type SAF in the design scheme under consideration could reduce the noise level to 45 dBA.

Green spaces and a small acoustic shield under the accepted initial conditions did not provide the required level of noise protection, which was associated with insufficient length and/or height of the protective barrier.

The main conclusion of the research is that a semi-enclosed gazebo-type SAF with a blind back wall can be considered as a promising local noise protection solution combining acoustic and urban planning functions.

The results obtained require further verification through instrumental confirmation in field conditions and analysis of other types of SAFs and noise load scenarios to ensure accuracy.

References

1. Voroshilov NV. Trends, Problems, and Prospects for Implementing the Russian National Project “Safe and High-Quality Roads”. *Territorial Development Issues*. 2022;10(2):3. (In Russ.) <https://doi.org/10.15838/tdi.2022.2.62.3>
2. Zaytsev OB, Artyomov AV. Green environmental standards in construction: reality and prospects. In: *Forestry Engineering Universities in the Implementation of the Concept of Reviving Engineering Education: Socio-Economic and Environmental Problems of the Forest Complex: Proceedings of the X International Scientific and Technical Conference, Yekaterinburg, May 18–19, 2015*. Yekaterinburg: Ural State Forest Engineering University, 2015. P. 167–169. (In Russ.) URL: <https://elar.usfeu.ru/handle/123456789/5336?locale=en> (accessed 14.04.2026).
3. May IV, Koshurnikov DN. Accounting the Noise Factor when Placing Residential Buildings as a Condition for Ensuring a Favorable Urban Environment. *Bulletin of Perm National Research Polytechnic University. Applied Ecology. Urban Development*. 2021;3(43):27–38. (In Russ.) URL: <https://fcrisk.ru/node/2266> (accessed 14.04.2026).
4. Iliria Ibrahimi Asllani, Riaz Agahi. Impact of Residential Noise Exposure on Neurological Health: A Systematic Scoping Review. *Journal of Urban Health*. 2025;102: 1175–1197. <https://doi.org/10.1007/s11524-025-01026-2>

5. Xia Chen, Mingliang Liu, Lei Zuo, Xiaoyi Wu, Mengshi Chen, Xingli Li, et al. Environmental Noise Exposure and Health Outcomes: An Umbrella Review of Systematic Reviews and Meta-Analysis. *European Journal of Public Health*. 2023;33(4):725–731. <https://doi.org/10.1093/eurpub/ckad044>
6. Yuliang Lan, Roberts H, Mei-Po Kwan, Helbich M. Transportation Noise Exposure and Anxiety: A Systematic Review and Meta-Analysis. *Environmental Research*. 2020;191:110118. <https://doi.org/10.1016/j.envres.2020.110118>
7. Ziyatdinova AR, Fahrutdinova IA. Design Approaches for Neighboring Spaces in a Context of Sociological Theories of Creating a Friendly Urban Environment. *News of the Kazan State University of Architecture and Engineering*. 2017;2(40):60–69. (In Russ.) URL: <https://clck.ru/3VEJtE> (accessed 14.04.2026).
8. Kovyazin VF, Glushkova NA. Protection of the Residential Area of the Settlement from Noise Using Acoustic Screens. *Innovative Science*. 2015;12–2:67–70. (In Russ.) URL: <https://clck.ru/3VEK43> (accessed 14.04.2026).
9. Chermnykh VA, Utkina MS, Shutova OA. Analysis of the Application of Noise Screens to Reduce Traffic Noise during the Construction of Residential Complex. *Modern Technologies in Construction. Theory and Practice*. 2018;2:107–115. (In Russ.)
10. Atkina LI, Efimova NA. Features of Planning Solutions for Educational Objects of Limited Use. *Forests of Russia and Economy in Them*. 2023;4(87):78–87. (In Russ.) <https://doi.org/10.51318/FRET.2023.87.4.008>
11. Aistov VA, Shubin IL. Studies of the Influence of the Shape of the Noise Shield on Its Acoustic Efficiency. *Academia. Architecture and Construction*. 2009;5:200–208. (In Russ.) URL: <https://clck.ru/3VEKTW> (accessed 14.04.2026).
12. Ivanov NI, Shashurin AE, Boiko IS. Influence of the Material on the Acoustic Efficiency of the Noise Barriers. *Noise Theory and Practice*. 2016;2(4):24–28. (In Russ.)
13. Kondratev SA, Ivanov II, Tyurina NV. Influence of Noise Barrier Design Parameters on Its Acoustical Insertion Loss. *Noise Theory and Practice*. 2025;11(3):121–132. (In Russ.) URL: <https://clck.ru/3VEKkV> (accessed 14.04.2026).
14. Tyurina NV. Actual Problems of Designing Acoustic Transport Screens. In: *Protection from Increased Noise and Vibration. Proceedings of the V All-Russian Scientific and Practical Conference with International Participation, St. Petersburg, March 18–20, 2015*. St. Petersburg: Aising Limited Liability Company; 2015. P. 685–693. (In Russ.)
15. Kalinichenko M.V. About the Possibility of Using Acoustic Screens, Made on the Basis of Helmholtz Resonators, to Reduce Noise. *Noise Theory and Practice*. 2015;1(1):45–54. (In Russ.) URL: <https://clck.ru/3VEKx6> (accessed 14.08.2026).
16. Vasilev A, Li-Ko-Shin Y, Kudaev AV, Kuklin DA, Matveev PV. The Effectiveness of Small Noise Barriers for Protection of Railway Noise. *Noise Theory and Practice*. 2016;2(3):45–49. (In Russ.)
17. Lukyanets AG. Decreasing of Noise Level Depending on Plantings Structure Parameters. *Polythematic online scientific journal of Kuban State Agrarian University*. 2011;65(1):253–263. (In Russ.)
18. Gordeev YuA, Kulagin AA. Effect of Shade-Trees Plantations on the Noise Level of Urbanized Territories. *Izvestia Orenburg State Agrarian University*. 2014;2(46):151–155. (In Russ.)

About the Authors:

Artyem V. Artyemov, Cand. Sci. (Eng.), Associate Professor of the Department Technology of Pulp and Paper Production and Processing of Polymers, Ural State Forest Engineering University (37, Siberian Tract, Yekaterinburg, 620100, Russian Federation), [SPIN-code](#), [ORCID](#), artemovav@m.usfeu.ru

Evgenii S. Kurkin, Head of the Federal State Institution “Uralupravtodor” (620026, Yekaterinburg, Lunacharsky Street, 203), kurkines@inbox.ru

Pavel S. Zakharov, Cand. Sci. (Eng.), Assistant Lecturer of the Department Technology of Pulp and Paper Production and Processing of Polymers, Ural State Forest Engineering University (37, Siberian Tract, Yekaterinburg, 620100, Russian Federation), [SPIN-code](#), [ORCID](#), zaharovps@m.usfeu.ru

Tat'yana V. Shteba, Cand. Sci. (Eng.), Associate Professor of Department of Fire Safety of Technological Processes and Production, Ural Institute of State Fire Service of EMERCOM of Russia (22, Mira St., Yekaterinburg, 620062, Russian Federation), [SPIN-code](#), [ORCID](#), shtebatv@yandex.ru

Claimed Contributorship:

AV Artyemov: conceptualization, writing – review & editing.

ES Kurkin: methodology, data curation, validation.

PS Zakharov: investigation, formal analysis, writing – original draft preparation.

TV Shteba: visualization, writing – original draft preparation.

Conflict of Interest Statement: the authors declare no conflict of interest.

All authors have read and approved the final version of manuscript.

Об авторах:

Артём Вячеславович Артёмов, кандидат технических наук, доцент кафедры «Технологии целлюлозно-бумажных производств и переработки полимеров» Уральского государственного лесотехнического университета (620100, Российская Федерация, г. Екатеринбург, Сибирский тракт, д. 37), [SPIN-код](#), [ORCID](#), artemovav@m.usfeu.ru

Евгений Сергеевич Куркин, начальник ФКУ «Уралуправтодор» (620026, Российская Федерация, г. Екатеринбург, ул. Луначарского, д. 203), kurkines@inbox.ru

Павел Сергеевич Захаров, кандидат технических наук, ассистент кафедры «Технологии целлюлозно-бумажных производств и переработки полимеров» Уральского государственного лесотехнического университета (620100, Российская Федерация, г. Екатеринбург, Сибирский тракт, д. 37), [SPIN-код](#), [ORCID](#), zaharovps@m.usfeu.ru

Татьяна Валерьевна Штеба, кандидат технических наук, доцент кафедры пожарной безопасности технологических процессов и производств Уральского института Государственной противопожарной службы МЧС России (620062, Российская Федерация, г. Екатеринбург, ул. Мира, 22), [SPIN-код](#), [ORCID](#), shtebatv@yandex.ru

Заявленный вклад авторов:

А.В. Артёмов: разработка концепции, написание рукописи, внесение замечаний и исправлений.

Е.С. Куркин: разработка методологии, курирование данных, валидация результатов.

П.С. Захаров: проведение исследования, формальный анализ, написание черновика рукописи.

Т.В. Штеба: визуализация, написание черновика рукописи.

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 28.05.2026

Reviewed / Поступила после рецензирования 22.06.2026

Accepted / Принята к публикации 10.07.2026

TECHNOSPHERE SAFETY

ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ



UDC 504.064

Original Empirical Research

<https://doi.org/10.23947/2541-9129-2026-10-3-247-255>

Integration of Computer Vision and Hydrodynamic Modeling Methods to Improve Environmental Safety by Identifying Sources of Negative Impact on Water Bodies

Andrey V. Gusev

Russian State Social University, Moscow, Russian Federation

gusevandre2015@yandex.ru

EDN: BRDTZS

Abstract

Introduction. Traditional water body monitoring systems often demonstrate insufficient effectiveness in promptly locating the source of an emergency or non-stationary discharge, which hinders timely management decisions. This problem is further exacerbated by the rapid spread of pollutants in conditions where observational data is incomplete, delayed, or fragmented. These circumstances emphasize the need for methods that can not only detect pollution but also reconstruct the coordinates of its source based on its concentration field. The literature provides a wide range of approaches based on advection-diffusion equations, numerical hydrodynamic modeling, and satellite data analysis. However, the integration of computer vision methods with hydrodynamic models to solve the inverse problem of source identification remains under-researched. Theoretically, such integration is justified by the possibility of automated delineation of water area boundaries through semantic segmentation and a physically meaningful description of passive impurities transport. However, there is a scientific gap due to the lack of verified computational schemes that combine these two approaches. The aim of this study is to develop and verify an approach that integrates computer vision and hydrodynamic modeling to accurately identify the source of a negative impact.

Materials and Methods. The methodology included two interconnected modules. The first computer vision module performed semantic segmentation of satellite images or aerial photography data using convolutional neural networks. The result was a binary mask of the water area; its external contours were extracted using OpenCV with morphological post-processing. The second module implemented a two-dimensional numerical advection-diffusion model based on the finite volume method with a steady velocity field. The inverse identification algorithm generated a set of virtual candidate points along the perimeter of the water body. For each point, a direct calculation of the concentration field was performed, after which a candidate was selected using the root-mean-square error, ensuring the best fit to the observed distribution. Validation was carried out on three synthetic scenarios (pH, dissolved oxygen, free chlorine) in 300 computational experiments.

Results. Three hundred computational experiments were conducted using randomly assigned source coordinates. The computer vision module accurately generated a water area mask in all trials. The inverse identification algorithm, which iterated through candidates in 50-meter increments, identified the true source with absolute accuracy in 285 cases (95%). It was found that 12 out of 15 erroneous cases were due to the source being located less than 1 m from the water area boundary, where the influence of turbulent diffusion and boundary conditions led to the “blurring” of the pollution trace. The key limitations of the method were identified: errors in the two-dimensional hydrodynamic approximation for stratified water bodies, and a decrease in accuracy under sharply non-stationary hydrodynamics. Visualization of the results confirmed the high quality of spatial localization of the source.

Discussion. The results obtained confirmed that the integration of these methods created a synergistic effect. Computer vision ensured the speed and objectivity of spatial data processing, while hydrodynamic modeling provided physical and mathematical validity for the analysis. This approach overcame the key limitation of traditional monitoring by allowing us not only to detect pollution, but also to determine its causes. This is consistent with current trends in predictive analytics.

Conclusion. The developed concept forms the foundation for creating decision-support operational systems and “digital twins” of water bodies. Its implementation in environmental monitoring practices creates the prerequisites for transitioning from reactive response to proactive risk management, and can contribute to enhancing the validity and effectiveness of measures to ensure environmental safety of water resources. Prospects for further research lie in adapting methods for working with real-time online monitoring data and different types of water bodies.

Keywords: environmental safety, computer vision, hydrodynamic modeling, pollution source identification, digital twin, environmental monitoring, water bodies, machine learning

Acknowledgements. The authors would like to thank the Editorial board of the journal and the anonymous reviewers for their comments and valuable recommendations, which helped improve the quality of the article.

For Citation. Gusev AV. Integration of Computer Vision and Hydrodynamic Modeling Methods to Improve Environmental Safety by Identifying Sources of Negative Impact on Water Bodies. *Safety of Technogenic and Natural Systems*. 2026;10(3):247–255. <https://doi.org/10.23947/2541-9129-2026-10-3-247-255>

Оригинальное эмпирическое исследование

Интеграция методов компьютерного зрения и гидродинамического моделирования для повышения экологической безопасности за счет идентификации источников негативного воздействия на водные объекты

А.В. Гусев 

Российский государственный социальный университет, г. Москва, Российская Федерация

 gusevandre2015@yandex.ru

Аннотация

Введение. Традиционные системы мониторинга водных объектов нередко демонстрируют недостаточную эффективность при оперативной локализации источника аварийных либо нестационарных сбросов, что препятствует своевременному принятию управленческих решений. Проблема обостряется в условиях быстрого распространения загрязнителя при неполноте, запаздывании и фрагментарности данных наблюдений. Указанные обстоятельства актуализируют разработку методов, обеспечивающих не только фиксацию факта загрязнения, но и ретроспективное восстановление координат источника по полю концентрации. В литературе достаточно широко представлены подходы, базирующиеся на уравнениях адвекции-диффузии, численном гидродинамическом моделировании и анализе спутниковых данных. Однако интеграция методов компьютерного зрения с гидродинамическими моделями для решения обратной задачи идентификации источника остаётся малоизученной. Теоретически такая интеграция обоснована возможностью автоматизированного выделения границ акватории посредством семантической сегментации и физически содержательного описания переноса пассивной примеси. Существующий научный пробел обусловлен отсутствием верифицированных вычислительных схем, объединяющих оба направления. Целью настоящего исследования является разработка и верификация подхода, интегрирующего компьютерное зрение и гидродинамическое моделирование для точной ретроспективной идентификации источника негативного воздействия.

Материалы и методы. Методология включает два взаимосвязанных модуля. Первый модуль компьютерного зрения выполняет семантическую сегментацию спутниковых снимков или данных аэрофотосъёмки с применением свёрточных нейронных сетей. Результатом является бинарная маска акватории, её внешние контуры извлекаются средствами OpenCV с морфологической постобработкой. Второй модуль реализует двумерную численную модель адвекции-диффузии на основе метода конечных объёмов со стационарным полем скоростей. Алгоритм обратной идентификации генерирует множество виртуальных точек-кандидатов по периметру водоёма, для каждого выполняется прямой расчёт поля концентрации, после чего с использованием среднеквадратической ошибки отбирается кандидат, обеспечивающий наилучшее соответствие наблюдаемому распределению. Валидация проведена на трёх синтетических сценариях (рН, растворённый кислород, свободный хлор) в 300 вычислительных экспериментах.

Результаты исследования. Проведено 300 вычислительных экспериментов со случайным заданием координат источника. Модуль компьютерного зрения безошибочно формировал маску акватории во всех испытаниях. Алгоритм обратной идентификации, осуществляющий перебор кандидатов с шагом 50 м, в 285 случаях (95 %) абсолютно точно определил истинный источник. Установлено, что 12 из 15 ошибочных случаев обусловлены расположением источника на расстоянии менее 3 м от границы акватории, где влияние турбулентной диффузии и граничных условий приводит к «размыванию» следа загрязнения. Выявлены ключевые ограничения метода: погрешности двумерного гидродинамического приближения в стратифицированных водоёмах и снижение точности при резко нестационарной гидродинамике. Визуализация результатов подтверждает высокое качество пространственной локализации источника.

Обсуждение. Полученные результаты подтверждают, что интеграция методов создает синергетический эффект: компьютерное зрение обеспечивает скорость и объективность обработки пространственных данных, а гидродинамическое моделирование — физическую и математическую обоснованность анализа. Такой подход преодолевает ключевое ограничение традиционного мониторинга, позволяя не только констатировать факт загрязнения, но и устанавливать его причину, что согласуется с современными тенденциями развития предсказательной аналитики.

Заключение. Разработанная концепция формирует основу для создания операционных систем поддержки принятия решений и «цифровых двойников» водных объектов. Ее внедрение в практику экологического мониторинга создаёт предпосылки для перехода от реактивного реагирования к проактивному управлению рисками и может способствовать повышению обоснованности и эффективности мер по обеспечению экологической безопасности водных ресурсов. Перспективы дальнейших исследований связаны с адаптацией методов для работы с реальными данными онлайн-мониторинга и различными типами водных объектов.

Ключевые слова: экологическая безопасность, компьютерное зрение, гидродинамическое моделирование, идентификация источника загрязнения, цифровой двойник, экологический мониторинг, водные объекты, машинное обучение

Благодарности. Авторы благодарят редакционную команду журнала и анонимных рецензентов за высказанные замечания и ценные рекомендации, которые позволили повысить качество статьи.

Для цитирования. Гусев А.В. Интеграция методов компьютерного зрения и гидродинамического моделирования для повышения экологической безопасности за счет идентификации источников негативного воздействия на водные объекты. *Безопасность техногенных и природных систем.* 2026;10(3):247–255. <https://doi.org/10.23947/2541-9129-2026-10-3-247-255>

Introduction. The task of promptly identifying the source of an emergency or discharge of pollutants into a water body arises when the consequences of an incident are eliminated and those responsible are brought to justice. Traditional monitoring, which relies on a network of stationary posts and sampling, records concentrations at individual points [1]. However, such data does not allow specialists to quickly restore a complete spatial and temporal picture of the spread of impurities. The processes of advection and turbulent diffusion quickly "blur" the trace of the source [2].

As the practice of implementing environmental control systems at industrial enterprises demonstrates, the gap between two classes of methods remains.

The first group includes computer vision (CV) and deep learning, which analyze satellite images [3]. Semantic segmentation distinguishes water areas [4]. Spectral indices (NDWI) record anomalies in water color [5]. However, CV only displays visible effects on the surface, leaving the dynamics of transport in the water column unexplained.

The second group consists of hydrodynamic modeling. Advection-diffusion equations predict impurity dispersion in a physically reasonable way [6]. However, the model needs prior knowledge of the coordinates and strength of the source, which are unknown in the classical formulation.

It would be beneficial to examine the limitations of current approaches in more detail.

Satellite monitoring and CV. Yusuf et al. [1] generalized effect-oriented methods for the aquatic environment, achieving high sensitivity to a wide range of substances. However, the authors did not propose any mechanisms for restoring source parameters. Chen et al. [2] performed a review of remote sensing data, demonstrating the high speed of obtaining spatial information. However, their study was limited to simply stating the fact of contamination without addressing the inverse problem. Wang et al. [5] analyzed surface water quality models, most of which operated in a direct predictive mode rather than being intended for retrospective source identification.

Water area selection tools. Program registration certificates [3] and [4] described automated tools for morphometric analysis and identification of water bodies. These tools solved the problem of identifying the water area, but they were not integrated with hydrodynamic transport models.

Digital twins and artificial intelligence. Maksoud and Mohamed [6] analyzed the use of digital twins in the water sector and concluded that the concept was promising, but required algorithms for automatic calibration based on observational data. Frincu [7] reviewed the use of AI to assess water quality. The main disadvantage of the review was the lack of physically sound transfer models. Only statistical methods were used.

Inverse identification of the source. Existing works [8] used hydrodynamic modeling and optimization algorithms [9]. However, the geometry of the water area was set manually or derived from static maps in these works, which prevented their operational use when new images were received.

The experience of processing more than a hundred Sentinel-2 images has shown that manually selecting the boundaries of a reservoir can take from 20 to 60 minutes per object in an emergency situation. This time is unacceptable.

Therefore, there is a need for a method that can:

- automatically extract the geometry of a water area from satellite data using CV;
- use this geometry in a hydrodynamic model to inverse identify the source;
- perform this in a time acceptable for rapid response (minutes, not hours).

The research aims to develop and validate an approach that combines computer vision (semantic segmentation of satellite imagery and cartographic data) with hydrodynamic modeling (two-dimensional advection-diffusion equation) to retrospectively identify the coordinates of an emergency discharge source using the observed concentration field.

Tasks:

- to implement the semantic segmentation module of water surface;
- to create a hydrodynamic model of passive impurity transfer;
- to develop a reverse identification algorithm by iterating through virtual sources and comparing the mean-square error (MSE);
- to validate the approach using synthetic data with a controlled error.

Materials and Methods. Methodological basis of the study was a sequential data processing algorithm (Fig. 1), in which information went from a raw image to a quantitative conclusion on the location of the source of pollution. The architecture of the solution included two fundamental interconnected modules operating in a single geographic information coordinate system.

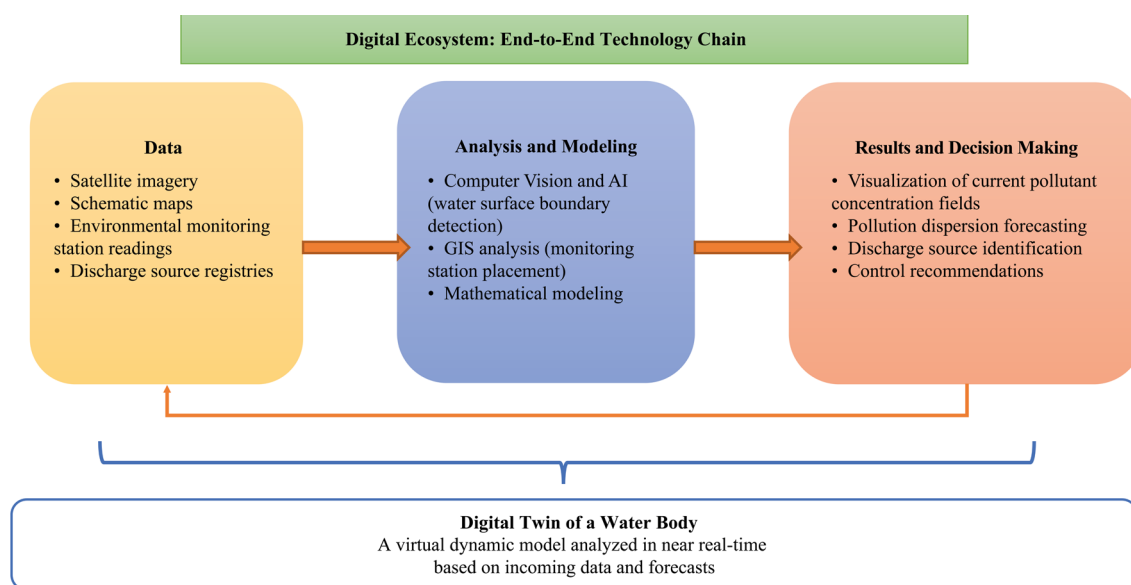


Fig. 1. Integrated algorithm workflow

A module for intelligent spatial data processing based on computer vision. This module was responsible for automated preparation of initial information for physical modeling and initial diagnostics. The system received an image of the water area under study, obtained from medium-resolution satellite platforms, such as Sentinel-2 and Landsat, using aerial photography from UAVs, or representing a digitized cartographic image. After the preprocessing stage, which included geometric and radiometric correction, as well as conversion to a single coordinate system, semantic segmentation of the water surface became a key task. To solve this problem, deep learning algorithms were used. These algorithms were specially adapted for analyzing images of the Earth and were often based on convolutional neural networks [10]. They were trained on mapped out sets of satellite images to accurately classify each pixel as “water” or “non-water”. The use of modern frameworks and libraries made it possible to achieve high segmentation accuracy even in difficult conditions such as cloud cover, glare on the water or a non-uniform coastline. The result of the module was a binary mask of the water area, which served as the basis for constructing the computational domain of the hydrodynamic model [11]. This stage completely eliminated subjective errors and significant time costs associated with manually selecting the contours of the reservoir [12].

After receiving the binary mask of the water area (the result of semantic segmentation), the contours of water bodies were highlighted. The `cv2.findContours` function from the OpenCV library (Python) was used for this. The `cv2.RETR_EXTERNAL` parameter ensured that only the outer contours were extracted, ignoring the inner cavities (for example, islands). The `cv2.CHAIN_APPROX_SIMPLE` parameter was used to compress the contour: redundant points lying on the same straight line were removed, which reduced the amount of data without losing the shape of the contour. Before selecting the contours, the mask was morphologically processed: closing operations (filling small gaps inside the water area) and opening operations (removing small noise fragments outside the reservoir) were performed sequentially. A 5×5 pixel core was used, with 2 iterations for closing and 2 iterations for opening.

Hydrodynamic modeling module and the inverse identification algorithm.

This module was the computing core of the system. A two-dimensional 2D model based on the advection-diffusion equation was used to describe the transport of pollutants in a reservoir [13]. This choice was determined by a compromise between computational efficiency, which was critical for multiple calculations when solving the inverse problem, and the adequacy of the description for most reservoirs [14], where horizontal scales significantly prevailed over vertical ones, and mixing could be considered quite intense. The transfer equation of the passive impurity concentration [15] C is as follows:

$$\frac{\partial C}{\partial t} + \kappa \frac{\partial C}{\partial t} + \nu \frac{\partial C}{\partial t} = D_h \left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} \right) + S(x, y, t),$$

where κ and ν — components of the horizontal flow velocity vector (m/s); D_h — horizontal turbulent diffusion coefficient (m²/s); $S(x, y, t)$ — source function describing power, localization, and time mode of discharge. For the numerical solution, the finite volume method was used, which guaranteed the conservation of mass [15]. Flow velocity fields κ and ν could be set analytically for simple scenarios, read from the results files of a separate hydrodynamic model, or reconstructed from measurement data. It should be noted that, depending on the scale of the water area, the complexity of the currents, and the required accuracy, the system could use various numerical methods to solve equation (1). For most scenarios, especially when working with large bodies of water, the finite volume method was used to ensure mass conservation and stability of the solution. However, for problems with high dynamics or the need for increased accuracy in areas of intense concentration gradients, adaptive methods such as Runge-Kutta methods or finite-difference schemes of increased order could be used. This made it possible to optimize computational costs and increase the accuracy of source identification in various hydrodynamic conditions.

The algorithm of inverse identification of the source formalized the search problem solution. When the contamination zone was fixed (under the conditions of a synthetic experiment, simulated concentration field $C_{obs}(x, y)$ in the area of possible location of sources (for example, along the entire perimeter of the reservoir specified by the computer vision module), a set of N virtual candidate points was generated. For each i -th point with coordinates (x_i, y_i) , a direct calculation was performed using equation (1), in which source function $S(x, y, t)$ corresponded to the position of this candidate. The result was model field of concentrations ($C_{mod,i}(x, y)$). The similarity measure was calculated for quantitative comparison of each model with the observed field, for example, the mean square error (MSE):

$$MSE_i = \frac{1}{A} \iint_{\varpi} (C_{mod,i}(x, y) - C_{obs}(x, y))^2 dx dy,$$

where ϖ — water body area; A — its area. The source of contamination was the virtual candidate for which the proximity measure was minimal: $(x_s, y_s) = \min(MSE_i)$. Thus, the complex inverse problem was reduced to solving many direct problems and choosing the best match, which ensured the visibility and stability of the result.

Research Results. To objectively verify operability and evaluate accuracy of the proposed approach, a series of computational experiments were conducted using synthetic data. This allowed us to eliminate the influence of uncertainties inherent in real-world measurements and focus on testing the algorithm's performance. An oval-shaped water area with a stationary current field was modeled. Three independent scenarios were simulated, each representing the discharge of different types of pollutants. Each scenario had its own background value, runoff concentration, and maximum permissible concentration (MPC). The detailed parameters for each scenario are summarized in Table 1.

Table 1

Parameters of synthetic scenarios for validation of the identification algorithm

Scenario parameter	Scenario 1 (pH)	Scenario 2 (O ₂)	Scenario 3 (Cl ⁻)
Modeled indicator	Hydrogen index (pH)	Dissolved oxygen (O ₂), mg/l	Free chlorine concentration (Cl ⁻), mg/l
Background value	7.0 (neutral medium)	8.0 (normal)	0.01 (below the MPC)
The maximum value in the discharge	3.0 (acid waste)	2.0 (O ₂ deficiency)	1.5 (high pollution)
MPC(Standard) ¹	6.0 – 9.0	6.0	0.5
Diffusion coefficient D_h , m ² /s	0.5	0.5	0.5
Current velocity, m/s	0.01	0.01	0.01

¹ Sanitary Rules and Regulations of (as amended on 17 March, 2025) SanPiN 1.2.3685-21 “Hygienic Standards and Requirements for Ensuring the Safety and (or) Harmlessness of Environmental Factors for Humans”. (In Russ.) URL: https://www.consultant.ru/document/cons_doc_LAW_375839/ (accessed: 20.01.2026).

In each of the 300 tests, 100 for each parameter, the true source coordinate was randomly selected. The computer vision module accurately processed the input data, generating an accurate mask of the water area. The inverse identification algorithm, sorting candidates in 50-meter increments, demonstrated high efficiency consistently. Statistical analysis of the results revealed that in 285 cases (95%), the algorithm correctly identified the true source.

Despite the high efficiency of the proposed approach, there were several conditions that should be taken into account when considering the accuracy of the method. Firstly, the analysis of 15 cases with inaccurate results showed that most of the errors (12 out of 15) occurred when the source was located less than three meters from the water's edge. Near the shoreline, turbulent diffusion and boundary conditions became comparable to advection, leading to a “blurring” of the pollution trace and a decrease in the uniqueness of the inverse problem solution. Secondly, the method relied on a two-dimensional hydrodynamic model, which was justified for reservoirs with a well-mixed water column where horizontal scales dominated over vertical scales. However, in stratified bodies of water, for example, in deep lakes with a pronounced thermocline, or in areas with intense vertical currents, two-dimensional approximation could give significant errors. Thirdly, the developed algorithm required specifying a stationary or quasi-stationary field of flow velocities. With sharply unstable hydrodynamics, for example in tidal estuaries or during floods, the accuracy of identification could decrease without additional calibration of the model based on the hydrological data relevant to the time of the incident. The validation of the method was performed only on synthetic data, which allowed us to judge only its fundamental operability.

Visualization of the results clearly confirmed the high quality of the algorithm. Figures 2 and 3 show the final simulation maps for some of the parameters under research.

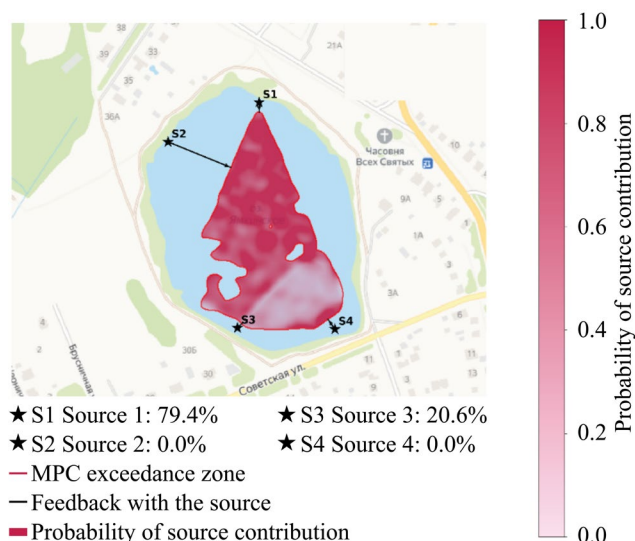


Fig. 2. Simulation map of discharge sources based on the hydrogen index parameter (pH)

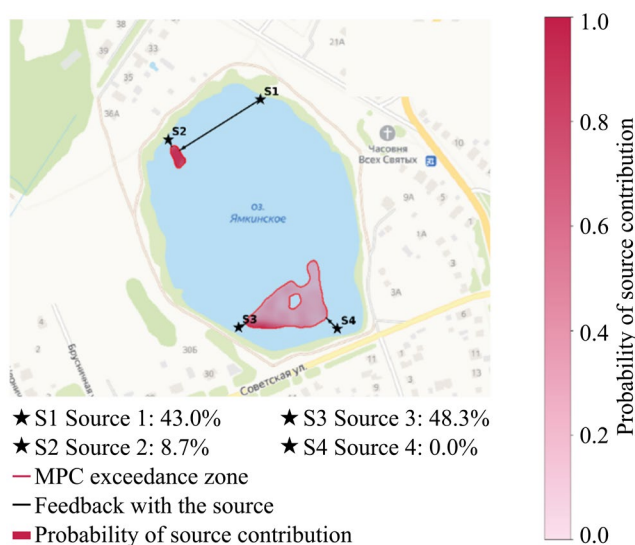


Fig. 3. Simulation map of discharge sources based on the free chlorine parameter (Cl)

The color field shows the spatial distribution of the concentration (or deviation from the background), clearly highlighting the area affected by the discharge. It is important to note that the algorithm not only created a field, but also calculated a probable point of contamination. In all visualizations, the red marker accurately indicated the location calculated by the inverse analysis algorithm. In most tests, this location coincided with the coordinates of the source specified in the scenario. These graphs serve as convincing evidence that the system is able not only to detect contamination, but also accurately indicate its origin.

Discussion. Computational experiments showed that the accuracy of source identification was 95% (285 out of 300 tests). However, 5% of errors (15 cases) were not random. Twelve of them were related to the location of the source at a distance of less than 3 m from the water area boundary. Near the shore, diffusion and boundary conditions distorted the pollution trace, which reduced the uniqueness of the solution to the inverse problem.

As the practice of preparing computational domains showed, discretization at 50-meter intervals was a compromise between speed and accuracy. At 25-meter intervals, the computing time increased by 4 times, while the increase in accuracy did not exceed 2% (tested in test scenarios). Therefore, to ensure efficiency, it was decided to use 50-meter intervals. However, this was a potential source of error: a source shifted by 25–30 m could be attributed to a neighboring grid node.

Comparison with the literature data confirmed the competitiveness of the approach. Jiang et al. [8] reported an accuracy of above 90% for river spills, but their calculated area was created manually. Tao et al. [16] achieved high efficiency on distributed systems, but the geometry of the water area was set a priori. This method fully automated the selection of boundaries through semantic segmentation [4]. This reduced the pre-processing time from 20–60 minutes for manual work to 1–2 minutes.

Automation had its price. The quality of segmentation depended on the resolution of the image, clouds, and glare. Processing of more than a hundred Sentinel 1–2 scenes showed that when cloudiness was more than 30%, the accuracy of the binary mask dropped to 85–88%. Contour selection errors, expressed in a shift of 1–2 pixels, led to a displacement of the calculated area and, as a result, to an identification error of up to 50 m. In the current implementation, such distortions were not modeled. This is the task for the next stages.

The limits of the method's applicability were clearly defined by the assumptions made. (1) The two-dimensional model was only suitable for reservoirs with intense vertical mixing. For stratified lakes deeper than 10 meters with a thermocline, horizontal diffusion failed to describe the vertical concentration gradient, leading to errors exceeding 30%. (2) The passive impurity model ignored chemical transformations, which was incorrect for pH. Acid waste was neutralized by water's buffering properties, but in synthetic scenarios, pH was treated as a conservative tracer. This simplification reduced accuracy in real-world conditions. (3) The flow velocity field was assumed to be stationary. In practice, hydrodynamics change during floods and tides within a few hours. Without current data-based calibration, identification errors would increase.

In addition to the sources of error listed above, the choice of diffusion coefficient in all scenarios was also a source of error. In a real water body, this coefficient could vary depending on wind and turbulence. At the same time, a 2-fold increase in the diffusion coefficient shifted the source estimate by 30–50 m downstream. However, the coefficient used in the work was set as a constant, which was a weakness in the study. Adaptive assessment based on observational data was outside the scope of this research.

Another limitation was the synthetic nature of validation. The observed concentration field $C_{obs}(x, y)$ in the experiments was free from measurement noise, data omissions, and ambiguity of spectral indices. In real conditions, the satellite image gives an integral concentration in the surface layer, rather than over the entire depth. This is acceptable for dissolved oxygen and chlorine, but not for pH. Thus, the stated accuracy of 95% is the top estimate. Based on real data, it is expected to decrease to 70–85%, depending on hydrological conditions.

The reliability of the conclusions lies in the fact that the proposed method has proven its fundamental operability. It is suitable for operational use in well-mixed water bodies, such as reservoirs, canals, and flat rivers, with a known or measured current field. For stratified or dynamic systems, a transition to a three-dimensional model and consideration of nonstationarity is required. The practical interpretation of the results is that the algorithm allows for the specification of a probable source area with an uncertainty radius of approximately 50 meters in 10–15 minutes. This timeframe is sufficient for on-site inspection and sampling.

The development prospects are related to the replacement of synthetic data with real satellite images with simultaneous field measurements. It is also necessary to calibrate the diffusion coefficient for the inverse problem. Without these steps, the method remains a prototype.

Conclusion. An algorithm for the inverse identification of the source of emergency pollution discharge into a water body has been developed and programmed. The algorithm consists of two modules: a computer vision module for semantic segmentation of satellite images and a two-dimensional hydrodynamic model of passive impurity transfer.

The computer vision module automatically identifies the water area and reduces the preprocessing time from 20–60 minutes (manually) to 1–2 minutes. This eliminates human errors. The hydrodynamic modeling module solves the advection-diffusion equation. The inverse identification algorithm iterates through virtual sources and selects the one with the minimum mean squared error (MSE) between the modeled and observed concentration fields.

Verification was conducted on synthetic data (300 tests for pH, dissolved O₂ and Cl⁻). The algorithm correctly determined the coordinates of the source in 285 cases. The accuracy was 95%.

The method is suitable for operational use in well-mixed water bodies (reservoirs, channels, flat rivers) with a known field of currents. The prospects: adaptation to real satellite data and calibration of the diffusion coefficient for the inverse problem.

References

1. Azeez Yusuf, O'Flynn D, White B, Holland L, Parle-McDermott A, Lawler J, et al. Monitoring of Emerging Contaminants of Concern in the Aquatic Environment: A Review of Studies Showing the Application of Effect-Based Measures. *Analytical Methods*. 2021;13(43):5120–5143. <https://doi.org/10.1039/d1ay01184g>
2. Jinyue Chen, Shuisen Chen, Rao Fu, Dan Lli, Hao Jiang, Chongyang Wang, et al. Remote Sensing Big Data for Water Environment Monitoring: Current Status, Challenges, and Future Prospects. *Earth's Future*. 2022;10(2):1–33. <https://doi.org/10.1029/2021EF002289>
3. Gusev AV. *Software for Automated Calculation of Morphometric Characteristics of Water Bodies*. Certificate of State Registration of the RF Computer Program No. 2025668927. 2025. 1 p. (In Russ.) URL: <https://fips.ru/EGD/0b4cdf99-068b-4c27-8142-426a7df83ced> (accessed: 12.17.2025).
4. Gusev AV. *Software for Automated Identification of Water Bodies on Cartographic Schemes and Satellite Images*. Certificate of State Registration of the RF Computer Program No. 2025668441. 2025. 1 p. (In Russ.) URL: <https://fips.ru/EGD/c7d3b1b1-22bb-4240-bbb8-7673e8998e54> (accessed: 12.17.2025).
5. Qinggai Wang, Shibei Li, Peng Jia, Changjun Qi, Feng Ding. A Review of Surface Water Quality Models. *The Scientific World Journal*. 2013;231768. <https://doi.org/10.1155/2013/231768>
6. Maksoud N, Mohamed MM. Digital Twins Applications in the Water Sector. *AIP Conference Proceedings*. 2023;2928 (1):160014. <https://doi.org/10.1063/5.0170525>
7. Frincu RM. Artificial Intelligence in Water Quality Monitoring: A Review of Water Quality Assessment Applications. *Water Quality Research Journal*. 2025;60(1):164–176. <https://doi.org/10.2166/wqj.2024.049>
8. Dexun Jiang, Hao Zhu, Peng Wang, Jie Liu, Fengfan Zhang, Yuanlong Chen. Inverse Identification of Pollution Source Release Information for Surface River Chemical Spills Using a Hybrid Optimization Model. *Journal of Environmental Management*. 2021;294:113022. <https://doi.org/10.1016/j.jenvman.2021.113022>
9. Penenko A, Rusin E. Parallel Implementation of a Sensitivity Operator-Based Source Identification Algorithm for Distributed Memory Computers. *Mathematics*. 2022;10(23):4522. <https://doi.org/10.3390/math10234522>
10. Razhev AO, Nedostup AA. Development of a Mathematical Model, Augmented Reality Technology and Computer Vision for Automation of Data Collection in Fish Farms. *Marine Intellectual Technologies*. 2024;4(1):349–358. <https://doi.org/10.37220/MIT.2024.66.4.041>
11. Ruo-Qian Wang, Pacheco-Crosetti G, Calderon CV, Cohen J, Smyth E. An Integrative Framework for AI-Supported Coastal Hydrodynamics Monitoring and Analysis. *Scientific Reports*. 2025;15(1):12403. <https://doi.org/10.1038/s41598-025-94791-8>
12. Kun Shi, Yunlin Zhang, Boqiang Qin, Botian Zhou. Remote Sensing of Cyanobacterial Blooms in Inland Waters: Present Knowledge and Future Challenges. *Science Bulletin*. 2019;64(20):1540–1556. <https://doi.org/10.1016/j.scib.2019.07.002>
13. Ruixiao Ma, Hao Han, Zhaoan Zhang. An Integrated Hydrological–Hydrodynamic Model Based on GPU Acceleration for Catchment-Scale Rainfall Flood Simulation. *Atmosphere*. 2025;16(7):809. <https://doi.org/10.3390/atmos16070809>

14. Mahmoud S Salem, Nashaat M Hussain Hassan, Marwa M Aly, Youssef Soliman, Peters RW, Mohamed K Mostafa. Integrating Deep Learning and Process-Based Modeling for Water Quality Prediction in Canals: CNN-LSTM and QUAL2K Analysis of Ismailia Canal. *Sustainability*. 2025;17(17):7743. <https://doi.org/10.3390/su17177743>
15. Sibren Loos, Chang Min Shin, Sumihar J, Kyunghyun Kim, Jaegab Cho, Weerts AH. Ensemble Data Assimilation Methods for Improving River Water Quality Forecasting Accuracy. *Water Research*. 2020;171:115343. <https://doi.org/10.1016/j.watres.2019.115343>
16. Fei Tao, He Zhang, Ang Liu, Nee AYC. Digital Twin in Industry: State-of-the-Art. *IEEE Transactions on Industrial Informatics*. 2019;15(4):2405–2415. <https://doi.org/10.1109/TII.2018.2873186>

About the Author:

Andrey V. Gusev, Postgraduate Student of the Department of Ecology and Environmental Protection, Russian State Social University (4, Bldg. 8, Vilgelma Pika St., Moscow, 129226, Russian Federation), [SPIN-code](#), [ORCID](#), gusevandre2015@yandex.ru.

Conflict of Interest Statement: the author declares no conflict of interest.

The author has read and approved the final version of manuscript.

Об авторах:

Андрей Вячеславович Гусев, аспирант кафедры «Экология и природоохранная деятельность» Российского государственного социального университета (129226, Российская Федерация, г. Москва, ул. Вильгельма Пика, д. 4, стр. 8), [SPIN-код](#), [ORCID](#), gusevandre2015@yandex.ru

Конфликт интересов: автор заявляет об отсутствии конфликта интересов.

Автор прочитал и одобрил окончательный вариант рукописи.

Received / Поступила в редакцию 12.06.2026

Reviewed / Поступила после рецензирования 25.07.2026

Accepted / Принята к публикации 05.08.2026

TECHNOSPHERE SAFETY

ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ



UDC 537.531

Original Empirical Research

<https://doi.org/10.23947/2541-9129-2026-10-3-256-265>

Assessment of Electromagnetic Radiation Intensity from Smartphones in Video Communication Mode

Tatyana A. Budykina^{ID}, Andrey A. Blokhin^{ID}

Civil Defense Academy of the Ministry of Emergency Situations of Russia, Khimki, Russian Federation

✉ tbudykina@yandex.ru

EDN: KXPYFN

Abstract

Introduction. The 2020s have brought the issue of electromagnetic radiation (EMR) in video conferencing (VC) to the forefront. Such services have become widespread due to pandemic-related self-isolation, falling smartphone prices, and the increased mobility of students and workers. Human tissues heat up locally during conversations and video calls because the device emits non-ionizing electromagnetic radio waves. Their effect on the body has been described in several studies, but only the situation of audio calls is considered. There is no data on how harmful EMR is in VC. Accordingly, it is impossible to substantiate recommendations for video communication safety, in particular for “protection by distance”. This study aims to fill this gap by determining the level of EMR emitted by smartphones during video conferences.

Materials and Methods. The radiation was measured using a PZ-41 device. The manufacturer was Special Design Bureau PiTON, located in Nizhny Novgorod. The antenna recorded the maximum and average values of the energy flux density (EFD). Conditions: EFD — 0.26–100,000 $\mu\text{W}/\text{cm}^2$, frequency used to determine EFD — 2450 MHz, and the averaging time for the parameter before it was displayed on the screen — 1 minute. Smartphones with iOS and Android operating systems with and without Wi-Fi were tested. Measurements were taken at distances of 0 and 15 cm from the top and bottom speakers. Five experiments were conducted in each case.

Results. During video calls, EMR was higher than during a conversation. For each device, the maximum and average values of EFD in the video call mode with Wi-Fi enabled and disabled were summarized in tables. We obtained 40 indicators for each of the four cases (two devices and two modes), with minimum and maximum values: 0.365 and 9.732; 3.813 and 72.136; 0.01 and 0.633; 0.781 and 30.271. We noted the data with interference modeling and poor Internet connection. For each experiment, we derived average values. EFD from iOS turned out to be higher than from Android. EFD_{avg} excess with Wi-Fi was indistinguishable (0.6) in 0 cm from the top speaker and more than 85 in 15 cm from the bottom one. The absolute values were low: 0.549 and 0.985 and 0.854 and 0.010, respectively.

Discussion. Protection by distance worked at a distance of 15 cm from the speaker with Wi-Fi (similar EFD_{max} and EFD_{avg} values were obtained). Interference both reduced and increased EFD. There was no pattern. Unstable Internet doubled the average EFD. Wi-Fi reduced the EFD by a factor of 3.1–26.9 for iOS and by a factor of 3.8–167.5 for Android (due to the router’s short range, the smartphone did not need a powerful transmitter). For iOS, high EFDs were recorded at the bottom speaker; for Android — at the top one. Android demonstrated the maximum reduction in EFD_{avg}: with Wi-Fi 15 cm away from the bottom speaker, the value decreased by a factor of 115; at the top speaker, by a factor of 167.

Conclusion. Device holders distance the smartphone from the user and enhance the VC safety. A failure in Internet connection increases radiation. In the future, it would be advisable to study other smartphone models and work out the regulation of EMF during calls.

Keywords: video conferencing via smartphone, energy flux density during video calls, electromagnetic radiation during video calls, “protection by distance” during video calls

Acknowledgements. The authors would like to express their gratitude to the Head of the Fire Safety Department of the Civil Defense Academy of the Ministry of Emergency Situations of Russia, Candidate of Military Sciences, Associate Professor Sergey M. Lyashenko for his invaluable material support in conducting the experiment. He provided the necessary measuring equipment for our research.

For Citation. Budykina TA, Blokhin AA. Assessment of Electromagnetic Radiation Intensity from Smartphones in Video Communication Mode. *Safety of Technogenic and Natural Systems*. 2026;10(3):256–265. <https://doi.org/10.23947/2541-9129-2026-10-3-256-265>

Оригинальное эмпирическое исследование

Оценка интенсивности электромагнитных излучений от смартфонов в режиме видеосвязи

Т.А. Будыкина , А.А. Блохин 

Академия гражданской защиты МЧС России, г.о. Химки, Российская Федерация

✉ tbudykina@yandex.ru

Аннотация

Введение. 20-е годы XXI века актуализировали проблему электромагнитного излучения (ЭМИ) при видео-конференц-связи (ВКС). Такие сервисы распространились из-за пандемийной самоизоляции, снижения цен смартфонов, мобильности студентов и работников. Ткани человека локально нагреваются при разговоре и видеосвязи, т.к. аппарат излучает неионизирующие электромагнитные радиоволны. Их влияние на организм описано в нескольких работах, однако рассматривается только ситуация аудиосозвона. Нет данных, насколько вредно ЭМИ при ВКС. Соответственно, невозможно обосновать рекомендации по безопасности видеосвязи, в частности по «защите расстоянием». Представленная работа восполняет эти пробелы. Цель — определить уровень ЭМИ от смартфонов при ВКС.

Материалы и методы. Излучение измерялось прибором ПЗ-41. Производитель — ООО «СКБ ПиТОН», г. Нижний Новгород. Антенна фиксировала максимальные и средние значения плотности потока энергии (ППЭ). Условия: ППЭ — 0,26–100 000 мкВт/см², частота при определении ППЭ — 2450 МГц, время усреднения параметра до вывода на табло — 1 минута. Тестировались смартфоны с операционными системами «Айос» (iOS) и «Андроид» (Android) с работающим и отключенным вайфаем (Wi-Fi). Измерялись показатели на расстоянии 0 и 15 см от верхнего и нижнего динамика. Провели по пять экспериментов.

Результаты исследования. При видеозвонках ЭМИ выше, чем при разговоре. Для каждого аппарата обобщили в таблицах максимальные и средние значения ППЭ в режиме видеосвязи с включенным и выключенным вайфаем. Получили по 40 показателей для каждого из четырех случаев (два аппарата и два режима) с минимумами и максимумами: 0,365 и 9,732; 3,813 и 72,136; 0,01 и 3,633; 0,781 и 30,371. Отметили данные с моделированием помех и плохим интернет-соединением. По каждому опыту вывели усредненные значения. ППЭ от «Айоса» оказалась выше, чем от «Андроид». Превышение по ППЭ_{средн} с вайфаем малоразлично (0,6) в 0 см от верхнего динамика и более 85 — в 15 см от нижнего. Абсолютные показатели невелики: 0,549 и 0,985 и 0,854 и 0,010 соответственно.

Обсуждение. Защита расстоянием срабатывает в 15 см от динамика с вайфаем (получены сходные ППЭ_{макс} и ППЭ_{средн}). Помехи и снижают, и повышают ППЭ. Закономерность не выявлена. Нестабильный интернет вдвое увеличил среднюю ППЭ. Вайфай снизил ППЭ в 3,1–26,9 раза для «Айоса» и в 3,8–167,5 раза для «Андроид» (из-за малого радиуса действия роутера смартфону не нужен мощный передатчик). Для «Айоса» высокие ППЭ фиксируются у нижнего динамика, для «Андроид» — у верхнего. Максимальное снижение ППЭ_{средн} продемонстрировал «Андроид»: с вайфаем в 15 см от нижнего динамика показатель сократился в 115 раз, у верхнего — в 167 раз.

Заключение. Держатели для гаджетов удаляют смартфон от человека и повышают безопасность ВКС. Сбой в интернет-связи усиливает излучение. В перспективе целесообразно изучить другие модели смартфонов и проработать нормирование ЭМИ при созвонах.

Ключевые слова: видео-конференц-связь по смартфону, плотность потока энергии при видеозвонках, электромагнитное излучение при видеозвонках, «защита расстоянием» при видеозвонках

Благодарности. Авторы выражают благодарность заведующему кафедрой пожарной безопасности Академии гражданской защиты МЧС России, кандидату военных наук, доценту Ляшенко Сергею Михайловичу за материальное обеспечение эксперимента — предоставление измерительного оборудования.

Для цитирования. Будыкина Т.А., Блохин А.А. Оценка интенсивности электромагнитных излучений от смартфонов в режиме видеосвязи. *Безопасность техногенных и природных систем*. 2026;10(3):256–265. <https://doi.org/10.23947/2541-9129-2026-10-3-256-265>

Introduction. In the 2020s, the issue of participants' exposure to electromagnetic radiation during video conferencing (VC) has become increasingly important. The widespread use of these services is primarily due to coronavirus pandemic-related self-isolation. Other reasons include the mobility of students and employees, the proliferation of remote and hybrid work arrangements, and lower prices for mobile devices with video capabilities. This transformation can be demonstrated through the following example. Prior to the pandemic, a well-known free solution existed. During the time of self-isolation, six new products with similar functionality were added to the market. Later, two more appeared [1].

Since 2019, hardware and software terminals, server systems, cloud services, and smartphone applications have been used to make video communication more accessible. Yandex Telemost, VK Calls, MTS Link, and Max are the leaders in the Russian segment of online communication.

Non-ionizing electromagnetic radio waves that occur during VC can cause local heating of tissues. The question of how harmful this is requires comprehensive research. The authors of this article found out, that publicly available publications did not consider the massive use of video content on mobile devices, which led to the hypothesis that electromagnetic radiation (EMR) from smartphones is amplified in modern VC scenarios. Considering this, it is advisable to investigate the effect of Wi-Fi on the EMR values, as this particular issue has not been addressed in the literature. However, there are studies that assess the effects of mobile phones on the human body during conversation, that is, when using the device for its intended purpose. Nikitina V.N. and Vtornikova N.I. note the increased thermal effect of electromagnetic radiation, which is unfavorable for humans [2]. First of all, the adverse effect affects the brain [3], visual and auditory analyzers, and the thyroid gland [4]. According to some reports, direct contact of a mobile phone with a person's head causes a risk of long-term consequences and increases the likelihood of brain tumors [5], Alzheimer's disease, and early dementia [6].

Khorseva N.I. [7] notes fatigue, significant deterioration in performance indicators, sensorimotor reactions, fatigue, and cognitive functions in children and adolescents due to the use of mobile communication devices. Belpomme D. and Rakhmanin Yu.A. prove that mobile phones are the cause of changes in neurodevelopment and neurobiological behavior [8], as well as memory disorders, learning difficulties, attention problems, and behavioral issues in children [9].

Direct contact of the device with the human head clearly explains the identified negative effects on the nervous system and analyzers. However, there are other, non-obvious dependencies that require further study. Thus, the use of mobile phones for more than four hours per day affects the reproductive performance of both men [10] and women [11].

Thus, it can be argued that researchers' attention has been focused on studying the risks associated with using a mobile phone while talking without headphones, with the device in contact or near contact with the head. However, the situation where the user is engaged in video conferencing has not been considered, and the EMR has not been determined for such cases. As part of this study, we have attempted to address this gap by conducting a survey for the first time and subsequently proposing safety recommendations. To our knowledge, no similar surveys have been conducted before. The aim of this research is to determine the level of electromagnetic radiation emitted by smartphones during video communication sessions over the mobile internet and Wi-Fi networks.

To achieve this goal, we have set the following tasks:

- determination of the maximum and average values of electromagnetic radiation (energy flux density, EFD) at a distance of 0 cm and 15 cm from the top and bottom speakers of two devices (smartphones) during video calls;
- assessment of the impact of Wi-Fi usage on the EMR value;
- identification of points with the highest electromagnetic radiation levels in smartphones.

Materials and Methods. The level of electromagnetic radiation emitted by smartphones was measured using a PZ-41 device, which included three antenna converters: AC-1, AC-2, and AC-3. High-frequency electromagnetic field was converted into a constant voltage that was then applied to a measuring device. This device processed information and displayed the parameters of the electromagnetic field on a screen. The manufacturer of this device is Special Design Bureau PiTON, located in Nizhny Novgorod.

Using the AP-1 antenna, the maximum and average values of the energy flux density (EFD_{max} , EFD_{avg} , $\mu W/cm^2$) were recorded under the following conditions:

- averaging time of the measured parameter displayed on the instrument panel — 1 minute;
- range of measured frequencies — 0.3–40 GHz;
- energy flux density — 0.26–100,000 $\mu W/cm^2$;
- frequency for EFD determination — 2450 MHz.

It should be noted that Russian mobile operators operate in subscriber ranges from 790 MHz to 2700 MHz. 4G (LTE) mobile data transmission standards use a frequency of 2600 MHz [12]. When using Wi-Fi technology, the operating frequency is 5150–5850 MHz.

Figure 1 illustrates the operation of the PZ-41 device for evaluating the EFD at frequencies of 2450 MHz and 5150 MHz, measuring both maximum and average values during a 1-minute exposure.



Fig. 1. PZ-41 device interface when measuring EFD_{max} and EFD_{avg} at frequencies of 2450 MHz and 5150 MHz
 a — determination of EFD_{max} at a frequency of 2450 MHz; b — determination of EFD_{avg} at a frequency of 2450 MHz;
 c — determination of EFD_{max} at a frequency of 5150 MHz; d — determination of EFD_{avg} at a frequency of 5150 MHz

EFD was measured at the Fire Safety Department of Civil Defense Academy of the Ministry of Emergency Situations of Russia on a laboratory bench simulating a work surface with a scale-coordinate paper attached. The smartphone was attached to a dielectric tripod in an upright position (MG 4.3.2501–09¹), and the measuring device with an antenna was attached to a special holder. The antenna of the PZ-41 was located at a distance of 0 and 15 cm from top and bottom speakers of the smartphone (Fig. 2).

¹ Methodological Guidelines 4.3. *Methods of Control. Physical Factors. Measurement of Electromagnetic Fields of Personal Mobile Cellular Communication Systems*. Date of introduction 2009-06-20. (In Russ.) URL: <https://docs.cntd.ru/document/1200076309> (accessed: 13.07.2026).

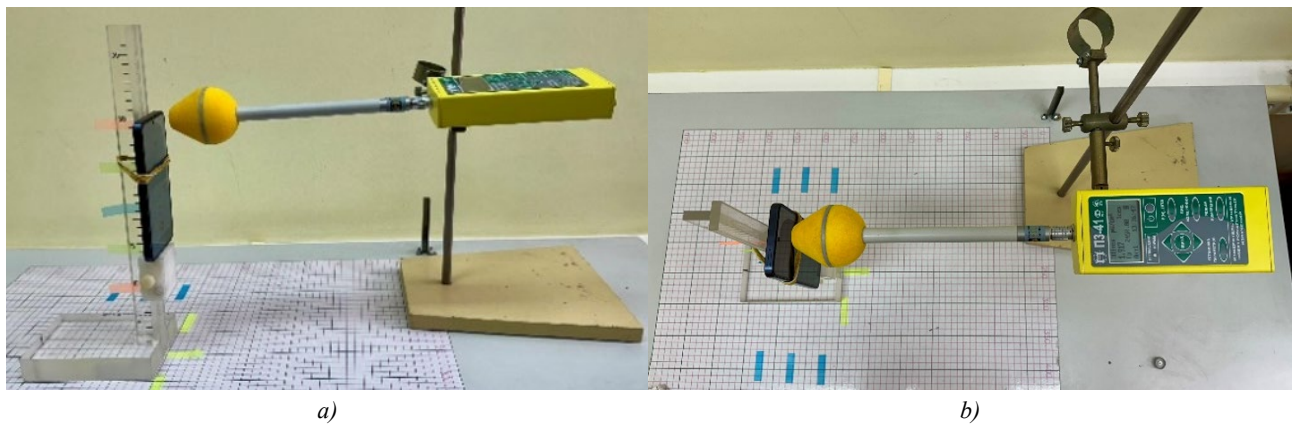


Fig. 2. Experiments at 2450 MHz and 5150 MHz:
 a — measurement of the top speaker, side view; b — same, top view

Two mobile devices of different telecom operators, of the same year of manufacture, were tested. Each of them was in operation for 2.5 years.

Specifications of device No. 1:

- iOS operating system (iPhone 14 Pro);
- iOS version — 26.3.1(a);
- device memory capacity — 128 GB;
- telecom operator — Tele2.

Specifications of device No. 2:

- Android operating system (Samsung Galaxy A35 5G);
- version — Android 14;
- device memory capacity — 128 GB;
- telecom operator — MTS.

Smartphones were tested:

- without enabling Bluetooth and NFC modules (always);
- with the Wi-Fi module running (mentioned separately) and with Wi-Fi disabled.

The video was transmitted using the Yandex Telemost service. The product of the Russian company, Yandex, has been operating on iOS and Android platforms since the summer of 2020.

To create a permanent live video conference, a training video with sound was played on tablet (device 3). The content was transmitted from smartphone 1 to smartphone 2 using the internet. Devices 1 and 2 were located in different rooms. During the experiment, we simulated the interference of people moving around and making gestures near the phone. Such cases were marked with * in the table. Data received through a poor internet connection was marked with #.

When using Wi-Fi, the distance from the router was not more than 10 meters, taking into account the obstacle in the form of a reinforced concrete wall.

We considered the hypothesis of increased EMR during smartphone operation in video communication mode. To assess its validity, we measured the EMR of devices in call mode without turning off Wi-Fi.

When measuring the EMR of device 1 in talk mode, we obtained the following average results:

- 0 cm from the bottom speaker — $EFD_{\max} = 1.101 \mu\text{W}/\text{cm}^2$, $EFD_{\text{avg}} = 0.258 \mu\text{W}/\text{cm}^2$;
- 0 cm from the top speaker — $EFD_{\max} = 0.633 \mu\text{W}/\text{cm}^2$, $EFD_{\text{avg}} = 0.221 \mu\text{W}/\text{cm}^2$;
- 15 cm from the bottom speaker — $EFD_{\max} = 0.396 \mu\text{W}/\text{cm}^2$, $EFD_{\text{avg}} = 0.014 \mu\text{W}/\text{cm}^2$;
- 15 cm from the top speaker — $EFD_{\max} = 0.276 \mu\text{W}/\text{cm}^2$, $EFD_{\text{avg}} = 0.027 \mu\text{W}/\text{cm}^2$.

There were small EFD values in the talk mode, especially at a distance of 15 cm. The data collected was important for comparing EFD results with video call mode.

Research Results. Tables 1–4 show the results of measurements of $EFD_{\max}$ and EFD_{avg} in video call mode at two control points — at a distance of 0 cm and 15 cm from the top and bottom speakers of smartphones at a frequency of 2450 MHz. The tables present five EMR values according to the order of measurements. Measurements 1–5 were conducted on the same day and in the same order.

Table 1

Maximum and average EFD values for device 1 in video communication mode using the Yandex Telemost application with Wi-Fi or signal reception

Measured value, $\mu\text{W}/\text{cm}^2$	Experiment no.					Averaged value for experiments 1–5
	1	2	3	4	5	
Measuring point — 0 cm from the top speaker						
EFD _{max}	4.133	4.881	9.732 [#]	3.315	1.551*	4.722
EFD _{avg}	0.570	0.548	0.548	0.568	0.514*	0.549
Measuring point — 0 cm from the bottom speaker						
EFD _{max}	8.197	6.877*	6.752	5.299	3.674	6.159
EFD _{avg}	5.121	4.622*	4.981	0.436	0.365	3.105
Measuring point — 15 cm from the top speaker						
EFD _{max}	2.186	1.696	2.049	1.794	2.293	2.004
EFD _{avg}	0.638	0.927	0.952	1.130	1.262	0.982
Measuring point — 15 cm from the bottom speaker						
EFD _{max}	2.616	1.832	2.694	1.325	1.860	2.065
EFD _{avg}	0.651	0.904	0.922	0.887	0.904	0.854

Table 2

Maximum and average EFD values for device 1 in video communication mode using the Yandex Telemost application without Wi-Fi or signal reception

Measured value, μW/cm ²	Experiment no.					Averaged value for experiments 1–5
	1	2	3	4	5	
Measuring point — 0 cm from the top speaker						
EFD _{max}	28.110	20.412	20.033	19.321	27.372	23.049
EFD _{avg}	15.939	15.652	15.303	14.216	12.870	14.796
Measuring point — 0 cm from the bottom speaker						
EFD _{max}	62.679	61.704	69.125	60.016	72.136	65.132
EFD _{avg}	33.024	45.233	43.580	46.344	51.335	43.903
Measuring point — 15 cm from the top speaker						
EFD _{max}	5.317	5.548	6.002	7.201*	7.089	6.231
EFD _{avg}	4.002	4.227	4.493	4.146*	4.169	4.207
Measuring point — 15 cm from the bottom speaker						
EFD _{max}	7.767	5.735	6.532	5.866	7.252	6.630
EFD _{avg}	4.180	3.813	4.459	4.444	4.015	4.182

Table 3

Maximum and average EFD values for device 2 in video communication mode using the Yandex Telemost application with Wi-Fi or signal reception

Measured value, $\mu\text{W}/\text{cm}^2$	Experiment no.					Averaged value for experiments 1–5
	1	2	3	4	5	
Measuring point — 0 cm from the top speaker						
EFD _{max}	2.136	3.126	3.633	2.398	1.656	2.589
EFD _{avg}	1.015	0.896	1.338	0.836	0.839	0.985
Measuring point — 0 cm from the bottom speaker						
EFD _{max}	0.655	1.566	0.947	0.838	0.661	0.933
EFD _{avg}	0.218	0.336	0.257	0.214	0.208	0.246
Measuring point — 15 cm from the top speaker						
EFD _{max}	0.574	0.472	0.544	0.360	0.002	0.392
EFD _{avg}	0.021	0.020	0.012	0.010	0.001	0.013
Measuring point — 15 cm from the bottom speaker						
EFD _{max}	0.268	0.602	0.490	0.073	0.094	0.305
EFD _{avg}	0.014	0.027	0.008	0.001	0.002	0.010

Table 4

Maximum and average EFD values for device 2 in video communication mode using the Yandex Telemost application without Wi-Fi or signal reception

Measured value, μW/cm ²	Experiment no.					Averaged value for experiments 1–5
	1	2	3	4	5	
Measuring point — 0 cm from the top speaker						
EFD _{max}	25.587	30.371	19.764	17.900*	15.520	21.828
EFD _{avg}	14.640	14.718	11.432	9.015*	11.296	12.220
Measuring point — 0 cm from the bottom speaker						
EFD _{max}	3.283	3.281	3.096	3.596	4.734*	3.598
EFD _{avg}	1.819	1.408	1.677	2.126	2.250*	1.856
Measuring point — 15 cm from the top speaker						
EFD _{max}	3.599	3.394	2.996	3.026	3.794	3.362
EFD _{avg}	2.223	2.200	2.025	1.877	2.568	2.178
Measuring point — 15 cm from the bottom speaker						
EFD _{max}	1.905	2.163	3.000	2.994	2.382	2.489
EFD _{avg}	0.881	0.781	1.167	1.633	1.302	1.153

Table 5 summarizes the average values for the five measurements presented in Tables 1–4, as well as the difference between the EFD values recorded for iOS smartphones and Android. This difference was defined as the quotient of dividing a larger value by a smaller one. It is important to note that the iOS indicator was found to be higher in almost all experiments compared to that of Android.

Table 5

Averaged EFD values for devices 1 and 2 in video communication mode using the Yandex Telemost application with and without Wi-Fi

Measured parameter, $\mu\text{W}/\text{cm}^2$	Device 1			Device 2			Excess of EFD indicators of iOS in comparison with Android	
	Without Wi-Fi	With Wi-Fi	Excess	Without Wi-Fi	With Wi-Fi	Excess	Without Wi-Fi	With Wi-Fi
Measuring point — 0 cm from the top speaker								
EFD _{max}	23.049	4.722	4.9	21.828	2.589	8.4	1.1	1.8
EFD _{avg}	14.796	0.549	26.9	12.220	0.985	12.4	1.2	0.6
Measuring point — 0 cm from the bottom speaker								
EFD _{max}	65.132	6.159	10.6	3.598	0.933	3.9	18.1	6.6
EFD _{avg}	43.903	3.105	14.1	1.856	0.246	7.5	23.7	12.6
Measuring point — 15 cm from the top speaker								
EFD _{max}	6.231	2.004	3.1	3.362	0.392	8.6	1.9	5.1
EFD _{avg}	4.207	0.982	4.3	2.178	0.013	167.5	1.9	75.5
Measuring point — 15 cm from the bottom speaker								
EFD _{max}	6.630	2.065	3.2	2.489	0.305	8.2	2.7	6.8
EFD _{avg}	4.182	0.854	4.9	1.153	0.010	115.3	3.6	85.4

Discussion. The data in Tables 1–5 allow us to make ten reasonable conclusions.

1. For device 1, when measured at a distance of 0 cm from the speakers using Wi-Fi, higher EFD values were recorded for the bottom speaker (6.159 $\mu\text{W}/\text{cm}^2$ and 3.105 $\mu\text{W}/\text{cm}^2$). The corresponding indicators for the top speaker were 4,722 $\mu\text{W}/\text{cm}^2$ and 0.549 $\mu\text{W}/\text{cm}^2$. At a distance of 15 cm, there were no significant differences in the values of EFD_{max} and EFD_{avg}. The values for EFD_{max} were 2.004 and 2.065; for EFD_{avg}, they were 0.982 and 0.854. This confirmed the safety principle of “protection by distance”. Intense interference near smartphones did not significantly affect EFD, in contrast to the unstable internet, which doubled the average value (Table 1).

2. For device 1 without Wi-Fi, at a distance of 0 cm, extremely high values were obtained for the bottom speaker: EFD_{max} — $65.132 \mu W/cm^2$, EFD_{avg} — $43.903 \mu W/cm^2$. The top one had figures of 23.049 and 14.796, respectively, which were more than 10 times higher than those obtained with Wi-Fi enabled. At a distance of 15 cm, the values of EFD_{max} and EFD_{avg} of the lower speaker decreased by 10 times. Interference had almost no effect on the result (Table 2).

3. For device 2, at a distance of 0 cm with Wi-Fi, the values of 2.589 (maximum) and 0.985 (average) were recorded at the top speaker. These values were higher than those for the bottom speaker (0.933 and 0.246, respectively). No significant differences were found between the top and bottom speakers at a distance of 15 cm. For EFD_{max} — 0.392 and 0.305; for EFD_{avg} — 0.013 and 0.010 (Table 3).

4. For device 2, without Wi-Fi, when measured at a distance of 0 cm, extremely high values were recorded for the top speaker: 21.828 for EFD_{max} and 12.220 for EFD_{avg} . The corresponding measurement results for the bottom speaker were $3.598 \mu W/cm^2$ and 1,856. At a distance of 15 cm, the values of EFD_{max} and EFD_{avg} decreased by 5–7 times for the top speaker and by approximately 1.5 times for the bottom speaker. Interference can both reduce and increase EFD, but the pattern needs to be further investigated (Table 4).

5. The use of Wi-Fi technology for video communication mode could reduce EFD_{max} and EFD_{avg} by 3.1–26.9 times for device 1 and 3.8–167.5 times for device 2 (Table 5).

6. The use of Wi-Fi technology for video communication mode reduced EFD_{avg} more significantly than EFD_{max} . This was true for both devices (Table 5).

7. At a distance of 0 cm, higher EFD values were recorded for the bottom speaker of device 1 and for the top speaker of device 2. This was due to their design features (Table 5).

8. In comparison with device 2, device 1 had a higher EFD, it reached 85 times. This result was obtained when measuring the bottom speaker at a distance of 15 cm with Wi-Fi (Table 5).

9. The highest decrease in EFD_{avg} for device 2 was 115 times and 167 times for the bottom and top speakers, respectively. Such indicators were recorded at a distance of 15 cm with Wi-Fi (Table 5).

10. In case of failures in the Internet network, the EFD values increased.

The results support the hypothesis that there is an increase in electromagnetic radiation during video calls on a smartphone. This research fills a gap in our knowledge in this area. It opens up the possibility for further studies to explore and understand more about EMR radiation while using smartphones for video conferencing, online gaming, virtual and augmented reality, etc.

An important finding of the study is a significant reduction in electromagnetic radiation when using Wi-Fi technology for video communication on a smartphone. This can be attributed to the characteristics of communication via Wi-Fi, as the short range of the router means that the smartphone does not require a powerful transmitter.

Conclusion. The principle of “protection by distance” has been experimentally confirmed: when you move away from a smartphone by 15 centimeters, electromagnetic radiation decreases. This means that there is a safe way to make video calls. We recommend using gadget holders to create distance between the person and the device. Do not wear the device on your body or lean against it during a video call, and make sure to remove it at least 15 centimeters from your body.

For different models of mobile devices, high EMR values were found at different points, which could be explained by the design features of smartphones. For an iOS device, the bottom speaker was found to have high values, while the top speaker was found to have high values on the Android platform. Users should study the design of the device to form their own safety rules. Further research is needed to build the EMP fields of personal mobile communication systems.

It has been proven that, due to the characteristics of the transmitter, a failure in the internet connection can lead to an increase in energy flux density. This should be communicated to users.

The results obtained are of practical importance and offer promising prospects for future research. They may include:

- construction of fields of spatial distribution of the energy flux density from a smartphone in video communication mode,
- conducting similar measurements with other smartphone models,
- development of recommendations for safe operation,
- introduction of EMR norms during remote communication using smartphones.

References

1. Chernyshova MS. *A Brief History of Video Communication. Part 2. From Commercial Premium Service to “Pocket” Technology.* (In Russ.) URL: <https://trueconf.ru/blog/news/history-of-video-conferencing> (accessed: 20.02.2026).
2. Nikitina VN, Kalinina NI, Dubrovskaya EN. On the Issue of the Influence of Electromagnetic Fields of the Radio Frequency Range on the Health of the Population (Review). *Preventive and Clinical Medicine.* 2023;3(88):15–23. (In Russ.) URL: <https://clck.ru/3VRS2K> (accessed: 20.02.2026).

3. Vtornikova NI, Babalyan AV, Karelin AA, Ivanov VA. Evaluation of EMF Exposure of Mobile Phones on Human Head. *The Scientific Notes of the Pavlov University*. 2017;24(4):75–81. (In Russ.) <https://doi.org/10.24884/1607-4181-2017-24-4-75-81>
4. Nikitina VN, Kalinina NI, Lyashko GG, Dubrovskaya EN, Plekhanov VP. Methodological Approaches to Measuring and Evaluating the Effects of Electromagnetic Fields Generated by Smartphones. *Hygiene and Sanitation*. 2022;101(8):855–860. <https://doi.org/10.47470/0016-9900-2022-101-8-855-860> (In Russ.)
5. Sage C, Burgio E. Electromagnetic Fields, Pulsed Radiofrequency Radiation, and Epigenetics: How Wireless Technologies May Affect Childhood Development. *Child Development*. 2018;89(1):129–136. <https://doi.org/10.1111/cdev.12824>
6. Jin-Hwa Moon. Health Effects of Electromagnetic Fields on Children. *Clinical and Experimental Pediatrics*. 2020;63(11):422–428. <https://doi.org/10.3345/cep.2019.01494>
7. Khorseva NI, Grigoriev YuG, Grigoriev PE. Hazard Assessment of Electromagnetic Fields of Mobile Phones for Children and Teenagers. The Results of the World's Only Lasted 14–Years Physiological Studies. In: *Actual Issues of Radiobiology and Hygiene for Non-Ionizing Radiation Proceedings of Scientific Conference*. Moscow: Russian National Committee on Non-Ionizing Radiation Protection; 2019. P. 148–151. ISBN 978-5-6041530-0-0. (In Russ.) URL: http://bioemf.ru/conf/conf2/KHORSEVA_NI.pdf (accessed: 14.07.2026).
8. Belpomme D, Hardell L, Belyaev I, Burgio E, Carpenter DO. Thermal and Non-Thermal Health Effects of Low Intensity Non-Ionizing Radiation: An International Perspective. *Environmental Pollution*. 2018;242A:643–658. <https://doi.org/10.1016/j.envpol.2018.07.019>
9. Rakhmanin YuA, Onishchenko GG, Grigoriev YuG. Contemporary Issues and the Ways of Ensuring Electromagnetic Safety of Mobile Communication to the Health of the Population. *Hygiene & Sanitation*. 2019;98(11):1175–1183. (In Russ.) URL: https://www.rjhas.ru/jour/article/view/436?locale=ru_RU (accessed: 14.07.2026)
10. Lifanova RZ, Orlova VS, Tsetlin VV. Effects of Radiofrequency Electromagnetic Radiation on the Organism as a Whole and Structural Units (Literature Review). *Hygiene & Sanitation*. 2021;100(2):123–128. (In Russ.) <https://doi.org/10.47470/0016-9900-2021-100-2-123-128>
11. Auvinen A, Feychting M, Ahlbom A, Hillert L, Elliott P, Schüz J, et al. Headache, Tinnitus and Hearing Loss in the International Cohort Study of Mobile Phone Use and Health (COSMOS) in Sweden and Finland. *International Journal of Epidemiology*. 2019;48(5):1567–1579. <https://doi.org/10.1093/ije/dyz127>
12. Vereshchako GG. The Problems of Male Reproduction Due to the Use of Mobile Phone. *Russian Journal of Human Reproduction*. 2014;4:73–78. (In Russ.) URL: <https://www.mediasphera.ru/issues/problemny-reproduksii/2014/4/031025-72172014415?ysclid=mrkz73bux271346667> (accessed: 14.07.2026).

About the Authors:

Tatyana A. Budykina, Dr. Sci. (Eng.), Professor of the Fire Safety Department, Civil Defense Academy of the Ministry of Emergency Situations of Russia (1, Sokolovskaya Str., Novogorsk district, Khimki, Moscow Region, 141435, Russian Federation) [SPIN-code](#), [ORCID](#), [ScopusID](#), tbudykina@yandex.ru

Andrey A. Blokhin, Cand. Sci. (Eng.), Associate Professor of the Fire Safety Department, Civil Defense Academy of the Ministry of Emergency Situations of Russia (1, Sokolovskaya Str., Novogorsk district, Khimki, Moscow Region, 141435, Russian Federation), [SPIN-code](#), [ORCID](#), [ResearcherID](#), Blokhi-andrej@yandex.ru

Claimed Contributorship:

TA Budykina: conceptualization, conducting an experiment to determine the energy flux density from the smartphone, verifying the reproducibility of the experiment's results, writing — original draft preparation, constructing tabular dependencies, making comments and corrections to the manuscript.

AA Blokhin: conducting an experiment to determine the energy flux density from a smartphone, verifying the reproducibility of the experiment's results, writing — original draft preparation, constructing tabular dependencies, making comments and corrections to the manuscript.

Conflict of Interest Statement: the authors declare no conflict of interest.

All authors have read and approved the final version of manuscript.

Об авторах:

Татьяна Алексеевна Будыкина, доктор технических наук, профессор кафедры «Пожарная безопасность» Академии гражданской защиты МЧС России (141435, Российская Федерация, Московская обл., г.о. Химки, мкр. Новогорск, Соколовская ул., 1) [SPIN-код](#), [ORCID](#), [ScopusID](#), tbudykina@yandex.ru

Андрей Александрович Блохин, кандидат технических наук, доцент кафедры «Пожарная безопасность» Академии гражданской защиты МЧС России (141435, Российская Федерация, Московская обл., г.о. Химки, мкр. Новогорск, Соколовская ул., 1) [SPIN-код](#), [ORCID](#), [ResearcherID](#), Blokhi-andrej@yandex.ru

Заявленный вклад авторов:

Т.А. Будыкина: формулирование замысла исследования; выполнение эксперимента по определению плотности потока энергии от смартфона; проверка воспроизводимости результатов эксперимента; создание и подготовка рукописи статьи; построение табличных зависимостей; внесение замечаний и исправлений в рукопись.

А.А. Блохин: выполнение эксперимента по определению плотности потока энергии от смартфона; проверка воспроизводимости результатов эксперимента; создание и подготовка черновика рукописи статьи; построение табличных зависимостей; внесение замечаний и исправлений в рукопись.

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 24.04.2026

Reviewed / Поступила после рецензирования 15.05.2026

Accepted / Принята к публикации 02.06.2026

TECHNOSPHERE SAFETY

ТЕХНОСФЕРНАЯ БЕЗОПАСНОСТЬ



UDC 629.3.079

Original Empirical Research

<https://doi.org/10.23947/2541-9129-2026-10-3-266-276>

A Mobile Technical Module for the Production of Composite Sorbents for Petroleum Products

Vitaly V. Gaevskiy , Irina V. Odinkova , Irina Yu. Isaeva ✉,
Galina Yu. Ostaeva

Moscow Automobile and Road Construction State Technical University (MADI), Moscow,
Russian Federation

✉ irina-razumova-xim@yandex.ru



EDN: YWXXUA

Abstract

Introduction. Thousands of oil spills are recorded in Russia every year, many of which occur in remote regions such as Western Siberia, the Arctic zone, and the Far East. Oil production at all stages has a negative impact on the lithosphere, hydrological regime, and biodiversity. This impact increases with the scale of petrochemical and mining activities. An analysis of the literature shows that various sorbents and mobile solutions are used to eliminate spills, but there are still challenges with high transportation costs, limited shelf life, difficulty in selecting the right material for a specific type of contamination, and a lack of technological modules that can be delivered to hard-to-reach areas. The aim of this research was to transfer the previously developed technology for producing a composite sorbent to a mobile vehicle, and to determine the design and technical parameters of a mobile technological module (MTM) for the prompt elimination of oil spills.

Materials and Methods. The study was based on a stationary scheme previously developed by the authors for producing a composite sorbent from dichloroethane, cetylamine surfactant, vermiculite, and shredded polystyrene foam. The process involved converting polystyrene foam to a viscous state with a solvent, adding mineral filler, and drying the mixture. To design a mobile technological module, we calculated the production cycle time, the weight of the complex, and the area occupied by the equipment. The calculations took into account elements made of PTFE-4 fluoroplastic according to TU 6-05-810-88¹, a BYD NYP-3.6 gear pump, a Greenworks G24HG 24V heat gun, a capacitor, containers, mixers, a drying chamber, chutes, and hydraulic fittings. UAZ 23632 was chosen as a mobile vehicle because of its off-road capabilities, cargo capacity, and cargo platform dimensions.

Results. It was established that the composite sorbent could be produced in mobile conditions using a previously developed technological process, which included dissolving polystyrene foam, adding a filler, and drying the formed mass. The production cycle for a batch of 20 sorbent sheets measuring 210×297×5 mm took five hours when drying at a temperature of 22°C, and was reduced to four hours by using a heat gun. The total mass of the main elements of the mobile complex, excluding the sorbent components, amounted to 70 kg, and the working mass of the module with precursors reached 78 kg. The area occupied by the main equipment elements was 8900 cm², which corresponded to the area of a EUR-pallet (approximately 0.9 m²). The calculations confirmed that it was possible to place all components of the mobile technological module on a UAZ 23632 vehicle. During the study, it was also taken into account that the mineral filler could be reused for up to three cycles, after which the loss of sorption properties amounted to 35%.

Discussion. The research results demonstrated that converting the stationary production process for a composite sorbent into a mobile format was technically feasible and met the goal of providing a rapid response to emergency oil spills in hard-to-reach areas. Unlike solutions focused on delivering ready-made sorbents, the proposed approach involved transporting the components and producing the material directly near the spill site, which reduced the dependence on logistics and storage conditions. The comparison with literature data confirmed the relevance of this approach. Mobile technologies made it possible to customize the properties of the sorbent, reducing transportation costs and minimizing waste through material recovery. However, the limitations of this study included its design-based nature: the functionality of the module was assessed based on mathematical modeling and comparison with similar equipment. The practical significance of the results was that they confirmed the possibility of installing a compact production complex on an off-the-road vehicle without changing the basic process flow.

¹ TU 6-05-810-88. PTFE blanks. URL: <https://floroplast.com.ru/tu-6-05-810-88/> (accessed 10.06.2026).

© Gaevskiy VV, Odinkova IV, Isaeva IYu, Ostaeva GYu, 2026

Conclusion. During the study, the key parameters of the mobile technological module were calculated: duration of the production cycle, weight of the equipment, and the occupied area. It has been shown that a module weighing 78 kg and with an area of approximately 0.9 m² can be mounted on a UAZ 23632 vehicle and used to produce a composite sorbent directly at the site of an emergency spill. This solution makes it possible to increase the efficiency of pollution cleanup, reduce logistics costs, and lower the environmental impact by reducing the number of transport trips and the amount of recycled polystyrene foam waste. A mobile technological module can be recommended as a component of equipment for eliminating emergency oil spills in hard-to-reach areas.

Keywords: mobile technological module, mobile production of sorbents, mobile complexes

Acknowledgements. The authors would like to express their gratitude for the assistance provided by the Center for Emergency Rescue and Ecological Operations and Research and Production Enterprise “AREAL”.

For Citation. Gaevskiy VV, Odinkova IV, Isaeva IYu, Ostaeva GYu. A Mobile Technical Module for the Production of Composite Sorbents for Petroleum Products. *Safety of Technogenic and Natural Systems*. 2026;10(3):266–276. <https://doi.org/10.23947/2541-9129-2026-10-3-266-276>

Оригинальное эмпирическое исследование

Мобильный технический модуль для производства композитного сорбента нефтепродуктов

В.В. Гаевский , И.В. Одиноква , И.Ю. Исаева ✉, Г.Ю. Остаева 

Московский автомобильно-дорожный государственный технический университет (МАДИ), г. Москва, Российская Федерация

✉ irina-razumova-xim@yandex.ru

Аннотация

Введение. В России ежегодно фиксируются тысячи случаев аварийных разливов нефтепродуктов, при этом значительная их часть происходит в труднодоступных регионах, включая Западную Сибирь, Арктическую зону и Дальний Восток. Нефтепользование на всех этапах сопровождается негативным воздействием на литосферу, гидрологический режим и биоразнообразие, а его интенсивность возрастает с увеличением масштабов деятельности нефтехимической и добывающей отраслей. Анализ научной литературы показывает, что для ликвидации таких разливов используются разнообразные сорбенты, применяются различные мобильные решения, однако при этом сохраняются проблемы, связанные с высокой стоимостью транспортировки, ограниченными сроками хранения, сложностями в подборе материалов под конкретный тип загрязнения и отсутствием технологических модулей, адаптированных к доставке в труднодоступные районы. Цель данного исследования заключается в переносе ранее разработанной технологической схемы получения композитного сорбента на мобильный носитель и в определении конструктивно-технологических параметров мобильного технологического модуля (МТМ) для оперативной ликвидации разливов нефтепродуктов.

Материалы и методы. В основу исследования положена ранее разработанная авторами стационарная схема получения композитного сорбента из дихлорэтана, поверхностно-активного вещества цетиламина, вермикулита и измельчённого пенополистирола (ПС). Технологический процесс включал в себя перевод пенополистирола в вязкотекучее состояние с помощью растворителя, введение минерального наполнителя и последующее высушивание сформированной смеси. Для проектирования мобильного технологического модуля были рассчитаны время производственного цикла, масса комплекса и площадь, занимаемая оборудованием. При расчётах учитывались элементы из фторопласта ПТФЭ марки Ф-4 по ТУ 6-05-810-88, шестерёнчатый насос BYD NYP-3.6, строительный фен Greenworks G24HG 24V, конденсатор, ёмкости, смесители, сушильная камера, жёлобы и гидравлическая арматура. В качестве мобильного носителя предложен автомобиль УАЗ 23632, выбранный с учётом проходимости, грузоподъёмности и размеров грузовой платформы.

Результаты исследования. Было установлено, что композитный сорбент может быть получен в мобильных условиях по ранее разработанной технологической схеме, включающей в себя растворение пенополистирола, введение наполнителя и сушку сформированной массы. Производственный цикл для партии из 20 листов сорбента размером 210×297×5 мм составил пять часов при сушке при температуре 22 °С и сократился до четырех часов при использовании строительного фена. Общая масса основных элементов мобильного комплекса без учёта компонентов сорбента составила 70 кг, а рабочая масса модуля с прекурсорами достигла 78 кг. Площадь, занимаемая основными элементами оборудования, составила 8900 см², что соответствует площади EUR-палеты (около 0,9 м²). Расчёты подтвердили возможность размещения всех компонентов мобильного технологического модуля на автомобиле УАЗ 23632. Также в процессе исследования было учтено, что минеральный наполнитель может использоваться повторно до трёх циклов, после чего потеря сорбционных свойств составляет 35 %.

Обсуждение. Полученные результаты показывают, что перевод стационарной схемы производства композитного сорбента в мобильный формат технически реализуем и соответствует задаче оперативного реагирования на аварийные разливы нефтепродуктов в труднодоступных районах. В отличие от решений, ориентированных на доставку готовых сорбентов, предлагаемый подход предусматривает транспортировку компонентов и изготовление материала непосредственно вблизи места применения, что снижает зависимость от логистики и условий хранения. Сопоставление с литературными данными подтверждает актуальность такого направления: мобильные технологии позволяют регулировать свойства сорбентов, сокращать транспортные издержки и уменьшать объём отходов за счёт регенерации материалов. Ограничением исследования является расчётно-проектный характер валидации: работоспособность модуля оценивалась на основе математического моделирования и сопоставления с аналогичным оборудованием. Практическое значение результатов состоит в подтверждении возможности размещения компактного производственного комплекса на транспортном средстве высокой проходимости без изменения базовой технологической схемы.

Заключение. В ходе исследования были рассчитаны ключевые параметры мобильного технологического модуля: продолжительность производственного цикла, масса оборудования и занимаемая площадь. Показано, что модуль массой 78 кг и площадью около 0,9 м² может быть установлен на автомобиль УАЗ 23632 и использован для получения композитного сорбента непосредственно в зоне аварийного разлива. Такое решение позволяет повысить оперативность в ликвидации загрязнений, сократить логистические издержки и снизить экологическую нагрузку за счёт уменьшения числа рейсов транспорта и количества переработанных отходов пенополистирола. Мобильный технологический модуль может быть рекомендован как элемент оборудования для ликвидации аварийных разливов нефтепродуктов в труднодоступных районах.

Ключевые слова: мобильный технологический модуль, мобильное производство сорбентов, мобильные комплексы

Благодарности. Авторы выражают признательность за помощь в проведении исследований ОАО «ЦАСЭО» и НПП «Ареал».

Для цитирования. Гаевский В.В., Одиноква И.В., Исаева И.Ю., Остаева Г.Ю. Мобильный технический модуль для производства композитного сорбента нефтепродуктов. *Безопасность техногенных и природных систем*. 2026;10(3):266–276. <https://doi.org/10.23947/2541-9129-2026-10-3-266-276>

Introduction. Every year, thousands of oil and petroleum product spill incidents are recorded in the Russian Federation [1], most of which occur in hard-to-reach regions of Western Siberia, the Arctic, and the Far East [2]. These spills are difficult to clean up due to the remote location of these sites, poor transport accessibility, harsh natural conditions, and high costs associated with delivering specialized materials and equipment. This makes it a significant ecological, technological, and organizational challenge to respond quickly to oil spills.

Oil production at all stages of the life cycle, from geological exploration and the construction of drilling facilities to well drilling, intensification of production, fluid lifting to the surface, and preparation of hydrocarbons for storage and transportation, has a negative impact on the environment [3, 4]. The intensity of this impact depends on the scale of production activities, characteristics of the technologies used, and resilience of natural ecosystems to anthropogenic pressure. The main consequences of oil use on the environment include degradation of the lithosphere, disruption of hydrological balance, and damage to biodiversity.

Degradation of the lithosphere is manifested in the mechanical disruption of the soil cover, soil compaction, formation of anthropogenic landforms, creation of quarries, sinkholes, and overall transformation of the natural landscape. This disruption of the hydrological balance leads to the pollution and depletion of aquifers, flooding of territories with industrial wastewater, and deterioration of surface water quality due to increased mineralization and higher content of dissolved impurities. Damage to biodiversity is evident in changes to the species composition of ecosystems, decline in their productivity, shift in the ranges of individual species, and development of ecological degradation processes.

Emergency spills of oil and petroleum products pose a particular danger, as they can create short-term but intense peaks of anthropogenic impact, localized in the area of an incident. In remote areas, negative consequences of these accidents are exacerbated by the difficulty in timely delivery of sorbents and specialized equipment to the site of pollution [5]. Under these conditions, the traditional response scheme, which relies on transporting pre-made sorption materials from stationary production facilities or warehouses, may not always ensure the necessary speed and cost-effectiveness.

One promising approach to solving this problem is to produce sorbents close to the site of an accidental spill [6]. This allows for a faster response time, reduced logistics costs, and the possibility to adapt the sorbent's properties to specific contamination conditions. This approach is especially relevant for remote areas, where delivering pre-made materials requires a significant amount of time and financial resources.

The scientific literature provides a detailed discussion on the development of various sorbent materials, including biosorbents [7], modified polymer materials [8], composite sorbents, and materials for absorbing light hydrocarbons, heavy oils, emulsions, and multicomponent wastewater [9]. However, the analysis of current methods for producing and transporting finished sorbents reveals several limitations. These limitations include high transportation costs, which can account for 60–80% of the total cost of the material in some cases, a limited shelf life for some sorbents, particularly biosorbents and modified polymers, difficulty in selecting a suitable material for a particular type of contamination, and the risk of secondary pollution during storage, transport, and handling of spent sorbents [10].

An alternative to the traditional approach is mobile sorbent production. Instead of delivering the finished material to the site of application, the initial reagents or precursors are transported, from which the sorbent is produced directly on-site. This method allows for a reduction in the volume of materials transported, increased flexibility in the technological process, and the ability to produce material with specific characteristics based on the type of oil product, ambient temperature, characteristics of the contaminated surface, and requirements for subsequent regeneration or disposal.

The authors of several studies propose technical solutions for producing sorbents in conditions close to those encountered in the field. For example, L. Khimenko and co-authors describe a method for creating sorbent using thermally expanded graphite in their work. This method involves a sorbent block consisting of two sealed, interconnected containers [11]. One of them contains intercalated graphite and a heating mixture that ensures rapid heat release due to a highly exothermic reaction and the subsequent expansion of the graphite. The other container contains an initiation element connected to an independent or portable power source. This setup allows for the production of sorbent at the site of application, which reduces the dependence of the spill response process on centralized supplies of the ready-made material.

The production of polyurethane sorbents is a promising area of research, as the initial liquid components used during the foaming process result in a significant increase in the volume of the final product: 30–50 m³ of polyurethane foam can be produced from one ton of liquid ingredients [12]. In addition, the process of producing polyurethane sorbents allows for the modification of their key properties, such as density, the ratio of open and closed pores, hydrophobicity, oleophilicity, and mechanical strength. These characteristics can be customized by adjusting the formulation, including varying the amount of water, catalyst, and by introducing organosilicon modifiers or fluorinated additives.

A similar approach was implemented in the work of A.V. Mukhamedshin and co-authors, who proposed a sorbent based on a polyurethane matrix and vegetable filler [13]. The combination of these components provided high sorption capacity of the material, the ability to rapidly absorb petroleum products and retain the absorbed volume for long periods of time, ranging from 15 minutes to several days. This made it easier to transport the saturated sorbent to a processing facility. Additionally, the increased mechanical strength of the material creates the potential for. The authors also noted the possibility of organizing production not only at an enterprise, but also a mobile complex located at the site of an accident, which reduced response times and logistical costs.

Therefore, the mobile process module can be used to produce sorbents with various physical, chemical, and operational characteristics that are adapted to specific types of petroleum products and working conditions. The ability to quickly change the formulation and technological parameters is a significant advantage of this approach compared to using pre-manufactured and stored materials.

Practical feasibility of mobile sorbent production has been confirmed through studies on the production of sorption material using a mobile generator [14]. According to the authors of these studies, this equipment can be used to clean up oil and petroleum product spills, both on water surfaces and on land. In addition, mobile modules can be equipped with sorbent regeneration units, including systems for mechanical extraction, centrifugation, cyclic steam desorption, and drying of a sorbent [15].

The authors of article [16] propose an installation for the regeneration of oil-soaked sorbents such as zeolite and silica gel. The installation consists of a sorbent with heating elements, a vacuum pump, a working fluid tank, an oil storage tank, and a cooling radiator, all combined in a single metal casing. This design allows for the extraction of petroleum products from the sorption material and creates conditions for its reuse. The use of such technical solutions can reduce the amount of waste to be disposed of by up to 90%, which increases the environmental and economic efficiency of liquidation measures.

Despite the availability of advances in the field of mobile sorbent production and regeneration, their analysis shows that the problem of developing an effective mobile complex for work in hard-to-reach areas remains understudied. In particular, there is limited literature on transferring technological schemes for producing composite sorbents onto a mobile platform, as well as on the design and technical parameters of these systems. Many existing solutions are complex and difficult to manufacture, and do not involve the use of a passable wheelbase capable of transporting equipment and materials to the site of a spill.

Thus, it can be concluded that there is a lack of scientific knowledge regarding the development of constructive and technological solutions for the mobile production of composite sorbents to quickly eliminate oil spills in hard-to-reach areas. To address this gap, it is necessary to adapt existing technological schemes for mobile use, determine the parameters of equipment and assess its feasibility in the field.

The aim of this research is to adapt the previously developed technology for producing composite sorbents into a mobile vehicle, as well as to determine the design and technical specifications of a mobile unit for rapid elimination of oil spills.

To achieve this goal, it is necessary to solve the following tasks:

1. Analyze the previously developed technological process for the production of composite sorbents (dissolution of expanded polystyrene, introduction of filler, drying), and adapt it for a mobile design — select optimal process parameters (temperature, time of stages, component ratios), considering restrictions on energy consumption, equipment size and field operating conditions.

2. Form the composition and layout of the mobile technological module — determine the list of equipment, its placement, requirements for the support frame and fasteners, and ensure that the module's dimensions comply with the standard EUR-pallet for ease of transportation and installation.

3. Determine the MTM design and technical parameters — calculate and justify the load distribution on the vehicle, the maximum allowable weight of the module, the area for placement, as well as the requirements for the vehicle (using UAZ 23632 as an example) for safe integration and operation of the equipment.

4. Validate the proposed solution through mathematical modeling and comparison with data from similar installations in order to confirm the reproducibility of the technology on the equipment with similar characteristics, as well as to evaluate the possibility of scaling and replicating the module for use by other research and operational teams.

Materials and Methods. In their previous studies, the authors developed an algorithm [17] and a stationary process for producing a composite sorbent [18] (Fig. 1).

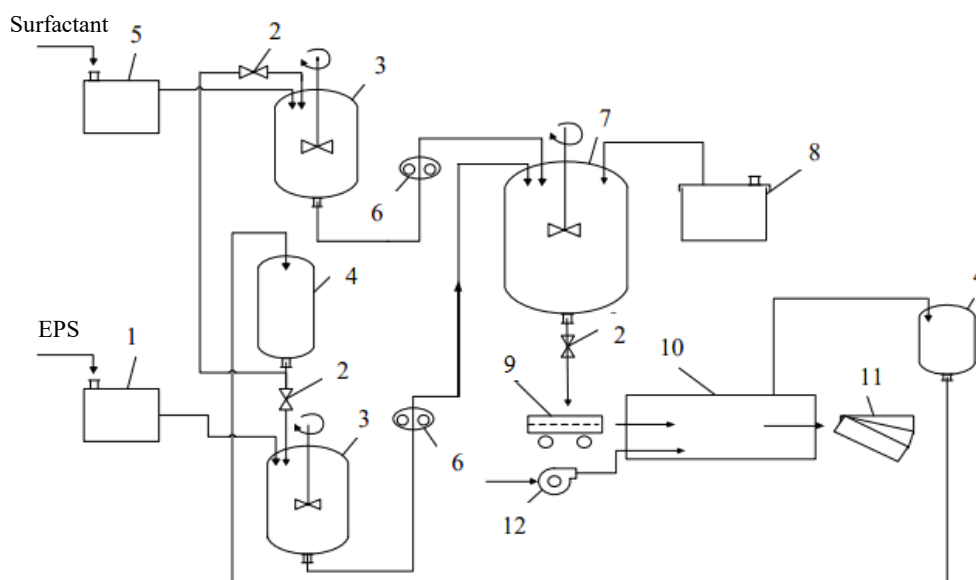


Fig. 1. Process flow diagram for producing a composite sorbent:

- 1 — storage container for expanded polystyrene (EPS); 2 — valve regulating the supply; 3 — mixers (dichloroethane, expanded polystyrene) and (surfactant, dichloroethane); 4 — solvent container; 5 — storage container for surfactants; 6 — pump for feeding the mixture; 7 — mixing container (surfactant solution, mineral filler and dichloroethane + expanded polystyrene are alternately supplied); 8 — storage tank for mineral filler; 9 — composite sorbent billet; 10 — drying unit; 11 — composite sorbent plates; 12 — heat gun [18]

The following components were used to produce the composite sorbent: dichloroethane, surfactant (cetylamine), vermiculite, and crushed polystyrene foam. After the composite sorbent was disposed of, the mineral filler was reused. The number of reuse cycles was three. It was established that after the third cycle, there was a significant loss of sorption properties, amounting to 25 %.

To determine the area needed to accommodate the module's components, several calculations were performed. These included the production cycle time, the total mass of the module, and the area occupied by the mobile technological module:

1. The production cycle time was calculated using formula 1. The formula for the sequential production method (when operations were performed one after another) was chosen:

$$T_{\text{ц}} = n \times (t_1 + t_2 + \dots + t_n) + T_{\text{обсл.}} + T_{\text{пост.}}, \quad (1)$$

where n — batch size (number of products); $t_1, t_2, \dots, t_n$ — time to perform each operation, min; $T_{\text{обсл.}}$ — module maintenance time, min.; $T_{\text{пост.}}$ — downtime, the time spent changing operating fluids, consumables (replacing filters and etc.).

Thus, $T_{\text{ц}} = 1 \times (20 + 20 + 40 + 180) + 20 + 20 = 300$ min., or 5 hours.

The calculation was conducted for a batch of 20 sorbent sheets with dimensions of 210×297×5 mm. The duration of the drying process was calculated at a temperature of 22°C. When a heat gun was used to dry the composite sorbent sheets, the time required was reduced to four hours.

2. Calculation of the total mass of the module. Its components were assembled from fluoroplastic (PTFE) and plates measuring 2×300×300 mm, grade F4, according to TU 6-05-810-88. Tables 1 and 2 list the characteristics of these plates as provided by the manufacturer.

Table 1

Characteristics of plates used to produce containers up to five liters in volume and a trough

Technical specifications from the manufacturer's catalog	
Thickness, mm	2
Width, mm	200
Length, mm	300
Weight, kg	0.45
GOST	TU 6-05-810-88 ²
Grade	F 4

Table 2

Characteristics of plates used to produce containers up to 20 liters

Technical specifications from the manufacturer's catalog	
Thickness, mm	2
Width, mm	1000
Length, mm	1000
Weight, kg	2.5
GOST	TU 6-05-810-88 ³
Grade	F 4

The number of sheets used in the MTM assembly is provided in Table 3

Table 3

Characteristics of the module elements assembled from PTFE plates

Element name	Number of sheets	Element weight, kg
1. EPS storage container	6	2.7
2. Solvent storage container	6	2.7
3. Mixer (dichloroethane, EPS)	6	2.7

² TU 6-05-810-88. PTFE blanks. URL: <https://floroplast.com.ru/tu-6-05-810-88/> (accessed 10.06.2026).

³ Ibid.

4. Mixer (surfactant, dichloroethane)	6	2.7
5. Surfactant storage container	1	0.45
6. Container for mixing all components	6	15
7. Container for storing mineral filler	6	2.7
8. Drying chamber	8	20
Total weight of elements made from PTFE plates		49

In addition, the weight of pumps for supplying the mixture (BYD NYP-3.6 gear pump) and heat gun (Greenworks G24HG, 24 V, without battery and charger) as well as the condenser were also taken into account. The total weight of the main components of the mobile technological module excluding the composite sorbent was 65 kg.

The weight of composite sorbent components, based on the volume of a five-liter container: dichloroethane — 6.25 kg, vermiculite — 0.6 kg, crushed polystyrene foam — 0.6 kg

Thus, the MTM working weight was 78 kg.

3. The area occupied by MTM was the sum of the areas of the individual module components (Table 4) plus the tolerances for the positioning of the troughs and hydraulic fittings.

Table 4

Area occupied by the module elements assembled from PTFE plates

Element name	Area, cm ²
1. EPS storage container	450
2. Solvent storage container	900
3. Mixer (dichloroethane, EPS)	900
4. Mixer (surfactant, dichloroethane)	900
5. Surfactant storage container	56
6. Container for mixing all components	2500
7. Container for storing mineral filler	900
8. Drying chamber	1800
Total area	8450

In order to solve the problem of quickly localizing and eliminating oil spills in difficult-to-reach areas, it was crucial to not only select an effective sorption material, but also to ensure its delivery. To this end, the authors considered using a UAZ 23632 pickup truck as a mobile technological module. This type of vehicle was chosen as optimal due to its combination of operational characteristics. Its increased off-road capability allowed it to navigate through areas with difficult terrain and soil conditions typical of remote and hard-to-access territories. At the same time, its load capacity and cargo area size made it possible to accommodate the necessary equipment for producing a composite sorbent on-site.

Research Results. During the experiments, we produced a composite sorbent in accordance with the previously developed technological scheme. The process consisted of the following stages: converting expanded polystyrene into a viscous-flow state by applying a solvent, adding mineral filler to the formed polymer gel, and then drying the resulting mixture until the mass stabilized and the required physical-mechanical characteristics were achieved.

The production cycle for a batch of 20 sorbent sheets with a nominal size of $210 \times 297 \times 5$ mm, took four hours using a heat gun as a heating source. This time included the total time required for dissolving the expanded polystyrene, evenly distributing the filler in the matrix, forming the sheets, and drying them. To ensure that the drying process was complete, gravimetric analysis was used to monitor the samples' mass after holding them for 15 minutes until stabilization.

The mass of the mobile technological module, including structural elements, technological equipment, consumables, and the precursors necessary for sorbent production, was 78 kilograms. This figure included the mass of the supporting frame, heating devices, containers for solvent and precursors, and means for fixing and transporting equipment. The weight distribution across the axles of the UAZ 23632 vehicle when MTM was placed on the cargo platform met the permissible standards and did not exceed 30% of the vehicle's maximum load capacity.

The dimensions of MTM ensured its compact placement, allowing it to fit within the standard EUR-pallet size, occupying an area of 0.9 m² (1200 x 800 mm). This layout allowed for efficient use of the cargo platform's working space and ensured convenience in loading and unloading operations. It also enabled quick deployment of the module in field conditions, while maintaining access to its main components for maintenance and monitoring of process parameters.

Additionally, several auxiliary parameters of the technological process were monitored: the heating temperature during the drying process was maintained between 60 and 70°C, which prevented thermal degradation of the polymer matrix and ensured uniform solvent removal. The degree of uniformity in the distribution of filler within the polymer matrix was assessed both visually and using optical microscopy. No large agglomerates were observed, and the mineral filler particles were evenly distributed across the cross-section of the sheet.

Discussion. The results obtained during the study confirmed the feasibility of the method proposed by the authors for producing a composite sorbent in a mobile configuration, and also demonstrated that the characteristics of MTM met the requirements for transportation and operation in conditions of limited space and complex road infrastructure.

The technical feasibility of installing all components of the sorption complex onto the platform of the chosen vehicle (UAZ 23632) has been established. During the design process, not only were the overall dimensions of the equipment taken into account, but also the requirements for stability during transport, load balancing on the vehicle's axles, and ensuring accessibility for servicing units in a confined space. The calculations showed that the total weight of the equipment, including consumables and fasteners, did not exceed the maximum load capacity of UAZ 23632, and the distribution of weight met the requirements for safe operation.

An important aspect of the research was the validation of the MTM to ensure its reproducibility and scalability. We verified the possibility of using the module in two stages. First, we used mathematical modeling to simulate the equipment's operating modes. Then, we compared the results with data from similar equipment. The simulation allowed us to assess the stability of technological parameters, including productivity and sorbent quality. This information will help us consider various operational options for different climatic conditions and road surfaces in the future.

The comparison with experimental data on existing installations confirmed the reproducibility of key process indicators when using the equipment with similar technical specifications.

The calculated data showed that to achieve the desired performance indicators of MTM, it was sufficient to replicate the installation, while maintaining the specified technical parameters — productivity, energy consumption, temperature-time regimes, and ratios of raw material components. At the same time, it was established that the technological process for producing a composite sorbent was not critical to the design features of individual units that make up the module. The determining factors here are the output parameters of the equipment, such as flow rate, temperature, pressure, and phase contact time, rather than their specific implementation. This significantly expands the replication potential of the proposed scheme, as researchers and operational teams can adapt the equipment composition to available resources, as long as regulated technological modes are maintained.

The authors have proved that the choice of the UAZ 23632 platform, combined with the modular principle of equipment layout and reproducibility of the technological process, provides high operational flexibility of MTM and confirms its suitability for use in conditions where traditional spill response methods are ineffective or technically impossible.

Conclusion. In the course of our research, we have calculated the production time for the composite sorbent, the total weight of the mobile module, and the area occupied by the technological equipment. The use of MTM in practice will ensure mobility, eliminate the cost of sorbent delivery, reduce logistical costs, and minimize the environmental burden by reducing the number of trips and associated CO₂ emissions. Recycling of polystyrene foam waste will further reduce the negative impact on the environment. These conclusions confirm the result obtained: the mobile technological module developed by the authors can be used to eliminate oil product spills in hard-to-reach areas and can be recommended as equipment for emergency response.

References

1. Nevskaya MA, Belyaev VV, Pasternak SN, Vinogradova VV, Shagidulina DI. Accidental Oil Spills in the Arctic: An Assessment of Potential Soil Damage. *The North and the Market: Forming the Economic Order*. 2024;27(3):107–122. (In Russ.) <https://doi.org/10.37614/2220-802X.3.2024.85.007>
2. Melkozerov VM, Kovaleva MA. Elimination of Emergency Oil and Petroleum Product Spills in the Arctic Waters. *Tsifrovoe Modelirovanie Ekonomiki*. 2024;3:65–70. (In Russ.) URL: <https://scholar.sfu.ru/author/0572277> (accessed: 10.06.2026).
3. Zakharova EA, Murko EV. The Influence of Modern Methods of Intensification of Hydrocarbon Production on the State of the Environment. *Current Issues in the Development of Science and Technology*. 2024;106-132. (In Russ.) URL: <https://clck.ru/3VG2Ya> (accessed: 10.06.2026).
4. Koval YuN, Martinovich NV. Optimization and Automation of Sorbents Production and Application at Contaminated and Reclaimed Soils. *Environmental Protection in Oil and Gas Complex*. 2026;2(329):19–26. (In Russ.) URL: <https://journal.gubkin.ru/journals/protection/2026/2-329/19-26/> (accessed: 10.06.2026).
5. Naumova TA, Naumov AG, Kotov YuS. Overview of Major Water Oil Spill Management Techniques and Evaluation of Their Efficiency. *Aquatic Bioresources & Environment*. 2023;6:16–29. (In Russ.) https://doi.org/10.47921/2619-1024_2023_6_2_16
6. Vasileva ZhV, Trishina AS. Assessing the Effectiveness of Local Organic Materials as Sorbents for Oil Spill Response in Arctic Waters. *MSTU Vestnik*. 2024;27(2):142–157. (In Russ.) URL: <https://vestnik.mauniver.ru/show.shtml?art=2217> (accessed: 10.06.2026)
7. Davletshin RR, Sokolov AV. *Method for Producing Polyurethane Foam Sorbent for Collecting Oil and Petroleum Products*. RF Patent, No. 2732185. 2020. (In Russ.)
8. Sirviö JA. Fabrication of Regenerated Cellulose Nanoparticles by Mechanical Disintegration of Cellulose after Dissolution and Regeneration from a Deep Eutectic Solvent. *Journal of Materials Chemistry A*. 2019;7(2):755–763. <https://doi.org/10.1039/C8TA09959F>
9. Tolstov AM, Naumova YA. On the Prospects for the Use of Polymeric Materials for Sorbents Intended for Water Purification from Oil Products. *Proceedings of the Voronezh State University of Engineering Technologies*. 2023;85(1):240–248. (In Russ.) <https://doi.org/10.20914/2310-1202-2023-1-240-248>
10. Gudyma VYa, Maiorenko DI. Sorbents Used for Cleaning Up Oil Contamination at the Site of a Simulated Accident on the 995-km Section Between Delbichinda Station and Daban Station on the Eastern Siberian Railway. *Molodoi Uchenyi*. 2019;15(253):166–170. (In Russ.) URL: <https://moluch.ru/archive/253/57993> (accessed: 10.06.2026).
11. Khimenko LL, Il'in AN, Minchenko LA, Yazev AS, Smirnov DV, Isaev OYu. *A Method for Producing a Sorbent in Field Conditions and a Device for Implementing It*. RF Patent, No. RU 2771413C1. 2021. (In Russ.)
12. Vasil'eva VS, Vydumchik SV, Gavrilenko OO, Ksenofontov MA. Penopurm Sorbent — An Innovative Commercial Product. In: *Proceeding the 2nd Belarusian-Latvian Forum “Science, Innovation, Investment”*. Minsk, 11–12 December, 2014. Minsk: Belarusian National Technical University; 2014. P. 67–69. (In Russ.) URL: <https://rep.bntu.by/handle/data/41488> (accessed: 10.06.2026).
13. Zenitova LA, Mukhamedshin AV, Ogorodnikova AV, Chikina NS. *Polyurethane Sorbent for Hydrocarbons and a Method for Cleaning Aqueous Media and Solid Surfaces from Hydrocarbon Contaminants*. RF Patent, No. 2345836 C1. 2009. (In Russ.)
14. Tereshchenko MD, Khimenko LL, Yazev AS, Isaev OYu, Minchenko LA, Ilyin AN. Mobile Sorbent Generator Used for Oil Spill Response. *PNRPU Aerospace Engineering Bulletin*. 2022;(71):182–190. (In Russ.) URL: <https://clck.ru/3VG3Pk> (accessed: 10.06.2026).
15. Skidan VI, Boichuk VI, Danilenko AP. *Sorbent Regeneration Unit*. RF Patent, No. 75958U1, 2008. (In Russ.)
- Vasiliev SI, Melkozerov VM, Velp AYa, Gorbunova LN, Sanacheva GS, Fedotova AS. Technique of Sorption and Biological Cleaning of Biosphere from Oil Products Pollution. *Systems. Methods. Technologies*. 2011;11:168–179. (In Russ.) URL: <https://clck.ru/3VG3Z9> (accessed: 10.06.2026).

16. Isaeva IYu, Odinkova IV, Ostaeva GYu, Morenko IV. Composite Sorbent from Natural Raw Materials and Polymer Waste: Composition Optimization. In: *Proceedings of the All-Russian Scientific and Practical Conference with International Participation "Modern Problems of Regional Ecology"*. Birk: Ufa University of Science and Technology; 2024. P. 12–16. (In Russ.)

17. Isaeva IYu, Odinkova IV, Ostaeva GYu, Eliseeva EA. Combustion Products of Polymer Waste as a Source of Environmental Pollution. *Polymer Science, Series D*. 2023;16:627–630. <https://doi.org/10.1134/S1995421223030127>

About the Authors:

Vitaly V. Gaevskiy, Dr. Sci. (Eng.), Professor of the Department of Automobiles, Moscow Automobile and Road Construction State Technical University (MADI) (64, Leningradsky Ave., Moscow, 125319, Russian Federation), [SPIN-code](#), [ORCID](#), [ScopusID](#), vit-life@rambler.ru

Irina V. Odinkova, Cand. Sci. (Eng.), Associate Professor of the Department of Hydraulics, Moscow Automobile and Road Construction State Technical University (MADI) (64, Leningradsky Ave., Moscow, 125319, Russian Federation), [SPIN-code](#), [ORCID](#), odinkova_iv@mail.ru

Irina Yu. Isaeva, Senior Lecturer of the Department of Road and Construction Materials and Chemical Technologies, Moscow Automobile and Road Construction State Technical University (MADI) (64, Leningradsky Ave., Moscow, 125319, Russian Federation), [SPIN-code](#), [ORCID](#), irina-razumova-xim@yandex.ru

Galina Yu. Ostaeva, Associate Professor of the Department of Road and Construction Materials and Chemical Technologies, Moscow Automobile and Road Construction State Technical University (MADI) (64, Leningradsky Ave., Moscow, 125319, Russian Federation), [SPIN-code](#), [ORCID](#), [ScopusID](#), [ResearcherID](#), galinaostaeva@mail.ru

Claimed Contributorship:

VV Gaevskiy: conceptualization.

IV Odinkova: writing — review & editing, comments and clarifications, data verification.

IYu Isaeva: writing — original draft preparation and its translation into a foreign language.

GYu Ostaeva: verification of the reproducibility of experimental results, research.

Conflict of Interest Statement: the authors declare no conflict of interest.

All authors have read and approved the final version of manuscript.

Об авторах:

Виталий Валентинович Гаевский, доктор технических наук, профессор кафедры «Автомобили» Московского автомобильно-дорожного государственного технического университета (МАДИ) (125319, Российская Федерация, г. Москва, Ленинградский проспект, 64), [SPIN-код](#), [ORCID](#), [ScopusID](#), vit-life@rambler.ru

Ирина Вячеславовна Одиноква, кандидат технических наук, доцент кафедры «Гидравлика» Московского автомобильно-дорожного государственного технического университета (МАДИ) (125319, Российская Федерация, г. Москва, Ленинградский проспект, 64), [SPIN-код](#), [ORCID](#), odinkova_iv@mail.ru

Ирина Юрьевна Исаева, старший преподаватель кафедры ДСМ и ХТ Московского автомобильно-дорожного государственного технического университета (МАДИ) (125319, Российская Федерация, г. Москва, Ленинградский проспект, 64), [SPIN-код](#), [ORCID](#), irina-razumova-xim@yandex.ru

Галина Юрьевна Остаева, кандидат химических наук, доцент кафедры ДСМ и ХТ Московского автомобильно-дорожного государственного технического университета (МАДИ) (125319, Российская Федерация, г. Москва, Ленинградский проспект, 64), [SPIN-код](#), [ORCID](#), [ScopusID](#), [ResearcherID](#), galinaostaeva@mail.ru

Заявленный вклад авторов:

В.В. Гаевский: формулирование замысла / идеи исследования, его целей и задач.

И. В. Одиноква: критический анализ черновика рукописи, формулировка замечаний и уточнений, проверка данных исследования.

И.Ю. Исаева: написание черновика рукописи, перевод ее на иностранный язык.

Г.Ю. Остаева: проверка воспроизводимости результатов экспериментов и исследования в рамках основных или дополнительных задач работы.

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

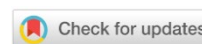
Все авторы прочитали и одобрили окончательный вариант рукописи

Received / Поступила в редакцию 19.05.2026

Reviewed / Поступила после рецензирования 17.06.2026

Accepted / Принята к публикации 01.07.2026

CHEMICAL TECHNOLOGIES, MATERIALS SCIENCES, METALLURGY ХИМИЧЕСКИЕ ТЕХНОЛОГИИ, НАУКИ О МАТЕРИАЛАХ, МЕТАЛЛУРГИЯ



UDC 669.1:66.04

Original Empirical Research

<https://doi.org/10.23947/2541-9129-2026-10-3-277-284>

Geometrical Parameters of 14G2 Steel Structure as a Material with High Ballistic Resistance

 Viktor N. Pustovoi^{ID}, Yuri V. Dolgachev^{ID}✉, Ivan V. Ivankov^{ID}

Don State Technical University, Rostov-on-Don, Russian Federation

✉ ydolgachev@donstu.ru

EDN: GBFWHH

Abstract

Introduction. Increasing the ballistic resistance of armor materials is a pressing scientific and technical challenge driven by the need to develop protective materials that can effectively resist high-speed impacts. Homogeneous isotropic steels, which provide protection through a combination of hardness and toughness, have limited effectiveness under high-speed stress of approximately 10^3 m/s. These materials typically undergo brittle fracture or complete penetration without significant energy dissipation. A promising alternative approach is the use of heterogeneous and anisotropic materials with a more complex, organized structure that can alter crack propagation trajectories and increase fracture energy intensity. Natural ferrite-martensitic composites (NFMCs), formed in steels quenched from the intercritical temperature range, are an example of such materials. NFMC steels, produced by quenching from the intercritical temperature range, are currently being actively researched. It has been shown that changing the quenching temperature affects the volume ratio of ductile ferrite and high-strength martensite layers, which in turn influences the mechanical properties of the material. However, existing studies have been conducted primarily under static tension or bending conditions. When subjected to ballistic loading with extremely high strain rates, the mechanisms of crack arrest may differ significantly. In this context, the geometric parameters of the structure such as the orientation, length, and thickness of the layers, as well as their ratios, become more important than the strength properties of individual phases. Currently, there is a lack of systematic data on which specific structural characteristics of NFMC are crucial for ballistic resistance, and what optimal values should be. Therefore, the aim of this research is to determine the geometric parameters of NFMC steel structures that ensure effective use in armor protection systems.

Materials and Methods. The study was conducted on 14G2 steel samples measuring $140 \times 70 \times 7$ mm. The NFMC structure was obtained by quenching the steel from the intercritical temperature range with an initial banded ferrite-pearlite structure. Bullet resistance tests were performed by shooting targets of this material at a distance of 50 m from a Dragunov sniper rifle with 7.62 mm cartridges with a heat-strengthened core at a bullet velocity of approximately 10^3 m/s. The geometric parameters of the structure were assessed using a metallographic method on a Neophot 21 microscope using ToupView software to obtain a quantitative assessment.

Results. The microstructure of the studied natural ferritic-martensitic composite, which was a composite material with reinforcing fibers of discrete length, was shown. The results of determining the characteristic parameters of the steel composite geometry in accordance with GOST R 54 570–2011¹ were presented. The misorientation angle in the structure was $7 \div 11^\circ$. The volume fraction of martensite was 28.37% when quenched from a temperature of 735°C.

¹ GOST R 54570-2011. *Steel. Methods for assessing the degree of banding or orientation of microstructures.* (In Russ.). URL: <https://internet-law.ru/gosts/gost/51810/> (Accessed: 17.05.2026).

The average width of the plates of the strengthening phase $\bar{h} = 0.0051$ mm and the average free path $\bar{\lambda}_1$ corresponding to the width of ferrite plates $\bar{c} = 0.0131$ mm were measured. The ratio c/h was 2.57. The calculated critical length of the martensite layer in NFMC from the condition of equilibrium of normal and shear stresses in it, in NFMC with a total rolling reduction of 70% was 18.3 μm . The data on the distribution of the size of martensite layers in 14G2 steel with the NFMC structure were shown.

Discussion. The obtained data on geometric parameters of the structure of 14G2 steel, quenched from the intercritical temperature range (735°C) and having NFMC organization, meet the requirements for the composite material. In a layered composite with optimal geometry, as a crack propagates successively from one layer to another along the interface and the crack tip approaches it, delamination can form, hindering the initial crack's propagation. Existing ferrite-martensite interfaces with a length greater than the critical value act as an effective barrier to crack propagation.

Conclusion. It was found that high ballistic resistance of the natural ferrite-martensite composite was achieved with an optimal combination of geometric parameters of the composite material structure. At the same time, achieving such an NFMC optimum as armor protection can be ensured by the correct hot rolling technology (total reduction of 70% and higher) and choosing the optimal quenching temperature in the intercritical range.

Keywords: composite, steel, martensite, ferrite, banding, ballistic resistance

Acknowledgements. The authors would like to thank the Editorial board for their valuable comments and the staff of the Department of Materials Science and Technology of Metals, DSTU: Head of the Department M.S. Egorov and Professor Yu.M. Dombrovsky for their help in obtaining and discussing the research results.

For Citation. Pustovoi VN, Dolgachev YuV, Ivankov IV. Geometrical Parameters of 14G2 Steel Structure as a Material with High Ballistic Resistance. *Safety of Technogenic and Natural Systems*. 2026;10(3):277–284. <https://doi.org/10.23947/2541-9129-2026-10-3-277-284>

Оригинальное эмпирическое исследование

Геометрические параметры структуры стали 14Г2 как материала с высокой баллистической стойкостью

В.Н. Пустовойт , Ю.В. Долгачев  , И.В. Иванков 

Донской государственный технический университет, г. Ростов-на-Дону, Российская Федерация

 ydolgachev@donstu.ru

Аннотация

Введение. Повышение баллистической стойкости броневых материалов представляет собой актуальную научно-техническую задачу, обусловленную необходимостью разработки защитных материалов, способных эффективно сопротивляться высокоскоростному ударному воздействию. При высокоскоростном нагружении порядка 10^3 м/с гомогенные изотропные стали, обеспечивающие защитные свойства за счёт сочетания твёрдости и вязкости, демонстрируют ограниченную эффективность: как правило, наблюдается либо хрупкое разрушение, либо сквозное пробитие без существенного рассеяния энергии. Перспективным альтернативным подходом является применение гетерогенных и анизотропных материалов, имеющих более сложную организованную структуру, способную изменять траекторию распространения трещин и повышать энергоёмкость разрушения. К таким материалам относятся естественные феррито-мартенситные композиты, формируемые в сталях при закалке из межкритического интервала температур (ЕФМК). В настоящее время активно исследуются ЕФМК-стали, получаемые закалкой из межкритического температурного интервала. Показано, что варьирование температуры закалки изменяет объёмное соотношение слоёв пластичного феррита и высокопрочного мартенсита, что, в свою очередь, оказывает влияние на механические свойства материала. Однако существующие исследования выполнены преимущественно в условиях статического растяжения или изгиба. При баллистическом нагружении, характеризующемся экстремально высокими скоростями деформации, механизмы торможения трещины могут принципиально отличаться. При этом на первый план выходят не столько прочностные характеристики фаз, сколько геометрические параметры структуры: ориентация, длина и толщина слоёв, а также их соотношение. В настоящее время отсутствуют систематические данные о том, какие именно структурные характеристики ЕФМК являются определяющими для баллистической стойкости и каковы их оптимальные значения. В связи с этим цель настоящего исследования заключается в определении геометрических параметров структуры ЕФМК-сталей, обеспечивающих эффективное применение данного материала в устройствах броневой защиты.

Материалы и методы. Образцами для исследования служили пластины из стали 14Г2 размером $140 \times 70 \times 7$ мм. Формирование структуры ЕФМК осуществляли путём закалки из межкритического температурного интервала, при этом исходной являлась строчечная феррито-перлитная структура. Оценку пулестойкости проводили при обстреле мишеней из указанного материала с дистанции 50 м из винтовки СВД патронами калибра 7,62 мм (термоупрочнённый сердечник, начальная скорость пули составляла порядка 10^3 м/с). Геометрические параметры структуры изучали металлографическим методом на микроскопе Neophot 21 с количественной обработкой изображений в программе TourView.

Результаты исследования. Показана микроструктура исследованного естественного ферритно-мартенситного композита, представляющая собой композиционный материал с упрочняющими волокнами дискретной длины. Представлены результаты определения характерных параметров геометрии стального композита в соответствии с ГОСТ Р 54570–2011². Угол разориентировки в структуре составил $7\text{--}11^\circ$. Объёмная доля мартенсита при закалке с температуры 735°C составила 28,37 %. Измерены средняя ширина пластин упрочняющей фазы $\bar{h} = 0,0051$ мм и средний свободный путь $\bar{\lambda}_1$, соответствующий ширине ферритных пластин $\bar{c} = 0,0131$ мм; при этом соотношение c/h составило 2,57. Расчётная критическая длина мартенситного слоя в ЕФМК, определенная из условия равновесия нормальных и касательных напряжений в нём, для ЕФМК с суммарным обжатием при прокатке 70 % составила 18,3 мкм. Приведены данные распределения величины мартенситных слоев в стали 14Г2 со структурой ЕФМК.

Обсуждение. Полученные данные о геометрических параметрах структуры стали 14Г2, закалённой из межкритического интервала температур (735°C) и характеризующейся формированием естественного феррито-мартенситного композита, соответствуют требованиям, предъявляемым к композиционным материалам. В слоистом композите с оптимальной геометрией при последовательном прохождении трещины из одного слоя в другой по поверхности раздела, а также при приближении её вершины к данной границе, возможно образование расслоения, затрудняющего дальнейшее распространение исходной трещины. Поверхности раздела феррит-мартенсит, длина которых превышает критическое значение, являются эффективными барьерами на пути её движения.

Закключение. Установлено, что высокая баллистическая стойкость естественного феррито-мартенситного композита достигается при оптимальном сочетании геометрических параметров структуры данного композиционного материала. При этом получение оптимальных характеристик ЕФМК как броневой защиты может быть обеспечено за счёт рациональной технологии горячей прокатки — суммарного обжатия 70 % и выше — и выбора оптимальной температуры закалки в межкритическом интервале.

Ключевые слова: композит, сталь, мартенсит, феррит, строчечность, баллистическая стойкость

Благодарности. Авторы благодарят редакцию журнала за ценные замечания и сотрудников кафедры «Материаловедение и технологии металлов» ДГТУ: заведующего кафедрой М.С. Егорова и профессора Ю.М. Домбровского за помощь в получении и обсуждении результатов.

Для цитирования. Пустовойт В.Н., Долгачев Ю.В., Иванков И.В. Геометрические параметры структуры стали 14Г2 как материала с высокой баллистической стойкостью. *Безопасность техногенных и природных систем*. 2026;10(3):277–284. <https://doi.org/10.23947/2541-9129-2026-10-3-277-284>

Introduction. Increasing the ballistic resistance of armor is a crucial issue in the design of modern military equipment [1]. At high impact rates, in addition to the basic mechanical characteristics, strict requirements are imposed on alloys regarding the specific geometric arrangement of their internal structure [2]. For homogeneous isotropic metal barriers, one of the key factors is the formation of a finely dispersed structure. The main challenge is that traditional homogeneous steels with an isotropic structure, such as tempered martensite, perform protective functions primarily through hardness and toughness. However, at high-energy, dynamic loads (about 10^3 m/s), the effectiveness of such barriers is significantly reduced: either brittle destruction or through-penetration of the target occurs without significant dissipation of the kinetic energy of the indenter [3]. An alternative approach involves the use of heterogeneous, anisotropic materials with a more complex structural arrangement [4]. This article examines in detail the microstructural characteristics of steels with a natural ferrite-martensite composite structure (NPMC), which are considered a promising material for armor protection.

Over the past few decades, extensive research has been conducted on materials with NPMC structure, formed by heat treatment at temperatures in the intercritical range [5]. These materials are referred to as “composites” due to significant differences in the properties between the two phase components that make up the material. Within this composition, highly ductile and relatively soft ferritic layers alternate with high-strength martensitic plates, creating a structure with a distinct texture that is oriented along the direction of rolling. The process of producing these multilayer composites is described in detail in our patent [6]. These alloys exhibit the ability to effectively inhibit crack

² GOST R 54570-2011. Steel. Methods for assessing the degree of banding or orientation of microstructures. (In Russ.). URL: <https://internet-law.ru/gosts/gost/51810/> (Accessed: 17.05.2026).

propagation by triggering interlayer delamination along interphase boundaries [7–9]. Earlier, the authors of publications [10, 11] found that targeted control of the heating temperature for quenching directly changed the volume proportions of soft and hard components, determining the final level of operational properties. However, most of the tests were based on static stretching or bending methods [12–14]. In contrast, ballistic loading, characterized by extremely high strain rates, has different mechanisms of crack braking: inertial effects and wave processes begin to dominate [3, 15]. In this case, the determining role is played not by the absolute strength of individual phases, but rather by the spatial parameters of the structure, such as orientation, length and thickness of the layers, their ratio, as well as the maximum length of the reinforcing layer. To date, the scientific literature has not provided comprehensive information on which structural parameters in the NFMC architecture are critical criteria for ensuring bullet resistance, nor have their optimal ranges been determined.

The aim of this research is to conduct a comprehensive analysis of geometric parameters of NFMC steel structure, including the grain-boundary angle, the dimensional proportions of cross-sectional layers, the critical length of martensitic layer, and other relevant metrics. The optimization of these parameters is expected to maximize the effectiveness of these steels in the design of armor protection systems. The relevance of the chosen factors is justified based on the following considerations: the amount of misorientation directly influences the level of shear stress that can cause the destruction of the high-strength phase; the ratio of the thicknesses of structural elements determines the predisposition to interfacial stratification; the critical length of martensitic layer makes it possible to evaluate the efficiency of load transfer from the matrix to the reinforcing phase. To successfully achieve this goal, it was necessary to consistently solve the following tasks:

- to assess the degree of orientation of NFMC alloy structure;
- to measure the volume fraction of the phases, the average cross-sectional width of the plates, as well as the average free path of the reinforcing phase in a soft ferritic base;
- to perform a theoretical calculation of the critical length of the martensitic layer;
- to analyze the ratio of the thicknesses of alternating ferritic and martensitic plates, which ensures the stable implementation of the mechanism for extinguishing the kinetic energy of a growing crack due to local interlayer stratification during intense high-speed impact.

Materials and Methods. The research was conducted on 14G2 steel samples with dimensions of 140×70×7 mm. The NFMC structure was formed by heat treatment — quenching of steel from the intercritical temperature range that initially had a banded ferrite-pearlite structure. The assessment of ballistic resistance was conducted using a comparative method. The characteristics of steel samples with NFMC structure and the same steel with the homogeneous structure of tempered martensite were compared.

Ballistic tests of targets made from these materials were performed from a distance of 50 m using a Dragunov sniper rifle (SVD). 7.62 mm caliber ammunition with a thermally reinforced core was used for firing. The flight speed of the damage agent was 103 m/s. Ten shots were fired at each type of obstacle.

As a result of the tests, we recorded a complete penetration of all targets with a homogeneous structure. However, when bullets hit plates with NFMC structure, we observed a ricochet effect, with only deformation depressions (dents) ranging from 1.5 to 2.0 millimeters remaining on the surface.

Geometric parameters of the structure were evaluated by a metallographic method using a Neophot 21 microscope and ToupView software to obtain quantitative data. At the same time, standard image preparation functions were used for subsequent analysis: framing, brightness adjustment, contrast adjustment, and other basic tools. In addition, built-in algorithms for applying a measuring grid and a scale were used, while the true size of the microstructures was determined by calibrating the micrometer object image. The automatic calculation of volume fractions of the structural components was conducted using the KOI-1 System software package, where stereological operations were performed based on setting brightness intervals. The study of the characteristics under consideration was performed on 15–20 fields of view for each individual sample. Micrographs were captured using a 10Mp ToupCam UA1000CA digital eyepiece camera with an optical resolution of 3584×2748 pixels. On the basis of the obtained microstructural data, the characteristic geometric parameters of the steel composite material were established according to standardized methods regulated by GOST R 54570–2011³.

Research Results. According to the ballistic tests results, high bullet resistance of the material with the structure of natural ferrite-martensitic composite (NFMC) was established. Only the ricochet of the striking elements was recorded. This indicator compared favorably with the characteristics of metal with a similar chemical composition that had a homogeneous tempered martensite structure, the samples of which penetrated. In this regard, the results of the research are presented below (Fig. 1) on the microstructure of the specified NFMC composite material [7] reinforced with discrete-length reinforcing fibers [8].

³ GOST R 54570-2011. *Steel. Methods for assessing the degree of banding or orientation of microstructures.* (In Russ.). URL: <https://internet-law.ru/gosts/gost/51810/> (Accessed: 17.05.2026).

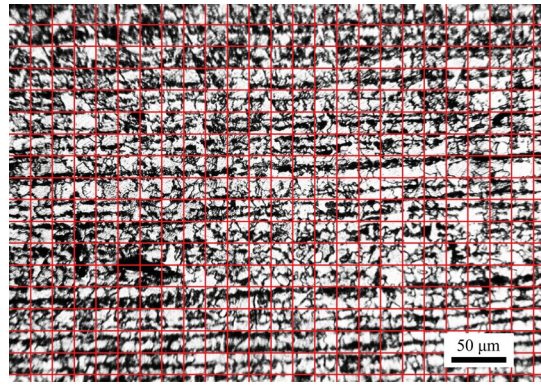


Fig. 1. Microstructure of 14G2 steel, oriented as a natural ferrite-martensitic composite (quenching at 735°C)

Table 1 provides the results of determining the characteristic geometry parameters of the steel composite according to GOST R 54570–2011⁴. Following the methodology of the mentioned standard, calculations were conducted based on the data obtained by superimposing the grid (Fig. 1) and then calculating the number of points of intersection of its lines with the studied phase.

Table 1

Calculation data for 14G2 steel according to Figure 1

$N_{L\perp}(\text{mm}^{-1})$	$N_{L\parallel}(\text{mm}^{-1})$	$Al(N_{L\perp}/N_{L\parallel})$	Ω_{12}	$P_{L\perp}(\text{mm}^{-1})$	$P_{L\parallel}(\text{mm}^{-1})$	$Al(P_{L\perp}/P_{L\parallel})$	Ω_{12}
54.92	29.62	1.85	0.352	109.83	59.24	1.84	0.352
$V = 28.37$		$SB_{\perp} = 0.0182 \text{ mm}$		$\lambda_{\perp} = 0.0131 \text{ mm}$			

where $N_{L\perp}$ — number of intersections of particles per unit length of the line perpendicular to the deformation axis; $N_{L\parallel}$ — number of intersections of particles per unit length of the line parallel to the deformation axis; $P_{L\perp}$ — number of boundary crossings per unit length of the line perpendicular to the deformation axis; $P_{L\parallel}$ — number of boundary crossings per unit length of the line parallel to the deformation axis; Al — anisotropy coefficient; Ω_{12} — degree of alignment of the linear elements of the structure; V — volume fraction of martensite; $SB_{\perp}$ — average distance (from the center to the center) for the alignment phase; $\lambda_{\perp}$ — average free path (from edge to edge) for the alignment phase.

The angle of misorientation of the strengthening phase (Fig. 1), determined by the method of superimposing secant lines along the orientation axis of the martensitic strips, was 7–11°.

The volume fraction of martensite, calculated by stereological analysis of the microstructure using the KOI-1 System software, reached 28.37% after quenching at a temperature of 735°C.

In this work, we used the recommendations of GOST R 54 570-2011⁵, to evaluate parameters such as the average distance between phase centers $SB_{\perp}$ and the average free path $\lambda_{\perp}$ (the distance between the phase boundaries) in the structure shown in Figure 1. After calculating these values, we found that the average thickness of the hardening phase plates was $\bar{h} = 0.0051 \text{ mm}$, and the average free path $\lambda_{\perp}$, representing the width of ferritic plates, was $\bar{c} = 0.0131 \text{ mm}$. Thus, the thickness ratio of the ferritic and martensitic phases was $c/h = 2.57$.

The most important factor in any composite material reinforced with discrete reinforcing fibers is the longitudinal length of these fibers. This length must exceed a critical value l_{kp} in order to ensure full loading of the martensitic layers of the composition under study. The critical length of the martensitic layer in naturally composite ferrite-martensitic materials (NFMC) was calculated based on the equilibrium condition of normal and tangential stresses within the material [11]:

$$\sigma_B \cdot h \cdot b = \tau \cdot l_{kp} (b + h), \quad (1)$$

where h , b — thickness and width of the reinforcing layer; $\tau = \sigma_T / 2$ — tangential stresses at the ferrite-martensite interface. It follows:

$$l_{kp} = \frac{\sigma_B \cdot h \cdot b}{\tau(b + h)}. \quad (2)$$

⁴ GOST R 54570-2011. *Steel. Methods for assessing the degree of banding or orientation of microstructures*. (In Russ.). URL: <https://internet-law.ru/gosts/gost/51810/> (Accessed: 17.05.2026).

⁵ Ibid.

According to the calculation results using equation (2), considering the values of h and b measured in the NFMC with a total compression of 70% during rolling, the value of $l_{kp} = 18.3 \mu\text{m}$ was obtained. A histogram of the distribution of value l in 14G2 steel with NFMC structure is shown in Figure 2.

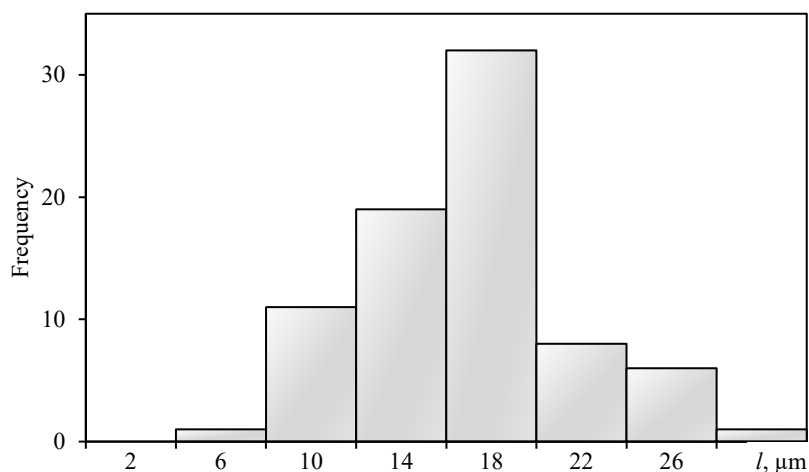


Fig. 2. A histogram of the length distribution of martensite plates in a 14G2 steel sample, the structure of which is shown in Figure 1

Discussion. The obtained data on the geometric parameters of 14G2 steel structure, hardened from the intercritical temperature range (735°C) and having NFMC organization, met modern requirements for composite materials. The high degree of structure orientation, the length of the reinforcing plates was higher than their critical value, the ratio of the thickness of the matrix and the reinforcing layer were within the optimal values.

Coincidence of the values of orientation degree Ω_{12} (Table 1), found by two different methods, confirmed the reliability of the results. A high degree of structure orientation was indicated by the condition $\Omega_{12} > 0$. When the impact was directed orthogonally to the rolling plane of steel composite, the misorientation of the reinforcing phase played a significant role. This fact was due to the dependence of the shear stress magnitude required to break the “fiber” on the misorientation angle. To achieve high impact resistance, it was important to minimize misorientation, which could be achieved by a significant degree of compression during hot rolling (at least 70%). The maximum allowable misorientation level [9] for these composites was 15° [10]. In the microstructure of the material studied, the misorientation angle ranged from 7° to 11° .

In the process of varying the quenching temperature, the ratio of volume fractions in the martensite-ferrite system could change. In particular, during the heat treatment of steel heated to lower temperatures, the volume fraction of martensitic component of the alloy decreased, but the carbon concentration increased at the same time. This presented an opportunity to deliberately adjust the mechanical properties of the material.

In numerous scientific papers dedicated to the study of the reasons for the high strength of composite materials [11], the importance of the critical volume (V_{kp}) of the composite reinforcement component was convincingly demonstrated [12]. The calculations of this parameter were conducted taking into account the strength limits of the matrix and hardening phase. The absolute value of the critical volume was estimated at approximately 50% [13]. At the same time, similar estimations were made for the conditions of static loading of composites under tension (along the reinforcing fiber) or bending [14], as well as during dynamic bending during impact strength tests [16]. The ballistic stability of NFMC was evaluated under conditions of orthogonal high-power impact upon impact at a speed of $\sim 10^3 \text{ m/s}$. It was shown [15] that at such speeds, the mechanical properties of composite components could not affect the dynamic resistance at all. Instead, the role of inertial forces, paths and methods of shock wave propagation increased dramatically [17]. In this case, the concept of V_{kp} lost its original physical meaning and the proportion of the volume fractions of ferrite and martensite was assumed to be approximately 80/20. This unambiguously determined the thickness ratio of ferritic (c) and martensitic (h) plates at the level of $c/h \geq 3$.

At this ratio, the growth of the crack was inhibited due to the stratification of the material within the ferritic matrix, significantly increasing the overall ballistic resistance [5]. The measured ratio for the structure under study was 2.57, which was slightly lower than the threshold value mentioned above. This naturally reduced the likelihood of delamination during high-speed crack propagation and reduced the chance of ricochet during high-speed impact. To achieve an optimal c/h ratio in this scenario, it would be advisable to adjust the quenching temperature from the intercritical range to below 735°C .

When conducting ballistic tests on plates with a thickness of 7 mm, according to the previously described methodology, a target sample with an isotropic tempered martensite structure broke through, whereas a projectile invariably ricocheted from a target with the NFMC structure. This was due to the fact that the layered composite, with optimal geometric characteristics in all parameters, was able to form local stratifications [5] as cracks propagated in it [12] sequentially from one layer to another along the interface and as the crack tip approached it. As shown in Figure 3, these stratifications created conditions for the initial crack to move to a new position, which did not contribute to its further development. Thus, the ferrite-martensite phase interface with a length of $l > l_{kp}$ could serve as an effective barrier to crack propagation. Figure 3a illustrates how the trajectory of the crack in the NFMC sample changed when a ricochet occurred. In this case, a bulge formed on the back of the target, and a crack could occur (Fig. 3b). However, there was no material shift beyond the back side.

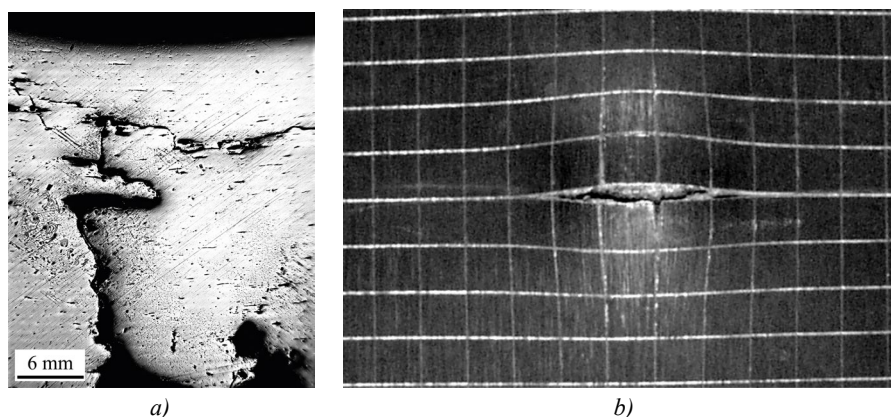


Fig. 3. The trajectory of a crack in the composite during a high-speed impact (a) and a crack on the back of the target (b) [5]

Conclusion. It has been established that the structure of NFMC steel has a high degree of orientation ($\Omega_{12} = 0.352$), and this circumstance plays an important role in the case of a powerful impact.

The ratio of the average widths of martensite and ferrite plates was 2.57. This suggests that it would be beneficial to reduce the quenching temperature from the intercritical range below 735°C to ensure an optimal structural balance. The data on the length distribution of martensitic plates showed a maximum that coincided with the calculated critical length of the reinforcing fiber (18.3 μm). This is a significant indicator, as the ferrite-martensite interfaces with lengths greater than the critical value can act as an effective barrier to crack propagation.

It has been proven that the excellent ballistic resistance of a natural ferrite-martensitic composite is achieved exclusively through the optimal combination of all geometric parameters in the microstructure of the composite material. At the same time, the successful achievement of the described NFMC configuration optimum (as a specialized armor protection) can only be guaranteed through the use of correct hot rolling techniques (total workpiece compression of 70% or more), as well as careful selection of optimal quenching temperatures within the intercritical range.

References

1. Crouch I. (ed.) *The Science of Armour Materials*. Woodhead Publishing; 2016. 722 p.
2. El Messiry M. *Protective Armor Engineering Design*. Apple Academic Press; 2019. 356 p.
3. Hazell PJ. *Armour: Materials, Theory, and Design*. CRC press; 2022. 498 p.
4. Bkhatnagar A. (ed.) *Lightweight Ballistic Materials*. Moscow: Tekhnosfera; 2011. 392 p. (In Russ.)
5. Pustovoi VN, Dolgachev YuV, Dombrovskii YuM, Duka VV. Structural Organization and Properties of a Natural Ferrite-Martensite Steel Composite. *Metal Science and Heat Treatment*. 2020;62(5–6):369–375. <https://doi.org/10.1007/s11041-020-00570-9>
6. Pustovoi VN, Dombrovskii YuM, Zheleva AV, Zaitseva MV. *A Method for Obtaining a Natural Ferrite-Martensitic Composite*. RF Patent, No. 2495141 C1. 2013. 7 p. (In Russ.)
7. Kelly A. (ed.) *Concise Encyclopedia of Composite Materials*. Elsevier; 2012. 380 p.
8. Vasiliev VV, Morozov EV. *Advanced Mechanics of Composite Materials and Structures*. Elsevier; 2018. 882 p.
9. Qing Quan Liang. *Analysis and Design of Steel and Composite Structures*. CRC Press; 2018. 458 p.
10. Gay D. *Composite Materials: Design and Applications*. CRC Press; 2022. 640 p.
11. Lizunov VI. *Composite Steels*. Moscow: Metallurgiya; 1978. 150 p. (In Russ.)
12. Bernshtein ML. *Steel Strength*. Moscow: Metallurgiya; 1974. 199 p. (In Russ.)
13. Grange RA. Fibrous Microstructures Developed in Steel by Thermomechanical Processing. In: *2nd International Conference of Strength of Metals and Alloys. Conference Proceedings*. 1970. P. 861–863.

14. Bernshtein ML, Odesskii PD, Gryunval'd TM. Features of the Destruction Process of Construction Steels Hardened According to the TMT Scheme with Deformation in the Intercritical Temperature Range. *Izvestiya vuzov. Chernaya metallurgiya*. 1985;(1):85–90. (In Russ.)

15. Pustovoyt VN, Dolgachev YuV, Inankov IV. Deformation and Fracture Resistance of Steel with a Structure of a Natural Ferrite-Martensite Composite under High-Speed Impact. *Metal Science and Heat Treatment*. 2024;66(1–2):1–4. <https://doi.org/10.1007/s11041-024-01009-1>

16. Sharma Rajan TV, Ashok Kumar Sharma, Sharma CP. *Heat Treatment: Principles and Techniques*. PHI Learning Pvt. Ltd.; 2023. 376 p.

17. Pustovoyt VN, Dolgachev YuV, Dombrovskii YuM. Ballistic Resistance of Steel with the Structure of a Natural Ferrite-Martensitic Composite. *Safety of Technogenic and Natural Systems*. 2022;(3):54–59. <https://doi.org/10.23947/2541-9129-2022-3-54-59>

About the Authors:

Viktor N. Pustovoyt, Dr. Sci. (Eng.), Professor of the Materials Science and Metal Technology Department, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation), [SPIN-code](#), [ORCID](#), [ScopusID](#), [ResearcherID](#), pustovoyt45@gmail.com

Yuri V. Dolgachev, Dr. Sci. (Eng.), Associate Professor of the Materials Science and Metal Technology Department, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation), [SPIN-code](#), [ORCID](#), [ScopusID](#), ydolgachev@donstu.ru

Ivan V. Ivankov, Postgraduate Student of the Materials Science and Metal Technology Department, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation), [ORCID](#), yanya.ivankov.99@gmail.com

Claimed Contributorship:

VN Pustovoyt: conceptualization, supervision, writing – review & editing.

YuV Dolgachev: analysis, writing – review & editing.

IV Ivankov: experimental data acquisition, calculations, writing – original draft preparation.

Conflict of Interest Statement: the authors declare no conflict of interest.

All authors have read and approved the final version of manuscript.

Об авторах:

Виктор Николаевич Пустовойт, доктор технических наук, профессор, профессор кафедры «Материаловедение и технологии металлов» Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), [SPIN-код](#), [ORCID](#), [ScopusID](#), [ResearcherID](#), pustovoyt45@gmail.com

Юрий Вячеславович Долгачев, доктор технических наук, доцент кафедры «Материаловедение и технологии металлов» Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), [SPIN-код](#), [ORCID](#), [ScopusID](#), ydolgachev@donstu.ru

Иван Вениаминович Иванков, аспирант кафедры «Материаловедение и технологии металлов» Донского государственного технического университета, (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), [ORCID](#), yanya.ivankov.99@gmail.com

Заявленный вклад авторов:

В.Н. Пустовойт: формирование основной концепции, цели и задач исследования, научное руководство, корректировка выводов.

Ю.В. Долгачев: анализ результатов исследований, доработка текста.

И.В. Иванков: получение экспериментальных данных, расчеты, подготовка текста, формулирование выводов.

Конфликт интересов, авторы заявляют об отсутствии конфликта интересов.

Все авторы прочитали и одобрили окончательный вариант рукописи.

Received / Поступила в редакцию 19.05.2026

Reviewed / Поступила после рецензирования 22.06.2026

Accepted / Принята к публикации 30.06.2026