

MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE
STATE UNIVERSITY OF INFRASTRUCTURE AND TECHNOLOGIES



TRANSPORT SYSTEMS AND TECHNOLOGIES



Issue 41



2023

МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ
ДЕРЖАВНИЙ УНІВЕРСИТЕТ ІНФРАСТРУКТУРИ ТА
ТЕХНОЛОГІЙ

ЗБІРНИК
НАУКОВИХ ПРАЦЬ
ДЕРЖАВНОГО УНІВЕРСИТЕТУ
ІНФРАСТРУКТУРИ ТА ТЕХНОЛОГІЙ

СЕРІЯ

«ТРАНСПОРТНІ СИСТЕМИ
І ТЕХНОЛОГІЇ»

ВИПУСК 41

Київ·2023

Збірник містить статті, присвячені теоретичним, методологічним і прикладним проблемам транспортної галузі. У статтях збірника розглядаються питання транспортної інфраструктури та рухомого складу, технології та організації транспортних процесів, інформаційних та комп'ютерних технологій на транспорті, математичного моделювання об'єктів транспорту, екологічної безпеки на транспорті.

Для науковців, викладачів, студентів вищих навчальних закладів і працівників транспорту та зв'язку.

Редакційна колегія:

О.М. Горобченко, доктор технічних наук, професор, професор кафедри «Електромеханіка та рухомий склад залізниць» (головний редактор);

Н.С. Брайковська, кандидат технічних наук, професор, ректор ДУІТ (заступник головного редактора);

В.М. Твердомед, кандидат технічних наук, доцент, директор Київського інституту залізничного транспорту, ДУІТ (заступник головного редактора);

О.В. Фомін, доктор технічних наук, професор, професор кафедри «Вагони та вагонне господарство», ДУІТ (заступник головного редактора);

Ю.П. Дудник, кандидат педагогічних наук, доцент, проректор з науково-педагогічної роботи, ДУІТ;

Е.І. Даніленко, доктор технічних наук, професор, професор кафедри «Залізнична колія та колійне господарство», ДУІТ, академік Транспортної академії України, лауреат Державної премії України в галузі науки і техніки, Заслужений діяч науки і техніки України;

О.І. Стасюк, доктор технічних наук, професор, професор кафедри «Автоматизація та комп'ютерно-інтегровані технології транспорту», ДУІТ, член-кореспондент Транспортної академії України, лауреат Державної премії України в галузі науки і техніки;

В.К. Мироненко, доктор технічних наук, професор, завідувач кафедри «Управління комерційною діяльністю залізниць», ДУІТ, академік ТАУ, академік Міжнародної академії життєдіяльності;

В.П. Ткаченко, доктор технічних наук, професор, завідувач кафедри «Електромеханіка та рухомий склад залізниць», ДУІТ;

Л.І. Тимченко, доктор технічних наук, професор, завідувач кафедри «Системи штучного інтелекту та телекомунікаційні технології», ДУІТ;

В.М. Самсонкін, доктор технічних наук, професор, професор кафедри «Управління процесами перевезень», ДУІТ;

С.Ю. Сапронова, доктор технічних наук, професор, професор кафедри «Вагони та вагонне господарство», ДУІТ;

М.Б. Кельріх, доктор технічних наук, професор, професор кафедри «Вагони та вагонне господарство», ДУІТ;

В.М. Іщенко, кандидат технічних наук, професор, завідувач кафедри «Вагони та вагонне господарство», ДУІТ;

В.В. Косарчук, доктор технічних наук, професор, завідувач кафедри «Теоретична та прикладна механіка», ДУІТ;

О.Г. Стрелко, доктор історичних наук, професор, декан факультету «Управління залізничним транспортом», ДУІТ;

О.А. Герцій, кандидат технічних наук, доцент, завідувач кафедри «Автоматизація та комп'ютерно-інтегровані технології транспорту», ДУІТ;

С.А. Ісаєнко, кандидат педагогічних наук, доцент, доцент кафедри «Іноземні мови», ДУІТ;

О.Я. Пилипчук, доктор біологічних наук, професор, завідувач кафедри «Екологія та безпека життєдіяльності», ДУІТ;

І.В. Грицук, доктор технічних наук, професор, професор кафедри експлуатації суднових енергетичних установок, Херсонська державна морська академія;

О.М. Шичула, доктор фізико-математичних наук, професор, професор кафедри «Комп'ютерні науки» Державного університету телекомунікацій;

Б.Г. Любарський, доктор технічних наук, професор, завідувач кафедри «Електричний транспорт і тепловозобудування» НТУ «Харківський політехнічний інститут»;

А.П. Фалендиш, доктор технічних наук, професор, завідувач кафедри «Транспортні технології підприємств» Приазовського державного технічного університету;

В. О. Каращук, кандидат технічних наук, доцент кафедри рухомого складу транспортних систем ДВНЗ «Приазовський державний технічний університет»;

В.І. Мацюк, доктор технічних наук, професор, професор кафедри «Торговельне підприємництво та логістика» Київського національного торговельно-економічного університету;

А.В. Прохорченко, доктор технічних наук, професор, професор кафедри «Управління експлуатаційною роботою» Українського державного університету залізничного транспорту;

В.Г. Пузир, доктор технічних наук, професор, завідувач кафедри «Експлуатація та ремонт рухомого складу» Українського державного університету залізничного транспорту;

С. Мечніковський (S. Mieszniowski), Dr. hab., Prof., кафедра ринку транспортних послуг, Гданський університет (Польща);

С. Андонова (S. Andonova), Assos. Prof. Eng., PhD, декан інженерного факультету Південно-Західний університет "Неофіт Рилські" (Болгарія);

Ю. Герліці (J. Gerlici), Prof., Dr. Ing., завідувач кафедри транспорту та підйомно-транспортних машин Жилінського університету (Словацька Республіка);

В. Хаусер (V. Hauser), Ing., PhD, науковий співробітник кафедри транспорту та підйомно-транспортних машин Жилінського університету (Словацька Республіка);

Я. Діжо (J. Dižo), Ing., PhD, доцент кафедри транспорту та підйомно-транспортних машин Жилінського університету (Словацька Республіка);

Р. Кершис (R. Keršys), PhD, Assoc. Prof., кафедра транспортної інженерії, Каунаський технологічний університет (Литва);

В. Пиштек (Václav Pištěk) Prof., Dr. Sc. Techn., Brno University of Technology, Technická, Brno (Чехія);

П. Кучера (Pavel Kučera) Assoc. Prof., PhD, Brno University of Technology, Technická, Brno (Чехія);

Г.М. Голуб, кандидат технічних наук, доцент, доцент кафедри «Автоматизація та комп'ютерно-інтегровані технології транспорту», ДУІТ (технічний секретар);

С.О. Гулак, кандидат технічних наук, доцент, доцент кафедри «Електромеханіка та рухомий склад залізниць», ДУІТ (технічний секретар);

Журнал включено до міжнародних наукометричних баз даних та електронних бібліотек: DOAJ (Directory of Open Access Journals), MJAR (Information Matrix for the Analysis of Journals), ICI World of Journals (Index Copernicus), Scilit, ResearchBib, BASE (Bielefeld Academic Search Engine), ROAD (Directory of Open Access scholarly Resources), OpenAIRE (Open Access Infrastructure for Research in Europe), Crossref, Worldcat, EuroPub, Наукова періодика України, Google Scholar.

Статті збірника проходять обов'язкове подвійне сліпе рецензування членами редакційної колегії та залученими рецензентами, друкуються мовою оригіналу. Редакція не обов'язково поділяє думку автора і не відповідає за фактичні помилки, яких він припустився.

Рекомендовано до друку Вченою радою ДУІТ (протокол № 10 від 25 травня 2023 р.).

Засновник і видавець – Державний університет інфраструктури та технологій
Свідоцтво про державну реєстрацію КВ № 23070-12910ПР від 27.12.2017

Збірник внесено до Переліку наукових фахових видань України,
в яких можуть публікуватися результати дисертаційних робіт на здобуття наукових ступенів доктора та кандидата наук у технічній галузі

(Додаток 11 до наказу Міністерства освіти і науки України 29.12.2014 № 1528)

та відноситься до категорії "Б" (відповідно до Порядку формування Переліку наукових фахових видань України, затвердженого наказом МОН України від 15 січня 2018 року № 32) періодичних фахових видань України.

<https://tst.duit.in.ua/>

© Державний університет інфраструктури та технологій, 2023

MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE
STATE UNIVERSITY OF INFRASTRUCTURE AND
TECHNOLOGIES

COLLECTION OF SCIENTIFIC
PAPERS
OF THE STATE UNIVERSITY OF
INFRASTRUCTURE AND TECHNOLOGIES

SERIES

«TRANSPORT SYSTEMS AND TECHNOLOGIES»

ISSUE 41

Kyiv·2023

UDC: 656:62

Collection of Scientific Papers of the State University of Infrastructure and Technologies of the Ministry of Education and Science of Ukraine: Series "Transport Systems and Technologies". № 41. Kyiv: SUIT, 2023. 224 p. DOI:10.32703/2617-9059-2023-41

e-ISSN 2617-9059

p-ISSN 2617-9040

The collection contains articles devoted to theoretical, methodological and applied problems of the transport industry. The articles of the collection consider the issues of transport infrastructure and rolling stock, technology and organization of transport processes, information and computer technologies in transport, mathematical modeling of transport facilities, environmental safety in transport.

For researchers, teachers, students of higher educational institutions and transport and communications workers.

Editorial board:

O. Gorobchenko, Doctor of Technical Sciences, Professor, Professor of the department "Electromechanics and rolling stock of railways", (Editor-in-Chief);

N. Braikovska, PhD in Technical Sciences, Professor, Rector of the State University of Infrastructure and Technologies (deputy editor-in-chief);

V. Tverdomed, PhD in Technical Sciences, Assoc. Prof., Director of the Kyiv Institute of Railway Transport SUIT (deputy editor-in-chief);

O. Fomin, Doctor of Technical Sciences, Prof., Professor of the Department "Railway Carriages and Carriage Facilities" (deputy editor-in-chief);

Yu. Dudnyk, PhD in pedagogical sciences, associate professor, vice-rector for scientific and pedagogical work of the State University of Infrastructure and Technology;

E. Danilenko, Doctor of Technical Sciences, Prof., Head of the department "Railway Track and Track Facilities", Academician of the Transport Academy of Ukraine, Laureate of the State Prize of Ukraine in the field of science and technology, Honored Worker of Science and Technology of Ukraine;

O. Stasiuk, Doctor of Technical Sciences, Prof., Professor of the department "Automation and Computer Integrated Transport Technologies", corresponding member of the Transport Academy of Ukraine, Laureate of the State Prize of Ukraine in the field of science and technology;

V. Myronenko, Doctor of Technical Sciences, Prof., Head of the department "Management of Commercial Activities of Railways", Academician of the Transport Academy of Ukraine, Academician of the International Academy of Vital Activity;

V. Tkachenko, Doctor of Technical Sciences, Prof., Head of the department "Electromechanics and rolling stock of railways";

L. Tymchenko, Doctor of Technical Sciences, Prof., Head of the department "Artificial intelligence systems and telecommunication technologies";

V. Samsonkin, Doctor of Technical Sciences, Prof., Professor of the department "Management of transport processes";

S. Sapronova, Doctor of Technical Sciences, Prof., Professor of the department "Railway Carriages and Carriage Facilities";

M. Kelrikh, Doctor of Technical Sciences, Prof., Professor of the department "Railway Carriages and Carriage Facilities";

V. Ishchenko, PhD in Technical Sciences, Prof., Head of the department "Railway Carriages and Carriage Facilities";

V. Kosarchuk, Doctor of Technical Sciences, Prof., Head of the department "Theoretical and Applied Mechanics";

O. Strelko, Doctor of Historical Sciences, Professor, Dean of the Faculty of Railway Transport Management;

O. Hertsii, PhD in Technical Sciences, Assoc. Prof., Head of the department "Automation and Computer Integrated Transport Technologies";

V. Matsiuk, Doctor of Technical Sciences, Professor, Professor of the Department of Trade Entrepreneurship and Logistics, Kyiv National University of Trade and Economics;

S. Isaienko, PhD in Pedagogical Sciences, Assoc. Prof., Associate Professor of the Department of Foreign Languages;

O. Pylypchuk, Doctor of Biological Sciences, Prof., Head of the department "Ecology and life safety";

I. Gritsuk, Doctor of Technical Sciences, Professor, Professor of the Department of Ship Power Plants Operation, Kherson State Maritime Academy

E. Shikula, Doctor of Physical and Mathematical Sciences, Professor, Professor of the Department of Computer Science, State University of Telecommunications;

B. Liubarskyi, Doctor of Technical Sciences, Prof., Head of the department "Electric transport and diesel locomotive construction" NTU "Kharkov Polytechnic Institute";

A. Falendysh, Doctor of Technical Sciences, Prof., Head of the department "Transport technologies of enterprises" Priazovskyi State Technical University;

A. Prokhorchenko, Doctor of Technical Sciences, Assoc. Prof., Professor of the department "Management of Operational Work" of the Ukrainian State University of Railway Transport;

V. Puzyr, Doctor of Technical Sciences, Prof., Head of the department "Maintenance and repair of rolling stock" of the Ukrainian State University of Railway Transport;

V. Karashchuk, PhD in Technical Sciences, Assoc. Prof. of the department of rolling stock of transport systems, "Priazov State Technical University";

M. Meng, PhD, Lecturer in Mechanical Engineering (Engineering, Computing and Mathematics), University of Plymouth, (United Kingdom);

S. Miecznikowski, Dr. hab., Prof., Department of Transport Services Market, University of Gdańsk, (Poland);

S. Andonova, Prof., Dr. Eng., Head of the department "Mechanical Engineering and Technologies", South-West University "Neofit Rilski" (Bulgaria);

J. Gerlici, Prof., Dr. Ing., Head of the Department of Transport and Handling Machines, University of Zilina (Slovak Republic);

V. Hauser, Ing., PhD, Researcher of the Department of Transport and Handling Machines, University of Zilina (Slovak Republic);

J. Džžo, Ing., PhD, Associate Professor of the Department of Transport and Handling Machines, University of Zilina (Slovak Republic);

R. Keršys, PhD, Assoc. Prof., Associate Professor of the Department "Transport Engineering", Kaunas University of Technology (Lithuania);

V. Pištěk, Prof., Dr. Sc. Techn., Brno University of Technology, Technická, Brno (Czech Republic);

P. Kučera, Assoc. Prof., PhD, Brno University of Technology, Technická, Brno (Czech Republic);

H. Holub, PhD in Technical Sciences, Associate Professor of department "Automation and Computer Integrated Transport Technologies" (technical secretary);

S. Goolak, PhD in Technical Sciences, Associate Professor of the department "Electromechanics and rolling stock of railways" (technical secretary)

Journal is included in the international scientific databases: DOAJ (Directory of Open Access Journals), MIAR (Information Matrix for the Analysis of Journals), ICI World of Journals (Index Copernicus), Scilit, ResearchBib, BASE (Bielefeld Academic Search Engine), ROAD (Directory of Open Access scholarly Resources), OpenAIRE (Open Access Infrastructure for Research in Europe), Crossref, Worldcat, EuroPub, Наукова періодика України, Google Scholar.

The articles of the collection undergo mandatory double blind peer review by members of the editorial board and invited reviewers, and are printed in the original language. The editorial board does not necessarily share the author's opinion and is not responsible for the factual errors that he made.

Recommended for publication by the Academic Council of DUIT (Minutes № 10 of May 25, 2023).

Founder and Publisher - State University of Infrastructure and Technologies
Certificate of state registration KB № 23070-12910ПП dated 27.12.2017

The journal is included in the List of Scientific and Professional Publications of Ukraine, in which the results of dissertations for obtaining the scientific degrees of doctor and candidate of sciences in the technical field can be published (Appendix 11 to the order of the Ministry of Education and Science of Ukraine dated 29.12.2014 No. 1528) and belongs to the "B" category (in accordance with the Procedure for the formation of the List of scientific specialized publications of Ukraine, approved by the order of the Ministry of Education and Science of Ukraine dated January 15, 2018 No. 32) of periodic specialized publications of Ukraine.

<https://tst.duit.in.ua/>

© State university of infrastructure and technologies, 2023

Sergiy Goolak¹, Ihor Kostenko², Robertas Keršys³, Ievgen Riabov^{4*}, Oleksandr Demydov⁵

¹Associate Professor, Department of Electromechanics and Rolling Stock of Railways, State University of Infrastructure and Technologies, 9, Kyrylivska str., Kyiv, 04071, Ukraine ORCID: <https://orcid.org/0000-0002-2294-5676>

²Postgraduate Student, Department of Electromechanics and Rolling Stock of Railways, State University of Infrastructure and Technologies, 9, Kyrylivska str., Kyiv, 04071, Ukraine, ORCID: <https://orcid.org/0009-0007-1156-8661>

³Associate Professor, Department of Transport Engineering, Kaunas University of Technology, 56, Studentų str., Kaunas, LT-51424, Lithuania, ORCID: <https://orcid.org/0000-0001-7785-722X>

⁴Associate Professor, Department of Electric Transport and Locomotive Engineering, National Technical University «Kharkiv Polytechnic Institute», 2, Kyrpychova str., Kharkiv, 61002, Ukraine, ORCID: <https://orcid.org/0000-0003-0753-514X>

⁵Senior Lecturer, Department of Electric Transport and Locomotive Engineering, National Technical University «Kharkiv Polytechnic Institute», 2, Kyrpychova str., Kharkiv, 61002, Ukraine, ORCID: <https://orcid.org/0000-0003-0532-9748>

*Corresponding author: riabov.ievgen@gmail.com

Analysis of operation modes of shunting diesel locomotives when performing shunting work

An overview of modern trends in updating shunting locomotives, which are based on the installation of on-board energy storage devices, multi-diesel propulsion power plants, and power plants operated on hydrogen energy sources, was carried out. The necessity to take into account the operating conditions of a shunting diesel locomotive when choosing an upgrade option is shown. The operation modes of shunting diesel locomotives during shunting operations at the Козятин-I freight station during three shifts were considered. By analyzing the data of the BIC-P onboard system and processing the route sheets, the parameters of the operating modes were determined. Calculations of diesel engine power utilization indicators were performed, according to which it was determined that the full use of the installed diesel generator power is 7.5...8.4%, and the maximum diesel power recorded under the studied operating conditions is about 50%. The duration of work with traction loads is 49.5...68.8% of the shift time. The longest - 55...60% of the total duration of work under traction - are modes with a power of 0...50 kW. The duration of work without load is 18.1...36.9% of the duration of the shift. The shunting work performed is related to the formation and disassembly of trains, including the use of a sorting slide, as a result of which the traction power transmission operates with a low efficiency. In order to reduce the consumption of fuel and energy resources when performing shunting work, it is necessary to update the fleet of locomotives for shunting work, the characteristics of which are adapted to the operating modes.

Key words: hybrid locomotive, modernization, shunting, energy efficiency, energy storage

Introduction. Maneuvering is an integral part of the transportation process. JSC "Ukrzaliznytsia" uses ChME3 series diesel locomotives for shunting operations, the inventory of which is more than 1,200 units [1] with 100% actual wear. For diesel locomotives that are in operation, there is a steady trend of increasing maintenance costs. According to [1], the priority way to improve the situation with shunting diesel locomotives is to restore them through major repairs and modernization of individual units. These works are planned to be carried out on the entire fleet required for shunting operations

(estimated at 870 diesel locomotives in 2033). Arguments for choosing this option are relatively small capital investments and the presence of a developed repair and technological base at all regional branches. At the same time, it is noted that during major repairs it is impossible to restore the passport characteristics of diesel locomotives, therefore significant costs for their current maintenance will remain, and due to the low quality of repairs, an increase in unplanned repairs is predicted. Alternative options for updating the fleet of shunting diesel locomotives, which are indicated in [1], are their complex modernization with remotorization (as well as the purchase of new diesel locomotives). The use of these options allows to improve the traction and energy characteristics of diesel locomotives, it is predicted that the cost of maintenance, repairs and fuel and lubricants will decrease, which will ultimately ensure a decrease in the cost of transportation. Taking into account the possibility of extending the service life of ЧМЕ3 diesel locomotives for 10...15 years [2], it is considered urgent to work out options for comprehensive modernization of these diesel locomotives to improve their traction and energy characteristics.

Analysis of recent research and problem statement. In Ukraine, remotorization of ЧМЕ3 diesel locomotives was carried out using the 4Д80Б diesel, in the CIS countries - using the 1-PD4B and 4-36DG diesel generators [3]. A deep complex modernization using a Caterpillar diesel engine, AC-DC power transmission (the traction motors were not changed), an electric drive for cooling fans and a compressor, and a microprocessor control system was carried out in Ukraine at Poltava Tractor Repair Plant, where diesel locomotives were modernized according to the designs of the ZOS company Zvolen (Fig. 1a) and CZ LOCO (Fig. 1b) [4]. The latter company's project was also used in the modernization of ЧМЕ3 diesel locomotives in the CIS and Baltic countries.



Fig. 1. Modernized ЧМЕ3 diesel locomotives

The paper [5] analyzed the fuel consumption of serial diesel locomotives ЧМЕ3 and modernized diesel locomotive ЧМЕ3P-№1744. It was established that the modernized diesel locomotive, despite the use of a more powerful diesel engine with a capacity of 1455 kW, consumes 29.4% less fuel than a serial diesel locomotive. Similar results were obtained during the operation of TEM2 diesel locomotives, which are modernized according to the same concept as ЧМЕ3II. Compared to the TEM TMX diesel locomotive with a 970 kW diesel engine, which was created using the crew part of the TEM18DM diesel locomotive and the equipment of modernized ЧМЕ3 diesel locomotives, the fuel consumption during shunting was 37.5%. In both cases, it is noted that fuel economy depends on the type of maneuvering. The greatest savings of 40...45% are observed when modernized diesel locomotives are used in export work. The smallest one is at hill work. It is worth noting that during the modernization, the traction characteristics of the diesel locomotive at the positions of the driver's controller and the applied electric drive of the motor cooling fans were changed. This also had an effect on reducing fuel consumption, but this is difficult to assess.

An alternative way to update shunting diesel locomotives is to create a hybrid locomotive. The paper [6] substantiates the feasibility of creating a hybrid locomotive based on the ЧМЕ3 diesel locomotive and the technical parameters of such a diesel locomotive for Ukrainian railways. In [7], a study was conducted on the use of combined storage units as part of the power plant of a shunting diesel locomotive. In [8], the application of a traction electric drive based on valve-inductor electric motors in

the traction system of a hybrid shunting locomotive was investigated. [9] shows the expediency of using traction asynchronous electric motors in the modernization of diesel locomotives of ChME3 type.

Hybrid shunting locomotives are becoming increasingly common in commercial operation [10, 11]. New locomotives Prima H3 (Fig. 2a) [12], Prima H4 (Fig. 2b) [13] and modernized locomotives of the BR203H series (Fig. 2c) [14] manufactured by Alstom, HD300 locomotives (Fig. 2d) [14] are in operation. 15] and HDB800 (fig.2f) [16] from Toshiba, locomotive FXN3D (fig.2g) [17] and 1004 (fig.2g) [18] from CRRC, locomotive GG20B (fig.2h) [19], created Railpower Technologies, locomotive CBD80 (fig.2i) [20] from Clayton Equipment, locomotive HLS-700 (fig.2j) [21] from TÜLOMSAŞ. Information about the development or experimental operation of hybrid locomotives can be found at almost every manufacturer of rolling stock.

Diesel locomotives with several diesel power plants are also used. For example, the diesel locomotive MDD5 (Fig. 3a) [22] manufactured by Express Service uses two diesel generator sets, the diesel locomotives 3GS21B (Fig. 3b) [23] from National Railway Equipment and RP20BD (Fig. 3c) [24] from Railpower Technologies – three diesel generators. At the same time, the RP20BD diesel locomotive has a modification where one diesel generator is replaced by an energy accumulator. In TEM2-UGMK diesel locomotive (Fig. 3d) [25] an auxiliary diesel engine is used, which is included in operation during long-term downtimes of the diesel locomotive. The main diesel generator set is not working at this moment.



Fig.2. Hybrid shunting diesel locomotives

At present, extensive research has gained application on locomotives of alternative primary sources of energy - fuel cells, gas engines or exclusively battery cells [26].

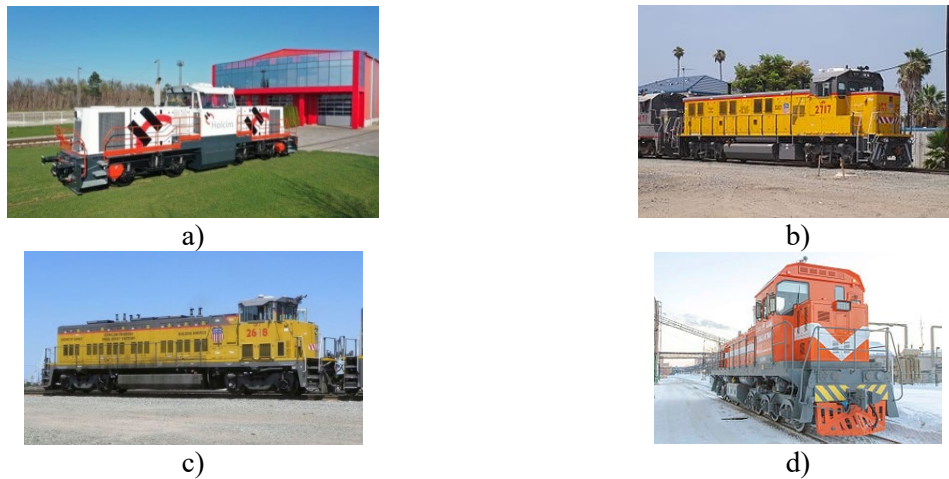


Fig. 3. Multi-diesel shunting diesel locomotives

The experimental sample of the SM42-6Dn locomotive (Fig. 4a) [27] on fuel cells created by the PESA company; the locomotive from CRRC (Fig. 4b) [28]; the MK1200G locomotive with a gas piston engine (Fig. 4c) [29]; the battery locomotive of the company Zarmen (Fig. 4d) [30]; CRRC battery locomotive (Fig. 4e) [31]; EMD Joule battery locomotive (Fig. 4f) [32] produced by Progress Rail; ES1000 series battery locomotive (Fig. 4g) and ES3000 (Fig. 4h) [33] produced by Express Service.

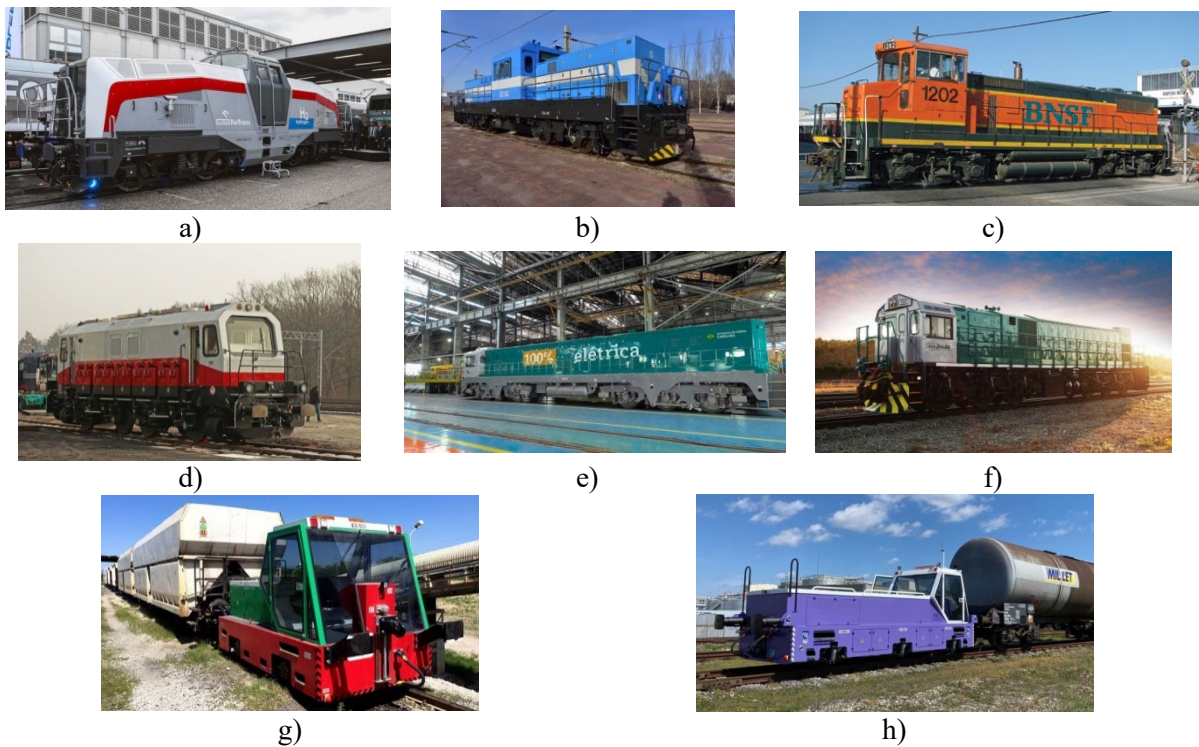


Fig. 4. Locomotives with alternative energy sources

Also implemented are projects for retrofitting diesel locomotives to run on natural gas (LNG, LPG, compressed gas) or biogas (TEM2 diesel locomotives in the Baltic countries and Kazakhstan, the

OptiFuel project), use of biodiesel (WDM7 locomotive of the Indian Railways on biodiesel), a mixture of gas and hydrogen in the piston engine (Freightliner Class 66).

It is worth noting that in the CIS countries, samples of hybrid diesel locomotives, two-diesel, with gas engines and biofuels have been created.

It is also worth emphasizing that the locomotives of foreign companies can be equipped with a power plant of any configuration in order to adapt to real operating conditions. In particular, locomotives can be powered by a contact network [34].

Thus, various technologies can be used in the modernization and creation of new shunting locomotives. Classic deep modernization with the use of a modern diesel engine is proven and it ensures a reduction in operating costs. An alternative to it is a hybrid shunting locomotive or electric shunting locomotive, as well as multi-diesel diesel locomotives. The use of fuel cells is considered to be extremely promising for rolling stock, but this technology is actually at a research stage. In addition, today the spread of hydrogen technologies is "impeded" by the high cost of hydrogen. The situation is similar with biofuel, the use of which for locomotives is at the experimental stage. Pure battery locomotives are used for a certain class of shunting operations, which is primarily related to the characteristics of battery cells. Therefore, according to the authors, the acceptable ways to modernize ChME3, in addition to the "classical" modernization with the use of a modern diesel engine, are the creation of hybrid shunting diesel locomotives and contact-battery shunting electric locomotives.

It was shown in [35] that the modes of operation of the ChME3 diesel locomotive depend significantly on the place of its operation, that is, on the types of shunting work performed by the diesel locomotive. Therefore, **the purpose of the researcher** is to analyze the modes of operation of a shunting locomotive during shunting operations, which will allow to specify the requirements for a modernized locomotive

Materials and methods of research. Data analysis from on-board systems installed on diesel locomotives is widely used to determine operating conditions [5, 6, 35]. The authors processed data on the operation of diesel locomotive ChME3 No. 1190 during three shifts in the period 23-25.03.2021 at Kozyatyn-I station. The diesel locomotive performed shunting operations to form and break up freight trains, including the release of wagons on the sorting chute. Data from the БIC-P system and entries in route sheets were analyzed. The indicators of the average power of the traction generator of the diesel locomotive are given in tables 1, 3 and 5. Tables 2, 4 and 6 show the characteristics of the maneuvering operation, the number of axles, the approximate mass of the train and the time of the start and end of the operation. The color of the cell in the table.1 and 2, 3 and 4 and 5 and 6 coincide and indicate one maneuver operation. The "Dismantling" operation includes the approach of the locomotive to the group of wagons, coupling with the group of wagons, release of automatic brakes in the group of wagons by "bleeding" air from the air distributors, moving the group of wagons to the sorting chute and disbanding the group of wagons through the sorting chute. The "Disbanding" operation is carried out by feeding a group of wagons to the sorting chute and then, depending on the need, new trains of wagons are formed by moving a group of turnouts. At the same time, the locomotive pushes the wagons up the hill at a speed of 2-3 km/h. The "Replenishment" operation is performed to complete the freight train according to weight standards or train length standards. For this, the diesel locomotive adds one or a group of carriages to the already formed composition of the train. The "Rearrangement" operation is the movement of one or a group of wagons from one track to another, or the coupling of wagons on one track into one warehouse, or any other movement of wagons in the fleet of formation and disassembly of trains.

Table 1. Indicators of the average generator power of ChME3 diesel locomotive №1190 during operation for the shift of March 23-24, 2021 from 8:00 p.m. to 8:00 a.m. in kW according to the BIC-P system diagram

Minutes	Hours											
	20-21	21-22	22-23	23-00	00-01	01-02	02-03	03-04	04-05	05-06	06-07	07-08
00-02	0	0	125	38	20	40	35	180	110	200	0	80
02-04	0	0	150	15	2	0	0	60	140	280	60	35
04-06	0	50	0	0	0	40	6	55	175	140	90	0
06-08	0	100	15	42	0	125	20	6	30	170	160	0
08-10	0	0	30	12	0	0	20	2	160	70	100	0
10-12	0	140	4	2	0	15	2	25	175	25	50	0
12-14	0	150	30	0	40	0	70	0	140	30	35	0
14-16	0	60	20	6	30	0	75	0	50	35	30	50
16-18	0	5	22	15	28	0	100	0	15	40	10	70
18-20	0	0	12	25	0	0	140	35	30	-1	150	40
20-22	0	12	20	15	25	115	80	35	175	25	60	0
22-24	0	25	0	16	25	235	75	6	175	0	65	15
24-26	15	0	15	30	20	0	80	0	185	0	40	50
26-28	48	0	20	2	0	0	90	0	220	10	6	15
28-30	50	0	36	0	12	0	0	0	420	120	0	30
30-32	48	12	80	2	40	0	0	40	120	0	8	10
32-34	0	4	36	162	0	0	40	170	0	50	6	20
34-36	0	0	34	170	0	0	-1	90	15	140	0	120
36-38	6	0	25	45	0	0	12	0	0	110	0	200
38-40	75	12	6	100	0	0	10	0	100	280	0	100
40-42	125	6	29	12	0	0	25	150	60	100	25	90
42-44	25	-1	4	0	0	65	28	180	100	260	35	70
44-46	0	4	75	60	50	115	0	165	200	160	0	2
46-48	0	12	25	62	10	90	0	180	140	0	0	40
48-50	65	15	40	40	0	80	115	175	30	6	0	0
50-52	12	70	2	50	45	25	230	180	0	40	3	2
52-54	0	15	110	0	60	60	90	175	0	35	12	170
54-56	50	65	125	0	0	25	220	65	0	60	25	110
56-58	8	12	200	6	0	40	200	15	40	110	60	20
58-60	4	48	150	12	0	30	190	90	165	0	30	0

Table 2. Characteristics of maneuvering operations for the shift of 03/23-24/2021

Dismantling, 500 tons, 32 axles, 20.24-20.32	Dismantling, 1500 tons, 156 axles, 01.20-02.32
Dismantling, 400 tons, 24 axles, 20.38-20.42	Replenishment, 900 tons, 48 axles, 02.48-03.12
Dismantling, 350 tons, 16 axles, 20.48-20.52	Rearrangement, 700 tons, 44 axles, 03.30-04.32
Replenishment, 1100 tons, 76 axles, 21.04-21.20	Rearrangement, 500 tons, 36 axles, 04.38 - 05.18
Rearrangement, 300 tons, 24 axles, 21.20-21.34	Dismantling, 600 tons, 32 axles, 05.26-06.28
Replenishment, 400 tons, 32 axles, 21.44-22.04	Dismantling, 300 tons, 16 axles, 07.14-07.56
Dismantling, 1000 tons, 156 axles, 22.12-23.04	Traffic reserve/hot standby
Dismantling, 500 tons, 52 axles, 23.14-23.26	Cold standby
Dismantling, 800 tons, 68 axles, 23.32-00.52	

Table 3. Indicators of the average power of the generator of the diesel locomotive ChME3 No. 1190 during work for the shift of 03/24/2021, from 08.00 to 20.00 in kW according to the diagram of the BIC-P system

Minutes	Hours											
	08-09	09-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20
00-02	0	0	0	0	25	50	10	0	0	10	200	0
02-04	0	25	130	120	15	80	35	0	12	20	270	0
04-06	0	30	200	120	20	275	0	18	20	0	20	0
06-08	0	0	160	220	35	150	60	20	18	0	5	0
08-10	0	0	230	70	30	180	12	22	18	0	45	15
10-12	0	15	40	100	0	375	20	25	8	20	50	0
12-14	0	20	8	135	70	0	35	22	10	50	-1	0
14-16	0	15	30	35	20	0	30	22	20	230	10	20
16-18	0	25	20	65	80	0	2	25	35	150	8	50
18-20	0	50	20	30	150	0	75	0	5	75	30	25
20-22	0	0	0	110	40	0	70	12	20	90	35	0
22-24	2	0	20	200	40	15	120	35	0	240	35	10
24-26	35	25	0	150	60	2	180	65	0	80	30	20
26-28	2	30	300	85	65	0	75	25	0	85	0	25
28-30	45	10	150	110	150	165	2	22	10	50	20	0
30-32	45	0	160	75	80	250	12	22	0	2	25	0
32-34	90	15	290	0	25	190	5	60	0	20	20	10
34-36	90	140	260	40	50	40	2	25	0	8	5	35
36-38	85	130	20	35	60	5	35	2	165	40	0	2
38-40	10	220	45	25	8	0	40	225	260	15	45	2
40-42	0	150	250	8	25	80	25	200	270	12	10	0
42-44	2	120	250	25	30	240	8	110	220	15	30	0
44-46	100	8	240	20	0	120	60	5	170	80	25	5
46-48	150	0	170	25	0	230	20	0	120	200	25	0
48-50	165	0	180	100	25	120	35	125	200	120	0	0
50-52	200	160	70	70	0	12	65	240	350	50	15	15
52-54	100	0	0	20	5	28	70	10	225	120	0	0
54-56	165	0	0	20	250	0	70	25	300	20	0	0
56-58	25	0	0	18	350	30	70	15	35	150	8	10
58-60	50	0	0	30	45	50	0	0	110	110	10	30

Table 4. Characteristics of shunting operations for the shift of 03/24/2021

Dismantling, 1500 tons, 68 axles, 8.28-9.02	Dismantling, 900 tons, 40 axles, 13.58 - 14.16
Dismantling, 700 tons, 32 axles, 9.06-9.24	Dismantling, 2000 tons, 84 axles, 14.18 - 15.04
Dismantling, 1900 tons, 224 axles, 9.30-10.22	Dismantling, 1500 tons, 60 axles, 15.18 - 15.56
Dismantling, 3600 tons, 208 axles, 10.24- 11.34	Dismantling, 1000 tons, 56 axles, 15.58 - 16.28
Dismantling, 1600 tons, 80 axles, 11.42- 12.08	Dismantling, 4100 tons, 208 axles, 4:30 - 6:50
Dismantling, 1000 tons, 48 axles, 12.10-12.48	Traffic reserve/hot standby
Dismantling, 2200 tons, 96 axles, 12.50 - 13.22	Cold standby
Dismantling, 3500 tons, 232 axles - 13.26 - 13.56	

Table 5. Indicators of the average power of the generator of the ChME3 diesel locomotive No. 1190 during the shift work on March 24-25, 2021, from 8 p.m. to 8 a.m. in kW according to the diagram of the BIC-P system

Minutes	Hours											
	20-21	21-22	22-23	23-00	00-01	01-02	02-03	03-04	04-05	05-06	06-07	07-08
00-02	0	0	120	0	125	0	15	30	5	150	15	35
02-04	0	2	200	0	150	120	0	25	0	120	0	2
04-06	0	0	260	0	0	60	0	0	100	60	165	0
06-08	0	12	0	0	0	130	0	0	200	0	140	0
08-10	0	15	15	8	0	250	0	20	180	0	55	60
10-12	0	0	35	20	10	110	0	75	0	0	65	140
12-14	0	0	120	190	60	0	0	65	0	0	65	20
14-16	0	0	2	180	0	20	6	35	0	0	140	12
16-18	0	75	18	215	0	40	0	30	2	0	10	10
18-20	0	150	6	210	0	15	0	35	0	0	20	20
20-22	0	0	2	65	0	10	0	12	0	0	18	0
22-24	0	10	0	30	0	5	0	35	20	0	165	20
24-26	0	10	0	50	0	60	0	60	25	0	65	35
26-28	0	2	0	60	0	40	0	30	8	0	0	0
28-30	0	0	0	0	0	0	0	30	0	150	100	0
30-32	0	0	25	0	15	0	0	60	0	75	60	8
32-34	0	80	120	0	90	0	0	20	0	0	120	50
34-36	0	30	10	40	120	5	0	10	15	0	60	0
36-38	0	0	20	80	100	25	0	10	30	25	0	20
38-40	0	0	10	85	60	150	0	60	40	90	0	22
40-42	8	30	8	170	0	40	0	20	380	120	0	0
42-44	15	0	70	70	30	40	0	8	400	55	0	0
44-46	0	2	20	120	35	180	0	8	460	0	0	0
46-48	50	25	18	80	0	8	0	25	110	35	10	0
48-50	275	6	0	0	40	2	0	190	2	0	0	0
50-52	120	0	15	0	2	100	0	20	100	0	0	0
52-54	30	0	140	0	5	320	75	2	0	75	0	0
54-56	45	0	10	0	12	70	240	25	0	2	0	0
56-58	0	0	20	0	90	12	360	5	55	12	0	0
58-60	35	0	0	0	5	6	150	2	100	115	0	0

Table 6. Characteristics of maneuvering operations for the shift of 03/24-25/2021

Dismantling, 104 axles, 2100 tons, 20.44 - 21.06	Dismantling, 224 axles, 4000 tons, 01.50 - 03.02
Dismantling, 80 axles, 1700 tons, 21.10 - 21.44	Rearrangement, 40 axles, 700 tons, 03.04 - 03.32
Dismantling, 228 axles, 3000 tons, 21.50 - 22.46	Rearrangement, 56 axles, 1000 tons, 03.34 - 04.22
Dismantling, 112 axles, 2300 tons, 22.48 - 23.26	Dismantling, 184 axles, 2450 tons, 04.28 - 05.46
Rearrangement, 48 axles, 800 tons, 23.28 - 00.10	Dismantling, 136 axles, 2300 tons, 05.48 - 06.46
Dismantling, 84 axles, 1000 tons, 00.14 - 00.42	Rearrangement, 76 axles, 1200 tons, 07.04 - 07.36
Dismantling, 232 axles, 1600 tons, 00.46 - 01.14	Traffic reserve/hot standby
Dismantling, 96 axles, 1800 tons, 01.16 - 01.46	Cold standby

Fig. 5 shows the power dependence of the generator of diesel locomotive ChME3 No. 1190 during shift operation on March 23-24, 2021, from 8:00 p.m. to 8:00 a.m. (Fig. 5a), on 03/24/2021 from 8:00 a.m. to 8:00 p.m. (Fig. 5b), on 03/24-25/2021 from 8:00 p.m. to 8:00 a.m. (Fig. 5c).

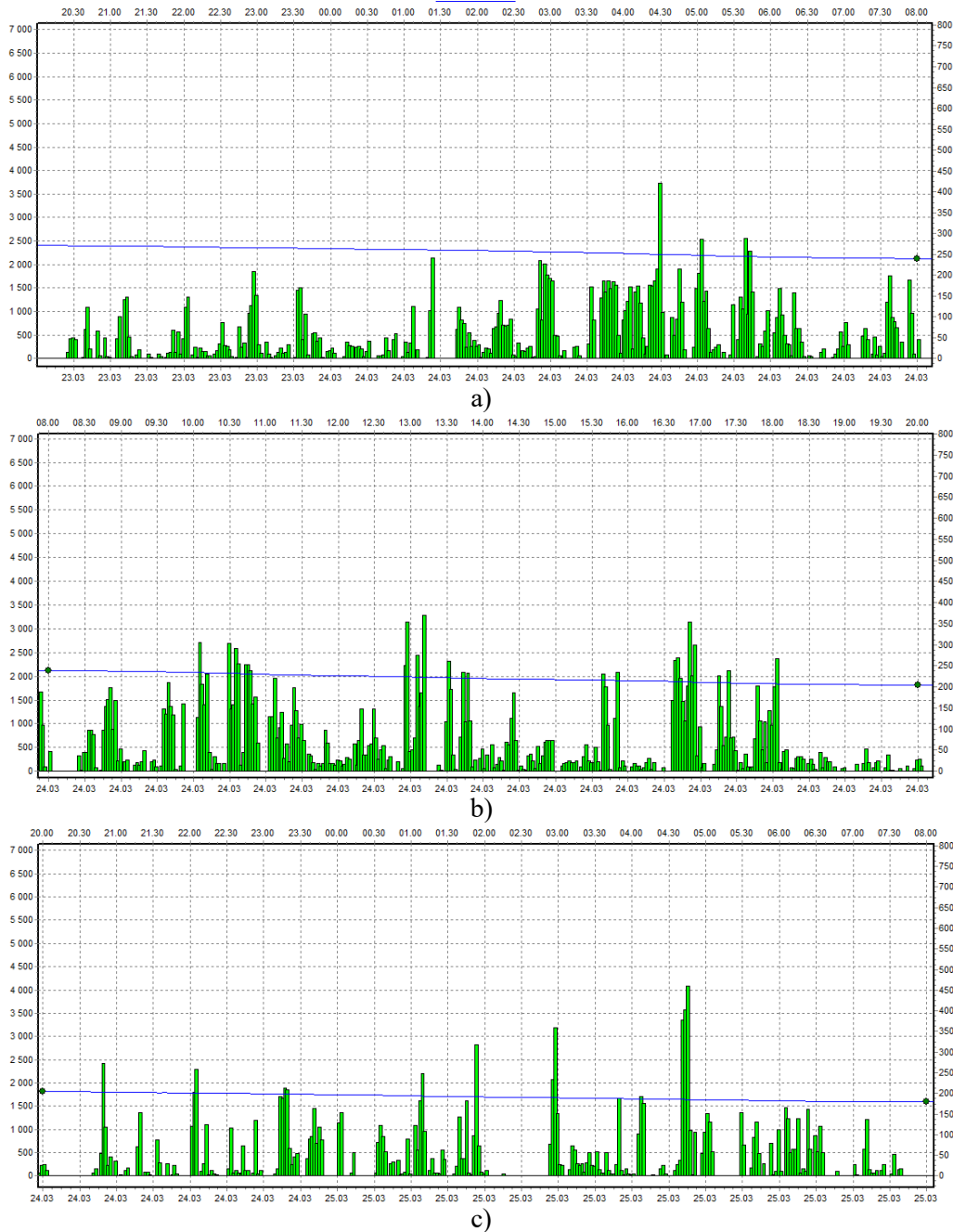


Fig.5. Traction generator power diagrams according to BIC-P system data

In fig. 6 shows the distribution of working time in a certain range of power depending on the total working time in traction mode. It should be noted that the BIC-P registers the average power for 2 minutes of operation, and therefore the actual power cannot be determined from them.

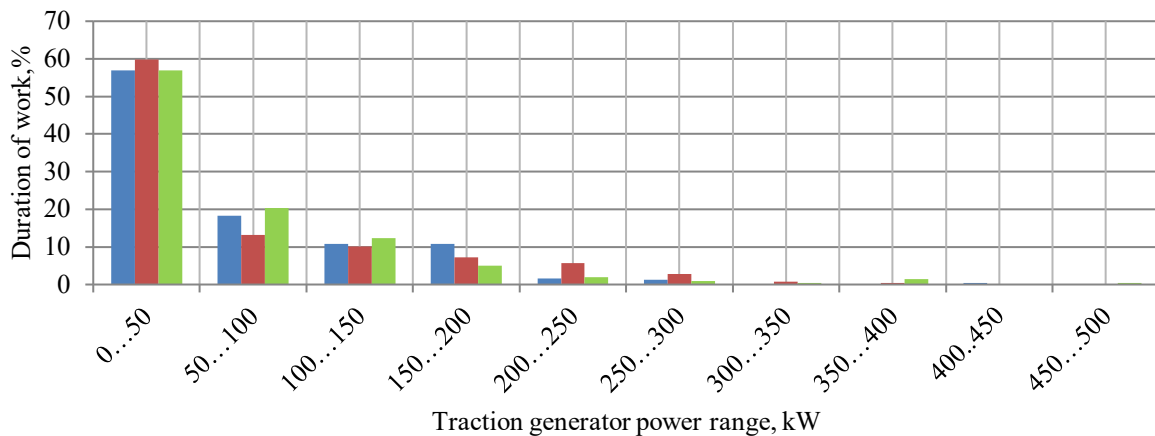


Fig. 6. Distribution of the duration of work (in blue is the data for the 23-24.03.2021 shift, in red - for the 24-24.03.2021 shift, in green - for the 24-25.03 shift)

From fig. 6, it can be seen that for more than half of the working time in the traction mode (both when moving with wagons and when moving in reserve), the average power is within limits that do not exceed 50 kW, with an average power of 50...100 kW, the diesel locomotive works no more than 20% of the time. With larger values - 100...150 kW and 150...200 kW - power duration is 5...10%. With the maximum capacity, the diesel locomotive works at 0.5...1.0%.

The analysis of the mass of trains and groups of wagons shows that they varied from 300 t to 4100 t, and the mass of a significant part belongs to the range of 1000...2000 t. A comparison of the data on power and the type of shunting operation shows that when rearranging wagons, the diesel locomotive works with greater power, than in other types of work. This can be explained by the need to maintain a certain speed of movement, for which it is necessary to spend energy to overcome movement resistance. The operations of formation and de-formation are carried out at speeds close to zero by the method of "shocks", and therefore the energy consumption is related to displacements of the composition from its place and its acceleration. For this case, the position of the driver's controller is selected from the condition of realizing a certain traction force.

Table 7 shows the quantitative indicators characterizing the modes of operation of the diesel locomotive during the investigated shifts, as the following values are used.

The coefficient that determines the full use of the installed capacity of the diesel engine for powering the traction electric drive [35, 36]

$$K_p = \frac{E_F}{E_N}, \quad (1)$$

where E_F – the actual energy that is transmitted to the traction electric motors,
 E_N – theoretical value of the energy that can be given under the condition of operation of a diesel generator with nominal power.

The actual energy supplied to the traction electric motors is determined by the expression

$$E_F = \Delta t \sum_{i=1}^N P_i, \quad (2)$$

where Δt – the time interval over which the power is averaged,
 P_i – power at the i -th reading,
 N – the number of intervals at which traction electric motors are powered.

Accordingly, the theoretical energy value is calculated by the expression

$$E_N = P_N \cdot \Delta t \cdot N, \quad (3)$$

where P_N – power at the generator terminals at the nominal speed of the diesel engine is 890 kW.

The coefficient that determines the full use of the maximum available traction power (for powering the traction electric drive)

$$K_M = \frac{P_{max}}{P_N}, \quad (4)$$

where P_{max} – the highest average power per shift.

Also, from the input data, we determine the duration of shunting operations with wagons, reserve movement, operation of the diesel generator without load (hot idle and coasting) and cold idle. The results are shown in Table 7.

Table 7. Results of experimental data processing

Parameters	Units	Shift	Shift	Shift
		23-24.03.2021	24.03.2021	24-25.03.2021
The actual energy supplied to the traction motors	kWh	576,7	696,3	452,2
Theoretical energy	kWh	7446,3	8277,0	5992,7
Maximum average power	kW	420	375	460
Coefficient K_P	%	7,74	8,41	7,55
Coefficient K_M	%	47,2	42,1	51,7
The duration of shunting operations with wagons during the shift	min	440	496	356
	%	61,2	68,8	49,5
Duration of movement in reserve	min	70	82	52
	%	9,7	11,4	7,2
Duration of operation of the diesel generator without traction load (hot idling and coasting)	min	196	130	266
	%	27,2	18,1	36,9
Duration of cold standby time	min	14	12	46
	%	1,9	1,7	6,4

Figure 7 shows the duration of work modes during the shift. From Table 7 and Fig. 7 it follows that the duration of traction modes when moving with wagons is 49.5...68.8% of the shift duration, the duration of traction when moving with a reserve is 7.2...11.4%. The duration of operation of the diesel engine without a traction load is 18.1...36.9% of the duration of the shift, and falls on both "preparatory" operations, which are necessary for performing maneuvers, and simple "inside" maneuvering operations. From 1.7 to 6.4% of the shift duration, the diesel does not work on the diesel locomotive.

Table 7 shows that the K_P coefficient does not exceed 10%, and the maximum value of the K_M coefficient does not significantly exceed 50%, which indicates that for the studied operating conditions, the full power of the diesel engine is not used.

In general, for the studied case of operation of the ChME3 diesel locomotive in shunting work, it is established:

- its power is redundant,
- more than 50% of the time, the traction electric drive consumes power up to 50 kW, the most demanded power reaches 200 kW, which corresponds to positions 1...4 of the driver's controller, peak power is 460 kW;

- when the weight of the composition increases, work is carried out with higher power values.

Thus, the above information testifies the possibility and expediency of using a less powerful diesel engine on a locomotive in cases of its use, similar to the one under study.

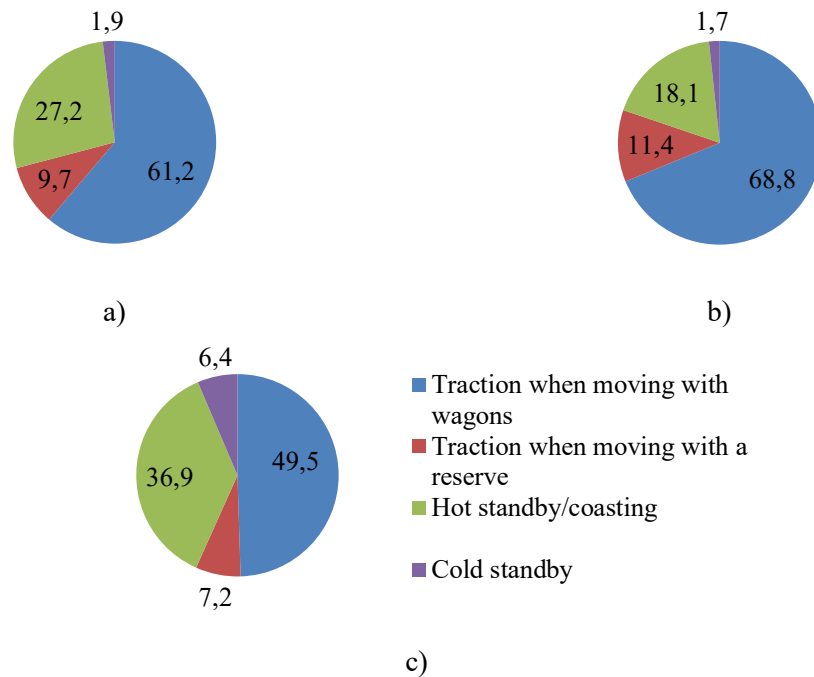


Fig.7. Duration (relative) of locomotive operating modes (a – shift 03.23-24.2021, b – shift 03.24.2021, c – shift 03.24-25.2021)

An important direction of improving the traction and energy characteristics of the locomotive for shunting work is the use of energy-efficient traction electric motors and optimization of their control. Traction motors TE006 are used in ЧМЕ3 diesel locomotive, in accordance with the recommendations [37]. The calculation of their efficiency taking into account the parameters of the external characteristics of the generator at the positions of the driver's controller [38] shows that the efficiency of the electric motors varies from 27% to 50% at high current values, that flow through the traction electric motors, when the locomotive moves and moves at low speeds. And it is precisely these modes of operation that prevail during the "disassembly" of trains on the sorting slide or maneuvers with "shocks". Since such modes of operation are the most common, it is advisable to use traction electric motors that have significantly higher energy efficiency indicators in such modes. The paper [9] proposed the use of asynchronous traction electric motors simultaneously with the replacement of axial gearboxes. In [8], the use of valve-inductor motors is proposed. When creating the HD300 diesel locomotive, synchronous electric motors with excitation from permanent magnets were used [39]. In [40], the structure of the traction system of a hybrid shunting diesel locomotive was investigated.

The wide range of changes in the mass of the train also draws attention, and therefore the possibility of optimizing the number of working traction motors depending on the mass of the trains: it is advisable to turn off part of the traction motors when working with trains of small mass, because this reduces losses in the traction electric drive.

An important aspect of energy saving is the optimization of locomotive auxiliary systems, which can account for up to 20% of total energy consumption. Reduction of energy consumption is provided both by the use of energy-efficient equipment and by controlling its operating modes.

Since energy accumulators can be used on locomotives, in order to reduce operating costs, it is advisable to provide for the possibility of charging the on-board energy accumulator from an external source with a low energy cost [41-44].

Thus, the analysis of the parameters of the operational modes of the ЧМЕ3 diesel locomotive when performing shunting work shows the inconsistency of its characteristics for this work. To improve a diesel locomotive, and even more so when creating a new one, it is necessary to take into account the operating conditions and the application of modern energy-saving technologies.

Conclusions. Modern trends in the modernization and creation of shunting locomotives are considered. Currently, the most common for old diesel locomotives is remotorization with the renewal of traction electrical equipment. When creating new locomotives, hybridization of their power plants is used.

The operating parameters of the shunting diesel locomotive at the Kozyatyn-I station were analyzed. Based on the results of the analysis, it was established that for the studied case of shunting operation, the power of the diesel locomotive is excessive, and its traction electric drive operates with low efficiency. The use of the ChME3 diesel locomotive in such conditions leads to increased consumption of fuel and energy resources for shunting operations.

For the investigated case of shunting work, it is advisable to use a locomotive with a power of about 500 kW. The type and structure of the power plant and traction electric drive must be optimized for low-speed operating conditions.

REFERENCES

1. JSC "Ukrzaliznytsia" (2021). Kontsepsiia (prohnozna) roboty z parkom lokomotyviv AT «Ukrzaliznytsia» do 2033 roku (The concept (forecast) of working with the locomotive fleet of JSC "Ukrzaliznytsia" until 2033). Retrieved from <https://www.railway.supply/wp-content/uploads/2021/08/konczepczya-2033.-yak-ukrzalizniczya-planu%D1%94-zabezpechuvati-sebe-lokomotivami.pdf> [in Ukrainian].
2. Kara, S., Petrenko, V., Prokopenko, P. & Gordienko, T. (2019, March). Doslidzhennia nesuchykh konstrukttsii teplovoziv serii ChME-3 ta vyznachennia mozhlyvosti prodovzhennia terminu yikh ekspluatatsii (Study of load-bearing structures of diesel locomotives of the ChME-3 series and determination of the possibility of extending their service life). *Railway transport of Ukraine*, 3. Retrieved from http://nbuv.gov.ua/UJRN/ZTU_2019_3_4. [in Ukrainian].
3. PJSC "Gaivoronsky Locomotive Repair Plant" (2023). Teplovozy serii ChME3 (Diesel locomotives of the ChME3 series). Retrieved from <https://gtr.com.ua/the-diesel-locomotives-of-the-series-chme3/> [in Ukrainian].
4. LLC "Poltava Locomotive Repair Plant" (2023) Modernizatsiia tiahovoho rukhomoho skladu (Modernization of traction rolling stock). Retrieved from <https://tr.com.ua/modernization-ua/> (in Ukrainian) [in Ukrainian].
5. Volodarets, M. (2011). Analiz vytrat palyva teplovozamy serii ChME-3 ta ChME-3-P pid chas vykonannia manevrovoi roboty (Analysis of fuel consumption by diesel locomotives of the ChME-3 and ChME-3-P series during shunting). *Coll. of science works of DonIERT.*, 27, 99-104 [in Ukrainian].
6. Volodarets, M. (2016). Udoshkonalennia metodiv ta modelei vyznachennia tekhniko-ekonomichnykh pokaznykiv hibrydnykh lokomotyviv (Improvement of methods and models for determining technical and economic indicators of hybrid locomotives). Candidate dissertation. Ukraine State University of Railway Transport, Ukraine. [in Ukrainian].
7. Yarovy, R. (2019) Pidvyshchennia ekspluatatsiinykh kharakterystyk manevrovykh teplovoziv shliakhom vykorystannia kombinovanykh nakopychuvachiv enerhii (Increasing operational characteristics of shunting diesel locomotives by using combined energy storage). Candidate dissertation. Eastern Ukraine national University named after Volodymyr Dahl, Ukraine. [in Ukrainian].
8. Denis, I. (2019). Pokrashchennia dynamichnykh pokaznykiv roboty hibrydnoho teplovozu z ventylno-induktornym pryvodom (Improvement of the dynamic performance of the hybrid diesel locomotive with a valve-inductor drive). Candidate dissertation. State University of Infrastructure and Technologies, Ukraine. [in Ukrainian].
9. Kuznetsov, V., Kardas-Cinal, E., Golebiowski, P., Liubarskyi, B., Gasanov, M., Riabov, I., Kondratieva, L. & Opala, M. (2022) Method of Selecting Energy-Efficient Parameters of an Electric Asynchronous Traction Motor for Diesel Shunting Locomotives—Case Study on the Example of a Locomotive Series ChME3 (ЧМЭ3, CME3, CKD S200). *Energies*, 15, 317-350. <https://doi.org/10.3390/en15010317>.
10. Konarzewski, M., Niezgodna, T., Stankiewicz, M., & Szurgott, P. (2013). Hybrid locomotives overview of construction solutions. *Journal of KONES*, 20, 127-134.
11. Oldknow, K., Mulligan, K. & McTaggart-Cowan, G. (2021). The trajectory of hybrid and hydrogen technologies in North American heavy haul operations. *Rail. Eng. Science*, 29, 233–247. <https://doi.org/10.1007/s40534-021-00242-1>.
12. Alstom (2016a). Alstom to deliver two Prima H3 shunting locomotives to Metrans. Retrieved from <https://www.alstom.com/press-releases-news/2016/2/alstom-to-deliver-two-prima-h3-shunting-locomotives-to-mettrans>.

13. Alstom (2016b) Alstom Platform H3/H4 SBB Aem 940 Lokomotive. Retrieved from https://tst-suisse.ch/wcms/ftp//tst-suisse.ch/uploads/sbbaem940_vortrag_tst_20160609mw.pdf.
14. Kache, M. (2014). Hybridlokomotive – Ein globaler Überblick. Retrieved from https://tu-dresden.de/bu/verkehr/ibb/sft/ressourcen/dateien/forschung/Volltexte_Forschung/ETR_10_2014.pdf?lang=en [in German].
15. Toshiba (2023a). Hybrid Locomotives. Retrieved from <https://www.global.toshiba/ww/products-solutions/railway/locomotives/hybrid.html>.
16. Toshiba (2023b). Hybrid Locomotive Equipped with Energy-Saving Electrical Equipment for European Market. Retrieved from [https://www.global.toshiba/content/dam/toshiba/migration/infrasolution/www/infrastructure/en/railway/assets/pdf/Toshiba%20Review%20\(Hybrid%20Locomotive\).pdf](https://www.global.toshiba/content/dam/toshiba/migration/infrasolution/www/infrastructure/en/railway/assets/pdf/Toshiba%20Review%20(Hybrid%20Locomotive).pdf).
17. RAILINKS (2022) CRRC FXN3D revival hybrid shunting locomotive officially rolled off the production line. Retrieved from <https://www.railinks.cn/crrc-fxn3d-revival-hybrid-shunting-locomotive-officially-rolled-off-the-production-line/>.
18. Eisenbahn-Kurier (2023). Die chinesischen Hybrid-Lokomotiven für die DB. Retrieved from <https://www.eisenbahn-kurier.de/startbeitraege/5845-die-chinesischen-hybrid-lokomotiven-fuer-die-db> [in German].
19. American-Rails.com (2023). Genset/Green Goat Locomotives. Retrieved from <https://www.american-rails.com/gensets.html>.
20. Clayton Equipment (2023). Clayton Equipment secure two Hybrid+™ CBD80 Locomotive order from Sellafeld Ltd. Retrieved from <https://claytonequipment.co.uk/clayton-equipment-secure-two-hybrid-cbd80-locomotive-order-from-sellafeld-ltd/>.
21. Rail Turkey (2023). Turkey's first hybrid loco to unveil. Retrieved from <https://railturkey.org/2018/09/11/turkeys-first-hybrid-loco-to-unveil/>.
22. Express Service (2023a). Diesel Locomotives. Retrieved from <https://lz1866.com/diesel-locomotives>.
23. NRE (2023). New locomotive offerings. Retrieved from <https://nre.com/locomotives/new/>.
24. Honc, R., Fritz, S., Osborne, D., Grisier, R. & Carpenter, S (2009, May). Exhaust Emissions and Fuel Consumption of a Railpower RP20BD Switcher Locomotive. *Proceedings of the ASME 2009 Internal Combustion Engine Division Spring Technical Conference*. In *ASME 2009 Internal Combustion Engine Division Spring Technical Conference*. Milwaukee, Wisconsin, USA (pp. 379-387). ASME. <https://doi.org/10.1115/ICES2009-76026>.
25. Csetvei, G., Csuka, B. & Szóráth, P. (2017) A korszerűsített TEM2 és TGM4B típusú mozdonyok bemutatása. *VASÚTGÉPÉSZET*, 1, 30-38. URL http://vasutgepeszet.hu/wp-content/uploads/vasutgepeszet_2017-1_Csetvei_Csuka_Szorath.pdf.
26. Stobnicki, P. & Gallas, D. (2022). Adoption of Modern Hydrogen Technologies in Rail Transport. *Journal of Ecological Engineering*, 23(3), 84–91 <https://doi.org/10.12911/22998993/145291>.
27. Pesa (2023). The shunting locomotive with a hydrogen drive. Retrieved from <https://pesa.pl/en/produkty/hydrogen-ready/sm42-6dn-hydrogen/>.
28. Green Car Congress (2021) First China-developed hydrogen fuel cell locomotive starts trial runs. Retrieved from <https://www.greencarcongress.com/2021/11/20211102-chinah2loco.html>.
29. O'Connor, L. (1994, April). Building natural gas locomotives. *Mechanical Engineering-CIME*, 116(4), 82-87. Retrieved from <https://link.gale.com/apps/doc/A15178179/AONE?u=anon~d030b0bf&sid=googleScholar&xid=a0737a91>.
30. Chojnacki, A. (2022). First Battery-Powered Shunting Locomotive Produced in Poland Advanced Rail Technologies. *IK Newsletter: April, May, June*.
31. International Mining (2023). Vale receives second 100% battery electric locomotive – this time from China's CRRC Zhuzhou. Retrieved from <https://im-mining.com/2022/05/02/vale-receives-second-100-battery-electric-locomotive-this-time-from-chinas-crrc-zhuzhou/>.
32. Progress Rail (2023). EMD® Joule Battery Electric Locomotives. Retrieved from <https://www.progressrail.com/en/Segments/RollingStock/Locomotives/FreightLocomotives/EMDJoule.html>.
33. Express Service (2023b). Battery Locomotives. Retrieved from <https://lz1866.com/battery-locomotives>.
34. Riabov, I., Overianova, L., Iakunin, D., Bilokon, I., & Goolak, S. (2022). Zastosuvannia Manevrovoykh Elektrovoziv Dlia Peredatnoi Ta Vyviznoi Roboty (Application of Maneuvering Electric Locomotives for Transmission and Export Work). *Transport systems and technologies*, 40, 47-62. <https://doi.org/10.32703/2617-9040-2022-40-5>. [in Ukrainian].
35. Syrotenko, Yu. (2014). Vyznachennia potuzhnosti manevrovoho teplovoza z urakhuvanniam mistisia yoho ekspluatatsii (Determining the power of a shunting diesel locomotive taking into account the place of its operation). *Eastern European journal of advanced technologies*, 1(8), 41-45 [in Ukrainian].
36. Kondratieva, L., Bogdanovs, A., Overianova, L., Riabov, I., Goolak, S., (2023). Determination of the working energy capacity of the on-board energy storage system of an electric locomotive for quarry railway transport during working with a limitation of consumed power. *Archives of Transport*, 65(1), 119-135. <https://doi.org/10.5604/01.3001.0016.2631>.
37. Tsyplenkov, D.V.; Ivanov, O.B.; Bobrov, O.V.; Kuznetsov, V.V.; Artemchuk, V.V. & Babyak, M.O. (2020) Proiektuvannia elektrychnykh mashyn: navch. posib (Design of electric machines: training. manual). *National technical university "Dniprovskaya Polytechnic", Dnipro: NTU "DP"*. [in Ukrainian]
38. Zayonchkovsky, V. M.; Masliev, V.G. & Yakunin D.I. (2008). Zahalna budova, teplovi rozrakhunky enerhetychnykh ustanovok i pytannia tekhnologii vyhotovlennia ekipaznoi chastyny teplovoziv [Tekst] (General structure, thermal calculations of power plants and issues of manufacturing technology of the crew part of diesel locomotives [Text]). *National Technical University "Kharkiv Polytechnic Institute", Kharkiv: NTU "KhPI"*. [in Ukrainian].

39. Ogawa, T., Kanno, H., Soeda, T. & Sugiyama, Y. (2012). Environmental evaluation of a diesel hybrid shunting locomotive. *2012 Electrical Systems for Aircraft, Railway and Ship Propulsion*, Bologna, Italy, 1-6, <https://doi.org/10.1109/ESARS.2012.6387402>.

40. Serhiy, B., Artem, M., & Danylo, P. (2019, September). Searching of the optimum configuration of the traction electric transmission of the shunting locomotive. In *2019 IEEE International Conference on Modern Electrical and Energy Systems (MEES)* (pp. 22-25). IEEE. <https://doi.org/10.1109/MEES.2019.8896525>.

41. Wu, J., Ji, Q., Zhang, C., Zhu, Z., Zhao, B., & Yin, Z. (2021). Design and Modeling of Diesel-Electric Hybrid Shunting Locomotive. In *The Proceedings of the 9th Frontier Academic Forum of Electrical Engineering* (Vol. 1, pp. 655-665). Springer Singapore. https://doi.org/10.1007/978-981-33-6606-0_60.

42. Novák, J., Sadílek, O. & Mašek, Z. (2019) Battery Charger for Hybrid Locomotive. *Transactions on Electrical Engineering*, 8(3), 40-43 <https://doi.org/10.14311/TEE.2019.3.040>

43. Butko, T., Babanin, A., & Gorobchenko, A. (2015). Rationale for the type of the membership function of fuzzy parameters of locomotive intelligent control systems. *Eastern-European Journal of Enterprise Technologies*, 1(3), 4-8. <https://doi.org/10.15587/1729-4061.2015.35996>.

44. Gorobchenko, O., & Nevedrov, O. (2020). Development of the structure of an intelligent locomotive DSS and assessment of its effectiveness. *Archives of Transport*, 56(4), 47-58. <https://doi.org/10.5604/01.3001.0014.5517>.

Сергій Гулак¹, Ігор Костенко², Robertas Keršys³, Євген Рябов^{4*}, Олександр Демидов⁵

¹Доцент, Кафедра «Електромеханіка та рухомий склад залізниць», Державний університет інфраструктури та технологій, вул. Кирилівська, 9, м. Київ, 04071, Україна, ORCID: <https://orcid.org/0000-0002-2294-5676>

²Аспірант, Кафедра «Електромеханіка та рухомий склад залізниць», Державний університет інфраструктури та технологій, вул. Кирилівська, 9, м. Київ, 04071, Україна, ORCID: <https://orcid.org/0009-0007-1156-8661>

³Доцент, Кафедра «Транспортна інженерія», Каунаський технологічний університет, вул. Студентська, 56, Каунас, LT-51424, Литва, ORCID: <https://orcid.org/0000-0001-7785-722X>

⁴Доцент, Кафедра «Електричний транспорт та тепловозобудування», Національний технічний університет «Харківський політехнічний інститут», вул. Кирпичова, 2, м. Харків, 61002, Україна, ORCID: <https://orcid.org/0000-0003-0753-514X>

⁵Старший викладач, Кафедра «Електричний транспорт та тепловозобудування», Національний технічний університет «Харківський політехнічний інститут», вул. Кирпичова, 2, м. Харків, 61002, Україна, ORCID: <https://orcid.org/0000-0003-0532-9748>

Аналіз режимів експлуатації маневрових тепловозів при виконанні маневрової роботи

Виконано огляд сучасних напрямів оновлення маневрових локомотивів, які засновані на застудванні бортових накопичувачів енергії, багатодизельних силових енергетичних установок, енергетичних установок на основі водневих джерел енергії. Показано необхідність врахування умов експлуатації маневрового тепловоза при виборі варіанту оновлення. Розглянуто режими експлуатації маневрових тепловозів при виконанні маневрових операцій на вантажній станції Козятин-І протягом трьох змін. Шляхом аналізу даних бортової системи БІС-Р та опрацювання маршрутних листів визначено параметри експлуатаційних режимів. Виконано розрахунки показників використання потужності дизельного двигуна, за якими встановлено, що повноту використання встановленої потужності дизель-генератора складає 7,5...8,4%, а максимальна потужність дизеля, яка зафіксована у досліджуваних умовах експлуатації, складає близько 50%. Тривалість роботи з тягових навантаженням складає 49,5...68,8% часу зміни. Найбільш тривалими – 55...60% загальної тривалості роботи під тягою – є режими з потужністю 0...50 кВт. Тривалість роботи без навантаження складає 18,1...36,9% тривалості зміни. Виконувана маневрова робота пов'язана з формуванням і розформуванням составів, у тому числі з використанням сортувальної гірки, внаслідок чого тягова передача потужності працює з низьким коефіцієнтом корисної дії. Для зниження споживання паливно-

енергетичних ресурсів при виконанні маневрової роботи необхідно оновлення парку локомотивів для маневрової роботи, характеристики яких адаптовані до режимів експлуатації.

Ключові слова: *гібридний тепловоз, модернізація, маневрова робота, енергоефективність, накопичувач енергії*

Anton Ozulu¹, Boris Lyubarsky²

¹ Ph.D. student, Department of Electric Transport and Diesel Engineering, National Technical University "Kharkiv Polytechnic Institute", st. Kirpychova, 2, Kharkiv, 61002, Ukraine, ORCID: <https://orcid.org/0000-0001-9524-8006>.

² Professor, Department of Electric Transport and Diesel Engineering, National Technical University "Kharkiv Polytechnic Institute", st. Kirpychova, 2, Kharkiv, 61002, Ukraine, ORCID: <http://orcid.org/0000-0002-2985-7345>.

*Author responsible for correspondence: anton.ozulu96@gmail.com

Calculation of the parameters of the electromechanical shock absorber of the high-speed electric train

The article examines the issue of the chassis system of a high-speed electric train with body inclination and a vibration recovery system. The advantages of using an electromechanical shock absorber over hydraulic, pneumatic and similar systems are described. The authors considered the main characteristics of the DC electromechanical shock absorber. The main overall parameters of the shock absorber were presented. Attention is paid to the relevance of using an electromechanical shock absorber of a linear type, in comparison with analogues, including the ability to recover energy. Attention is drawn to the structure of the DC electromechanical shock absorber. The functional control scheme of the electromechanical shock absorber is considered and the control algorithm is described. The calculation areas of the parameters of the electromechanical shock absorber are determined. A 3D model of an electromechanical shock absorber in the Ansys Electronics software environment is presented. A finite-element mesh was built for further calculations of the magnetic field and inductance. In the article, attention is paid to the calculation of the magnetic field in the most intense mode. A picture of the shock absorber's magnetic field at the maximum working clearance was obtained and interim results were discussed. The results of calculating the inductance depending on the operating gap of the shock absorber are presented. Conclusions were made based on the results of calculations of magnetic and electrical parameters of an electromechanical shock absorber based on a linear direct current motor.

Keywords: *electromechanical shock absorber, recuperation, body tilt, electric rolling stock, oscillations.*

Introduction. Modern railway transport is a complex logistics system that requires solving issues related to traffic safety and the speed of electric rolling stock, which is primarily determined by its driving performance [1]. These indicators depend on many factors: the traction system, which over time has undergone many improvements in the control system, the traction motor and the undercarriage system (suspension) [2, 3].

One of the ways to increase the speed of rail transport is the use of electric rolling stock with body tilting mechanisms. This technology allows you to significantly increase the speed of trains when passing curved sections of the path, which is an alternative to creating a new infrastructure for high-speed railways. The prospect of applying body tilting technology for high-speed traffic is confirmed by the successful operation in 15 countries of the world of more than 60 types of trains, which are created by the world's leading manufacturers of railway electric rolling stock.

The application of the technology of tilting car bodies in railway rolling stock has a history of more than 50 years. The first studies and experiments on reducing the centrifugal force affecting passengers and increasing the speeds of movement in curves were carried out from the end of the 1930s by the

companies Deischl and Van Dorn & Beemer. In 1938, the Pullman Palace Car Company built an experimental car with a tilting body, but the lack of vibration damping provoked the appearance of symptoms of "seasickness" in passengers. In 1956, the Pullman Palace Car Company built two Train-X trains, the first tilting trains in commercial operation. These trains were equipped with a passive body tilt drive and were withdrawn from service after a short period of time due to unsatisfactory running qualities [4].

Analysis of recent research and problem statement. In high-speed trains, pneumatic, hydraulic, and electromechanical systems are used as body tilt drives, which have few advantages and disadvantages [5]. The hydraulic system has a large number of lines and devices that work under high pressure, which reduces the overall reliability of the system and increases the likelihood of leaks of the working fluid. The pneumatic system, the device of which, in fact, is similar to the hydraulic one, has an increased activation time due to the low density of the working medium - air. However, its elements are directly present in every type of pneumatic spring suspension without which it is already impossible to imagine modern high-speed electric trains. The electromechanical system used on modern trains does not provide the ability to independently return the body to its original position in the event of a power outage or other emergency situations, which directly affects traffic safety. Also, a large amount of energy is required for the operation of the described body tilting systems [6].

Currently, there are many energy accumulators in trains, which can be additionally fed with the energy that occurs when damping oscillations with an electromechanical shock absorber [7, 8].

Thanks to the installation of an electromechanical system of tilting the body and recovery of oscillations in the undercarriage of electric locomotives, it is possible to increase the carrying capacity of the railway, thereby solving the problem of long-term passenger transportation in Ukraine. When using this system together with the pneumatic system, it is possible to cover the entire frequency range of oscillations and stabilize the oscillatory characteristics of the body, which will increase the comfort for passenger transportation [9].

It was previously determined that the use of a direct current electromechanical shock absorber can provide several functions: tilting of the body when turning with rolling stock, and recuperation of oscillations, which will ensure the accumulation of energy for its own needs [10]. At the same time, the system requires less maintenance than pneumatic or hydraulic systems, and is less complicated to operate.

The electromechanical shock absorber control system can be based on a microcontroller that can monitor the angle of the body relative to the horizon in real time, and perform its work both on the basis of algorithms and on the basis of artificial intelligence [11].

The purpose and tasks of the research. Presentation of the main weight and size characteristics of an electromechanical shock absorber. Construction of a 3D model of an electromechanical shock absorber in the Ansys Electronics software environment for calculating the inductance of the stator windings at a different set angle of inclination of the body (working gap of a linear motor) [12]. Obtaining a picture of the magnetic field of an electromechanical shock absorber in the working range.

Research materials and methods. The electromechanical drive, which is installed in the suspension system of moving vehicles (usually automotive equipment [13]) is a combination of a stepping electric motor, a reducer and a screw pair that ensures linear movement of the rod. The presence of a screw pair in this type of drive eliminates self-return of the body to its initial position due to its jamming when the power is turned off. However, this type of power drive has balanced weight and size indicators, high speed, low maintenance, and a wide range of adjustment. This led to the use of an electromechanical drive on most trains with tilting bodies currently produced.

Air-spring suspension meets the requirements of electric rolling stock, but requires additional equipment and its maintenance, therefore, an electromechanical shock absorber can be part of the chassis of a high-speed electric train together with air-spring suspension, which will allow covering the entire range of oscillations [14, 15]. The most effective application of an electromechanical shock absorber is when damping frequencies in the range of 1-500 Hz. A comparison of a synchronous type linear motor

and a direct current linear motor was considered, where the advantages of a linear motor were described. First of all, it is ease of management and maintenance.

Thus, let's focus on the design shown in fig. 1.

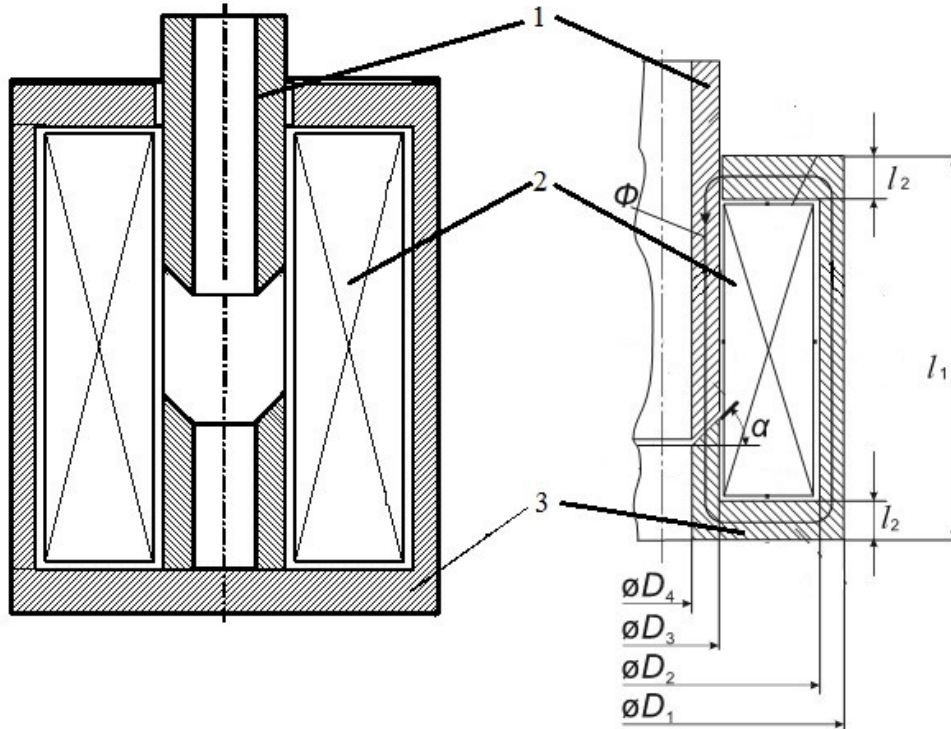


Fig. 1. DC electromechanical shock absorber: 1 – anchor; 2 – stator winding; 3 – stator

Table 1 shows the main overall characteristics of the electromechanical shock absorber.

Table 1. The main overall characteristics of the electromechanical shock absorber

Parameter	Value	Notes
D_1	450 mm	The diameter of the electromechanical shock absorber
D_2	400 mm	The diameter to the end of the stator winding
D_3	292 mm	The diameter of the anchor assembly
D_4	110 mm	The diameter of the anchor pipe
l_1	510 mm	The length of the electromechanical shock absorber
l_2	56 mm	The length to the stator winding
α	5°	The angle of inclination of the tip of the anchor

This type of motor is distinguished by its simple design, the stator winding has one phase.

The functional diagram of the control system for two linear direct current motors is shown in figure 2. The motors are controlled as follows: a AC voltage to the diode rectifier (block 1), after which a direct current voltage is obtained at the output of the block and passes to the direct current (DC) link (DCL - block 2). The DCL includes a passive filter, namely: a capacitor and an inductor. The DCL is connected to the thyristor blocks (block 4, 5), which supply voltage to the linear motors (block 6, 7). Thyristors are controlled by a microcontroller block (MC - block 3), while the optimal pulse width modulation (PWM) frequency is 1-3 kHz [16, 17]. Measuring the angle of inclination relative to the horizon can be done using an accelerometer, which can provide initial position information, and a gyroscope, which measures angular velocity.

The control scheme is similar to the control scheme of a synchronous linear motor, but differs in the absence of transistors and the presence of thyristors, which reduces the cost of the control system. At the same time, the force is practically not affected by the position of the anchor relative to the frame, which ensures the stability of the damping forces in the case of gaps between the body and the trolley.

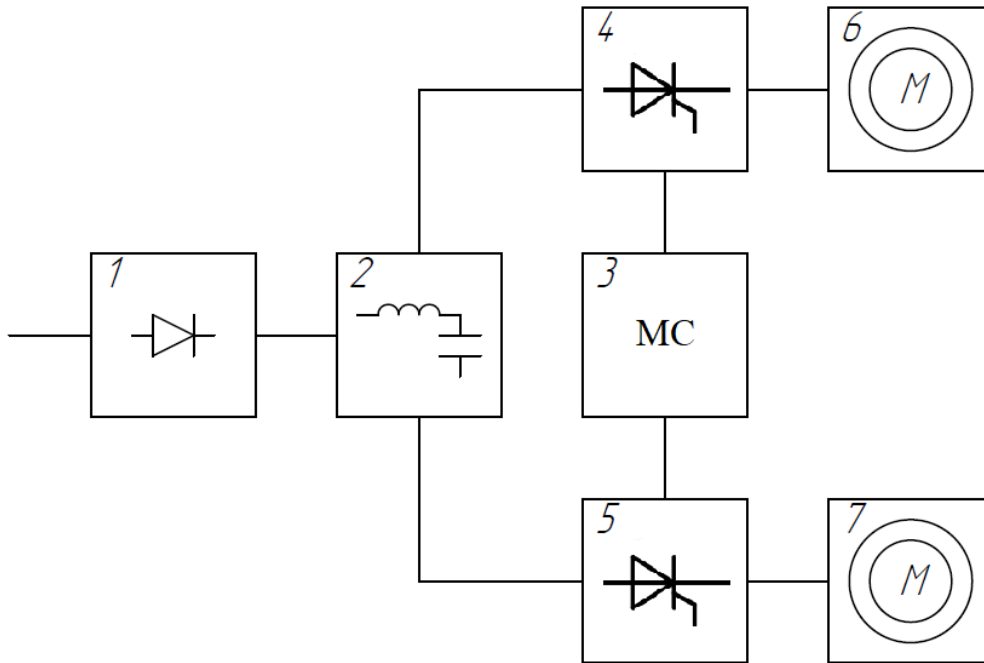


Fig. 2. Functional control scheme of a direct current linear motor

The calculated range of electromechanical shock absorber parameters consists of the following parts:

- subarea of the stator of the electric motor (Fig. 5): material – electrical steel 2211;
- subarea of the electric motor armature (Fig. 5): material – electrotechnical steel 2211;
- subarea of the armature winding of the electric motor (Fig. 5): the material is copper, while the magnetomotive force (MMF) of the armature is 70,000 A (working gap 70 mm), with the number of turns 175;
- subarea of the air (Fig. 5): material – air;
- an additional subarea of the working gap of the electric motor (Fig. 5): the material is air, which is necessary for the correct calculation of the magnetic field in the air gap.

At the same time, the steel filling ratio is 0.95; the sheet thickness is 0.5 mm for both the stator and the armature.

The calculation of the magnetic field by the finite element method was carried out using the Ansys Electronics software complex.

Based on the maximum angle of inclination of the high-speed electric train body; and the traction and loading characteristics of the electromechanical shock absorber, which is presented in Figure 3 (where x is the working clearance of the linear shock absorber), it is rational to obtain a picture of the magnetic field in the most intense mode of operation of the tilt drive - critical and modes close to it at a maximum tilt angle of 7° , which is equal to the working gap of 70 mm. At the same time, for further simulations of the slope and recovery of oscillations in the MATLAB Simulink software environment, and the obtained polynomial, the inductance calculation must be performed over the entire operating range of the electromechanical shock absorber, which corresponds to the value from 0 to 70 mm, with an optimal step of 5 mm.

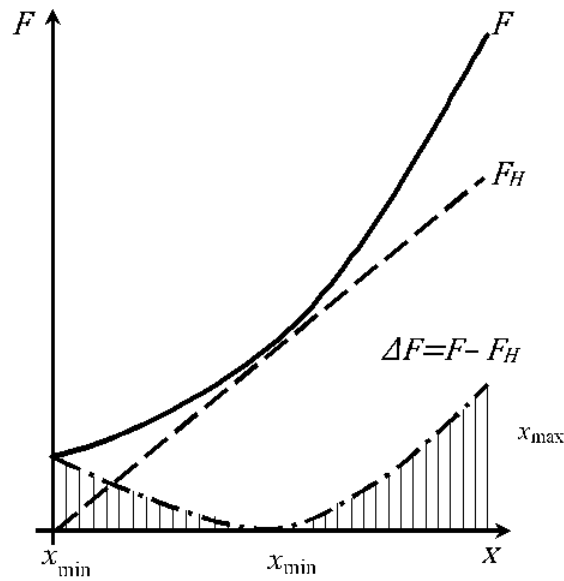


Fig. 3. Traction and loading characteristics of an electromechanical shock absorber

A 3D model of an electromechanical shock absorber was built in the Ansys Electronics software environment, which is presented in Figure 3.

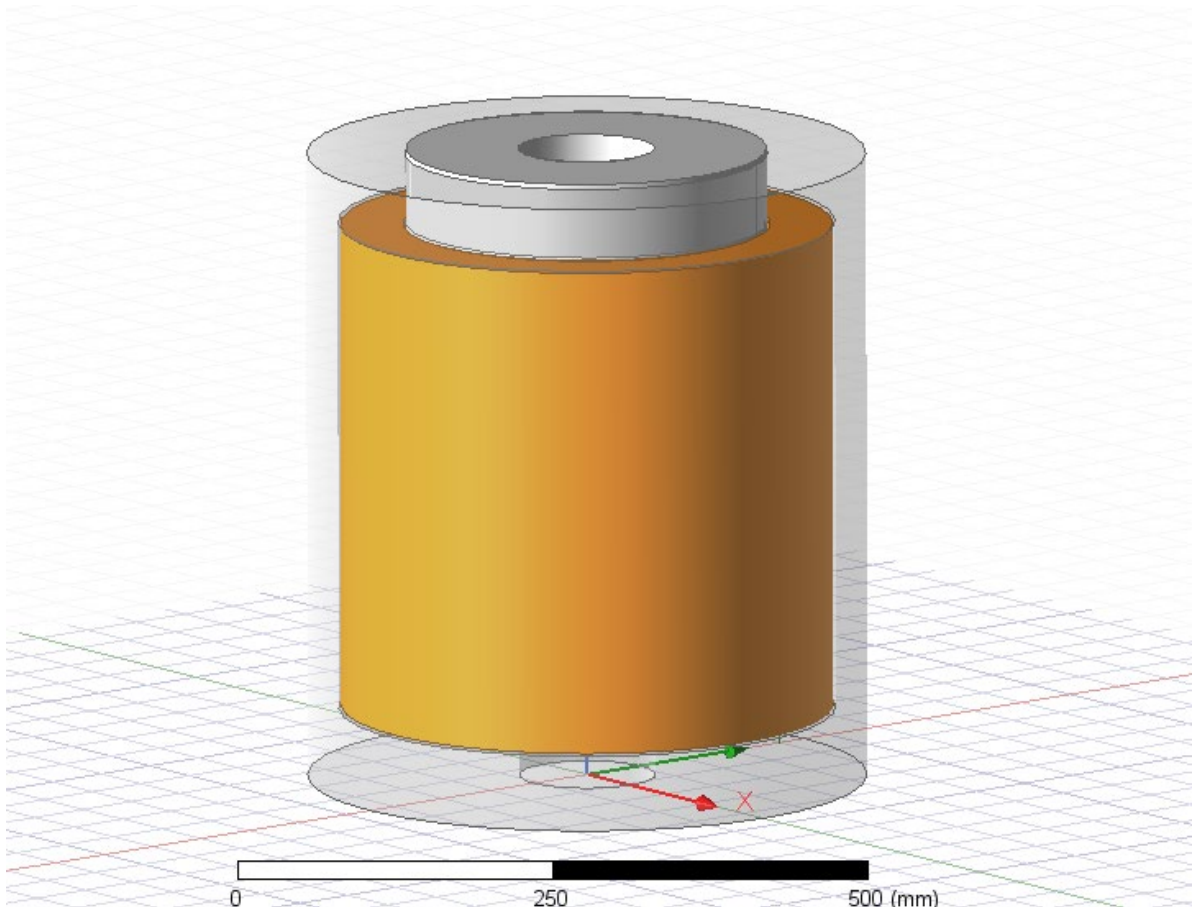


Fig. 4. 3D model of an electromechanical shock absorber (working gap 0 mm)

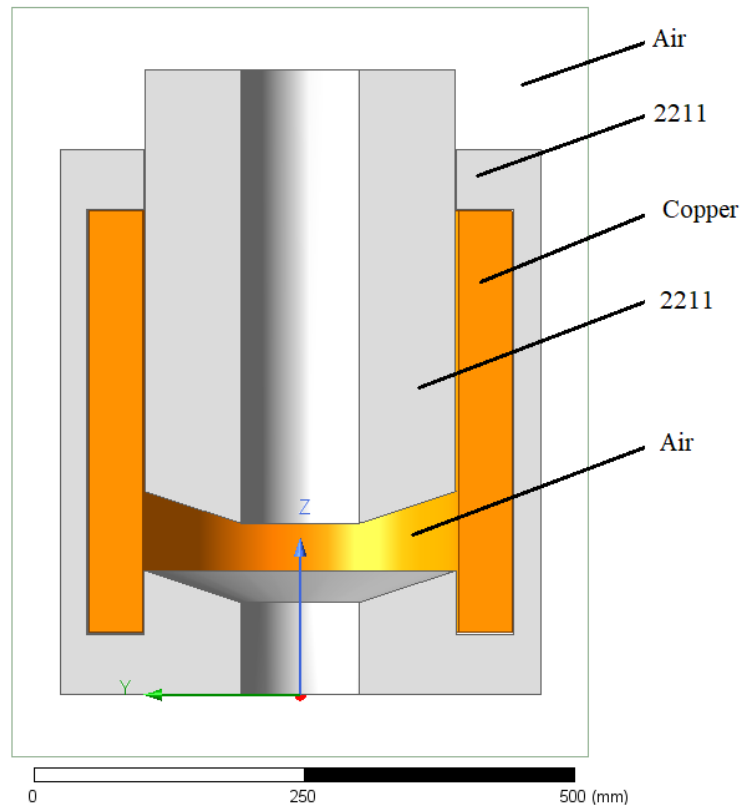


Fig. 5. Cross-sectional model of an electromechanical shock absorber (working clearance 70 mm)

In fig. 5 shows the resolution of the problem of calculating the magnetic field using the finite element method in an axially symmetric form. To limit the calculation area, an additional surface is introduced, which when setting the problem is Region (Fig. 3).

To correctly calculate the electromagnetic force, it is necessary to calculate the magnetic field in the air gap. The following mesh generation parameters are set: for the sub-region of the working gap, the initial radius of the mesh generation is 0.5 mm, and for other sub-regions, it is set to adaptive (Fig. 7).

Electrical steel 2211 has a magnetization curve, which is presented in the figure 6.

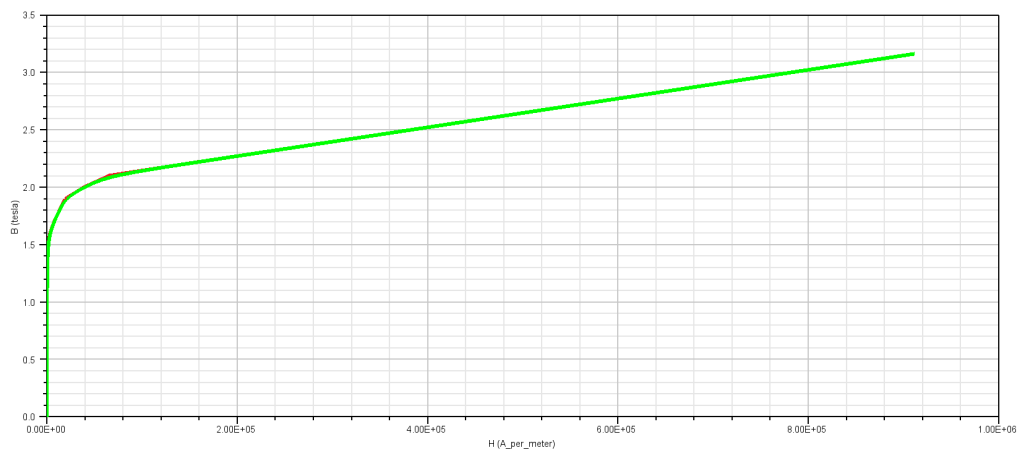


Fig. 6. The main magnetization curve of electrical steel 2211

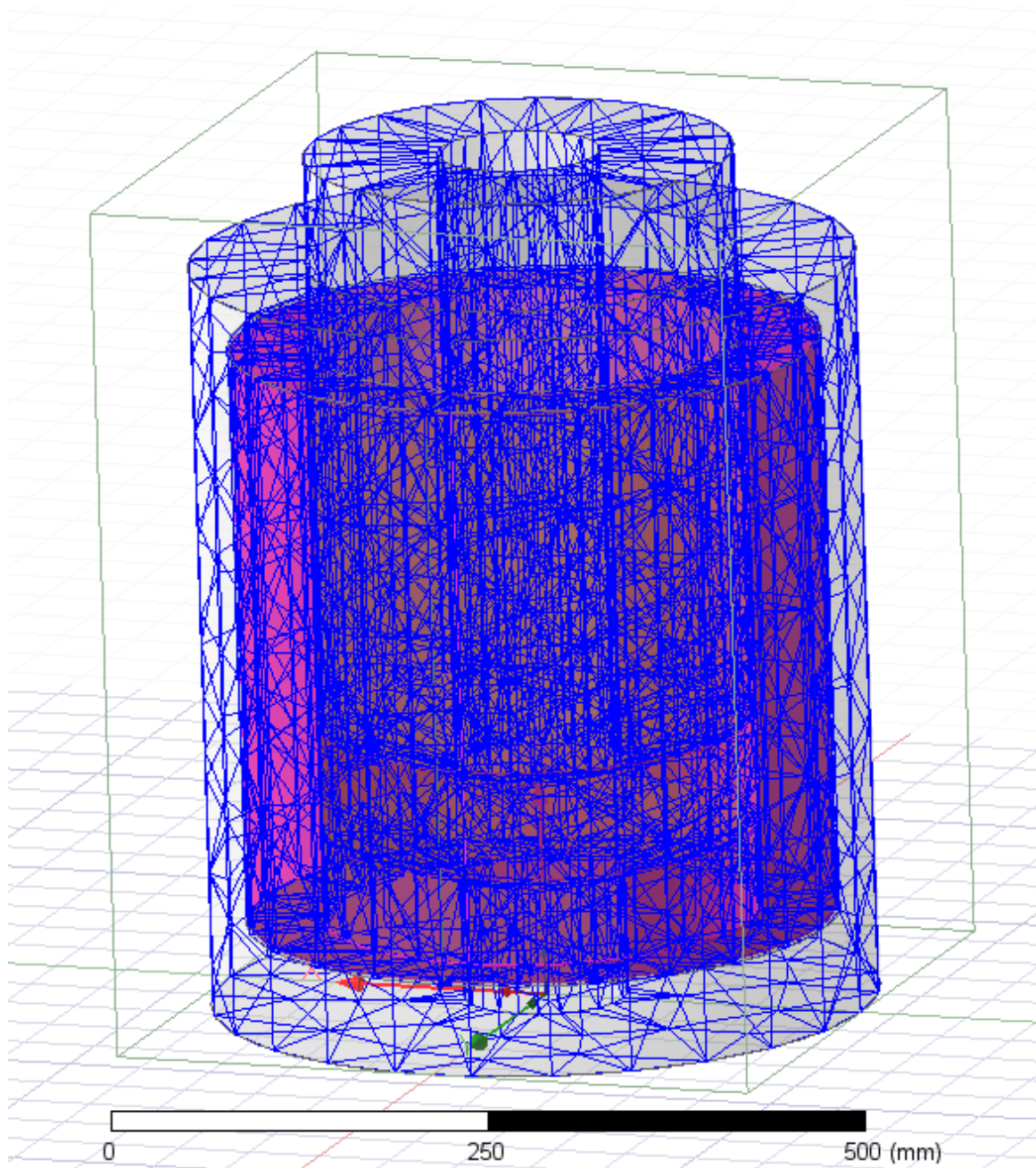


Fig. 7. Finite element mesh

Maxwell's stress tensor determines the force on a unit area due to the magnetic field on the surface. The differential force is calculated according to the formula 1.

$$dF = \frac{1}{2} [H_m \cdot (B \cdot n) + B \cdot (H_m \cdot n) - (H_m \cdot B) \cdot n_m], \quad (1)$$

where n means the normal state of the direction to the surface at the calculated point, B , H_m – magnetic field induction and stress at the calculated point.

Further, in the paper, calculations of the magnetic field for an air gap of 70 mm were carried out using the finite element method. Pictures of magnetic fields are given in the figure 8.

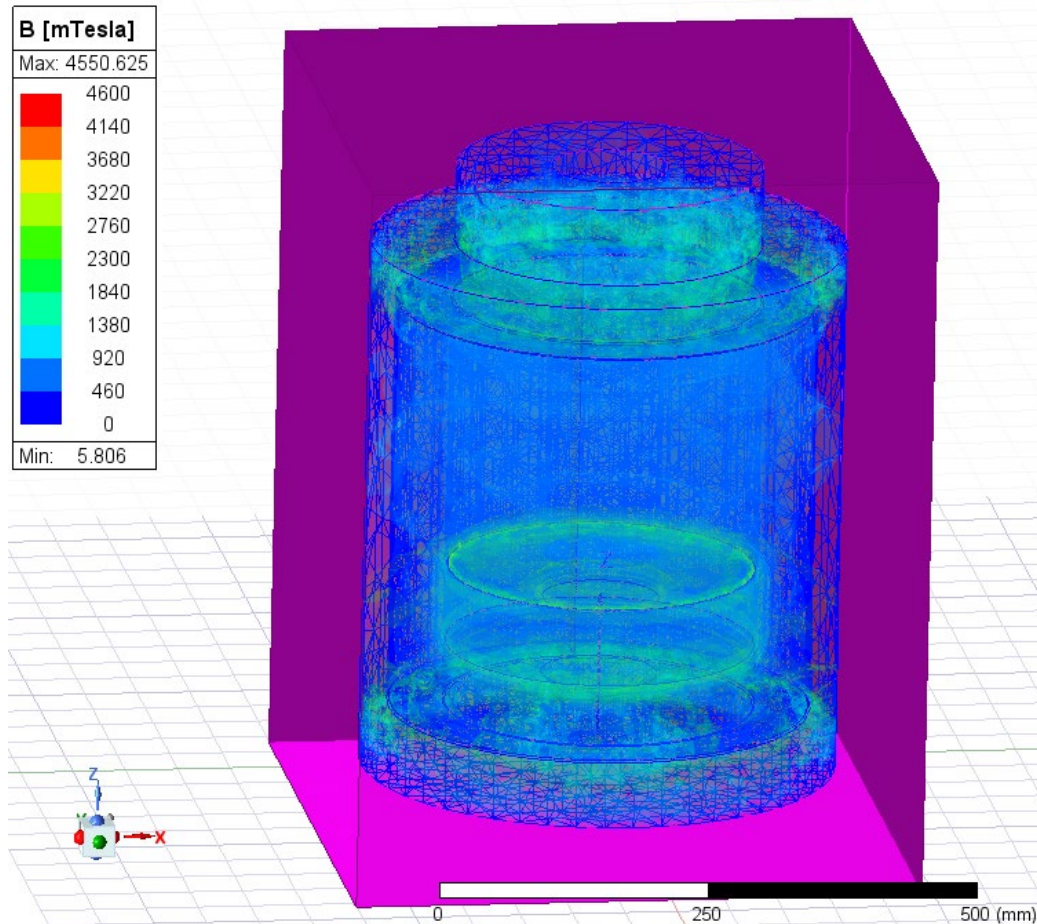


Fig. 8. The model of the coaxial linear direct current electromagnetic type motor and the results of the calculation of the magnetic field at a maximum working gap of 70 mm

Based on the obtained result of the calculation of the magnetic field of the electromechanical shock absorber with a maximum working gap of 70 mm, and the data from Figure 6, namely, the main magnetization curve of electrical steel 2211, we can fully conclude that in the most critical mode of operation from body inclination and vibration recovery (the angle of inclination is 7°), the magnetic wire does not enter the saturation mode, which will provide us with the predicted operation of the shock absorber as part of the suspension system of the high-speed electric train.

Further, in the work, the inductance of the linear type electromechanical shock absorber was calculated depending on the working gap of the shock absorber in the Ansys Electronics (Magnetostatic) software environment:

- the range of the working gap of the shock absorber 0 mm-70 mm;
- the step of the working gap is 5 mm.

The result of calculating the inductance with a maximum working gap of 70 mm is presented in Figure 8. The results of calculating the inductance in the entire given range are presented in Table 2.

	\$move	Matrix1.L(Winding1,Winding1) [mH] Setup1 : LastAdaptive
1	0.000000	32.066860

Fig. 8. The result of calculating the inductance of the shock absorber with a maximum working gap of 70 mm

Table 2. The result of the calculation of the inductance of the electromechanical shock absorber depending on the working gap (range of the working gap 0 mm-70 mm)

№	Working gap of the shock absorber, mm	Inductance, mH
1	0	40,6
2	5	39,8
3	10	39,1
4	15	38,9
5	20	37,7
6	25	37,2
7	30	36,7
8	35	35,9
9	40	35,4
10	45	34,8
11	50	34,4
12	55	33,6
13	60	33,3
14	65	32,6
15	70	32,1

Conclusions.

1. An alternative system of the undercarriage of a high-speed electric train is presented, which will allow performing the work of tilting the body and recuperating vibrations, and at the same time have a number of advantages over hydraulic and pneumatic systems, including in terms of speed and ease of maintenance.

2. A 3D model of an electromechanical DC shock absorber was built in the Ansys Electronics software environment. The criteria of the finite-element mesh, calculation zones, etc. are defined.

3. The results of the calculation of the magnetic field at the maximum operating gap of the electromechanical shock absorber of 70 mm are presented, showing the maximum value of induction in the steel of the shock absorber of 2.2 T, i.e., it does not enter the saturation mode, which ensures the predicted operation of the shock absorber.

4. Calculations of the inductance of the electromechanical shock absorber depending on the angle of tilt of the body in the range from 0° to 7° (the working gap of the electromechanical shock absorber in the range from 0 mm to 70 mm) are presented, from which a polynomial will be obtained in the future and synthesized into a mathematical model of a high-speed electric train in the software MATLAB Simulink environment.

REFERENCES

1. Michell, M., Martin, S. & Laird, P. (2014). Building a railway for the 21st century: bringing high speed rail a step closer. In *Conference on Railway Excellence, Proceedings* (pp. 612-621). Australia: Railway Technical Society of Australasia.
2. Goolak, S., Liubarskyi, B., Saponova, S., Tkachenko, V., Riabov, I., & Glebova, M. (2021). Improving a model of the induction traction motor operation involving non- symmetric stator windings. *Eastern-European Journal of Enterprise Technologies*, 4(8(112)), 45-58. <https://doi.org/10.15587/1729-4061.2021.236825>.
3. Liubarskyi, B., Petrenko, O., Iakunin, D., & Dubinina, O. (2017). Optimization of thermal modes and cooling systems of the induction traction engines of trams. *Eastern-European Journal of Enterprise Technologies*, 3(9(87)), 59-67. <https://doi.org/10.15587/1729-4061.2017.102236>.
4. Smith, R.A., & Zhou, J. (2014). Background of recent developments of passenger railways in China, the UK and other European countries. *Journal of Zhejiang University Science A*, 15, 925–935.
5. Karimi Eskandary, P., Khajepour, A., Wong, A., & Ansari, M. (2018). Analysis and optimization of air suspension system with independent height and stiffness tuning. *International Journal of Automotive Technology*, 5, 807–816. <https://doi.org/10.1007/s12239-016-0079-9>.

6. Yeritsyan, B. (2016). Syntez kombinovanoyi systemy nakhyly kuzova shvydkisnoho elektrychnoho rukhomoho skladu [Synthesis of the combined body tilt system of high-speed electric rolling stock]. *Doctor's thesis. Kharkiv: NTU "KhPI"* [in Ukraine].
7. Yatsko, S., Sidorenko, A., Vashchenko, Y., Lyubarskyi, B., & Yeritsyan, B. (2019). Method to improve the efficiency of the traction rolling stock with onboard energy storage. *International Journal of Renewable Energy Research*, 9(2), 848-858.
8. Zuo, L., Scully, B., Shestani, J., & Zhou, Y. (2010). Design and characterization of an electromagnetic energy harvester for vehicle suspensions. *Smart Materials and Structures*, 19, 1–11.
9. Choi, S. B., Seong, M. S., & Kim, K. S. (2009). Vibration control of an electrorheological fluid-based suspension system with an energy regenerative mechanism. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 223(4), 459-469. <https://doi.org/10.1243/09544070JAUTO968>.
10. Ozulu, A., & Liubarskyi, B. (2021). Perspektyvni elektromekhanichni amortyzatory. *Collection of scientific papers DUIT. "Transport systems and technologies" series*, 38, 133-140. <https://doi.org/10.32703/2617-9040-2021-38-130-12>. [in Ukrainian].
11. Maemori, K. I., Tanigawa, N., & Shi, F. H. (2004, January). Optimization of a Semi-Active Shock Absorber Using a Genetic Algorithm. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (Vol. 46946, pp. 123-130). <https://doi.org/10.1115/DETC2004-57115>.
12. Gandzha S., Bakhtiyor K., & Aminov D. (2019). Application of the ansys electronics desktop software package for analysis of claw-pole synchronous motor. *Machines*, 7, 65. <https://doi.org/10.3390/machines7040065>.
13. Kakandikar, G., & Nandedkar, V. (2018). Springback optimization in automotive shock absorber cup with genetic algorithm. *Manufacturing Review*, 5, 1. <https://doi.org/10.1051/mfreview/2017013>
14. Gysen, B. L., van der Sande, T. P., Paulides, J. J., & Lomonova, E. A. (2011). Efficiency of a regenerative direct-drive electromagnetic active suspension. *IEEE transactions on vehicular technology*, 60(4), 1384-1393. <https://doi.org/10.1109/tvt.2011.2131160>.
15. Liubarskyi, B., Lukashova, N., Petrenko, O., Pavlenko, T., Iakunin, D., Yatsko, S., & Vashchenko, Y. (2019). Devising a procedure to choose optimal parameters for the electromechanical shock absorber for a subway car. *Eastern-European Journal of Enterprise Technologies*, 4(5(100)), 16-25. <https://doi.org/10.15587/1729-4061.2019.176304>.
16. Kimura, F., Yamamoto, A., & Higuchi, T. (2011, June). FPGA implementation of a signal synthesizer for driving a high-power electrostatic motor. In *2011 IEEE International Symposium on Industrial Electronics* (pp. 1295-1300). IEEE. <https://doi.org/10.1109/ISIE.2011.5984345>.
17. Xu, Y., Zhao, J., & Huang, J. (2014, October). Multiple linear motor control system based on FPGA. In *2014 17th International Conference on Electrical Machines and Systems (ICEMS)* (pp. 2327-2331). IEEE. <https://doi.org/10.1109/ICEMS.2014.7013875>.

Антон Озулу¹, Борис Любарський²

¹Аспірант, Кафедра електричного транспорту та тепловозобудування, Національний технічний університет «Харківський політехнічний інститут», вул. Кирпичова, 2, м. Харків, 61002, Україна, ORCID: <https://orcid.org/0000-0001-9524-8006>

²Професор, Кафедра електричного транспорту та тепловозобудування, Національний технічний університет «Харківський політехнічний інститут», вул. Кирпичова, 2, м. Харків, 61002, Україна, ORCID: <http://orcid.org/0000-0002-2985-7345>

Розрахунок параметрів електромеханічного амортизатора швидкісного електропоїзда

Стаття розглядає питання системи ходової частини швидкісного електропоїзду з нахилом кузова та системою рекуперації коливань. Описано переваги використання електромеханічного амортизатора перед гідравлічною системою, пневматичною та аналогічними. Авторами було розглянуто основні характеристики електромеханічного амортизатора постійного струму. Було представлено основні габаритні параметри амортизатора. Приділяється увага актуальності використання електромеханічного амортизатора лінійного типу, у порівнянні з аналогами у тому числі й у можливості рекуперувати енергію. Звертається увага на структуру електромеханічного амортизатора постійного струму. Розглянута функціональна схема керування електромеханічним амортизатором та описано алгоритм керування. Визначені розрахункові області параметрів електромеханічного амортизатора. Представлена 3D модель електромеханічного амортизатора у програмному середовищі Ansys Electronics. Побудована кінцево-елементна сітка для подальших розрахунків магнітного поля та індуктивності. У статті

приділяється увага розрахунку магнітного поля у найбільш напруженому режимі. Отримано картину магнітного поля амортизатора при максимальному робочому зазорі та обговорено проміжкові підсумки. Представлені результати розрахунку індуктивності в залежності від робочого зазору амортизатора. Зроблено висновки за результатом розрахунків магнітних та електричних параметрів електромеханічного амортизатора на базі лінійного двигуна постійного струму.

Ключові слова: електромеханічний амортизатор, рекуперація, нахил кузова, електрорухомий склад, коливання.

Valerii Makarenko¹, Olga Voitovych², Yurii Mieshkov^{3*}, Oleh Kliuiev⁴, Yuliia Makarenko⁵.

¹Professor, Department of transport systems and technical service. Kherson National Technical University, 24 Berislavske highway, Kherson, 73008, Ukraine, ORCID: <http://orcid.org/0000-0001-9178-9657>

²Associate Professor, Department of transport systems and technical service. Kherson National Technical University, 24 Berislavske highway, Kherson, 73008, Ukraine, ORCID: <https://orcid.org/0000-0003-0510-4362>

³Associate professor, Department of transport systems and technical service. Kherson National Technical University, 24 Berislavske highway, Kherson, 73008, Ukraine, ORCID: <https://orcid.org/0000-0002-2506-7020>.

⁴Associate professor, Department of transport systems and technical service. Kherson National Technical University, 24 Berislavske highway, Kherson, 73008, Ukraine, <http://orcid.org/0000-0001-6803-0706>

⁵Bachelor's degree, "Manitoba" Medical University, Winnipeg, Canada, ORCID: <https://orcid.org/0000-0003-1252-4231>.

Corresponding author: mieshkov.yuri@gmail.com

Experimental studies of truck transport brake pads materials friction properties

The work presents the results of experimental systematic studies of "wheel-brake pad" friction pairs wear resistance and the effect of the wear-resistant coating on the wear, in particular, from metal-ceramic friction materials (ФМК-8), carbon composite materials (BBKM) in comparison with carbon steel of grade 45. It was established that the instantaneous values of brake pads friction coefficients during the tests on inertial stand are random in nature and require the use of mathematical statistics methods for their analysis. Change nature in pads and wheels friction force instantaneous values is determined by pressing forces. It is shown that the mathematical expectation of the friction coefficients values is within the normalized permissible interval. The probability of friction coefficients instantaneous values matching into the normalized interval at a pressing force of 10kN is 0,6-0,8 for speeds up to 60 km/h, for the rest is more than 0,8 at pressing force of 20kN, the specified probability exceeds 0,85 for the entire range of speeds. With a pressing force of 20kN, the probability of values exceeding the normalized interval does not exceed 0,15, with a pressing force of 10kN, the friction coefficients exceeded the maximum normative values more than 0,35 for speeds up to 40 km/h. It has been established that the most wear-resistant pads are coated with metal-ceramic material (ФМК-8) and carbon-carbon composite materials (BBKM). It is shown that the described technique based on the mathematical statistic application allows to perform more in-depth analysis of freight wheeled road trains brake pads frictional properties.

Keywords: *mathematical statistics, friction, destruction, friction materials, friction pairs wear resistance.*

Introduction. In modern period of development of industry manufacture of Ukraine, the problem of basic foundations creation for transport equipment development has arisen. It concerns, in particular, issues of friction and wear in transport machines. The relevance is due to the fact that the current state of technology development is characterized by strict conditions of the most diverse transport systems operation, which is associated with an increase in specific loads due to increase in capacities; speeds; by the action of complex static cyclic and dynamic loads; under the impact of various corrosive-active environments as well as temperature [1-3]. It is known from operational practice that 70-80% of disruptions in normal functioning or complete failure of technical systems are caused by the failure of

tribosystems elements due to surface destruction as a result of wear and tear and other accompanying processes - fretting erosion, etc. Therefore, increasing the friction units durability was and remains one of the most important technical problems of modern times in terms of reliability increasing and service life extending for transport vehicles [4-7]. However, despite the large volume of publications on this topic, it can be noted that the diversity, large volume of experimental material and often uncertainty and contradiction of information regarding the tribological properties of the material [8, 9] involved in friction and wear pairs leads to the need to find an additional resource in increasing the wear resistance properties of brake pads material, in particular of transport trucks [10, 11].

Therefore, we provided additional research on brake pads frictional properties in the conditions of experimental stands, which were as close as possible to the real kinematic and dynamic conditions of transport trucks operation.

Research purpose and task is to provide systematic experimental studies of brake pads frictional properties made of different materials.

Research Materials and Methods. Special stand shown in Figure 1 was used in the experiments. Express tests on dry friction were carried out for brake pads material selection (possible case of braking wheel pair operation in the dry friction mode was simulated on the stand) together with specialists of Powder Metallurgy, SPA (Belarus) and the Institute of Electric Welding named after Ye. O. Paton of the National Academy of Sciences. Pads samples with coatings testing for wear resistance during dry friction was carried out for 45 minutes at a specific pressure of 0.6 MPa and a counterbody rotation frequency of 80min^{-1} , the counterbody was a disc made of hardened steel 40XH. Carbon structural high-quality steel 45 was used as a reference sample of brake pads. Pads were made of two types: $\Phi\text{MK-8}$ metal-ceramic friction (iron-based), "carbon-carbon" composite materials BBKM. In the first case, the main characteristics that were subject to registration were determined, in particular: wheel rotation linear speed; time from the start of braking to complete stop of the wheel; instantaneous value of pad pressing force on the wheel; instantaneous value of friction force; wheel heating temperature.

The results of experimental studies are shown in Figures 1-10.

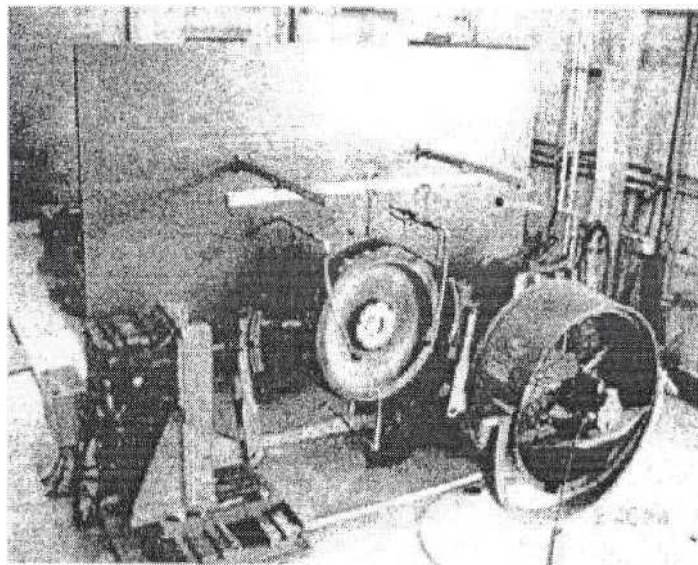


Fig. 1. Stand for Determining the Frictional Properties of Brake Pads

The instantaneous friction coefficient is defined as instantaneous value of the friction force to instantaneous value of the pressing force ratio. It was established that the registered parameters are

random values, so their processing requires the use of statistical methods of analysis.

Pressing forces, friction forces and friction coefficients changes during braking data analysis (Fig. 2) shows that the instantaneous values of pressing forces change according to the harmonic law relative to the average nominal value, while the change in friction forces has a deterministic nature.

Decisive factor affecting the nature of change in the instantaneous values of friction coefficients is the pressing force (Fig. 2), therefore it is appropriate to determine the instantaneous values of friction coefficients as instantaneous values of friction force to nominal (average) value of pressing force ratio.

For statistical processing, the entire set of measured parameters was divided into separate arrays according to fixed braking speeds with an interval of 5km/h, while the initial speed was 20km/h [12, 13].

As a statistical law of pad pressing the wheel force distribution, the normal distribution law was adopted, for which the distribution function and probability density have the form:

$$F(x) = \frac{1}{\sqrt{2 \cdot \pi} \cdot \sigma} \int_{-\infty}^x e^{-\frac{(x-a)^2}{2 \cdot \sigma^2}} dx \quad (1)$$

$$\varphi(x) = \frac{1}{\sqrt{2 \cdot \pi} \cdot \sigma} \cdot e^{-\frac{(x-a)^2}{2 \cdot \sigma^2}} \quad (2)$$

where α and σ^2 - are the mathematical expectation and variance of the random variable x .

Confidence intervals for mathematical expectation were determined by the formula:

$$\bar{x} - z_{p1} \cdot \frac{\sigma}{\sqrt{n-1}} < a < \bar{x} + z_{p2} \cdot \frac{\sigma}{\sqrt{n-1}} \quad (3)$$

where \bar{x} – is sample average of n independent values;

z_{p1} - is the quantile of the normalized normal distribution

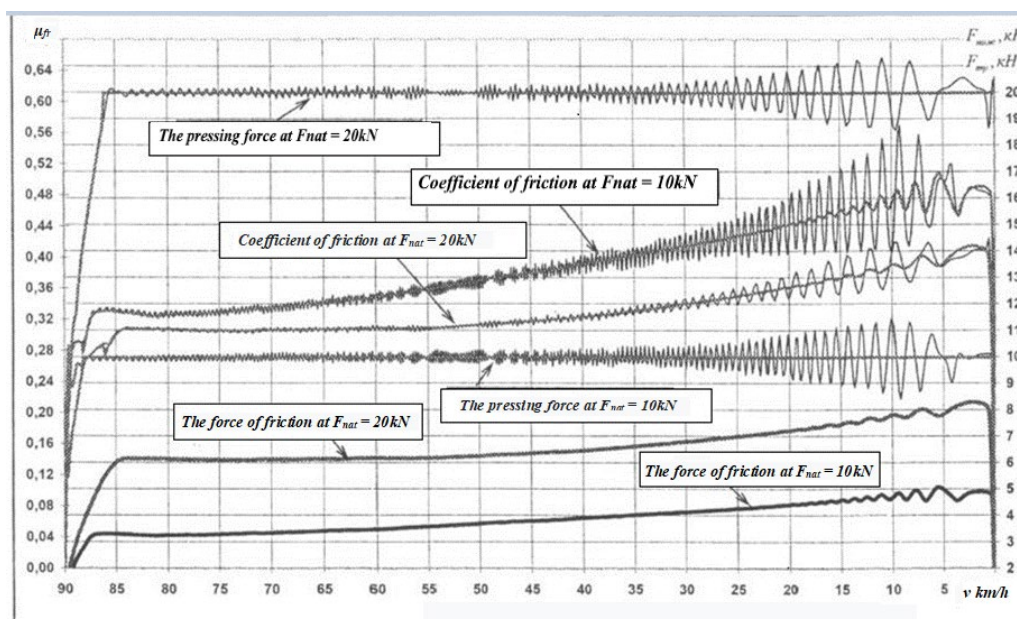


Fig. 2. Processes of changes in registered parameters during braking with an initial speed of 80km/h.

Probability distribution densities of instantaneous friction coefficients (Figs. 3, 4) show that their value increases as the rate of dispersion of changes decreases. The instability of the friction coefficient at low speeds of wheel rotation can be due to the impact of the temperature of both the wheel itself and the brake pad, however, this statement requires experimental confirmation, since during tests on an inertial stand, the temperature is measured only on the wheel.

Despite the fact that the average values of friction coefficients (Figs. 5, 6) are in the given normalized range of permissible values of friction coefficients [14], nevertheless, in order to evaluate the braking properties of experimental pads, it is necessary to take into account the probability that the instantaneous value of the friction coefficient will be within the permissible range ($[\mu(v)]_{min}, [\mu(v)]_{max}$).

Probability of random value is equal to the integral of probability density within these limits [15]:

$$P(\mu \geq [\mu(v)]_{max}) = \int_{\mu_1}^{\infty} p(\mu) \cdot d\mu = 1 - F([\mu(v)]_{max}), \quad (4)$$

where $[\mu(v)]_{min}, [\mu(v)]_{max}$ are, respectively, minimum and maximum normalized values of friction coefficients established [15] for speed v .

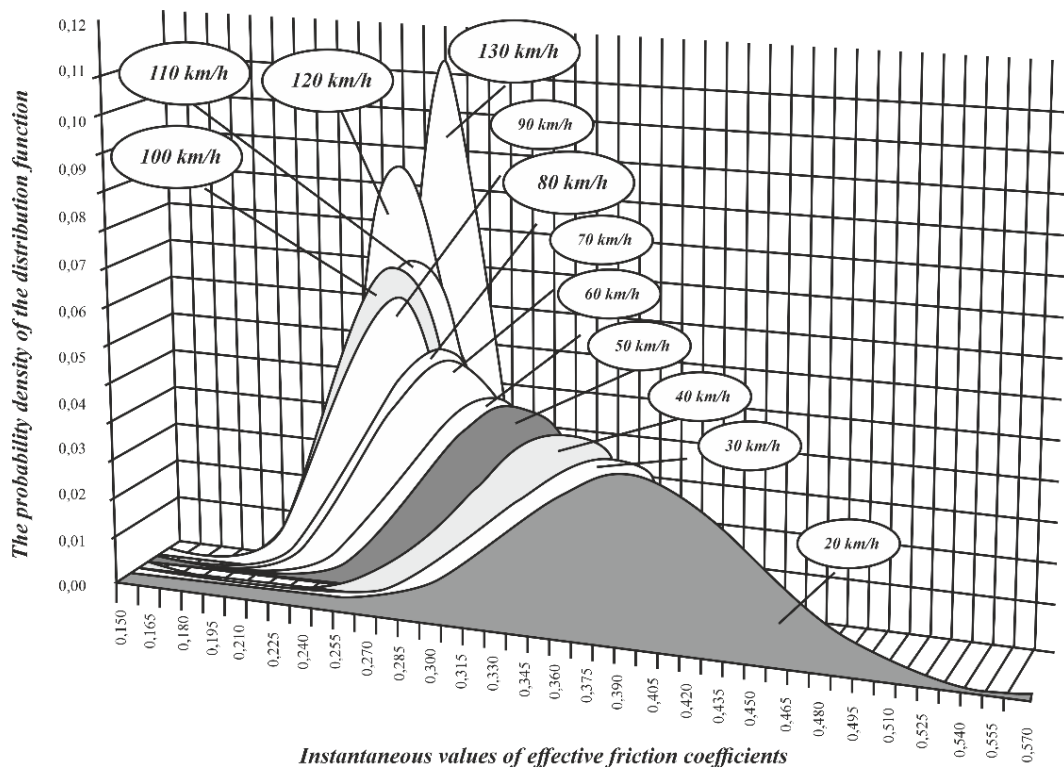


Fig. 3. Density of Friction Coefficients Instantaneous Values Distribution at Pad Pressing the Wheel Force of 10kN.

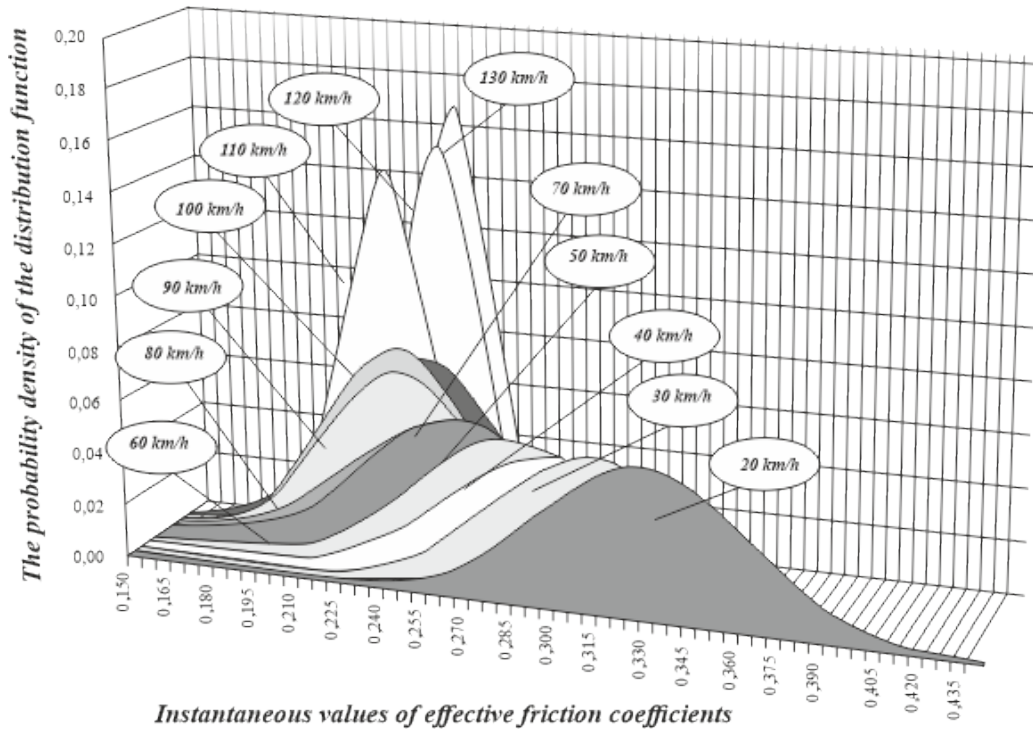


Fig. 4. Density of Friction Coefficients Instantaneous Values Distribution at Pad Pressing the Wheel Force of 20kN

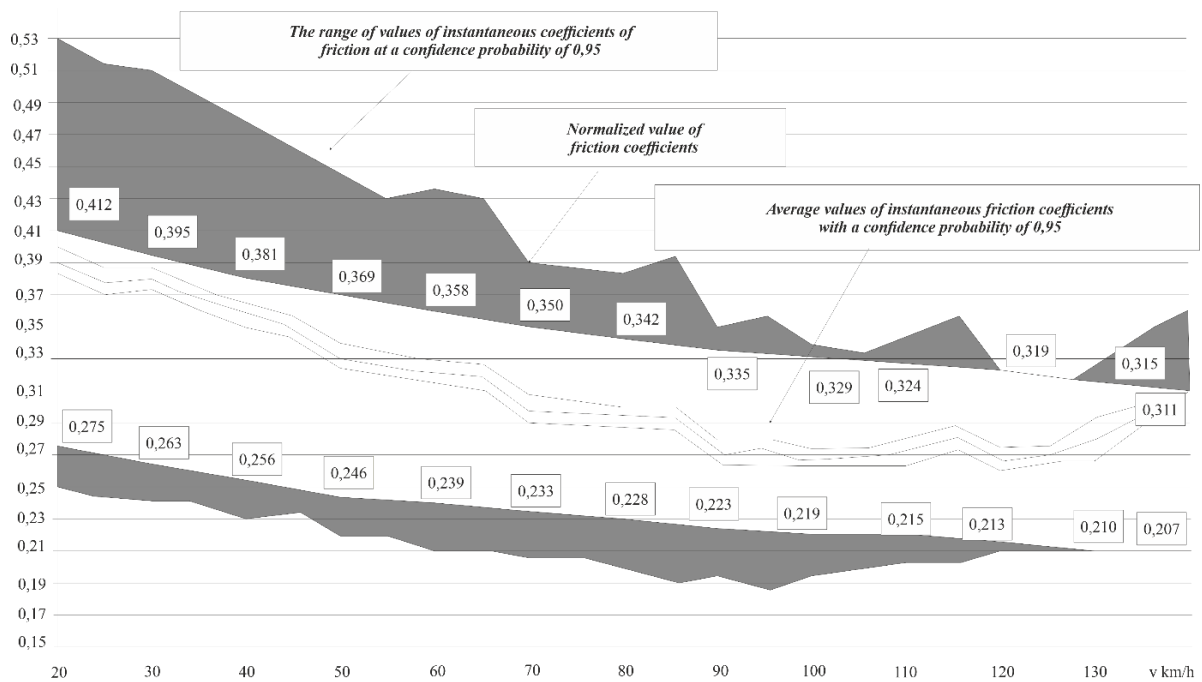


Fig. 5. Friction Coefficients Average Values at Pad Pressing the Wheel Force of 10kN

The performed calculations showed that the probability of friction coefficients instantaneous values matching into the normalized interval [14] at a pressing force of 10kN is 0,6-0,8 for speeds up to 60km/h, for the rest is more than 0,8 at pressing force of 20kN, the specified probability exceeds 0,85 for the entire range of speeds.

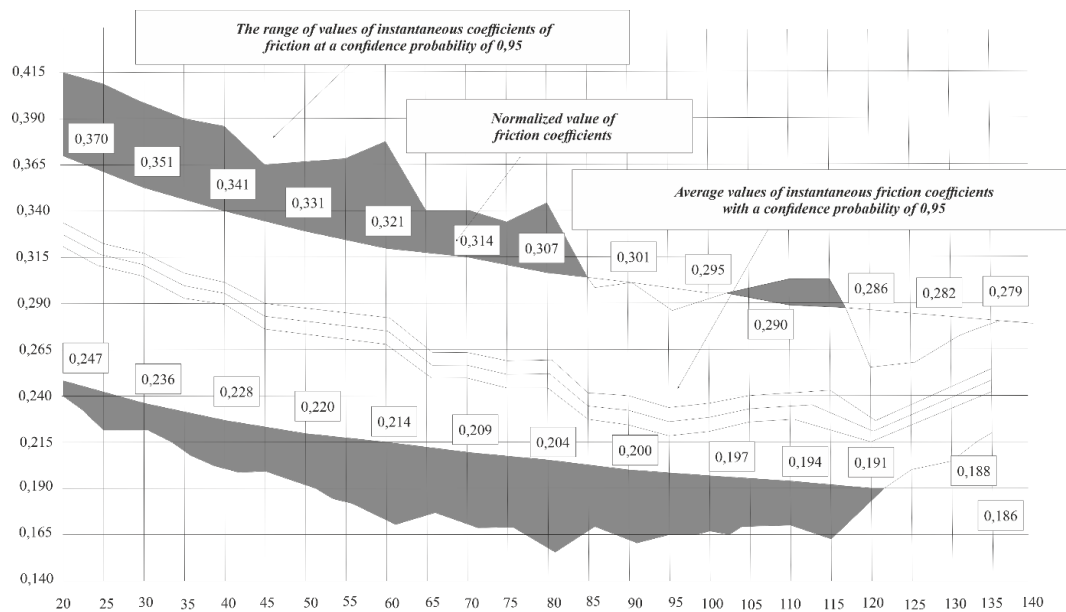


Fig. 6. Friction Coefficients Average Values at Pad Pressing the Wheel Force of 20kN

When analyzing the friction properties of a brake pad, it is necessary to analyze the maximum and minimum values of friction coefficients, since high friction coefficients can lead to damage to the surface of wheel pairs during braking, and low ones - to insufficient braking efficiency of a truck. The probability of the pad friction coefficients exceeding the maximum normalized value is determined by formula (5)[2], and the probability that the friction coefficients will be below the minimum normalized value is determined by formula (6) [2]

$$P(\mu \geq [\mu(v)]_{max}) = \int_{\mu_1}^{\infty} p(\mu) \cdot d\mu = 1 - F([\mu(v)]_{max}) \quad (5)$$

$$P(\mu \leq [\mu(v)]_{min}) = \int_{-\infty}^{\mu_1} p(\mu) \cdot d\mu = F([\mu(v)]_{min}) \quad (6)$$

Calculation studies show that with a pressing force of 20kN, the probability of the values of friction coefficients exceeding the normalized interval does not exceed 0,15, and with a pressing force of 10kN, the probability of the friction coefficients exceeding the normative values for speeds up to 40km/h inclusive is more than 0,35.

The high probability of the friction coefficients exceeding the maximum normative values at a pressing force of 10kN requires an analysis to be carried out under the condition of preventing a sliding situation. As a criterion, the limit coefficient of wheels adhesion with asphalt was used. Results of the calculation showed that the maximum probability of slipping is 0,55, that is, it should be expected that out of a hundred cars operated on experimental composite pads, only five vehicles can have a slip on wheel pairs.

Friction coefficients instantaneous values coefficients of variation (range) which are defined as standard deviation to the mathematical expectation ratio, show that with a pressing force of 10kN, the maximum values of the coefficients of variation correspond to speeds up to and including 40km/h, and with a pressing force of 20kN - the range of rates (60-80) km/h

In the second part of the experiments, samples wear resistance was assessed by the weight method. All samples were pre-treated before testing.

Experiments results showed that the brake pads made of metal-ceramic materials have the highest wear resistance, and it was noticed that the wear resistance increases with a decrease in the fraction of material used. These data are in good agreement with the results known from the literature, where it is recommended to use finely dispersed powders - fractions less than 20µm in order to obtain high-quality wear-resistant coatings from ceramic materials. The tests were carried out on the MI-IM friction machine with a special device for introducing a friction pair of abrasive suspended in lubricant to the point of contact. A lubricant-abrasive mixture was used, which consisted of industrial lubricant И-20 and 2% boron carbide, with a grain size of 4-5µm. The test mode was as follows: friction speed 0,7-1,0 m/s; pressure in the friction pair 2-3 MPa; friction path during one cycle is 3-7km; cycle duration 1-1,5 hours. Wear was determined using I3B-1 length gauge with 1µm divisions in two mutually perpendicular planes along two sections. The insert that was worn was measured in the central plane along two sections.

The intensity of wear during the set period was estimated by the formula:

$$I_O = \frac{I_{sw}}{I_{fp}}, \quad (7)$$

where I_{sw} - is wear of the sample in diameter, µm;

I_{fp} - is friction path during the test period, km.

The friction path during the test period is determined by the formula:

$$I_{fp} = \pi \cdot D \cdot N \cdot 10^{-6}, \quad (8)$$

where D - is the sample diameter, mm;

N - is the rotation frequency of the sample, min.⁻¹.

During the test, the moment of friction of the "wheel - counterbody" pair was determined on the scale of the registration mechanism after every ten minutes of testing.

Friction coefficient was determined by the moment of friction and the applied load

$$\mu = \frac{M_{mf}}{(R_{sr} \cdot P)}, \quad (9)$$

where M_{mf} - is the moment of friction;

R_{sr} - is sample radius;

P - is applied load.

Test results analysis (Fig. 7-10, designations for figures are the same) shows that the wear resistance of the coating made of metal-ceramic powder (fraction 14 µm) is higher than the wear resistance of the coatings made of powder "carbon-carbon" composite materials and the wear resistance of samples made of steel 45. In the process of samples with coatings wear, the phenomenon of salting the coatings was observed, i.e. wear gradually decreased after a certain time after the tests beginning. At the same time, the friction pair accretion period was about 1 hour on average. The end of accretion process was estimated by the moment of friction and wear stabilization (Fig. 10).

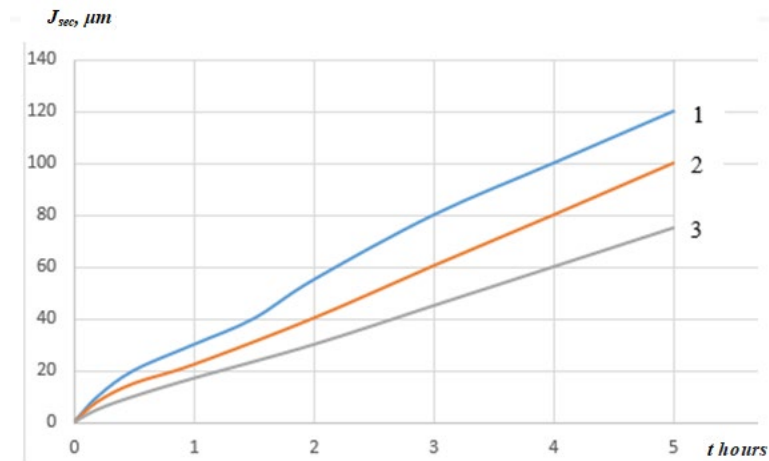


Fig. 7. Graphs of sample wear dependence on test intensity:
 1 - reference sample made of steel 45; 2 - sample from BBKM; 3- sample from ФМК-8.

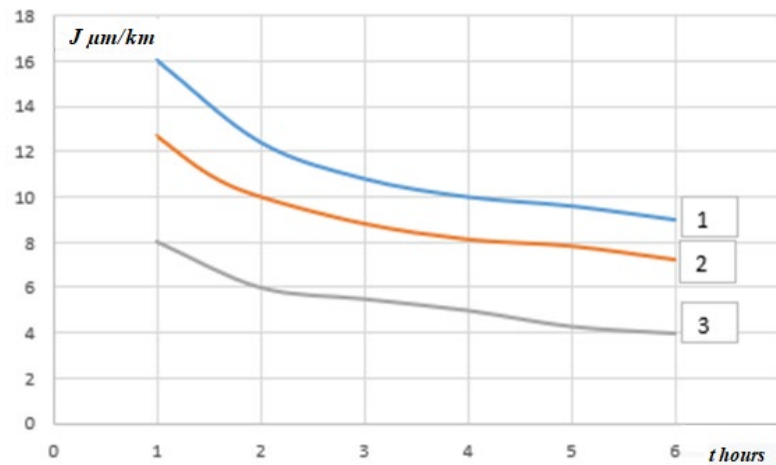


Fig. 8. Graphs of Wear Intensity Dependence on Tests Duration.

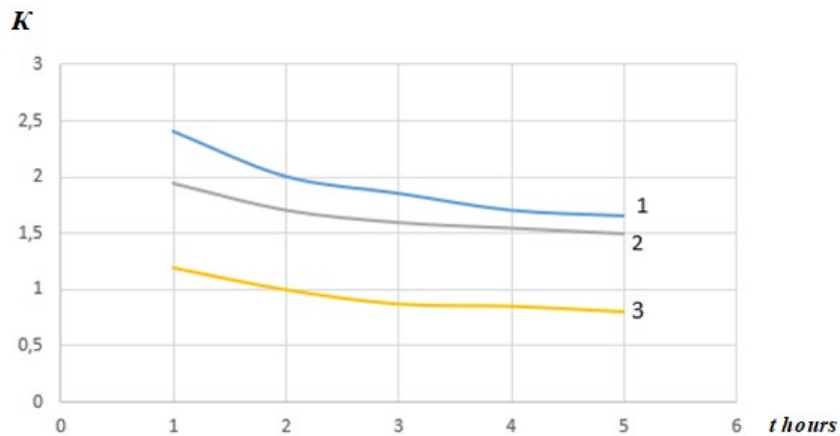


Fig. 9. Graphs of the dependence of the wear coefficient K on the duration of the tests.

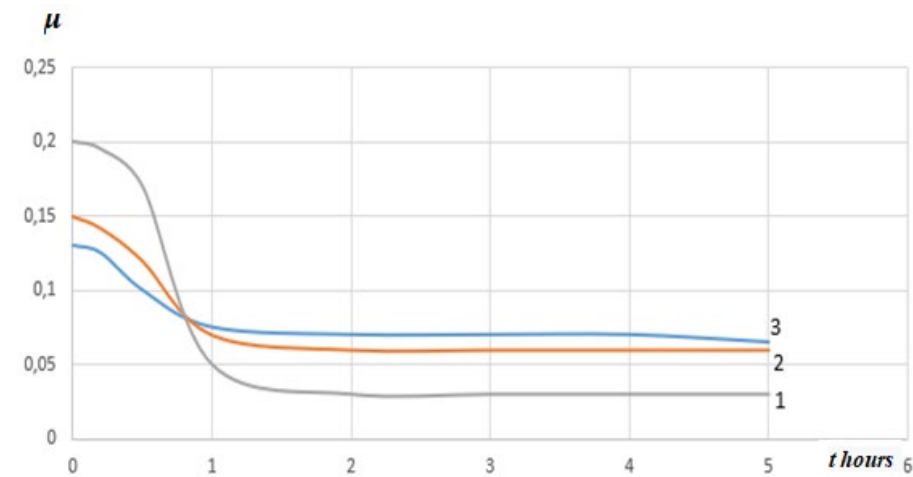


Fig. 10. Graphs of Friction Coefficient Dependence on Tests Duration.

Conclusions

1. It was established that the instantaneous values of brake pads friction coefficients during the tests on inertial stand are random in nature and require the use of mathematical statistics methods for their analysis. Change nature in pads and wheels friction force instantaneous values is determined by pressing forces.

2. It is shown that the mathematical expectation of the friction coefficients values is within the normalized permissible interval. The probability of friction coefficients instantaneous values matching into the normalized interval at a pressing force of 10kN is 0,6-0,8 for speeds up to 60 km/h, for the rest is more than 0,8 at pressing force of 20kN, the specified probability exceeds 0,85 for the entire range of speeds.

3. With a pressing force of 20kN, the probability of values exceeding the normalized interval does not exceed 0,15, with a pressing force of 10kN, the friction coefficients exceeded the maximum normative values more than 0.35 for speeds up to 40 km/h. The maximum probability of slipping corresponds to a speed of 30 km/h with a pressing force of 10kN and is 0,55. At the same time, the variation coefficient at a pressing force of 10kN corresponds to the speed range of (20-40) km/h, and at a pressing force of 20kN - (60-80) km/h.

4. It has been established that the most wear-resistant pads are coated with metal-ceramic material (ФМК-8) and carbon-carbon composite materials (BBKM).

5. It is shown that the described technique based on the mathematical statistic application allows to perform more in-depth analysis of freight wheeled road trains brake pads frictional properties.

REFERENCES

1. Gavrilyuk, V.P. (2007) Tribology of casting alloys. *K: FTIMS of the National Academy of Sciences of Ukraine*. [in Ukrainian].
2. Dmytrychenko, M.F. (2006) Tribotechnics based on the reliability of machines. *K.: INFORMAVTODOR*. [in Ukrainian].
3. Zaporozhets, V. V. (1987). Diagnostics of friction units and special machines. *K.: KNYGA*. [in Ukrainian].
4. Kuzmenko, A.G. (2007). Contact friction and wear of lubricated surfaces. *Khmelnyskyi: KhNU*. [in Ukrainian].
5. Labunets, V. F. (1989). Wear resistance of boride coated. *K.: Technology*. [in Ukrainian].
6. Kostetskyi B. I., Nosovsky I. G., Karaulov A. K. and others. (1976). Surface strength of materials under friction. *K.: Technika*. [in Ukrainian].
7. Shevelya, V.V. (2006). Tribochemistry and rheology of wear resistance. *Khmelnyskyi: KhNU*. [in Ukrainian].

8. Blau, P. J., Jolly, B. C., Qu, J., Peter, W. H., & Blue, C. A. (2007). Tribological investigation of titanium-based materials for brakes. *Wear*, 263(7-12), 1202-1211. <https://doi.org/10.1016/j.wear.2006.12.015>.
9. Miyachi, T., Nakayama, J., Fujiwara, N., Shimoda, K., Nakazawa, S., & Fukagai, S. (2013). Friction and wear performance of nickel and molybdenum-reduction cast iron composite brake blocks including ceramic foams. *Wear*, 302(1-2), 1436-1443. <https://doi.org/10.1016/j.wear.2012.11.025>.
10. Pascu, L. V. (2015). *Cercetări privind îmbunătățirea calității saboților de frână destinați materialului rulant*. Timișoara: Editura Politehnica.
11. Kiss, I., Cioata, V., Alexa, V., & Ratiu, S. (2016). Investigations on the selection of friction materials destined to railway vehicles applications. *Annals of the Faculty of Engineering Hunedoara*, 14(4), 231.
12. Yerina A.M. (2001). Statistical modeling and forecasting. *Kyiv: KNTU*. [in Ukrainian].
13. Nazarov O.I., Klets D.M., & Nazarov I.O.. (2015). Mathematical model of wear of galvanic disk mechanisms of cars in the minds of exploitation. *Bulletin of NTU "KhPI". Series: "Mathematical modeling in engineering and technology"*. [in Ukrainian].
14. Nazarov O.I., & Nazarov V.I. (2016). Reduced speed of wear of drum galvanized mechanisms installed on the front axle of double cars. *Bulletin of KHNADU*. [in Ukrainian].
15. Kindrachuk M. V., Labunets V. F., Pashechko M. I., Korbut E. V. (2000). Tribology. Kyiv: National Publishing House. aviation "NAU-Druk" University. [in Ukrainian].

Валерій Макаренко¹, Ольга Войтович², Юрий Мешков³, Олег Ключев⁴, Юлія Макаренко⁵.

¹Професор, Кафедра транспортних систем і технічного сервісу. Херсонський національний технічний університет, Бериславське шосе 24, м. Херсон, 73008, Україна, ORCID: <http://orcid.org/0000-0001-9178-9657>

²Доцент, Кафедра транспортних систем і технічного сервісу. Херсонський національний технічний університет, Бериславське шосе 24, м. Херсон, 73008, Україна, ORCID: <https://orcid.org/0000-0003-0510-4362>

³Доцент, Кафедра транспортних систем і технічного сервісу. Херсонський національний технічний університет, Бериславське шосе 24, м. Херсон, 73008, Україна, ORCID: <https://orcid.org/0000-0002-2506-7020>

⁴Доцент, Кафедра транспортних систем і технічного сервісу. Херсонський національний технічний університет, Бериславське шосе 24, м. Херсон, 73008, Україна, ORCID: <http://orcid.org/0000-0001-6803-0706>.

⁵Бакалавр Медичний університет "Манітобо", м.Вінніпег, Канада, <https://orcid.org/0000-0003-1252-4231>.

Автор, відповідальний за листування: E-mail: mieshkov,yuri@gmail.com; Конт. тел. 095-175-72-09.

Експериментальні дослідження фрикційних властивостей матеріалів гальмівних колодок вантажного транспорту

В роботі наведені результати експериментальних системних досліджень зносостійкості пар тертя "колесо-гальмівна колодка" і вплив на зношування зносостійкого покриття, зокрема з металокерамічних фрикційних матеріалів (ФМК-8) вуглецевих композитних матеріалів ВВКМ в порівнянні з вуглецевою сталлю марки 45. Встановлено, що миттєві значення коефіцієнтів тертя гальмівних колодок при випробуваннях на інерційному стенді мають випадковий характер і вимагають для свого аналізу застосування методів математичної статистики. На характер зміни миттєвих значень сили тертя колодок і коліс визначаючий вплив здійснюють сили натискання. Показано, що математичне сподівання значень коефіцієнтів тертя знаходиться в межах нормованого допустимого інтервалу. Імовірність попадання миттєвих значень коефіцієнтів тертя в нормований інтервал при силі натискання 10кН складає для

швидкостей до 60км/год, 0,6-0,8 для решети – більше 0,8 при силі натискання 20кН, вказана імовірність перевищує 0,85 для всього діапазону швидкостей. При силі натискання 20кН імовірність виходу значень за нормований інтервал не перевищує 0,15, при силі натискання 10кН перевищення коефіцієнта тертя максимальних нормативних значень для швидкостей до 40км/год складає більше 0,35. Встановлено, що найбільшою зносостійкістю володіють покриття колодок з металокерамічного матеріалу (ФМК-8) і вуглець-вуглецеві композитні матеріали (ВВКМ). Показано що викладена методика на основі застосування апарату математичної статистики дозволяє проводити більш глибокий аналіз фрикційних властивостей гальмівних колодок вантажних колісних автопоїздів.

Ключові слова: математична статистика, тертя, руйнування, фрикційні матеріали, зносостійкість пар тертя.

Oleksandr Aharkov^{1*}, Volodymyr Tverdomed²

¹Assistant professor, Theoretical and Applied Mechanics Department, State University of Infrastructure and Technologies, 9, Kyrylivska str., Kyiv, 04071, Ukraine, ORCID: <https://orcid.org/0000-0001-8250-6280>

²Assistant professor, Railway Track and Track Facilities Department, State University of Infrastructure and Technologies, 9, Kyrylivska str., Kyiv, 04071, Ukraine, ORCID: <https://orcid.org/0000-0002-0695-1304>

*Corresponding author: agarkov_ov@gsuite.duit.edu.ua

Comparative analysis of damages and defects in rails of different railway transport systems

This article provides an analysis of the accumulation of detected damages and defects in the rails of two transportation systems - urban (metro) and mainline railway transport. Summarizing the analysis conducted, it should be noted that defects according to figures 10 and 11 are more often encountered on the tracks of the Kyiv Metro. At the same time, defects according to figure 27 are more often encountered on the tracks of the mainline railway transport, and it is also worth noting a wider range of defects, the share of which does not exceed 5%. According to the authors, this is related to the peculiarities of the conditions for operating transportation systems, particularly the load on the axle of the moving equipment, the movement characteristics, and other operational parameters. In order to make more accurate conclusions, it is necessary to perform a number of works using mathematical modeling methods to take into account the influence of individual parameters on the accumulation of defects and damages in rails.

Keywords: rolling stock, transport system, wheel pair, rail, railway track, defect, damage, fatigue, cracking.

Introduction. One of the most common types of transportation in every country in the world is rail transport. This type of transport provides passenger transportation in large cities, intercity and international connections. A significant share of freight transportation falls precisely on rail transport [1]. To ensure the transportation process, the railway transport system must provide uninterrupted and safe train traffic. The railway infrastructure is a significant part of the railway transport system, and the organization of a safe and timely transportation process depends largely on its technical condition [2, 3].

The interaction of the rolling stock and the railway track (the weight of the wagon, the speed of movement, the intensity of the applied loads), the influence of natural factors - air temperature (frost causes cracks in the railway track, heat - track buckling, primarily in continuous welded rail), precipitation (rain, snow melting lead to washouts or moistening of the ballast layer), and human factors (untimely or poor elimination of malfunctions that arose during operation) have a significant impact on the speed of appearance of damage and defects in the elements of the railway track and rolling stock.

To ensure the safety of trains traveling at established speeds, periodic monitoring of the condition of railway infrastructure is carried out. One of the components of the system for ensuring the trouble-free operation of railway infrastructure is the technical diagnostics of rails using a complex of non-destructive testing methods. The management of the lifecycle of rails plays an important role in optimizing the overall costs of railway infrastructure and includes the optimal selection of rail types, rail diagnostics, and maintenance. This article analyzes the accumulation of detected damages and defects in the rails of two transportation systems - urban (metro) and mainline railways.

Analysis of recent research and problem statement. During operation, the condition of rails gradually deteriorates and their load-bearing capacity decreases, which leads to the need for individual or overall replacement of rails due to defects formation in them.

Management of damages and defects in rails during rolling contact is of crucial importance for transport safety worldwide, as uncontrolled development of these defects can cause railway accidents, including derailments.

A large number of scientific papers and research projects have been published that consider railway defects from the aspects of metallurgy, testing methods, railway infrastructure, and transport means [6, 7, 8].

The article [9] provides a critical analysis of the classification of rail defects. The general system of classification of defects in the main transportation system based on their localization, causes, and external appearance was considered. Special attention was paid to the correspondence of the names and code numbers of rail defects used in EN standards and UIC recommendations. In addition, recommendations were presented for improving the coding system based on experience with defects in the Serbian main transportation system.

The authors proposed a database of rail defects, which should consist of defect photographs, information about the localization of defects, methods of detecting and classifying rail defects. Fragments of information contained in the database should be used for planning maintenance activities. To ensure effective management of rail defects, it is necessary to consolidate data on the design of each structural element of the track superstructure. The collected data on rail defects and the conditions of maintenance of the railway transportation system should be prepared for planning comprehensive maintenance of the railway infrastructure, which allows coordinating structural units responsible for maintaining the railway infrastructure.

An important factor that affects the speed of defect formation and growth is the stress-strain state of the structural element being considered. Therefore, it is advisable to use mathematical modeling methods [10, 11, 12], which make it possible to estimate the stress-strain state of the structure for the real geometry of the wheel and rail.

To ensure the rapid detection of defects and the determination of priority work on their localization or timely replacement of defective rails, so as not to allow emergency situations in operation and to improve the reporting system on defects and damages for their research and analysis in the development of specific measures to increase the operational work of rails, a catalog of defects and damages of railway rails of Ukraine [13] has been developed and put into operation.

In curved sections of the railway track, additional forces of interaction with the moving rolling stock arise [14], which leads to an increase in stresses and strains in rails and as a result to the acceleration of defect formation and growth in rails.

To form a technical plan for servicing the railway infrastructure of various railway transport systems, the manager should have information on the types and patterns of accumulation of damages and defects in rails depending on the type of rolling stock and operating conditions.

The purpose and tasks of the study. The aim of the work is to establish regularities in the appearance of damages and defects in rails when interacting with various types of rolling stock and operating conditions. Establishing the main operational, design, and technological reasons for their appearance.

Tasks:

- conducting a statistical analysis of the appearance of damages and defects in rails in railway transport systems with different operating conditions;
- establishing the causes of damages and defects in rails depending on the design features of the rolling stock running gear and train operation modes.

Materials and methods of research. To compare the influence of rolling stock and operating conditions, rail defect data from the Kyiv Metro and mainline railway transport were analyzed. These data were obtained during periodic diagnostic measures of non-destructive rail testing.

When analyzing the operating parameters of these transport systems, it should be noted that the maximum axle load on the Kyiv Metro tracks is set at 150 kN, while the maximum allowable axle load for rolling stock on mainline railway tracks is 250 kN [15].

The operating conditions on the Kyiv Metro tracks are characterized by passenger rolling stock only, short interstation distances with a large number of accelerations and decelerations.

In turn, the operating conditions of mainline railway transport are characterized by a mixed traffic of passenger and freight trains with a higher average axle load.

We should also note that most of the operating sections of the Kyiv metro are located in tunnels, which ensures consistent operating conditions, ambient temperatures, and the absence of the influence of atmospheric phenomena such as rain, snow, wind, etc.

Data on detected defects on the rails of the Kyiv metro over five years of operation and on the tracks of the mainline railway over two years of operation were analyzed. The entire sample of data on detected defects was sorted by their code. We will analyze the detected defects separately for each year of the study, first for the tracks of the Kyiv metro, and then for the tracks of the mainline transport.

Figure 1 shows the distribution of defect codes detected in the rails of the Kyiv metro in the first year of the study.

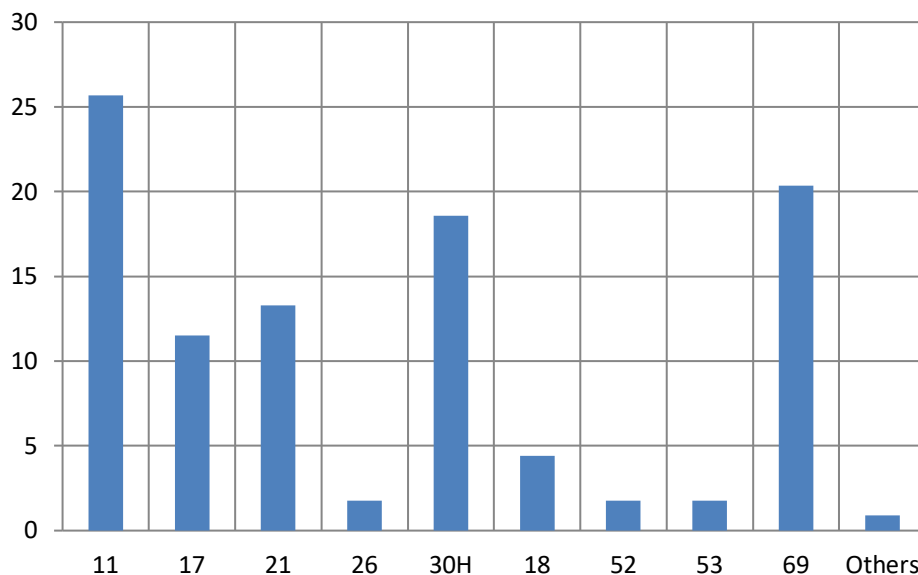


Fig. 1. Statistical distribution of detected defects in the rails of the Kyiv metro in the first year of the study

As can be seen from the figure, the largest number (26%) is represented by defects with code 11. Slightly less defects were detected with codes 69 (20%) and 30H (19%). The number of defects with code 21 was 13%, and with code 17 - 11%.

Figure 2 shows the distribution of defect codes detected in the rails of the Kyiv metro in the second year of the study.

As can be seen from the diagram, the percentage of defects under codes 11 and 17 increased to 32%. The percentage of defects under code 21 was 11%, while defects under codes 30H and 19 were 7% and defects under code 69 were 6%. It should be noted that there were no defects under code 19 detected in the previous year.

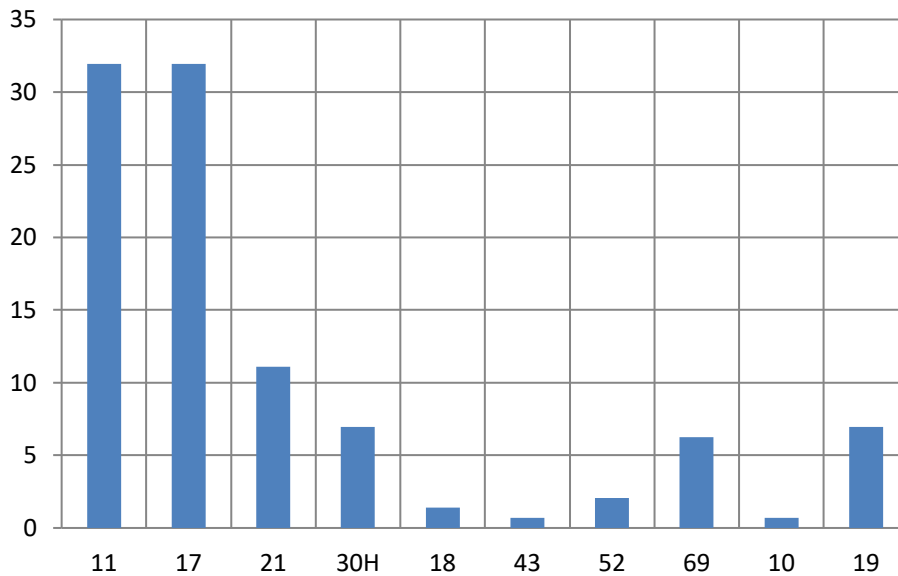


Fig.2. Statistical distribution of detected defects in the rails of the Kyiv metro in the second year of the study

Figure 3 shows the statistical distribution of defects detected in the rails of the Kyiv metro on the third year of research.

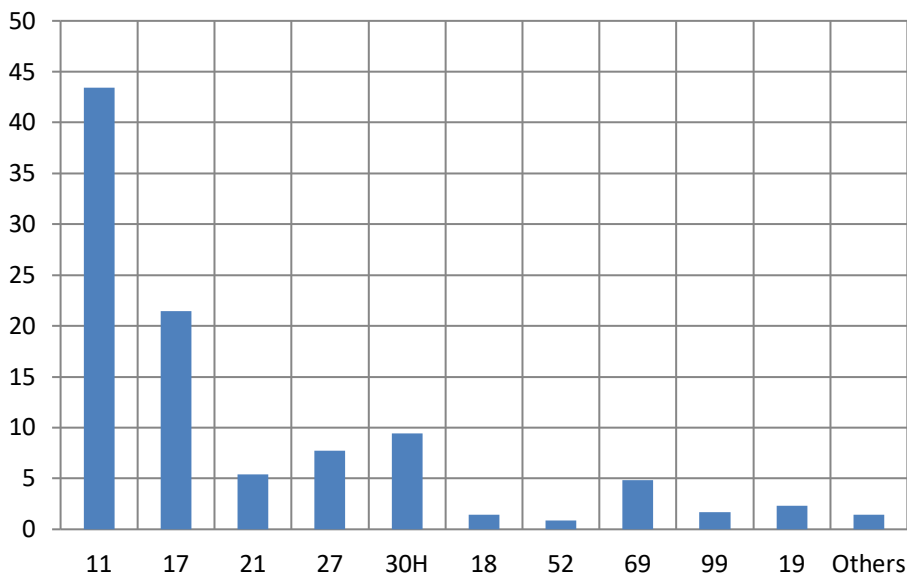


Fig.3. Statistical distribution of detected defects in the rails of the Kyiv metro on the third year of the study

On the third year of research, the percentage of defects detected under code 11 increased to 43%. The percentage of defects under code 17 also increased to 21%. The percentage of defects under code 30H was 10%. The number of defects under code 27 increased. While there were no defects under this code in the first and second years of research, their percentage of the total defects detected in the third year was 8%. Unlike the previous year, no defects under code 19 were detected. The percentage of defects under code 69 was 5%. Unlike the two previous years, defects under code 99 were detected, although their percentage was only 2%.

Figure 4 shows the statistical distribution of defects detected in the rails of the Kyiv metro on the fourth year of research.

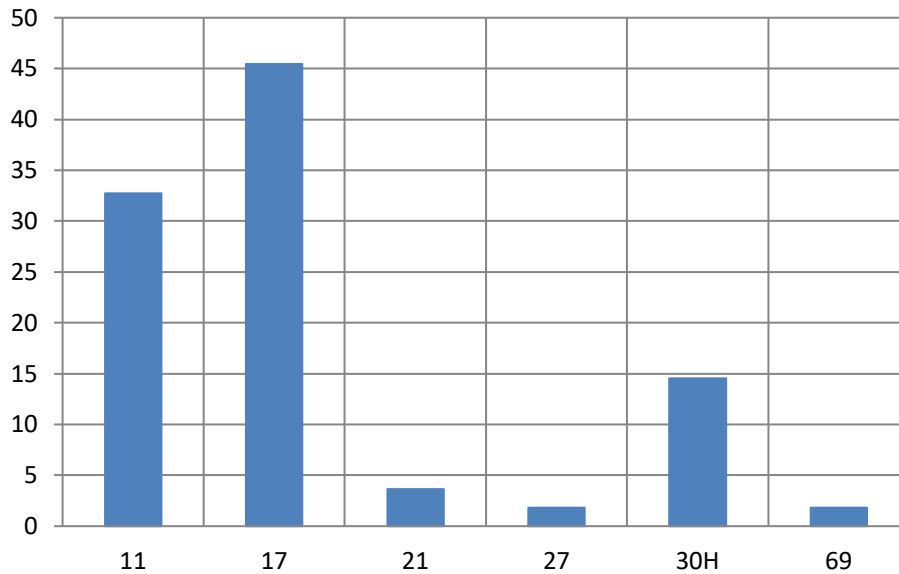


Fig.4. Statistical distribution of detected defects in the rails of the Kyiv metro on the fourth year of the study

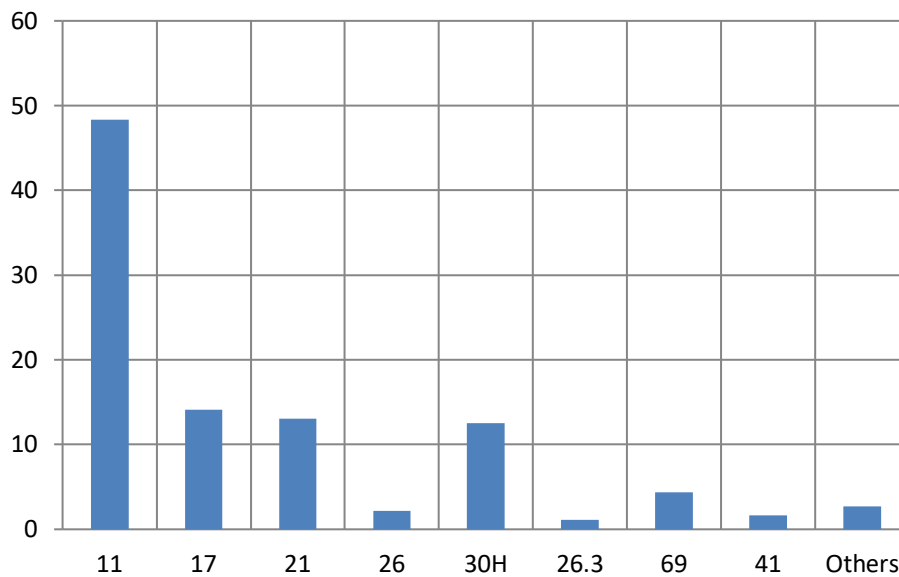


Fig.5. Statistical distribution of detected defects in the rails of the Kyiv metro on the fifth year of the study

The percentage of defects coded as 17 was 45%, 33% for code 11, and 14% for code 30H. No defects were found this year for codes 19 and 99.

Figure 5 shows the statistical distribution of defects detected in the Kiev Metro on the fifth year of research.

The highest proportion of defects were coded as 11, accounting for 48%. Defects coded as 17 accounted for 14%, 21 accounted for 13%, and 30H accounted for 13%.

Figure 6 shows the statistical distribution of defects detected on the mainline railway tracks in the first year of research.

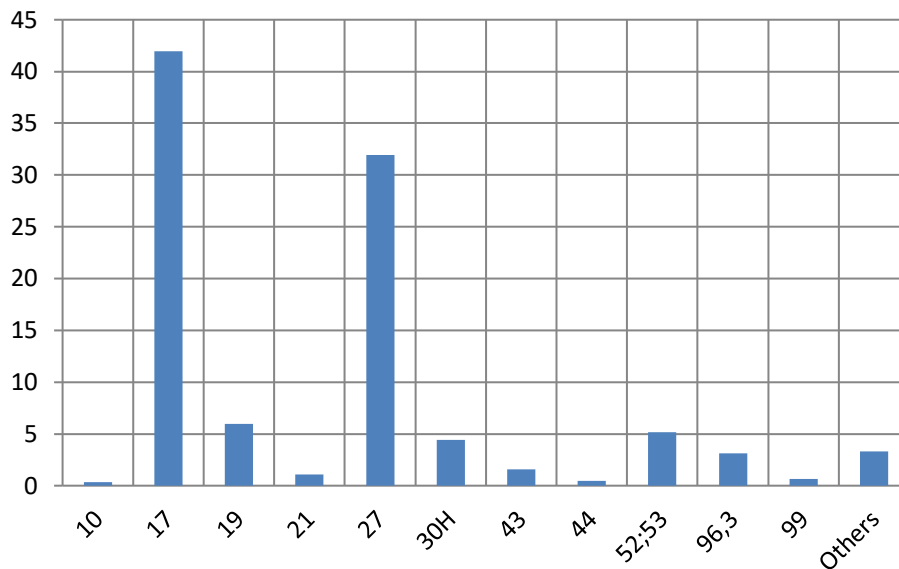


Fig.6. Statistical distribution of detected defects in rails of the mainline railway transport in the first year of the study

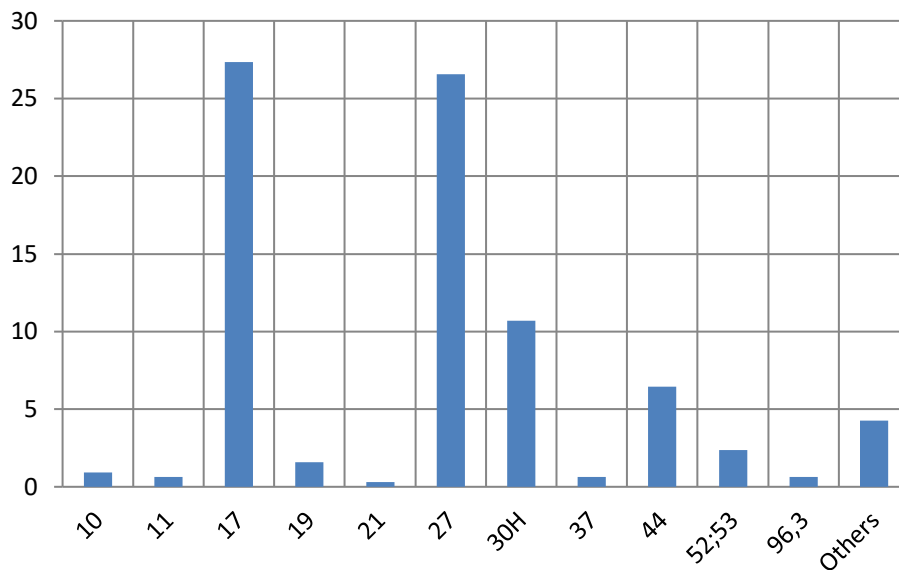


Fig.7. Statistical distribution of detected defects in rails of the mainline railway transport in the second year of the study

The highest number of defects were coded as 17, accounting for 42%, followed by 27 at 32%, 19 at 6%, 52 and 53 at 5.2%, and 30H at 4.4%. Figure 7 shows the statistical distribution of defects detected on the mainline railway tracks in the second year of research.

As shown in the diagram, the highest number of defects this year were coded as 17, at 27.4%. The number of defects coded as 27 sharply increased to 26.6%. The number of defects coded as 30H also increased to 10.7%. The proportion of defects coded as 44 accounted for 6.5%, while the proportion of defects coded as 52 and 53 decreased to 2.4%.

In summary of the analysis conducted, it can be noted that defects depicted in figures 10 and 11 are more common on the tracks of the Kyiv metro. Meanwhile, on the tracks of the main railway transport, defects depicted in figure 27 are more frequent, and a wider range of defects was observed, with none exceeding 5% frequency.

Conclusions. The dependence of the appearance of various types of damages and defects in rails on the design characteristics of the running gear of rolling stock and the operating conditions has been confirmed:

- on tracks within the urban transportation system, specifically in the metro, the more prevalent damages and defects include metal spalling or shelling on the rail head surface (constituting 26-48% of such defects). This is due to lower axle loads (150 kN) and a constant acceleration-braking regime between stations due to shorter distances;
- on mainline railway tracks, the following defects are more intensively observed: transverse cracks in the rail head with fractures across them, horizontal "H" and vertical "V" cracks in the rail head. This may be attributed to higher axle loads (up to 250 kN), maximum train speeds of 160 km/h, and train weights reaching 8000 tons.

The results of the conducted statistical analysis regarding the accumulation of rail defects and damages in the two transportation systems can be used for further scientific research in predicting the occurrence of rail defects under different operating conditions in both urban and mainline rail transport. These results should also be taken into account when developing technical, technological, and structural measures for their prevention.

To extend the service life of rails, an individual approach is necessary for the track maintenance system of each transportation system, considering its specific operating conditions.

Conducting scientific research using modern methods of computer modeling of the interaction between rolling stock and rail tracks in different transportation systems, taking into account the individual parameters of the wheel-rail system, will allow for determining the influence of structural and operational factors on the accumulation of defects and damages in rails.

REFERENCES

1. Popović, Z., & Lazarević, L. (2013). The role of railway in the european transport policy. *Izgradnja*, 67(7), 285-291. Retrieved from www.scopus.com.
2. Popović, Z., Lazarević, L., Brajović, L. J., & Gladović, P. (2014). Managing rail service life. *Metalurgija*, 53(4), 721-724. Retrieved from www.scopus.com.
3. Popović, Z., Lazarević, L., Brajović, L., Mičić, M., & Mirković, N. (2020). Improvement recommendations for railway infrastructure maintenance. In *E3S Web of Conferences* (Vol. 157, p. 01001). EDP Sciences. <https://doi.org/10.1051/e3sconf/202015701001>.
4. Micic, M., Brajovic, L., Lazarevic, L., & Popovic, Z. (2023). Inspection of RCF rail defects—review of NDT methods. *Mech. Syst. Signal*, 182, 109568. <https://doi.org/10.1016/j.ymsp.2022.109568>.
5. Danylenko, E. I., Kosarchuk, V. V., Karpov M. I. ta in. (2014). Vyznachennia umov ekspluatatsii reioik na koliaikh Kyivskoho metropolitenu [Determination of the conditions of operation of rails on the tracks of the Kyiv metro] / Ye. I. Danylenko, V. V. Kosarchuk, Kyiv, Derzhavnyi ekonomiko-tekhnologichnyi universytet transportu. [in Ukrainian].
6. Tao, H., & Zhang, P. (2022). Characterization and mitigation of wheel-rail impact at a singular rail defect. *Journal of Vibration and Control*, 10775463221122111. <https://doi.org/10.1177/10775463221122111>.
7. Kou, L. (2022). A review of research on detection and evaluation of the rail surface defects. *Acta Polytech. Hung*, 19, 167-186. <https://doi.org/10.12700/APH.19.3.2022.3.14>.
8. Murakami, Y., Takagi, T., Wada, K., & Matsunaga, H. (2021). Essential structure of S-N curve: Prediction of fatigue life and fatigue limit of defective materials and nature of scatter. *International Journal of Fatigue*, 146, 106138] <https://doi.org/10.1016/j.ijfatigue.2020.106138>.
9. Popovic, Z., Lazarevic, L., Micic, M., & Brajovic, L. (2022). Critical analysis of RCF rail defects classification. *Transport. Res. Proc.*, 63, 2550–2561. <https://doi.org/10.1016/j.trpro.2022.06.294>.
10. Kosarchuk, V.V., Danilenko, E.I. & Agarkov, A.V. (2020). Effect of Railcar Wheel Tire Profiles on the Contact Stress Level in Subway Rails. *Strength Mater*, 52, 398–406. <https://doi.org/10.1007/s11223-020-00190-x>.
11. Marques, F., Magalhães, H., Pombo, J., Ambrósio, J., & Flores, P. (2016). A three-dimensional approach for contact detection between realistic wheel and rail surfaces for improved railway dynamic analysis. *Mech. Mach. Theory*, 149, 1–28.
12. Sadeghi, J., Khajehdezfuly, A., Esmacili, M., & Poorveis, D. (2016). Investigation of rail irregularity effects on wheel/rail dynamic force in slab track: comparison of two and three dimensional models. *Journal of Sound and Vibration*, 374, 228-244. <https://doi.org/10.1016/j.jsv.2016.03.033>.

13. Klasyfikatsiia ta kataloh defektiv i poshkodzen elementiv strilochnykh perevodiv Ukrainy [Tekst]. (2013). TsP-0285; K.: Vydavnytstvo TOV «Inpres», 196 p. [in Ukrainian].

14. Tverdomed, V. M., Voznenko, A. D., & Boiko, V. D. (2016), Rozrakhunok poperechnykh horyzontalnykh syl u kryvykh diliankakh reikovoï kolii [Calculation of cross horizontal forces in the curved sections of railway tracks]. Zbirnyk naukovykh prats Derzhavnoho ekonomiko-tekhnologichnoho universytetu transportu. Serii: Transportni systemy i tekhnologii, 29, 134-142. [in Ukrainian].

15. DBN V.2.3-19-2018 Sporudy transportu. Zaliznytsi kolii 1520 mm. Normy proektuvannia. [in Ukrainian].

Олександр Азарков^{1*}, Володимир Твердомед²

¹Доцент, Кафедра теоретичної та прикладної механіки, Державний університет інфраструктури та технологій, вул. Кирилівська, 9, м. Київ, 04071, Україна, ORCID: <https://orcid.org/0000-0001-8250-6280>

²Доцент, Кафедра залізничної колії та колійного господарства, Державний університет інфраструктури та технологій, вул. Кирилівська, 9, м. Київ, 04071, Україна, ORCID: <https://orcid.org/0000-0002-0695-1304>

Порівняльний аналіз пошкоджень і дефектів в рейках різних залізничних транспортних систем

У статті проведено аналіз накопичення виявлених пошкоджень і дефектів рейок двох транспортних систем – міського (метро) та магістрального залізничного транспорту. Підсумовуючи проведений аналіз, слід зазначити, що дефекти згідно з рисунками 10 та 11 частіше зустрічаються на коліях Київського метрополітену. При цьому дефекти згідно з рисунком 27 частіше зустрічаються на коліях магістрального залізничного транспорту, а також варто відзначити більш широкий спектр дефектів, частка яких не перевищує 5%. На думку авторів, це пов'язано з особливостями умов експлуатації транспортних систем, зокрема навантаженням на вісь рухомого обладнання, характеристиками руху та іншими експлуатаційними параметрами. Для більш точних висновків необхідно виконати ряд робіт з використанням методів математичного моделювання для врахування впливу окремих параметрів на накопичення дефектів і пошкоджень рейок.

Ключові слова: *рухомий склад, транспортна система, колісна пара, рейка, залізнична колія, дефект, пошкодження, втома, утворення тріщин.*

Igor Martynov^{1*}, Yuri Kalabukhin², Alyona Trufanova³, Stanislav Martynov⁴, Yaroslav Ostapenko⁵

¹Department of wagons engineering and product quality, Ukrainian State University of Railway Transport, Feuerbach Square, 7, Kharkov, 61050, Ukraine, ORCID: <https://orcid.org/0000-0002-0481-3514>.

²Department of marketing, business activity and economic theory", Ukrainian State University of Railway Transport, Feuerbach Square, 7, Kharkov, 61050, Ukraine, ORCID: <https://orcid.org/0000-0003-3693-7607>.

³Department of wagons engineering and product quality, Ukrainian State University of Railway Transport, Feuerbach Square, 7, Kharkov, 61050, Ukraine, ORCID: <https://orcid.org/0000-0003-1702-1054>.

⁴Department of operation and repair of rolling stock, Ukrainian State University of Railway Transport, Feuerbach Square, 7, Kharkov, 61050, Ukraine, ORCID: <https://orcid.org/0000-0003-1826-6053>.

⁵Department of wagons engineering and product quality, Ukrainian State University of Railway Transport, Feuerbach Square, 7, Kharkov, 61050, Ukraine, ORCID: <https://orcid.org/0009-0008-4341-0831>.

*Corresponding author: martinov.hiit@gmail.com

Determination of the efficiency of the modernization of passenger car bodies

The authors determined the intensity of the increase in wear of various elements of the body. It has been established that the lower trim, the roof slope and the lower part of the side wall have the greatest wear. It is proposed to use aluminum alloys for the modernization of passenger car bodies. The advantage of such a technical solution is an increase in the corrosion resistance of the body. The reduction of tare allows to reduce the specific resistance to train movement, reduce fuel and electricity costs for train traction. To reduce operating costs using the basic provisions of the locomotive traction theory, calculations were made to determine the energy consumption for the movement of a passenger train according to the profile conditions of the real section of the regional branch of the Southern Railway by diesel and electric locomotive traction with the base variant and the variant of passenger cars with reduced tare weight) in composition of the train. It has been established that the annual savings in energy costs for the traction of passenger trains when using passenger cars with a reduced tare weight is about 1 million UAH.

Key words: passenger car, body, resource, wear, modernization, economic effect.

Introduction. Railways of Ukraine have been the main element in passenger transportation for many years. They own up to 40% from the total passenger traffic.

But the share of passenger transportation by rail is steadily decreasing. One of the reasons is the significant wear and tear of rolling stock. The vast majority of the inventory of passenger cars owned by the "Passenger Company" branch has already exhausted its resource, since these cars were mainly built in the second half of the 20th century. Accordingly, outdated cars do not allow to increase the speed of movement. Not the least role is played by the poor quality of passenger service.

Increasing the efficiency of railways requires the use of new innovative technical solutions in the construction of non-traction rolling stock.

Analysis of recent research and problem statement. A number of researches both in our country and abroad are devoted to the issue of increasing the efficiency of the passenger economy. The results of studies [1, 2] indicate that significant capital investments are required to update the passenger fleet with new generation wagons and modernize the infrastructure. Given that passenger transportation for JSC Ukrzaliznytsia is unprofitable, own funds are insufficient. Involvement of third-party investors is necessary.

Articles [3, 4] give the results of the analysis of the technical condition of the fleet of passenger cars owned by Passenger Company JSC. The vast majority of passenger cars were built back in the times of the USSR. Accordingly, their wear is about 90%. The authors come to the conclusion that the state of passenger rolling stock has reached a critical limit and needs immediate updating.

As confirmation of these conclusions, the articles [5, 6] present the results of a statistical analysis of the amount of wear and damage of metal structures of the frame and body of passenger cars of different years of construction that have completed their service life.

The authors of the studies [7, 8] believe that in the conditions of chronic underfunding, the overhaul of passenger cars with the extension of their service life is a completely reasonable alternative to the purchase of newly built cars in order to provide railways of Ukraine with passenger cars of a modern level of safety and comfort.

The articles [9, 10] consider possible options for the organization of repair and maintenance of passenger cars after overhaul.

The structural requirements for the design of passenger cars are set out in the normative document [11]. The issue of the use of composite materials for the manufacture of rolling stock bodies is considered in the article [12].

The article [13] provides an assessment of the technical and economic indicators of the operation of the existing traction rolling stock when moving passenger trains, taking into account the operating conditions.

The authors of study [14] proposed to improve the method of calculating the operating costs of passenger transportation by determining the energy costs of train traction for various types of passenger traction rolling stock, taking into account the indicators that change under the influence of increasing speed, developed an economic-mathematical model that makes it possible to determine the operating costs and profitability of passenger train composition under various operating conditions.

In article [15], the issue of ensuring sustainable socio-economic development of railway transport of Ukraine is considered in particular, and a methodical approach to determining the social effect of maintaining passenger traffic in inactive areas is presented.

Paper [16] presents a methodical approach to determining the optimal running zones of passenger trains of various types, which is based on reducing their operating costs and increasing the speed of movement when changing the organization of traffic according to the new classification of trains, which will allow to increase the economic efficiency or reduce the unprofitability of passenger transportation and increase their competitiveness on the market of passenger transport services.

Article [17] examines ways of increasing the competitiveness of railway passenger transportation in Ukraine. Attention is focused on increasing the efficiency of passenger transport by increasing the speed of trains, increasing the quality of provided transport services and improving the comfort of passenger transportation. A new approach to the evaluation of the efficiency of railway passenger transportation is proposed.

Technical and economic indicators of railway passenger transportation are systematized in [18]. Also, this article provides an analysis of the dynamics of cost indicators and determines their impact on the efficiency of these transportations through the determination of the reasons for the decrease in the efficiency of the passenger complex of railway transport of Ukraine.

The purpose and tasks of the study. The purpose of this work is to study the effectiveness of improving the structures of the bodies of passenger cars that have exhausted their resource. To do this, it is necessary to determine which of the elements of the body structure have the greatest effectiveness in operation, to propose technical solutions for the modernization of passenger car bodies and to substantiate their economic feasibility.

Materials and methods of research. The diagnosis of wagons that have reached the end of their service life (28 years) was carried out in the scope of an examination of their technical condition and control tests of the metal structures of frames and bodies, over-spring beams and bogie frames of wagon samples in accordance with the "Methodology of technical diagnosis of passenger wagons that have

served the specified term, for the purpose of its continuation" ІІІ-0070, approved by the order of Ukrzaliznytsia No. 304-ІІ of June 25, 2008 [19].

Two types of cars were subject to inspection of the technical condition of the bodies of passenger cars that had exhausted their service life: rigid compartment models 47D, 47K, built at the Waggonbau plant Ammendorf (Germany), and non-compartment open-type (place card) models 61-425, 61-821, built at the Kalininsky (now Tver) wagon-building plant. In total, about 540 wagons of various ranges according to the years of construction were inspected.

Determining the technical condition of the cars was carried out by visual inspection followed by thickness measurements. At the same time, attention was paid to the presence of cracks, fractures, breaks, dents, wear, deformations, traces of repairs, corrosion damage, changes in the geometric shapes of the elements of the car body and frame. The results of the inspection and the actual thicknesses of the main load-bearing elements of the car were recorded in the technical condition maps. Measurements were made from both the boiler room and the non-boiler side of the car.

The nominal values of the thicknesses of the elements are determined according to the working drawings of the manufacturing plant. When inspecting the technical condition of the cars, schemes of compartment and open (reserved) passenger cars were used.

During the analysis, the results of inspections of metal structures of cars were divided into five conditional groups: cars with a service life of 29-32 years, 33-36 years, 37-40 years, 41-44 years, and more than 45 years. At the same time, the nominal values of the thickness of the structural elements of the car and the actual values of the thickness, taking into account the amount of wear, were compared. This article deals with damage to the most vulnerable elements of the body.

The lower harness of the car. In the cars, measurements of the amount of wear of the lower harness were carried out both on the left side and on the right side of the car (Fig. 1).

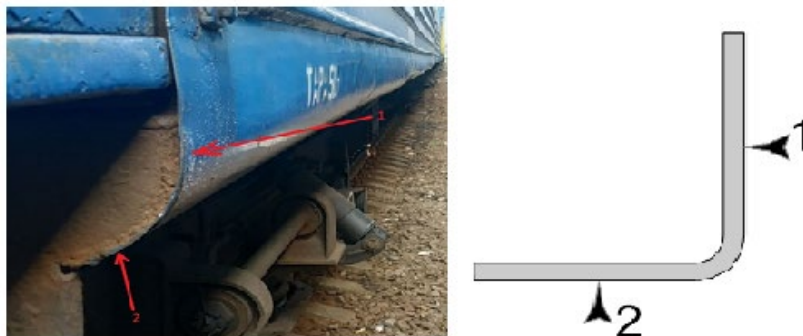


Fig. 1. The scheme of carrying out measurements of the lower binding

In open-type wagons, the maximum value of the trip was found on the working side of the vestibule at point 2. Its value was equal to 4.5 mm. This is approximately 32% wear from the nominal thickness of the metal. The maximum value of tripping in compartment cars was found, as in open-type cars, at point 2. Its value is equal to 7.1 mm, which is 51% of wear from the nominal size.

As a result of the study, the dependences of the increase in the intensity of activation for compartment cars and open-type cars by year were obtained (Fig. 2).

It is obvious that they have a character close to linear. And the intensity of activation in open-type carriages in all age groups is greater than in compartment carriages. This is especially typical for cars with a service life of more than 45 years (exceeding almost twice).

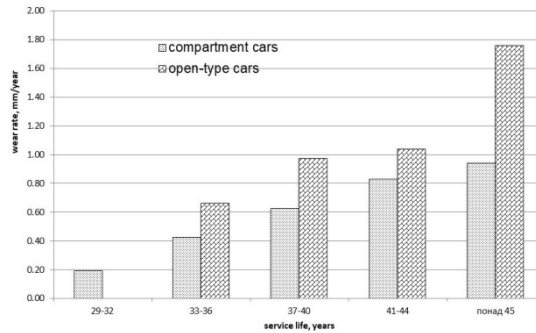


Fig. 2. Intensity of operation of the lower harness in compartment cars and open-type cars

Roof covering. The scheme for measuring the amount of wear of the roof cladding and displaying the node is shown in fig. 3.



Fig. 3. Scheme of roof sheathing measurements

The maximum value of the opening of the roof covering in non-compartment type cars on the left and right sides of the car was found at points 2 and 02 – 0.7 mm with a nominal thickness of 2 mm.

Accordingly, for compartment cars at these same points, the maximum amount of tripping was 0.6 mm.

The magnificent effect on the slopes of the roof is much greater. It is equal to 2 mm on both types of cars. This is due to the fact that the same factors (weather conditions, constant moisture, etc.) act on the slope of the roof cladding.

In fig. 4 shows the obtained dependences of the increase in the intensity of operation for rigid compartment cars and open-type cars of the service life.

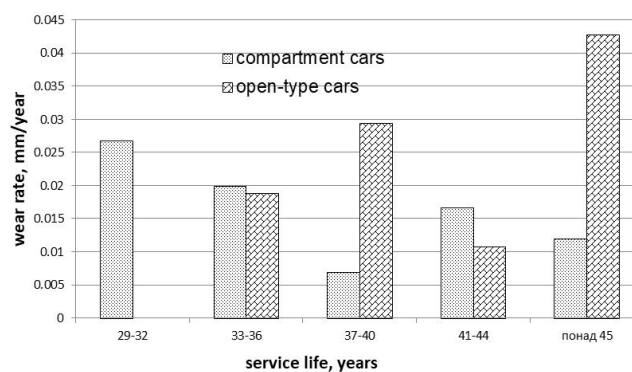


Fig. 4. Intensity of operation of the roof slope in compartment cars and open-type cars

If in open-type cars with an increase in the service life there is a tendency to increase the tripping, then in compartment cars – the opposite is the case.

Side wall. The measurement was made from both the right and the left side of the car in accordance with requirements. The scheme for measuring the wear of the side wall and displaying the node is shown in Fig. 5.



Fig. 5. Scheme of side wall paneling measurements

For open-type cars, increased corrosive wear of the side wall cladding in the lower part in the window space of the side wall is characteristic (point 4). The reason is the constant ingress of moisture in rainy weather through open windows into the windowsill pockets where the mechanisms for raising and lowering the windows are located. With closed windows in the compartment (or blind windows in the passage), the presence of condensation in the cold season causes the appearance of moisture. The maximum trigger value at point 4 was 1.8 mm.

The maximum value of the trip was detected from the side of the corridor along the car (ie in the area of the location of the side seats for passengers) and at point 2 it was 2.1 mm.

For rigid compartment cars, the maximum actuation value was found at point 4, both on the right side of the car along the side corridor, and on the left side, where the passenger compartments are located. The trigger value is 1.5 mm on the right side and 1.4 mm on the left, respectively.

In fig. 6 shows the obtained dependences of the increase in the intensity of operation for rigid compartment cars and open-type cars by year.

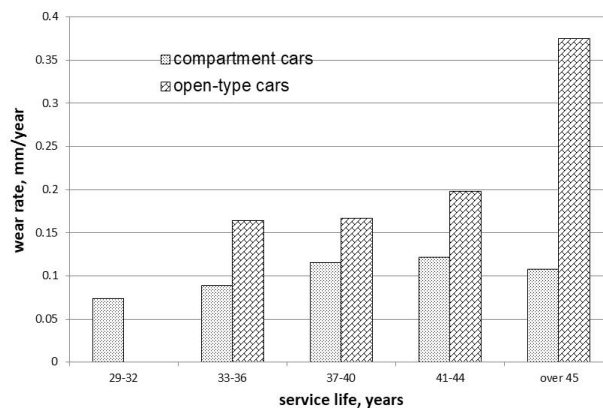


Fig. 6. Intensity of activation of side wall cladding in compartment cars and open-type cars

In open-type carriages, a sharp increase in the intensity of sidewall activation is observed already after 44 years of operation.

In compartment cars, the maximum intensity of side wall activation is typical for cars aged 41-44 years.

Spinal beam. The scheme for measuring the amount of wear of the spinal beam is shown in fig. 7.

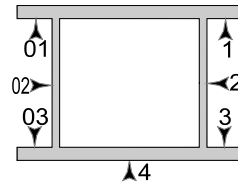


Fig. 7. Scheme of carrying out measurements of the spinal beam

For open type cars, the maximum trigger value is 6 mm, and for compartment wagons - 4 mm.

In fig. 8 the resulting dependences of the growth intensity of the spinal beam for rigid compartment cars and open-type cars by year are given.

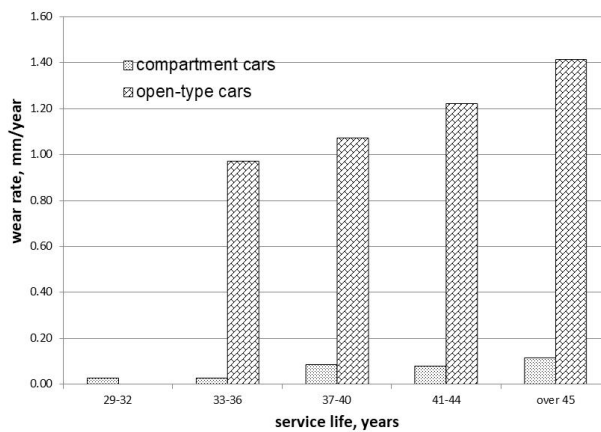


Fig. 8. Intensity of operation of the spinal beam in compartment cars and open-type cars

The intensity of operation for open-type cars significantly exceeds this indicator for compartment wagons. The nature of the distribution of the activation intensity is also different. If for open-type cars it has a linear nature of growth, then for compartment cars in the period of 28-36 years it practically does not change, and then there is an increase (more than 4 times).

End wall. Measurements were made from the working and non-working vestibule of the car. The scheme for measuring the wear of the end wall and displaying the node is shown in Fig. 9.

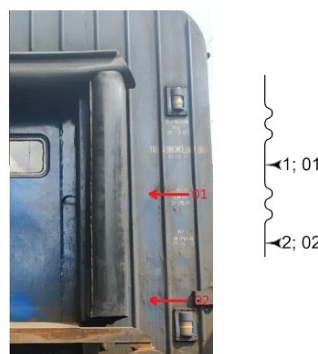


Fig. 9. Scheme of measurements of the end wall cladding

In open-type cars, the maximum value of the trip was detected from the boiler side of the car at point 2 and was equal to 0.9 mm at a nominal thickness of 2 mm. In compartment cars, the maximum trigger value was detected from the boiler side of the car at point 1 and was equal to 0.8 mm at a nominal thickness of 2 mm.

In fig. 10 the resulting dependences of the growth intensity of the end wall for rigid compartment cars and open-type cars by year are given.

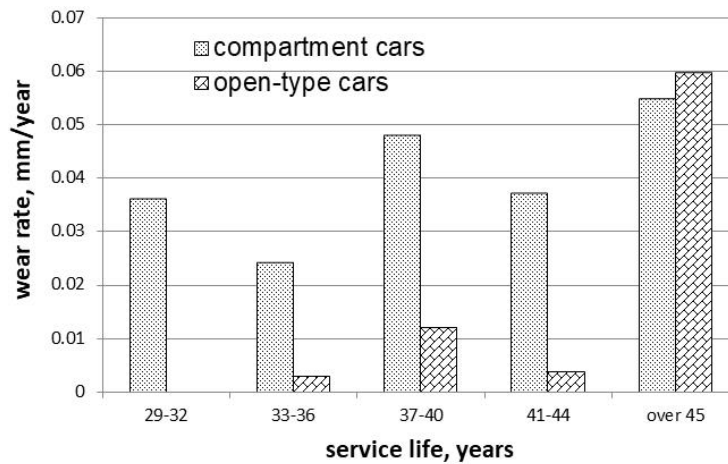


Fig. 14. Intensity of operation of the end wall in compartment cars and open-type cars

It is obvious that the patterns of operation are fundamentally different in different types of cars. If in compartment cars the intensity tends to a smooth linear increase, then in open cars that have already worked for more than 45 years, there is a six-fold increase in the intensity of operation.

The obtained results indicate that the lower harness, the roof slope and the lower part of the side wall are most often damaged during operation of passenger cars. Therefore, it is expedient to modernize the bodies of passenger cars during major renovations by replacing steel sheet and rolled steel with aluminum alloy [20] in the specified places. Among the advantages of such a technical solution is an increase in the corrosion resistance of the body, which significantly increases the service life of the wagons, and a decrease in the wagon's tare weight.

The latter, in turn, allows to reduce the specific resistance of trains. This circumstance determines the reduction of fuel and electricity costs for train traction, which allows to reduce the operating costs of railway transport for energy consumption.

In the calculations, we assume that for the movement of passenger trains, the TEP70 diesel locomotive is used for diesel traction, and the CHS4 AC electric locomotive is used for electric traction, as those serving the movement of passenger trains in the direction chosen for the calculation study.

We will use the provisions of the theory of locomotive traction [21, 13], as well as some studies of factors that affect the consumption of energy carriers [22, 23].

Determination of savings in yearly energy costs for train traction due to a reduction in the Mass of the passenger car under the conditions of running on a specific route

Decreasing the tare weight of a passenger car makes it possible that reduce the specific resistance of trains. This circumstance determines the reduction of fuel and electricity costs for train traction , which allows that reduce the operating costs of railway transport for energy consumption ..

In the calculations, we assume that for the movement of passenger trains the TEP70 diesel locomotive is used for diesel traction and the CHS4 AC electric locomotive is used for electric traction, as those serving the movement of passenger trains in the direction chosen for the calculation study.

Fuel consumption for train operation of a diesel locomotive G_d he the site is determined by the fuel consumption in even $G_{e,d}$ and odd $G_{o,d}$ directions:

$$G_{e,d} = \int_{\tau_s}^{\tau_{s+1}} G_{e,d}(\tau) \times d\tau, \tag{1}$$

$$G_{o,d} = \int_{\tau_s}^{\tau_{s+1}} G_{o,d}(\tau) \times d\tau. \quad (2)$$

where τ_s is passage time of the locomotive with the passenger train of the section profile element.

The specific fuel consumption per meter of operational work (1000 pas-km) is determined by the formula

$$b_p = \frac{\int_{\tau_s}^{\tau_{s+1}} G_{e,d}(\tau) \times d\tau + \int_{\tau_s}^{\tau_{s+1}} G_{o,d}(\tau) \times d\tau}{(P_{e,d} + P_{o,d}) \times l_T} \times 10^3, \quad (3)$$

where $P_{e,d}$, $P_{o,d}$ – the number of passengers following, respectively, in even and department directions, pas.;

l_T – the distance followed by the diesel locomotive at the head of the passenger train in an even or department direction, km.

Electricity consumption for train operation of an electric locomotive A_e he the section is determined by the consumption of electricity in the even $A_{e,d}$ and $A_{o,d}$ odd directions.

Electricity consumption by directions is determined by formulas:

$$A_{e,d} = \int_{\tau_s}^{\tau_{s+1}} A_{e,d}(\tau) \times d\tau, \quad (4)$$

$$A_{o,d} = \int_{\tau_s}^{\tau_{s+1}} A_{o,d}(\tau) \times d\tau. \quad (5)$$

The specific consumption of electricity per meter of operational work (1000 pass-km) is determined by the formula:

$$a_e = \frac{\int_{\tau_s}^{\tau_{s+1}} A_{e,d}(\tau) \times d\tau + \int_{\tau_s}^{\tau_{s+1}} A_{o,d}(\tau) \times d\tau}{(P_{e,d} + P_{o,d}) \times l_e} \times 10^3, \quad (6)$$

where l_e is the distance followed by an electric locomotive at the head of a passenger train in an even or department direction, km.

We will use the main provisions of traction calculations that determine the energy consumption for the movement of a passenger train under the conditions of the profile of the real section of the regional branch "Southern Railway" by thermal and electric locomotive traction with the basic version and the version of passenger cars with reduced tare weight (new version) in the composition train.

Characteristics of the profile of the area of the regional branch "Pivdenna zaleznytsia" are given in table 1 and fig. 15 and 16 [1, 3, 4]. As can be seen from the given data, in the department direction the prevailing profile is with a slope of 0...1‰, in the even direction - 0...1‰. The total length of the freight train rotation section is 344,502 km. The train has 6 stops he the section in both directions.

Table 1. Site profile characteristics

Tilt range	Percentage distribution of profile elements, %	Length, km	Percentage distribution of profile elements, %	Length, km
Even direction			Odd direction	
-16...-15	0.09	0.3	0	0
-15...-14	0	0	0	0
-14...-13	0	0	0.12	0.4
-13...-12	0.07	0.25	0.27	0.922
-12...-11	0.06	0.2	0.35	1,214
-11...-10	0.36	1.24	0.73	2,528
-10...-9	1.67	5.77	1.64	5,652
-9...-8	3.82	13,16	4.35	14,981
-8...-7	5.03	17,313	5.36	18,456
-7...-6	2.98	10.25	4.52	15,559
-6...-5	2.81	9,682	3.11	10,698
-5...-4	3.34	11,498	2.33	8,041
-4...-3	3.76	12.94	2.68	9,226
-3...-2	6.14	21,16	4.37	15,062
-2...-1	9.57	32,965	5.17	17,795
-1...0	7.03	24,207	7.40	25,495
0...1	17.08	58,853	16.71	57,575
1...2	6.00	20,655	9.70	33,415
3...4	2.56	8,826	3.93	13.55
4...5	2.82	9,721	3.46	11,923
5...6	2.62	9,021	2.88	9,907
6...7	3.89	13,403	2.52	8,695
7...8	6.00	20,659	4.93	16,988
8...9	4.23	14,562	4.27	14.7
9...10	1.90	6,551	2.03	7.01
10...11	0.93	3.2	0.42	1.44
11...12	0.52	1,792	0.06	0.2
12...13	0.35	1,222	0.07	0.25
13...14	0.06	0.2	0	0
14...15	0.06	0.2	0	0
15...16	0	0	0.09	0.3
Together	100	344,502	100	344,502

To carry out traction calculations, in addition to the characteristics of the section profile, it is necessary to specify the following data, both when using diesel locomotive and when using electric locomotive traction:

1. Mass of the train in tons.
2. The number of cars in the train by type.
3. The average population of a car of a passenger train.
4. Technical speed.

To determine these indicators, we will use the reference indicators of the schedule of passenger trains on the section of the regional branch "Yuzhnaya zheleznaya doroga" for the year 2023, which are given in Tables 2, 3 and 4.

Table 2. Output data for the traction calculation in the odd direction

Characteristic	Station							Together
	formation	1	2	3	4	5	6	
Distance, km		24.2	131.4	54.91	34.6	56,56	42.84	344.51
Arrival, h.:min.		23:00	0:47	1:55 a.m	2:28	3:24 a.m	4:02 a.m	
Departure, h.:min.	22:30	23:02	1:07 a.m	1:57 a.m	2:30 a.m	3:26 a.m		
Running time, hours		0.50	1.75	0.80	0.52	0.90	0.60	5.07
Time of stops , h.		0.03	0.33	0.03	0.03	0.03		0.47
Technical speed, km/h.		48.4	75.1	68.6	67.0	62.8	71.4	68.0
District speed, km/h.		45.4	63.1	65.9	62.9	60.6		62.3
Precinct speed coefficient		0.94	0.84	0.96	0.94	0.96		0.92

Table 3. Output data for traction calculation in even direction

Characteristic	Station							Together
	6	5	4	3	2	1	formation	
Distance, km		42.84	56,56	34.6	54.91	131.4	24.2	344.51
Arrival, h.:min.		1:19 a.m	2:12	2:43 a.m	3:33	5:51 a.m	6:27 a.m	
Departure, h.:min.	0:39	1:21 a.m	2:14 a.m	2:45	3:53	5:54 a.m		
Running time, hours		0.67	0.85	0.48	0.80	1.97	0.55	5.32
Time of stops , h.		0.03	0.03	0.03	0.33	0.05		0.48
Technical speed, km/h.		64.3	66.5	71.6	68.6	66.8	44.0	64.8
District speed, km/h.		61.2	64.0	67.0	48.5	65.2		59.4
Precinct speed coefficient		0.95	0.96	0.94	0.71	0.98		0.92

Table 4. Output data for traction calculation

Characteristic	Variant of the car	
	base	modernized
Total number of cars in the train	18	18
- compartment	15	15
- bedrooms	3	3
Number of seats in the carriage:		
- compartment	38	38
- bedroom	19	19
Tare mass of the wagon, i.e.:		
- compartment	56	54.5
- bedroom	56	54.5
Mass of the passenger with luggage, kg	100	100

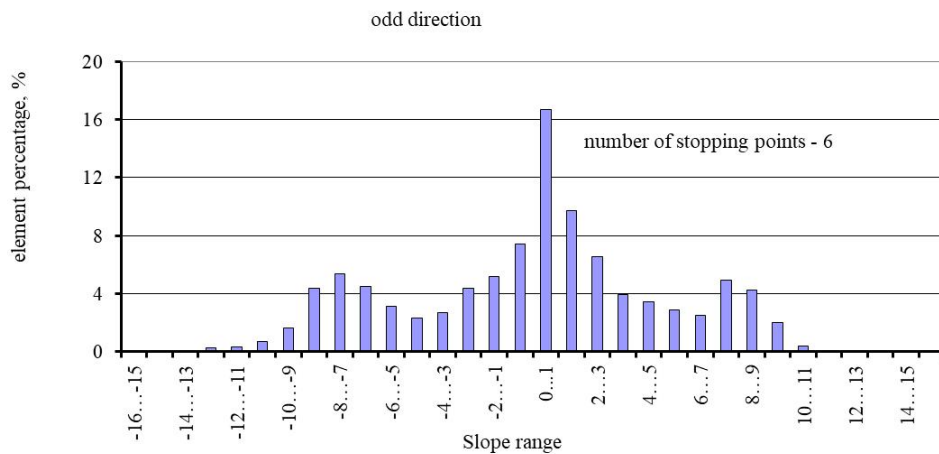


Fig. 15 – Histogram of distribution of site profile elements by slope in an odd direction

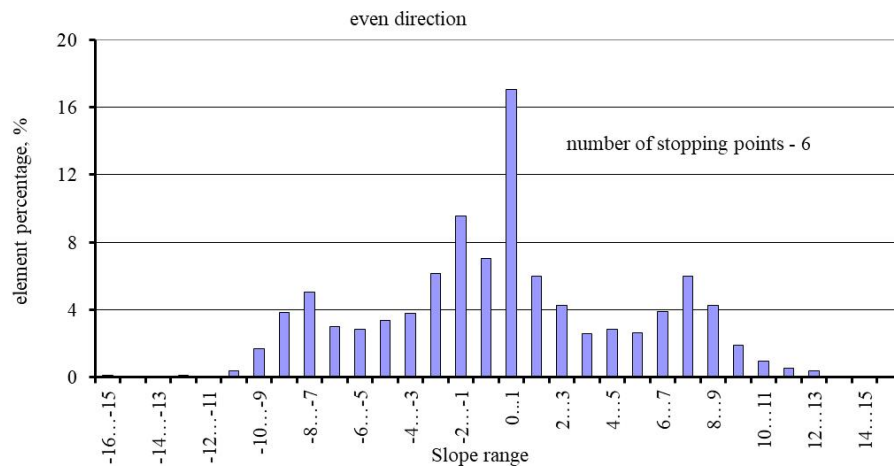


Fig. 16 – Histogram of distribution of site profile elements by slope in even direction

The average population of a car of a passenger train is determined by the formula

$$P_H = \frac{n_{c.c} \times M_{c.c} + n_{s.c} \times M_{s.c}}{n_{c.c} + n_{s.c}} \quad (7)$$

where $n_{c.c}$, $n_{s.c}$ – the number of passenger cars in the train, respectively, compartment and sleeping cars, weight.;

$M_{c.c}$, $M_{s.c}$ – the number of seats in the carriage, respectively, compartment and sleeper seats.

The mass of the passenger train is determined by the formula

$$m_c = q_{c.c} \times n_{c.c} + q_{s.c} \times n_{s.c} + \frac{P_H \times m_p}{1000} \times (n_{c.c} + n_{s.c}), \quad (8)$$

where $q_{c.c}$, $q_{s.c}$ – tare weight of the carriage, respectively, compartment and sleeper, i.e.;

m_p – mass of the passenger with luggage, kg

Tables 5 and 6 show the results of the calculation of the initial data for carrying out traction calculations according to the variants of passenger cars and types of locomotive traction.

Table 5. Results of calculation of raw data for carrying out traction calculations for variants of passenger cars with diesel traction

Characteristic	Odd direction		Even direction	
	base car	modernized car	base car	modernized car
Mass of the locomotive, i.e.	130	130	130	130
Number of cars in the train:	18	18	18	18
- compartment	15	15	15	15
- bedrooms	3	3	3	3
Tare mass of the car, i.e.:				
- compartment	56	54.5	56	54.5
- bedroom	56	54.5	56	54.5
Number of seats in the carriage:				
- compartment	38	38	38	38
- bedroom	19	19	19	19
Mass of the passenger with luggage, kg	100	100	100	100
The average population of the car, pas.	34.8	34.8	34.8	34.8
Mass of the composition, i.e.	1071	1044	1071	1044
Mass of the train, i.e.	1197	1170	1197	1170
Technical speed on interstation sections, km/h.	in table 2	in table 2	in table 3	in table 3
Interstation distance, km.	in table 2	in table 2	in table 3	in table 3

Table 6. Results of calculation of raw data for carrying out traction calculations for variants of passenger cars with electric locomotive traction

Characteristic	Odd direction		Even direction	
	base car	modernized car	base car	modernized car
Mass of the locomotive, i.e.	126	126	126	126
Number of cars in the train:	18	18	18	18
- compartment	15	15	15	15
- bedrooms	3	3	3	3
Tare mass of the wagon, i.e.:				
- compartment	56	54.5	56	54.5
- bedroom	56	54.5	56	54.5
Number of seats in the carriage:				
- compartment	38	38	38	38
- bedroom	19	19	19	19
Mass of the passenger with luggage, kg	100	100	100	100
The average population of the train, pas.	34.8	34.8	34.8	34.8
Mass of the composition, i.e.	1071	1044	1071	1044
Mass of the train, i.e.	1197	1170	1197	1170
Technical speed on interstation sections, km/h.	in table 2	in table 2	in table 3	in table 3
Interstation distance, km.	in table 2	in table 2	in table 3	in table 3

The results of the traction calculation according to the variants of passenger cars when moving by locomotive traction are shown in Table 7.

Table 7. Results of traction calculation according to variants of passenger cars when moving by diesel traction

Characteristic	Variant of the car	
	base	modernized
Odd direction		
Freight turnover, tkm . gross	368960	359659
Fuel consumption for traction, kg	1067.9	1055.6
Time on the route, hours	5.56	5.55
Technical speed km/h.	68.4	68.6
District speed km/h.	61.9	62
Precinct speed coefficient	0.90	0.90
Passenger turnover, pass-km	216008	216007.8
Specific fuel consumption per gauge, kg/1000 pass-km	4.94	4.89
Even direction		
Freight turnover, tkm . gross	368960	359659
Fuel consumption for traction, kg	1090.1	1077
Time on the route, hours	5.84	5.84
Specific fuel consumption per meter, kg/10 ⁴ tkm _ gross	29.5	29.9
Technical speed km/h.	64.2	64.3
District speed km/h.	58.9	59
Precinct speed coefficient	0.92	0.92
Passenger turnover, pass-km	216008	216007.8
Specific fuel consumption per gauge, kg/1000 pass-km	5.05	4.99
Average turnover		
Mass of the composition, t	1071	1044
Freight turnover, tkm . gross	737920.5	719318.0
Mileage of the train, train - km	689.2	689.2
Time on the route, hours	11.40	11.39
Technical speed km/h.	65.95	66.02
District speed km/h.	60.46	60,51
Precinct speed coefficient	0.917	0.917
Fuel consumption for traction, kg	2158.0	2132.6
Passenger turnover, pass-km	432016	432016
Specific fuel consumption per gauge, kg/1000 pass-km	5.00	4.94

The results of the traction calculation according to the variants of passenger cars when moved by electric traction are shown in Table 8.

Table 8. Results of traction calculation according to variants of passenger cars when moving by electric traction

Characteristic	Variant of the wagon	
	base	modernized
Odd direction		
Freight turnover, tkm . gross	368960	359659
Electricity consumption for traction, kWh.	7898.4	7403.4
Time on the route, hours	5.54	5.53
Technical speed km/h.	67.9	68.1
District speed km/h.	62.2	62.3
Precinct speed coefficient	0.92	0.91
Passenger turnover, pass-km	216008	216008
Specific consumption of electrical energy per meter, kWh/1000 pass-km	36,57	34,27
Even direction		
Freight turnover, tkm . gross	368960	35965 9
Electricity consumption for traction, kWh.	8171.3	7632.5
Time on the route, hours	5.76	5.76
Technical speed km/h.	65.3	65.3
District speed km/h.	59.9	59.8
Precinct speed coefficient	0.92	0.92
Passenger turnover, pass-km	216008	216008
Specific consumption of electrical energy per meter, kWh/1000 pass-km	37.83	35,33
Average turnover		
Mass of the composition, t	1071	1044
Freight turnover, tkm . gross	737920.5	719317.5
Mileage of the train, train - km	689.2	689.2
Time on the route, hours	11.30	11.29
Technical speed km/h.	66.59	66.65
District speed km/h.	60.99	61.05
Precinct speed coefficient	0.916	0.916
Electricity consumption for traction, kWh.	16069.7	15035.9
Passenger turnover, pass-km	432016	432016
Specific consumption of electrical energy per meter, kWh/1000 pass-km	37.20	34.80

Using the results of traction calculations, we will determine the consumption of energy resources by diesel and electric traction along the entire route of the passenger train according to the variants of cars. For this, the distance of service of the route by diesel and electric traction, which is given in table 9, should be taken into account.

Table 9. Distance of service of the route by locomotive and electric traction

Characteristic	Odd direction	Even direction	Together
The distance of service of the route by locomotive traction, km	155.6	155.6	311.2
The distance of service of the route by electric traction, km	333.4	333.4	666.8
Together	489	489	978

The results of calculating the consumption of energy resources by types of traction are shown in tables 10 and 11.

Table 10. Results of calculation of fuel consumption by locomotive traction for moving a passenger train by wagon variants

Characteristic	Variant of the car	
	base	modernized
Odd route direction		
The distance of service of the route by locomotive traction, km	155.6	155.6
Mass of the composition, t	1071	1044
Passenger turnover, pass-km	97561.2	97561.2
Technical speed km/h.	68.4	68.6
Specific fuel consumption per gauge, kg/1000 pass-km	4.94	4.89
Fuel consumption for traction, kg	482	477
Even direction of the route		
The distance of service of the route by locomotive traction, km	155.6	155.6
Mass of the composition, t	1071	1044
Passenger turnover, pass-km	97561.2	97561.2
Technical speed km/h.	64.2	64.3
Specific fuel consumption per gauge, kg/1000 pass-km	5.05	4.99
Fuel consumption for traction, kg	492	486
On average per revolution of the locomotive		
The distance of service of the flight by diesel locomotive, km	311.2	311.2
Mass of the composition, t	1071	1044
Passenger turnover, pass-km	195122.4	195122.4
Fuel consumption for traction, kg	975	963

Table 11. Results of calculation of fuel consumption by electric traction for moving a passenger train by car options

Characteristic	Variant of the car	
	base	modernized
1	2	3
Odd route direction		
The distance of service of the route by electric traction, km	333.4	333.4
Mass of the composition, t	1071	1044
Passenger turnover, pass-km	209041.8	209041.8
Technical speed km/h.	67.9	68.1
Specific consumption of electrical energy per meter, kWh/1000 pass-km	36,57	34,27
Electricity consumption for traction, kWh.	7644	7165

Table 11. Continued

1	2	3
Even direction of the route		
The distance of service of the route by electric traction, km	333.4	333.4
Mass of the composition, t	1071	1044
Passenger turnover, pass-km	209041.8	209041.8
Technical speed km/h.	65.3	65.3
Specific consumption of electrical energy per meter, kWh/1000 pass-km	37.83	35,33
Electricity consumption for traction, kWh.	7908	7386
On average per revolution of the locomotive		
The distance of service of the flight by electric traction, km	666.8	666.8
Mass of the composition, t	1071	1044
Passenger turnover, pass-km	418083.6	418083.6
Electricity consumption for traction, kWh.	15551.5	14551.0

The saving of energy resources for the traction of a passenger train per flight is determined by the following formulas:

with locomotive traction

$$\Delta G_d = G_d^b - G_d^m, \quad (9)$$

with electric traction

$$\Delta A_e = A_e^b - A_e^m. \quad (10)$$

where G_d^b , G_d^m is the fuel consumption for traction of a passenger train per flight, respectively, with basic and new cars, kg;

A_e^b , A_e^m – electricity consumption for traction of a passenger train per flight, respectively, with basic and new cars, kWh.

According to the schedule of traffic along the route (table 12), we will determine the turnover of the passenger train.

Table 12. Passenger train schedule by route

The name of the course route	Time		
	departure	arrival	on the route, hours
A forming station is a turnover station	22:30	6:10 a.m	7.67
The idle carriage by turnover			16.75
Turnover station-formation station	22:55	6:27 a.m	7.53
Idle wagon at the home depot			16.05
Turn of the passenger train			48.00

The number of turns of a passenger train per year is determined by the formula

$$N_o = \frac{365 \times 24}{O_{p.p}}, \quad (11)$$

where p.p is passenger train turnover, h.

The annual savings in energy costs for the traction of passenger trains under the conditions of running on a specific route is determined by the following formulas:

with locomotive traction

$$\Delta E_d = \Delta G_d \times N_o \times \Pi_f, \quad (12)$$

with electric traction

$$\Delta E_e = \Delta A_e \times N_o \times \Pi_e, \quad (13)$$

where Π_f , Π_e – the price, respectively, of the 1st kg of fuel and the 1st kWh. of electricity, UAH

Tables 13 and 14 show the results of determining the annual savings in energy costs for the traction of passenger trains under the conditions of running on a specific route.

Table 13. Results of determining the annual savings in fuel costs for the traction of passenger trains under the conditions of running on a specific route

Characteristic	indicator value
The number of passenger train turnovers per year	182.5
Economy of fuel consumption for traction per flight, kg.	11
Annual saving of fuel consumption for traction along the route, kg	2094
The price of 1 kg of fuel, UAH.	58.43
Annual savings in fuel costs for traction, thousand hryvnias.	122,332

Table 14. Results of determining the annual savings in electricity costs for the traction of passenger trains under the conditions of running on a specific route

Characteristic	indicator value
The number of passenger train turnovers per year	182.5
Savings in power consumption for traction per flight, kWh.	1000.5
Annual savings in electricity consumption for traction along the route, kWh.	182584
The price of 1 kWh. of electricity, UAH	4.6
Annual savings in electricity costs for traction, thousand UAH.	839,887

Thus, the annual saving of energy costs for the traction of passenger trains when using passenger cars with a reduced tare weight under the conditions of running on a specific route is

$$\Delta E = 122,332 + 839,887 = 962,219 \text{ thousand UAH.}$$

Conclusions. According to the results of statistical processing the results of the metal structures of compartment cars bodies technical condition and open-type cars that have already exhausted their resource it was determined that the lower strapping (more than 7 mm, 50% of the nominal size), the roof slope (more than 2 mm, 35% of the nominal size), and the lower part of the side wall (over 2 mm, 42% of the nominal size).

It is proposed to carry out modernization of the bodies of passenger cars by replacing the steel sheet and rolled metal with aluminum alloy in the above-mentioned places during capital renovations. This makes it possible to reduce the tare weight of the car and the consumption of fuel and electricity for train traction.

During the calculations, it was considered that for the movement of passenger trains, the TEP70 series diesel locomotive is used for diesel traction, and the CHS4 series alternating current electric locomotive is used for electric traction. Annual saving of energy costs for the traction of passenger trains when using passenger cars with a reduced tare weight 962,219 thousand UAH.

REFERENCES

1. Samsonkin, V. M. (2004) Pro pidvyshennia efektyvnosti pasazhurskikh vagoniv na zaliznychnomy transporti. *Zaliznychnyy transport Ukrayiny*, 1, 43-45. [in Ukrainian]
2. Samsonkin, V. M. et al. (2009) Osnovy reorhanizatsii pasazhyrskoho kompleksu zaliznychnoho transportu. *Visnyk ekonomiky transportu i promyslovosti*, 5, 78-81. [in Ukrainian]
3. Bozhok, N. O. et al. (2014) Doslidzhennya suchasnoho stanu parku pasazhyr'skykh vahoniv. *Zbirnyk naukovykh prats Dnipropetrovskoho natsionalnoho universytetu zaliznychnoho transportu imeni akademika V. Lazaryana "Problemy ekonomiky transportu"*, 8, 78-87. [in Ukrainian]
4. Loboyko, L. M. et al. (2007) Stan vahonnoho parku ta vahonoremontnoyi bazy v Ukrayini. *Zbirnyk naukovykh prats' Dnipropetrovskoho natsional'noho universytetu zaliznychnoho transportu imeni akademika V. Lazaryana "Problemy ekonomiky transportu"*, 19, 176-182. [in Ukrainian]
5. Martynov, I. E. et al. (2018) Analiz tekhnichnoho stanu kuzoviv pasazhyr'skykh vahoniv. *Visnyk Natsionalnoho tekhnichnoho universytetu "KHPI". Seriya: Novi rishennya v suchasnykh tekhnolohiyakh. Transportne mashynobudu-vannya*, 45(1321), 41-46. [in Ukrainian]
6. Shykunov, O. A. et al. (2012) Doslidzhennya hranychnoho stanu pasazhyr'skykh vahoniv. *Vahonnyy park*, 12, pp. 4-6. [in Ukrainian]
7. Yezhov, Yu. et al. (2018) Kapital'no-vidnovlyuval'nyy remont pasazhyr'skykh vahoniv lokomotyvnoyi tyahy yak zasib zabezpechennya zaliznyts' reykovym rukhomym skladom. *Zbirnyk naukovykh prats "Reikovy rukhomyi sklad"*, 17, 51-61. [in Ukrainian]
8. Barash, Yu. S. (2006) Stratehiya ratsional'noho onovlennya pasazhyr'skoho vahonnoho parku v umovakh de-fitsytu investytsiy. *Visnyk Dnipropetrovskoho natsional'noho universytetu zaliznychnoho transportu imeni akademika V. Lazaryana*, 10, 130-140. [in Ukrainian]
9. Ostapyuk, B. Ya. (2004) Podovzhennya terminu eksplua-tatsiyi pasazhyr'skykh vahoniv. *Visnyk Dnipropetrovskoho natsional'noho universytetu zaliznychnoho transportu imeni akademika V. Lazaryana*, 4, 165-173. [in Ukrainian]
10. Loboyko, L. M. (2006) *Problemy i perspektivy pasazhirskogo vagonostroyeniya v Ukraine*. *Zaliznychnyy transport Ukrayiny*, 3, pp. 3-9. [in Ukrainian]
11. EN 12663-2:2010, Railway applications, Structural requirements of railway vehicle bodies, Part 1: Locomotives and passenger rolling stock (and alternative method for freight wagons), 2010.
12. Kim, J.S., Lee, S.J., & Shin, K.B. (2007). Manufacturing and structural safety evaluation of a composite train carbody, *Composite Structures*. 78(4), 468-476.
13. Dan'ko, M. I. et al. (2009) Metodolohiya ta rezul'taty otsinky tekhniko-ekonomichnykh pokaznykiv roboty mahistral'nykh lokomotyviv pry pasazhyr'skykh perevezennyakh. *Zbirnyk naukovykh prats' Ukrayins'koyi derzhavnoyi akademiyi zaliznychnoho transportu*, 102, 191-201. [in Ukrainian]
14. Yer'omina, M. O. (2009) Udoskonalennya metodu rozrakhunku ekspluatatsiynykh vytrat pasazhyr'skykh zaliznychnykh perevezhen. *Ekonomika: problemy teorii ta praktyky*, VI, № 254, 1401-1405. [in Ukrainian]
15. Kalabukhin, Yu. Ye. et al. (2013) Urakhuvannya sotsial'noyi skladovoyi efektyvnosti tekhniko-orhanizatsiynykh zakhodiv pasazhyr'skykh perevezhen' zaliznychnoho transportu. *Efektivna ekonomika*, 3, 27-35. [in Ukrainian]

16. Barash, Yu. S. (2011) Teoretychno-metodychnyy pidkhdid do vyznachennya konkurentospromozhnosti posluh, shcho nadayut'sya pasazhyr's'kymy vydamy transportu. *Visnyk Dnipropetrovs'koho natsional'noho universytetu zaliznychnoho transportu imeni akademika V. Lazaryana*, 38, 233-237. [in Ukrainian]
17. Matushevych, O. O. (2013) Zasoby pidvyshchennya efektyvnosti zaliznychnykh pasazhyr's'kykh perevezen' ta metody yikh realizatsiyi. *Zbirnyk naukovykh prats' Derzhavnoho ekonomiko-tehnolohichnoho universytetu transportu. Ser. "Ekonomika i upravlinnya"*. 23-24, 142-149. [in Ukrainian]
18. Matushevych, O. O. (2013) Vartisni tekhniko-ekonomichni pokaznyky ta efektyvnist' zaliznychnykh pasazhyr's'kykh perevezen'. *Zbirnyk naukovykh prats' Dnipropetrovs'koho natsional'noho universytetu zaliznychnoho transportu imeni akademika V. Lazaryana "Problemy ekonomiky transportu"*. 5, 72-79. [in Ukrainian]
19. Donchenko, A. V. et al. (2008) Metodyka tekhnichnoho diahnostuvannya pasazhyr's'kykh vahoniv, shcho vysluzhyly pryznachenny termin, z metoyu yoho prodovzhenya CL-07. *UkrNDIV. Kyiv*, 63. [in Ukrainian]
20. Gevorkyan, E. S. (2015) Novi materialy ta yikh oderzhannya: pidruchnyk. *Kharkov: Disa+*. 344 p. [in Ukrainian]
21. Kalabukhin, Yu. Ye. (2010) Udoskonalennya metodolohiyi vyznachennya tekhniko-ekonomichnykh pokaznykiv funktsionuvannya tyahovoho rukhomoho skladu z urakhuvanniam zhyttyevoho tsyклу: *dys. d-ra tekhnichnykh nauk: 05.22.07. Kharkov: UkrDAZT*. 420 p. [in Ukrainian]
22. Kalabukhin, Yu. Ye. (2011) Rezul'taty doslidzhennya vplyvu ekspluatatsiynykh faktoriv na tyahovo-enerhetychni pokaznyky vykorystannya teplovoznoyi tyahy u vantazhnomu rusi. *Zbirnyk naukovykh prats' Ukrayins'koyi derzhavnoyi akademiyi zaliznychnoho transportu*. 122, 66-75. [in Ukrainian]
23. Kalabukhin, Yu. Ye. (2009) Metodolohiya ta rezul'taty otsinky tekhniko-ekonomichnykh pokaznykiv roboty mahistral'noho lokomotyva pry peremishchenni vantazhnoho poyizdu. *Visnyk Skhidnoukrayins'koho natsional'noho universytetu im. V. Dalya*, 2(132), 157-163. [in Ukrainian]

Ігор Мартинов¹, Юрій Калабухін², Альона Труфанова³, Станіслав Мартинов, Ярослав Остапенко⁵

¹Кафедра інженерії вагонів та якості продукції, Український державний університет залізничного транспорту, пл. Фейербаха, 7, Харків, 61050, Україна, ORCID: <https://orcid.org/0000-0002-0481-3514>.

²Кафедра маркетингу, комерційної діяльності та економічної теорії, Український державний університет залізничного транспорту, пл. Фейербаха, 7, Харків, 61050, Україна, ORCID: <https://orcid.org/0000-0003-3693-7607>.

³Кафедра інженерії вагонів та якості продукції, Український державний університет залізничного транспорту, пл. Фейербаха, 7, Харків, 61050, Україна, ORCID: <https://orcid.org/0000-0003-1702-1054>.

⁴Кафедра експлуатації та ремонту рухомого складу, Український державний університет залізничного транспорту, пл. Фейербаха, 7, Харків, 61050, Україна, ORCID: <https://orcid.org/0000-0003-1826-6053>.

⁵Кафедра інженерії вагонів та якості продукції, Український державний університет залізничного транспорту, пл. Фейербаха, 7, Харків, 61050, Україна, ORCID: <https://orcid.org/0009-0008-4341-0831>.

Визначення ефективності модернізації кузовів пасажирських вагонів

Пасажирські вагони АТ «Укрзалізниця» практично вичерпали свій ресурс. Підвищення ефективності роботи залізниць вимагає використання нових інноваційних технічних рішень. У статті проаналізовано технічний стан кузовів пасажирських вагонів, які відпрацювали свій ресурс. Всього перевірено 540 вагонів різних років побудови. У ході аналізу результатів перевірок товщини металоконструкцій вагонів були розділені на п'ять умовних груп залежно від терміну служби. При цьому порівнювалися номінальні значення товщин елементів конструкції автомобіля та фактичні значення. Встановлено, що найбільше спрацювання знос мають нижня обшивка, скат даху та нижня частина бічної стінки. Для модернізації кузовів пасажирських вагонів пропонується використовувати алюмінієві сплави. Перевагою такого технічного рішення є підвищення корозійної стійкості кузова, підвищення довговічності та зменшення ваги тари вагону. Зменшення тари дозволяє зменшити питомий опір руху поїзда та витрати палива та електроенергії на тягу поїзда. Для зниження експлуатаційних витрат з використанням основних положень теорії локомотивної тяги проведено розрахунки визначення енерговитрат

на рух пасажирського поїзда за профільними умовами реальної ділянки регіональної філії Південна залізниця дизель- та електричною локомотивною тяги з базовим та модернізованим варіантом пасажирських вагонів. Встановлено, що річна економія енерговитрат на тягу пасажирських поїздів при використанні пасажирських вагонів зі зниженою тарою становить близько 1 млн. грн.

Ключові слова: пасажирський вагон, кузов, ресурс, знос, модернізація, економічний ефект/

Olga Petrychenko^{1*}, Ievgenii Petrichenko², Igor Burmaka³, Alla Vynohradova⁴

¹Doctor of Philosophy, Theory and Structure of a Ship Department, National University “Odessa Maritime Academy, 8, Didrikhson str., Odessa, 65052, Ukraine, ORCID: <https://orcid.org/0000-0002-4893-8204>.

²Doctor of Philosophy, Maritime transportation Department, National University “Odessa Maritime Academy, 8, Didrikhson str., Odessa, 65052, Ukraine, ORCID: <https://orcid.org/0009-0008-2225-3152>.

³Doctor of Engineering Science, professor, head of the Ship’s handling department, National University “Odessa Maritime Academy, 8, Didrikhson str., Odessa, 65052, Ukraine, ORCID: <https://orcid.org/0000-0002-0853-6884>.

⁴Head of the laboratory of the Ship’s handling department, National University “Odessa Maritime Academy, 8, Didrikhson str., Odessa, 65052, Ukraine, ORCID: <https://orcid.org/0009-0007-9406-3203>.

*Corresponding author: oapetrychenko@gmail.com

Changes in modern university: challenges of today and development trends

Education is a process of interaction and communication among all participants, in which each of them has an impact on the outcome. Today, in the conditions of the modern world, cooperation between the teacher and the student acquires new forms and characteristics. The teacher is no longer just a source of knowledge but becomes a partner and helper for the student. The quality of communication between the student and the teacher depends on their readiness for dialogue and mutual understanding, absence of coercion and orders. A comprehensive approach to education and communication allows for a deep understanding of the processes and their improvement. Higher education institutions need to pay special attention to issues of strategic communication development, branding, and image. Clear and well-planned communication systems should be implemented at the level of structural units in order to achieve success. Providing adequate material and technical resources as well as information and communication technologies is crucial for effective use of various teaching methods and forms. However, communication between a teacher and a student should not only be about academic topics, but also about support, motivation, and personal development.

Keywords: adult higher education, communication, ergonomic technologies, higher education

Introduction. Monitoring of higher education has revealed the need for continuous learning to achieve success in any field. The modern world is fast-paced, with more and more processes being automated, and people are required to acquire new skills to meet the demands of digital transformation of the economy. This leads to an increase in demand for technical specialties that enable digital transformation and expand the range of people interested in obtaining education [1].

Moreover, the COVID-19 pandemic has accelerated the need for digital transformation, with remote work and online education becoming the new norm. This has further emphasized the importance of continuous learning and the acquisition of digital skills. As a result, universities and other educational institutions are adapting their programs to offer more technical and digital courses to meet the changing needs of the job market.

The growing availability of online courses and other forms of distance learning has made continuous learning more accessible than ever before. Students can now take courses from top universities around the world without leaving their homes, and working professionals can update their skills without having to take a break from their careers. This has opened up new opportunities for lifelong learning and professional development, and has made it easier for individuals to stay relevant and competitive in their fields.

However, the need for continuous learning goes beyond technical and digital skills. Soft skills such as communication, collaboration, and problem-solving are becoming increasingly important in today's workplace, and employers are looking for candidates who possess these skills in addition to technical expertise. Therefore, universities and other educational institutions must also focus on developing these skills in their students to prepare them for success in the workforce. Overall, continuous learning is essential for both personal and professional growth in today's rapidly evolving world.

Analysis of recent research and problem statement. Continuous learning has become essential not only for individual success but also for the success of organizations. Companies that invest in employee training and development have been shown to have higher productivity and profitability [2]. Therefore, employers are increasingly seeking out candidates with a willingness to learn and develop new skills.

Furthermore, continuous learning also plays a vital role in employee retention. When companies invest in their employees' professional growth and development, it fosters a sense of loyalty and commitment among the workforce. Employees feel valued and are more likely to stay with the company for a more extended period, reducing recruitment and training costs.

In today's knowledge-based economy, the value of a company is closely linked to the intellectual capital of its employees. Therefore, organizations that encourage continuous learning and create a culture of learning are more likely to attract and retain top talent. This creates a competitive advantage for companies in the long run, as they have a workforce with a diverse skill set and a willingness to adapt to new technologies and trends.

Continuous learning is essential for both individual and organizational success. It enables individuals to remain competitive and relevant in the job market, and organizations to stay ahead of the curve and attract top talent. As the pace of technological change continues to accelerate, continuous learning will become increasingly critical for all individuals and organizations. Continuous learning is critical in today's fast-paced and rapidly changing world. It enables individuals to remain competitive in the job market, organizations to stay ahead of the curve, and society to progress as a whole. Indeed, in the current age of digital transformation, continuous learning is more crucial than ever before. With technological advancements and automation replacing traditional job roles, individuals need to constantly acquire new skills to remain relevant in the job market. At the same time, organizations need to invest in their employees' professional growth and development to remain competitive and innovative.

Moreover, continuous learning not only benefits individuals and organizations but also has a positive impact on society as a whole. It promotes economic growth, social mobility, and personal fulfillment, as individuals are better equipped to contribute to society's needs and tackle complex challenges. Continuous learning is also essential for sustainable development, as it fosters a culture of innovation and creativity that can drive progress towards a more sustainable future.

The modern education system was formed in response to the beginning of industrialization, during the emergence and development of industrial enterprises. Such enterprises required a large number of workers who would perform narrow operations on a work schedule without unnecessary questions. To date, the education system in most countries has focused on accumulating knowledge. Currently, we are moving away from the era of industrialization, as all routine operations can be performed automatically through automation and digital technologies.

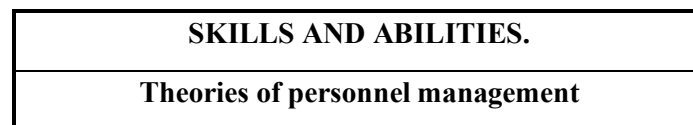
Furthermore, the traditional education system was designed to train individuals for specific careers or professions, with little emphasis on the development of soft skills or personal growth. However, in today's rapidly changing and interconnected world, the ability to communicate effectively, collaborate with others, and adapt to new situations is becoming increasingly important. Continuous learning allows individuals to develop these skills, which not only benefits their own personal and professional growth but also enhances their ability to contribute to society and create positive change.

Moreover, continuous learning plays a crucial role in addressing social and environmental challenges, such as poverty, inequality, and climate change. By acquiring new knowledge and skills, individuals can better understand the complexity of these issues and contribute to finding solutions. This, in turn, can lead to the creation of more sustainable and resilient communities and a better future for all.

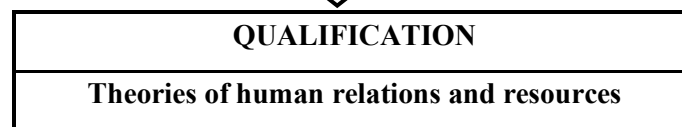
In summary, continuous learning is essential for personal, professional, and societal growth and development. It enables individuals to adapt to new challenges and opportunities, fosters innovation and creativity, and promotes sustainable development and social progress.

The purpose and tasks of the study. Modern learners need to be taught how to think critically, independently obtain and evaluate information, rather than just accumulate and memorize it [2]. Educational institutions are already forced to move from old, "industrial" educational programs to a system of learning that will prepare personnel for the innovative economy and information society. Consequently, teaching approaches will also change. Teachers will transform from knowledge transmitters to pedagogues-organizers. This has expanded the boundaries of personal and professional qualities, skills, and abilities of employees, which means a transition from a qualification approach to a competency-based one (Figure 1.1) [3].

Pre-industrial stage



Industrial stage



Post-industrial era

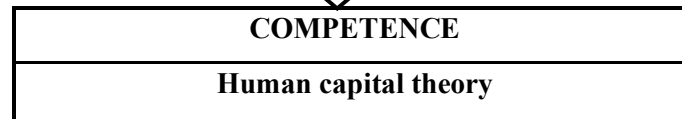


Fig. 1. Qualification requirements for teachers at different stages of development

Additionally, the focus of modern education is shifting towards fostering creativity, problem-solving skills, and collaboration, which are essential in the knowledge-based economy. The education system is also becoming more personalized, taking into account individual learning styles and preferences, and leveraging technology to provide flexible and accessible learning opportunities. As a result, learners are empowered to take control of their learning and pursue their interests and passions.

The competency-based approach to education emphasizes the development of specific skills and competencies, rather than simply acquiring knowledge. This approach is more aligned with the demands of the current job market, which requires individuals to possess a diverse set of skills and be able to adapt to new challenges and technologies. The competency-based approach also provides a more transparent and objective way of assessing learners' progress and capabilities, as it focuses on observable and measurable outcomes.

The shift towards a competency-based approach in education is a significant change in how learners are being taught. Rather than just acquiring knowledge, learners are now being taught how to apply that knowledge in real-world scenarios. This approach promotes critical thinking, problem-solving, and collaboration skills that are essential in the modern workforce. In addition, the use of technology and personalized learning styles provides learners with more flexibility and control over their education. The competency-based approach also helps to address the skills gap in the job market, by ensuring that learners are equipped with the skills that employers are looking for. Overall, the competency-based

approach is an effective way to prepare learners for success in the innovative economy and information society.

The education system is evolving to meet the needs of the innovative economy and information society. The focus is shifting towards developing competencies, critical thinking, creativity, and collaboration, rather than just accumulating knowledge. Teachers are transforming from knowledge transmitters to pedagogues-organizers, and learners are empowered to take control of their learning. The competency-based approach provides a more objective and transparent way of assessing learners' progress and capabilities, which is essential in the current job market.

Educational programs in the post-industrial era should be aimed at developing critical thinking, communication skills, creative inventiveness, and interpersonal interaction skills, as these are the most in-demand abilities in this era. As soon as any routine part of a given production process that is repetitive is automated, human labor in that part becomes no longer needed [4]. Such processes cannot be reverted.

The education system must adapt to the new demands of the economy and focus on developing skills that are uniquely human and cannot be automated. These skills include problem-solving, emotional intelligence, and adaptability, among others. The traditional classroom-based learning approach is becoming less effective in the digital age, where information is easily accessible through various digital devices. Therefore, educational institutions need to adopt innovative teaching methods, such as blended learning and gamification, to engage and motivate learners and provide them with personalized learning experiences.

The current education system must undergo adaptation to cater to the demands of the post-industrial era and prioritize the development of skills that are not susceptible to automation. This necessitates a transition towards a competency-based education framework and the adoption of innovative pedagogical approaches that foster critical thinking, creativity, and adaptability. By undertaking these measures, we can equip learners with the necessary skills to confront the challenges and seize the opportunities presented by the digital age, and contribute to the overall advancement of society.

The education system must also prioritize lifelong learning to ensure that individuals are equipped to adapt to the constantly changing demands of the job market. This means that education should not end after graduation but should be viewed as a continuous process that individuals need to engage in throughout their lives.

To promote lifelong learning, there needs to be a cultural shift towards valuing and prioritizing education and providing accessible and affordable learning opportunities for all individuals. This includes providing support for adult education, upskilling and reskilling programs, and recognition of non-formal and informal learning. The education system must continue to evolve and adapt to meet the demands of the post-industrial era. By prioritizing the development of uniquely human skills, promoting lifelong learning, and adopting innovative teaching methods, we can prepare individuals to succeed in the digital age and contribute to a more prosperous and sustainable society.

The educational process has so far been built on the principles of pedagogical ergonomics. In this case, the main attention was paid to the factor of the learning environment, which includes the territory of the academy, the building, classrooms, and workstations with educational equipment, visual aids, lighting equipment, design, and microclimate. Based on the impact on teachers and students, the aim was to make the learning environment comfortable, for which textbooks, educational and visual aids, reference books, dictionaries, maps, laboratory equipment, and so on were developed. When selecting them, information, motivational, managerial, and optimizing possibilities were taken into account. The selection of specialists changed depending on the didactic concept, objectives, content, methods, and conditions of the educational process.

However, with the rise of digital technologies and online education, the concept of the learning environment has evolved. Nowadays, learners can access educational resources and materials from anywhere in the world and at any time. The focus has shifted towards creating a virtual learning environment that can provide learners with access to interactive and engaging educational content. The new approach to education emphasizes the importance of technology in the learning process and considers the needs of individual learners. The role of teachers has also shifted from being mere

transmitters of knowledge to facilitators of learning, who can guide and support learners in their educational journey. Therefore, adapting the traditional educational system to the demands of the modern era and incorporating technology into the learning process is necessary to make it more accessible and effective.

This shift towards digital learning has also led to a greater emphasis on developing digital literacy skills. In addition to traditional subjects, individuals must now also be proficient in digital literacy, including understanding how to use technology for communication, information gathering, and problem-solving. The ability to navigate digital tools and platforms is crucial for success in the modern workplace and in everyday life. The education system must recognize the importance of developing uniquely human skills such as critical thinking, creativity, emotional intelligence, and adaptability. These skills cannot be easily automated and will become increasingly valuable in the post-industrial era. By prioritizing the development of these skills, we can ensure that individuals are prepared for the changing job market and are able to contribute to a more prosperous and sustainable society.

The future of education lies in promoting lifelong learning and adapting to the demands of the digital age. This requires a cultural shift towards valuing and prioritizing education, incorporating technology into the learning process, and developing uniquely human skills. By doing so, we can prepare individuals to succeed in a rapidly changing world and create a more equitable and prosperous society for all.

Materials and methods of research. Practice has shown that modern audiovisual (screen-sound) and multimedia (PCs with audio and video devices) have the most effective impact on students, providing an opportunity to automate intellectual activity. A systemic representation of education is an approach to organizing and understanding the educational process as a holistic system, which includes not only students and teachers, but also various educational resources, methods and technologies, as well as the social, economic, and political environment in which it takes place. This approach takes into account the interaction of all components of the system and aims to achieve the most effective fulfillment of educational goals. In systemic representation of education, not only traditional academic subjects and knowledge are important, but also the development of competencies, skills and abilities that can be applied in real life and in the workplace. The systemic representation of the educational process for preparing specialists is presented in Figure 1.2 [6-7]. In education, two paradigms, two approaches have been formed - traditional and competency-based. The former includes cultural, educational, didactic-centric, and functional-communicative approaches etc. Opinions about the essence of the competency-based approach, which involves instilling competence in the student as "a set of interrelated qualities of an individual, objects, defined in relation to a certain circle and processes," differ [8-9]. A competent modern specialist differs from a qualified one in the ability to implement knowledge, skills, and abilities in professional activity. They possess general competence, with the help of which specialized competence is formed, which is capable of meeting the demands of practice and is clearly outlined in the curricula and training programs for relevant specialists [10-11].

The competency-based approach is gaining popularity in the field of education, as it emphasizes the development of practical skills and abilities that are directly applicable in the workplace. This approach represents a departure from traditional education methods, which prioritize memorization and rote learning over practical application and learning outcomes. To effectively implement this approach, a clear understanding of the specific competencies required for a given profession is necessary, and training programs and curricula must be designed to align with these competencies. This approach ensures that the educational system is preparing individuals with the necessary skills and knowledge to succeed in their chosen careers, and ultimately contribute to the prosperity of society. The use of modern audiovisual and multimedia technologies is essential in supporting this process, providing learners with dynamic and engaging tools and resources to develop and apply their competencies.

The systemic representation of education, as described earlier, highlights the effectiveness of modern audiovisual and multimedia technologies in the educational process. In addition, it acknowledges the importance of developing competencies, skills, and abilities that can be applied in real-life situations and the workplace. The field of education has seen the emergence of two paradigms, the traditional and the competency-based approach. The latter emphasizes the development of practical skills and abilities,

which are directly applicable in the workplace, and is gaining popularity in the field of education. The competency-based approach ensures that educational programs align with specific competencies required for a given profession, thus preparing individuals with the necessary skills and knowledge to succeed in their chosen careers. The use of modern technologies, such as audiovisual and multimedia tools, is essential in supporting this process, as they provide learners with engaging resources to develop and apply their competencies effectively.

Instead of following the concept of "profession" as a set of skills is required to combine these skills to perform a given task. This approach is called the task-based approach and is becoming increasingly popular in modern education. The task-based approach emphasizes the importance of developing problem-solving skills and the ability to work in a team. It focuses on the practical application of knowledge and skills in real-life situations, rather than just theoretical understanding. This approach helps learners to develop a holistic understanding of a subject and to acquire the necessary skills to tackle complex problems. In the task-based approach, the emphasis is on the learning process rather than the result, as the process of solving a problem is just as important as the solution itself. Therefore, learners are encouraged to experiment, make mistakes, and learn from them.

The success of any professional is recognized that it depends largely on the skill and qualification of the teaching staff. Education is not just what happens in the classroom, it also encompasses a wider aspect of interaction between students and lecturers, curriculum, and even exams" [12-13].

Investing in the development and training of teachers is crucial for shaping the educational experience of learners. The use of modern teaching methods and technologies can enhance the quality of education and make it more engaging and effective. The professional development of teachers should also include opportunities for them to update their knowledge and skills regularly. Encouraging continuous learning among educators is important for the benefit of learners and society as a whole. Moreover, the evaluation of the effectiveness of the educational process should not be limited to the academic performance of the students but should also take into account the personal growth and development of learners.

Aside from investing in teacher development and training, Establishing a favorable environment for learners is crucial. This includes facilitating access to appropriate learning resources and technologies, as well as creating a welcoming and equitable learning atmosphere. Inclusivity is crucial in the education system to support learners with different abilities and from diverse cultural and socioeconomic backgrounds.

Evaluating the effectiveness of education should not be limited to just measuring students' academic performance, but should also consider their personal growth and development. This entails employing various assessment techniques that gauge not only cognitive knowledge but also non-cognitive skills such as communication, teamwork, and problem-solving. Assessments should be employed to advance the educational process and foster continuous learning, rather than simply as a means of measuring academic achievements.

Adopting a systemic representation of education highlights the importance of viewing education as a comprehensive system that comprises different elements such as students, teachers, resources, and the broader social, economic, and political context. The implementation of competency-based and task-based approaches, in addition to the use of modern teaching methodologies and technologies, can enhance the quality and effectiveness of education. Promoting lifelong learning and personal growth for learners necessitates the development and training of teachers, the establishment of a supportive learning environment, and the use of diverse assessment methods.

The teacher stops being a specialist-demonstrator and becomes an organizer-pedagogue. At the same time, more and more attention is paid to self-education and self-learning of students. In future exams, instead of knowing the numbers of articles and codes, etc., students will search for answers to questions such as what depends on the size of the reward, and the computer will record their searches [14]. Practical activities for students serve as the most adequate way to transform acquired knowledge into practical skills. The implementation of a competency-based approach to education will allow mitigating

the contradiction between the content of the student's educational component and the requirements of principals for the level of specialist education in general [15-16].

PRINCIPLES OF ORGANIZATION OF THE EDUCATIONAL PROCESS FOR MARITIME SPECIALISTS TRAINING		
System principles	Scientific and pedagogical principles	Ergonomic principles
Structural-functional	Adequacy of the content of the discipline	Chronometric consistency".
Communication	Methodological technological	Psychophysiological adaptability
Information-management	Motivational stimulation	Safety
Activity approach	The connection of education with life.	Reliability
Individualization.	Scientificness	Comfortability
Base link	Accessibility	Aesthetics
Historicity	Clarity	Informatization
Appropriateness	Predictiveness	Automation

Fig. 2. Principles of organizing the educational process for training specialists

As the education landscape evolves, the traditional role of teachers as knowledge providers is transforming into that of organizers and facilitators of the learning process. Students are now encouraged to engage in self-learning and self-education, with practical activities serving as an effective means to apply and transform acquired knowledge into practical skills. The competency-based approach to education emphasizes the practical application of knowledge and skills in real-life situations and helps to close the gap between what is taught in the classroom and the requirements of the job market. In evaluating the effectiveness of the educational process, but not only academic performance but also the personal growth and development of learners.

The modern economy is increasingly becoming digitized, and as a result, more and more young people are choosing technical specialties. The demand for IT professionals remains high, but as digital knowledge becomes more widespread, IT expertise will shift from being a specialty to a basic literacy skill, much like English language proficiency or translation skills [17-19]. In addition, interdisciplinary education is becoming more important as technology intersects with various fields such as healthcare, finance, and agriculture. Students need to have a broad knowledge base and the ability to work collaboratively with professionals in other fields to effectively utilize technology in solving complex problems. As the digital landscape continues to evolve, education must keep pace to ensure that students are equipped with the skills and knowledge necessary to thrive in the modern economy.

However, technical skills alone are insufficient for the development of the digital economy. Soft skills, communication skills, the ability to work in teams, adapt to others, and, as banal as it may sound, to look into the eyes of one's interlocutor rather than at a computer screen are all extremely important. Unfortunately, traditional educational institutions do not give enough attention to these skills[20]. Therefore, a holistic approach is important to consider as education that incorporates both technical and soft skills. Digital literacy should not only focus on the technical aspects of using technology but also

on its responsible and ethical use. Students should also be trained in critical thinking and problem-solving, creativity, and entrepreneurship, as these are essential skills for the digital age. Educational institutions should collaborate with the industry to provide practical experience and internships that enable students to develop their soft skills and gain real-world experience. By doing so, the education system can better prepare the workforce for the challenges and opportunities of the digital economy.

On this background, the role of the teacher is increasing not as a supplier of information, but as someone who engages in reflection and reasoning. Thus, the student learns to perceive information, reflect on it, and act on it, which can only be achieved through communication with professors and researchers. In this case, the educational process aims to develop the intellect of those who come as students [21-22].

This shift in the role of the teacher requires a significant change in the traditional approach to education. Teachers must now create a learning environment that promotes critical thinking, problem-solving, and creativity, rather than simply conveying information. To do this, teachers must themselves be lifelong learners and continuously update their knowledge and skills to keep up with the rapidly evolving world of technology and its impact on various industries. Moreover, teachers must be able to provide personalized and flexible learning experiences that cater to the unique needs of each student, helping them achieve their full potential. Overall, the modern teacher must be equipped with a diverse set of skills that goes beyond just subject matter expertise and includes pedagogical expertise, communication skills, and the ability to motivate and inspire students.

Conclusions. Developing intellect is a complex task that requires time, communication, and certain technologies. If we can accelerate solving this task by using digital technologies or other educational technologies, that's good, and we all benefit from it/ However, substituting the question of the tool for the question of the goal is not desirable. [23] Not only teaching students how to learn, but also conveying the importance and purpose of education is crucial [23-25]. Therefore, in addition to technical and soft skills, instilling in students a sense of purpose and a lifelong love of learning is important for teachers. By doing so, students will be better equipped to navigate the ever-changing landscape of the digital economy and to continue to develop their skills throughout their careers. Ultimately, the goal of education is not just to acquire knowledge or skills, but to cultivate a curious and adaptable mind that can thrive in any situation. This requires a holistic approach to education that considers not just technical skills, but also personal growth, social development, and a sense of purpose. Only then can we truly prepare the next generation of learners for the challenges and opportunities of the digital age.

While digital technologies and educational tools can accelerate intellectual development, The main idea of education is to develop a curious and adaptable mind that can succeed in any situation. Teachers should not only teach students how to learn but also inspire them by conveying the importance of education and instilling a sense of purpose and passion for lifelong learning. An all-encompassing approach to education is essential, including technical skills, personal growth, social development, and a sense of purpose, to equip students for the ever-evolving digital age and facilitate their skill development throughout their professional careers.

The development of intellect is a complex and multifaceted task that requires a holistic approach to education. While digital technologies and educational tools can be helpful, the ultimate goal of education is to cultivate a curious and adaptable mind with a sense of purpose and passion for lifelong learning. By focusing on personal growth, social development, critical thinking, and ethical considerations, we can prepare students for success in the digital economy and encourage them to make a positive impact on the world.

REFERENCES

1. Petrov, I. M., & Kuzmenko, E. S. (2018, February). Prospective transcontinental system of transport and energy communications. In *Proceedings of the VIII International Scientific and Practical Conference "Problems of Development of Transport Logistics" Inter-TRANSCLOG'2018 February 16-27, 2018 - Odessa-Batumi-Samsun: ONMU* (pp. 104-116).
2. Petrov, Y. M. (2018, April). The influence of ship parameters on the duration of their cargo processing. In *Proceedings of the International Scientific and Practical Conference "Strategic Imperatives of Modern Management and Current Problems*

of Social-Psychological Development of Competencies of Marine Industry Professionals", April 20, 2018. Izmail: DI NU "OMA" (pp. 140-144).

3. Evdokimova, V. A., Deevova, O. V., & Khayet, L. G. (2015, May). Crew Psychological Training as a Tool for Increasing Ship Safety. In *Proceedings of the Seventh International Scientific and Practical Conference "Modern Information and Innovative Technologies in Transport (MINTT-2015)" May 26-28, 2015. Kherson: Kherson State Maritime Academy.* (pp. 53-56).
4. Hryhorev, N., Dvynyn, A., & Nakonechnyi, M. (2017). Anxiety as a factor of accidents. *Morskoi flot*, 2(1530), 14-16.
5. Golikov, V. V., Obertyur, K. L., & Safin, I. V. (2012). Scenario-based study of the activities of marine transportation system operators based on guaranteed safety principles in emergency situations. *Ship power plants: scientific and technical collection*, 30, 194-203.
6. Cole, E. (2016). *Online Danger: How to Protect Yourself and Your Loved Ones From the Evil Side of the Internet.* BenBella Books.
7. Shakhov, A.V., & Bokareva, M.O. (2014). Risk management in ship repair projects. *Bulletin of the National Technical University "Kharkiv Polytechnic Institute". Series: Strategic Management, Portfolio Management, Programs and Projects Management*, 2(1045), 81-86.
8. Altbach, P. G. (2016). The Challenges Facing Higher Education Today. *International Higher Education*, 86, 2-4.
9. Sokol, I. V. (2011). Formation of professional competence of future navigators in the process of studying professional disciplines: abstract of the thesis for the degree of candidate of pedagogical sciences, specialty 13.00.04. *Kherson State University.*
10. Frolova, O.O. (2015). Formation of socio-cultural competence of future navigators in the process of studying professionally oriented disciplines: author's abstract of the thesis for the degree of candidate of pedagogical sciences, specialty 13.00.04. *Volodymyr Hnatyuk Ternopil National Pedagogical University.*
11. Torsky, V.G. (2016). The main requirement for successful maritime training - professionalism of the teaching staff. *International Journal "Marine Review"*, 1(61), 14.
12. Golikov, V. V., Obertyur, K. L., & Safin, I. V. (2012). Scenario-based study of the activities of marine transportation system operators on the principles of guaranteed safety in emergency situations. In *Marine Power Plants: Scientific and Technical Collection* (Is, 30, pp. 194-203). ONMA.
13. Kurland, A.M., & Morozova, I.V. (2015). The problems of preparing specialists for the maritime industry of Ukraine in modern conditions. In *Proceedings of the International Scientific and Practical Conference "European Choice of Ukraine: Problems of Development of Ferry Transportation in the Black Sea"* (pp. 74-77). Odessa: ONMU.
14. Mal'tsev, A.S. (2009). Optimization of personnel management. *Production Management*, 1, 14-19.
15. Hritsuk, I.V., Panchenko, S.V., Kagramanyan, A.O., Hritsuk, Yu.V., & Volkov, Yu.V. (2017). Features of remote identification of a vehicle under conditions of informational support for operational processes. In *Proceedings of the scientific-practical conference of KhHMA - 2017* (pp. 194-196).
16. Petrov, I.M. (2015). Heuristic algorithm of marine agent behavior in case of oil spills within the framework of service ergatic system. *Navigation: Collection of scientific works*, 25, Odessa: "IzdatInform", 135-145.
17. Scott, P. (2018). The challenge of transforming higher education. *International Higher Education*, 92, 4-5.
18. Brown, M. (2018). The fourth industrial revolution and higher education. *International Higher Education*, 95, 6-7.
19. Marginson, S. (2016). The Worldwide Trend to High Participation Higher Education: Dynamics of Social Stratification in Inclusive Systems. *High Education*, 72, 413-434. <https://doi.org/10.1007/s10734-016-0016-x>.
20. Kolb, D. A. (2014). Experiential learning: Experience as the source of learning and development. *FT press*.
21. Cantwell, B., & Kauppinen, I. (2014). Academic capitalism and university incentives for faculty entrepreneurship. *The Journal of Technology Transfer*, 39(3), 422-440.
22. Maldonado-Maldonado, A. (2016). Quality assurance and the challenge of the changing higher education landscape. *Quality in Higher Education*, 22(1), 1-7.
23. Clark, B. R. (2015). The modern integration of research activities with teaching and learning. *Journal of Higher Education Policy and Management*, 37(2), 151-163.
24. Altbach, P. G. (2018). The changing geopolitics of higher education. *International Higher Education*, 94, 3-5.
25. Altbach, P. (2019). The Past, Present, and Future of the Research University. *Prospects*, 48, 5-11.

Ольга Петриченко¹, Євгеній Петріченко², Ігор Бурмака³, Алла Виноградова⁴

¹Доцент, Кафедра теорії і устрою судна, Національний університет «Одеська морська академія», 8, вул. Дідрихсона., Одеса, 65052, Україна, ORCID: <https://orcid.org/0000-0002-4893-8204>.

²Доцент, Кафедра морських перевезень, Національний університет «Одеська морська академія», 8, вул. Дідрихсона., Одеса, 65052, Україна, ORCID: <https://orcid.org/0009-0008-2225-3152>.

³Доктор технічних наук, професор, Завідувач кафедри управління судно, Національний університет «Одеська морська академія», 8, вул. Дідрихсона., Одеса, 65052, Україна, ORCID: <https://orcid.org/0000-0002-0853-6884>.

⁴Завідувач лабораторії кафедри управління судном, Національний університет «Одеська морська академія», 8, вул. Дідрихсона., Одеса, 65052, Україна, ORCID: <https://orcid.org/0009-0007-9406-3203>.

Зміни в сучасному університеті: виклики сьогодення та тенденції розвитку

Освіта - це процес взаємодії та спілкування між усіма учасниками, кожен з яких має вплив на результат. Сьогодні, в умовах сучасного світу, співпраця між вчителем та студентом набуває нових форм та характеристик. Вчитель вже не є лише джерелом знань, а стає партнером та помічником для студента. Якість комунікації між студентом та вчителем залежить від їхньої готовності до діалогу та взаєморозуміння, відсутності примусу та наказів. Комплексний підхід до освіти та спілкування дозволяє глибоко розуміти процеси та покращувати їх. Вищі навчальні заклади повинні приділяти особливу увагу питанням стратегічного розвитку комунікації, брендування та іміджу. Чіткі та добре сплановані системи комунікації повинні бути впроваджені на рівні структурних підрозділів для досягнення успіху. Надання адекватних матеріально-технічних ресурсів, а також інформаційно-комунікаційних технологій є вирішальним для ефективного використання різних методів та форм навчання. Однак, комунікація між вчителем та студентом не повинна бути тільки про академічні теми, а також про підтримку, мотивацію та особистісний розвиток. Сучасний університет повинен враховувати зміни в суспільстві та економіці, використовувати нові методи та технології навчання, а також створювати умови для комфортної та продуктивної роботи студентів та викладачів.

Ключові слова: вища освіта дорослих, спілкування, ергономічні технології, вища освіта.

UDC 656.61.052

Igor Gritskuk¹, Pavlo Nosov^{2*}, Olena Dyagileva³, Mariia Masonkova⁴

¹Doctor of Technical Sciences, Professor, Professor of the Department of Operation of Ship Power Plants, Kherson State Maritime Academy, 73000, Kherson, Ushakov Avenue, 20, Ukraine, ORCID: <https://orcid.org/0000-0001-7065-6820>

²Candidate of Technical Sciences, Associate Professor, Associate Professor of the Department of Navigation, Kherson State Maritime Academy, 73000, Kherson, Ushakov Avenue, 20, Ukraine, ORCID: <https://orcid.org/0000-0002-5067-9766>

³Candidate of Pedagogical Sciences, Associate Professor, Vice-rector for Educational and Methodical Work, Kherson State Maritime Academy, 73000, Kherson, Ushakov Avenue, 20, Ukraine, ORCID: <https://orcid.org/0000-0001-9718-152X>

⁴Graduate student, Kherson State Maritime Academy, 73000, Kherson, Ushakov Avenue, 20, Ukraine, ORCID: <https://orcid.org/0000-0003-3741-4066>

*Corresponding author: pason@ukr.net

Improving safety of navigation by constructing a dynamic model of the navigator's actions in the conditions of navigation risks

This study tackles the complex task of constructing a dynamic model of a navigator, planning their experience trajectory, and making decisions under navigational risks in the maritime industry using automated control systems. The proposed mathematical model accounts for individual skills, experiences, and personalities, while considering unpredictable industry dynamics. The study asserts the importance of adaptable automated control systems capable of simulating navigation risk situations and determining suitable career and development paths. In addition, it discusses the importance of assessing external factors such as economic, technological, and regulatory changes and ensuring compliance with industry standards, data security, and privacy. The paper further emphasizes the necessity for scalability and flexibility, as well as the seamless integration of automated systems with existing organizational infrastructures. The study concludes that the proposed model, optimized for the "safety of navigation" parameter using the Pontryagin maximum principle, enhances recruitment processes, creates comprehensive professional profiles for seafarers, and supports career development. The paper suggests the potential of this model's application in other maritime and related professions, ultimately enhancing individualized training and operational efficiency.

Keywords: safety of navigation, automated system, maritime industry, human factor, navigation risks, training, dynamic model.

Introduction. Constructing a dynamic model of the navigator and planning his trajectory of experience, regarding decision-making in the conditions of navigational risks before becoming a specialist in the marine industry with the help of automated control systems is a multifaceted task. It must account for individual differences in navigators' skills, experiences, education, and personalities, making the creation of a universal model a complex task [1-3]. The dynamics in the maritime industry are often unpredictable and subject to change, which means that automated control systems must have adaptive capabilities to meet the changing needs of a navigator's career and training, especially in the simulation of navigation risk situations.

Moreover, assessing a navigator's competencies and skills necessitates the collection and analysis of vast amounts of data. The automated management systems in place should be efficient in evaluating this data and determining the most suitable career opportunities and development paths. The automated systems should also be integrated with training and development plans tailored to the navigator's needs and the requirements of the maritime industry.

External factors such as economic, technological, and regulatory changes in the maritime industry must be considered. The automated control systems should be adept at analyzing these factors and proposing appropriate strategies for the navigator's development. It is also essential for these systems to facilitate effective collaboration between navigators and other professionals or organizations, ensuring coordinated learning, experience and knowledge sharing, as well as collaborative project and task management.

In addition to these considerations, automated control systems should ensure transparency and quality control in the assessment, planning, and development of the navigator. They should also incorporate quality control mechanisms to ensure compliance with maritime industry standards and requirements. Data security and privacy are critical, with personal data and confidential information needing to be protected according to current security and data privacy standards.

Analysis of recent research and problem statement. Furthermore, these automated control systems should be scalable and flexible to adapt to various organizations in the maritime industry and changes in the recruitment, training, and development of navigators. The systems must also be able to integrate seamlessly with existing organizational systems and infrastructure, such as HR systems, training and development programs, accounting, and reporting systems.

Addressing these issues creating an effective automated control system for the development of a dynamic model of the navigator and planning the trajectory of improving his qualifications in decision-making under conditions of uncertainty requires a multidisciplinary approach. Experts from fields like information technology, human resource management, training and development, and the maritime industry must collaborate to create the latest automated systems [4].

In the context of a crewing company's seafarer selection process, several stages ensure the selection of qualified, reliable, and experienced seafarers for ship work. These stages include the preparation of candidate requirements, analysis of CVs, contract signing, paperwork, and employee support and development. However, despite its advantages, this approach presents certain disadvantages, such as the labor-intensive and time-consuming process, human factor potential, limited access to candidate information, lack of standardization, challenges in employee training and development, and weaknesses in the motivation system [5].

Implementing automated system of selection and process management systems can address these shortcomings by streamlining selection processes, enhancing the standardization of assessment criteria and methods, reducing human factor probability, and providing more effective employee training and development [6].

The purpose and tasks of the study. The goal of this research is to develop an integrated, dynamic model of the navigator within automated control systems, thereby improving recruitment, facilitating personalized career development, and enhancing decision-making skills under navigational risks in the maritime industry.

Main research material. There are automated management systems for the employment of seafarers. These systems, also known as "Maritime Recruitment Agencies" or "Crew Management Systems", offer platforms that connect seafarers with employers, facilitating the job search and recruitment process for ships.

Some examples of automated management systems for the employment of seafarers and their references:

- Martide: Crew Management and Recruitment Platform
- CrewInspector: Crew Management Software
- Hanseatic soft: Cloud Crewing
- CrewSmart: Crewing and Compliance Management Software
- SDSD: Matrix Crew Management Software
- Navatom: Crew Management System
- Adonis HR: Maritime HR and Crew Management Software

They may include features such as:

Registration and creation of profiles of seafarers, including uploading CVs, certificates and other documents.

Search for vacancies corresponding to the qualifications and experience of a seafarer.

Sending applications for vacancies and tracking the status of applications.

Automatic notification of seafarers about new vacancies that match their profile and preferences.

Selection systems for employers based on criteria such as experience, qualifications, language skills and other parameters.

Online interview features that allow employers and seafarers to communicate and conduct interviews from a distance.

Document management, including verification and storage of certificates, licenses and other necessary documents.

Organization and coordination of training, internships and certification for seafarers.

Management of contracts and employment contracts between seafarers and employers.

Reporting and analytics systems that allow employers to monitor the effectiveness of the recruitment process and develop strategies to improve the personnel policy.

Ensuring compliance with legislation and international standards in the field of employment of seafarers, including the MLK (Marine Labor Convention) and STCW (Convention for the Training, Certification and Watchkeeping of Seafarers) agreements.

Features to ensure the security and privacy of seafarers' and employers' data, including data encryption and measures to prevent unauthorized access.

Support for communication and feedback between seafarers and employers, including feedback, evaluation and recommendation functions.

Schedule management and scheduling systems that allow employers to optimize the allocation of seafarers to ships and control the availability of the required number of crew on board at different times.

Integration with other maritime systems and services, such as port authorities, insurance companies and medical institutions, to facilitate administrative processes and speed up the exchange of information.

Functions for managing salaries and payments, including automatic calculation of salaries, taxes, insurance premiums and other payments, taking into account the laws of different countries and the terms of contracts.

Modules for managing social and domestic issues such as onboard morale, holidays, social security and medical insurance.

Career and development support for seafarers, including career planning, mentoring and training functions, as well as providing opportunities for professional development and promotion to higher positions within the company or industry.

Creation of communities and networks for seafarers, allowing them to exchange experience, knowledge and information about work, as well as maintain social connections and mutual assistance in a professional environment.

Providing information about the maritime industry and news that may affect the employment and working conditions of seafarers, such as legislative changes, technological innovations and economic trends.

Integration with mobile applications and devices to provide access to the functions of the crew management system at any time and from anywhere in the world.

Providing support services and advice to seafarers and employers, helping to resolve emerging issues and problems related to employment, legislation and compliance with industry norms and standards.

Collaboration with professional associations and organizations such as the International Maritime Organization (IMO), the International Chamber of Shipping (ICS) and seafarers' unions to improve the quality of services and promote the development of the maritime industry.

Ensuring environmental sustainability and social responsibility by applying environmental and ethical standards in the recruitment, training and crew management processes.

In general, maritime recruitment agencies and automated crew management systems contribute to a more efficient and safe employment of seafarers, streamline work processes on ships and improve the quality of work in the maritime industry. They provide rich platforms for seafarers and employers that

streamline job search, recruitment, training, document and contract management, and ensure transparency and compliance with international regulations and laws.

These automated systems are constantly evolving and adapting to changes in the maritime industry, technological innovations and regulatory requirements. As a result, they contribute to raising the level of professionalism of seafarers, improving their working and living conditions, as well as increasing the efficiency and competitiveness of maritime companies and the industry as a whole [7,8]. An important aspect of these systems is to keep information up to date and to innovate quickly, ensuring their long-term relevance and value to seafarers and employers.

As can be seen from the analysis, with the development of digital technologies and their integration into the maritime industry, maritime recruitment agencies and automated crew management systems can introduce additional functions and capabilities, such as the use of artificial intelligence and machine learning to analyze data, predict staffing needs and determine the optimal personnel management strategies.

Thus, maritime recruitment agencies and automated crew management systems play an important role in today's maritime industry, providing convenient and reliable solutions for the employment of seafarers and crew management on ships. Their further development and integration with other industrial and digital technologies will further improve the quality of work, increase efficiency and create new opportunities for seafarers and shipowners. Possible directions for development include the improvement of analytical tools, the expansion of cooperation with international organizations and the standardization of processes within the global maritime industry.

However, there are certain aspects of seafarer employment that automated crew management systems may not fully address:

Personal Communication and Interpersonal Skills: Online platforms may not always convey the full range of interpersonal interactions that are important in assessing seafarers. Employers may have difficulty assessing the personality and communication skills of candidates based solely on online profiles and interviews.

Cultural and Diversity: Automated systems may not always accommodate cultural differences and crew diversity, which can affect the consistency and efficiency of ship operations.

Unforeseen Circumstances: Automated systems may not be able to handle unforeseen situations such as urgent crew changes or shipboard emergencies. In such situations, human involvement and decisions remain critical.

Morale and well-being of seafarers: Maintaining the morale and well-being of seafarers on board ship is an important factor that can affect their productivity and safety. Automated systems may not always be able to effectively assess and manage this aspect of seafarer employment.

Incomplete understanding of ship operating conditions: Automated systems may not always provide a complete picture of actual ship operating conditions. This can create a gap between the expectations of seafarers and the actual conditions they face on board.

Recognizing the gaps in current automated maritime recruitment and crew management systems, the next step in our research aims to further refine the selection process for seafarers, particularly for the position of an operator-navigator. While existing platforms already offer a range of features to aid the recruitment process, they may fall short in accurately assessing factors such as interpersonal skills, cultural differences, morale, and the ability to handle unforeseen circumstances. Additionally, these systems may not have a complete understanding of ship operating conditions, which can lead to a mismatch between seafarer expectations and actual shipboard life.

To address these shortcomings, we are proposing the development of a generalized mathematical modeling to enhance the assessment of potential operator-navigators. This model takes into account five key criteria and characteristics: Skills (S), Experience (E), Education (Ed), Personality Qualities (PQ), and Additional Certifications (C). These criteria are carefully selected to provide a holistic view of a candidate's suitability for the role of operator-navigator, going beyond the current capabilities of automated systems.

The proposed mathematical modeling will not only be able to evaluate a candidate based on their professional abilities but also their interpersonal skills and adaptability to various situations, thereby bridging the gaps identified in existing automated systems. This model seeks to bolster the efficiency and accuracy of the recruitment process, ultimately leading to a more productive and harmonious maritime working environment.

Based on the specified criteria and characteristics, the following mathematical modeling can be proposed for evaluating a candidate for the position of operator-navigator:

$$\text{Candidate Evaluation} = w_1 \cdot S + w_2 \cdot E + w_3 \cdot Ed + w_4 \cdot PQ + w_5 \cdot C$$

where: Candidate Evaluation - a numerical value representing the overall assessment of the candidate for the position of operator-navigator;

w_i - weight coefficients for each criterion (their values can be determined on the basis of expert knowledge or statistical analysis of the source data);

S, E, Ed, PQ, C - values of criteria and characteristics for each candidate.

To determine the weighting factors, you can use multi-criteria optimization methods, such as the analytical hierarchy of processes (AHP) or the weighted sum method [9,10].

These coefficients will determine the relative importance of each criterion in the candidate's overall assessment.

After determining the weighting factors, you can apply this model to evaluate candidates for the position of operator-navigator. First, for each candidate, it is necessary to collect data for each of the criteria (S, E, Ed, PQ, C). Then, using the obtained weight coefficients, you can calculate the numerical value "Candidate Evaluation" and compare the candidates with each other.

Based on the collected data, it is necessary to train a model that will predict the performance of the operator-navigator based on his characteristics and qualities. You can use various machine learning methods such as linear regression, support vector machine (SVM), random forest, or neural networks. The choice of method depends on the characteristics of the data, the sample size, and the complexity of the model required.

Also, to assess the accuracy of the model, cross-validation should be carried out using a test set. This will help determine how well the model generalizes the information and is able to predict the performance of navigators.

If the results of the model evaluation are satisfactory, it can be used to predict the performance of potential navigator candidates based on their characteristics and qualities.

The next step is to split the data into training and test sets. The training set will be used to train the model, and the test set will be used to evaluate its performance.

As an example, let's consider training a model using the random forest algorithm. The convergence of random trees plays an important role in machine learning and optimization. For example, random search algorithms in the navigator model formation space, like random forests, use stochastic processes to build decision trees and can be analyzed in terms of convergence and performance, which is important for obtaining a competitiveness criterion in the maritime industry.

In our case, this approach will work according to the following principle[11,12]:

1. Definition of hyper parameters for the random forest algorithm, such as:

$n_estimators$: number of decision trees in the forest; max_depth : maximum depth of trees; $min_samples_split$: the minimum number of observations required to split a node; $min_samples_leaf$: the minimum number of observations required for a leaf node; $max_features$: number of features considered when splitting a node; $random_state$: random value for model training reproducibility

2. Training the model on the training set (X_train, y_train) using the selected

hyperparameters: `RF_model = RandomForestClassifier(n_estimators, max_depth, min_samples_split, min_samples_leaf, max_features, random_state); RF_model.fit(X_train, y_train).`

3. Model performance evaluation: model performance on the test set (metrics: accuracy, recall, F1-measure or correlation coefficient). This will determine how well the model predicts the success of navigator-operators based on their characteristics.

3.1. Accuracy: Proportion of correctly classified objects among all objects
($\text{accuracy} = (\text{TP} + \text{TN}) / (\text{TP} + \text{TN} + \text{FP} + \text{FN})$).

3.2. Recall: Share of objects among positive objects ($\text{recall} = \text{TP} / (\text{TP} + \text{FN})$)
or Clarity: ($\text{precision} = (\text{TP} / (\text{TP} + \text{FP}))$).

3.3. F1-score: Harmonic mean between clarity and recall, used to account for the balance between the two ($\text{F1-score} = 2 * (\text{precision} * \text{recall}) / (\text{precision} + \text{recall})$).

3.4. Test use of the trained model to predict the target variable on the test set (X_{test}): $y_{\text{pred}} = \text{RF_model.predict}(X_{\text{test}})$.

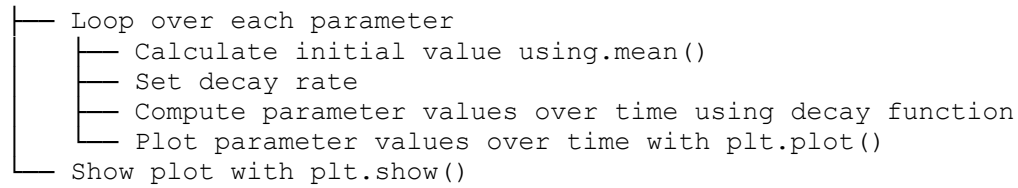
3.5. Compute model performance metrics based on true values of targetvariable (y_{test}) and predicted values (y_{pred}): $\text{accuracy} = \text{accuracy_score}(y_{\text{test}}, y_{\text{pred}})$; $\text{recall} = \text{recall_score}(y_{\text{test}}, y_{\text{pred}})$; $\text{precision} = \text{precision_score}(y_{\text{test}}, y_{\text{pred}})$; $\text{F1-score} = \text{f1_score}(y_{\text{test}}, y_{\text{pred}})$.

4. Construction a computer program in Python for automated calculation of model performance metrics [13,14]:

```

Import Libraries
├─ pandas as pd
├─ numpy as np
├─ sklearn.model_selection as model_selection
├─ sklearn.metrics as metrics
├─ sklearn.ensemble as ensemble
├─ matplotlib.pyplot as plt
Generate and Save Sample Data
├─ Create random dataset using np.random and pd.DataFrame
├─ Save dataset to CSV file with .to_csv()
Load and Prepare Data
├─ Load data from CSV file with pd.read_csv()
├─ Divide the data into feature matrix X and label vector y
using.drop() and slicing
Setup Cross-Validation
├─ Define the number of folds k
├─ Initialize KFold with k splits
Initialize Variables for Metrics
├─ Accuracy
├─ Recall
├─ Precision
├─ F1 Score
Choose Machine Learning Model
├─ RandomForestClassifier from ensemble
Training and Evaluation in K-Fold Cross-Validation Loop
├─ Loop over each fold in kf.split(X)
├─ Split data into training and validation sets
├─ Train model on training set with.fit()
├─ Make predictions on validation set with.predict()
├─ Calculate and store performance metrics (accuracy, recall,
precision, F1 score)
Compute Average Performance Metrics
├─ Calculate average accuracy, recall, precision, and F1 score using
np.mean()
├─ Print average metrics
Visualize Parameter Values Over Time
├─ Define decay function

```



The simulation data amounted to:

Average accuracy: 0.79; Average fullness: 0.7824;

Average (precision): 0.812; Average F1-measure: 0.7854.

The data obtained are the average values of the model performance metrics obtained as a result of cross-validation:

1. Average accuracy: The model has an average accuracy of 0.79, which means that it correctly classifies approximately 79% of the observations. This indicates a fairly good performance of the model, although it all depends on the context of the study.

2. Average fullness / recall: A value of 0.7824 means that the model correctly identifies about 78.24% of positive cases.

3. Precision: A value of 0.8120 means that about 81.20% of the predicted cases are actually positive.

4. Average F1-measure: The value of 0.7854 means that the F1-measure is about 78.54%, which is a fairly high figure at the stage of simulation and multifactorial.

We will conduct a simulation modeling of the decay of the safety parameter in maritime transport for ship navigators, if the following three models and observable circumstances are applied:

Exponential decay: This can be an appropriate option if the safety level quickly decreases without regular training or practice. For example, if a ship navigator has not been practicing his profession for some time, his crisis management skills may rapidly deteriorate, especially in the first months or years.

Power law decay (2): This might be suitable for situations where the safety level decreases over time, but at a more moderate pace. This can pertain to parameters that require regular practice but are not as critical to safety, such as communication skills and coordination with other crew members and shore services.

Logarithmic decay (3): This model might be appropriate for situations where the safety level gradually decreases but then remains stable. This could be associated with parameters that, once they reach a certain level, can remain stable even without continuous learning, for example, knowledge and compliance with maritime rules and regulations.

We have five parameters:

$P_1(t)$ - Knowledge of maritime rules and regulations

$P_2(t)$ - Crisis management skills

$P_3(t)$ - Level of safety training and simulations

$P_4(t)$ - Experience in difficult maritime conditions

$P_5(t)$ - Communication and coordination skills with other crew members and onshore services

Each of these parameters' decays over time according to one of three decay functions:

Exponential decay: $P_i(t) = P_{i0} e^{(-r_i t)}$;

Power law decay: $P_i(t) = P_{i0} / (t+1)^r$;

Logarithmic decay: $P_i(t) = P_{i0} - r_i \log(t+1)$,

where:

$P_i(t)$ - the value of the i -th parameter at time t ;

P_{i0} - the initial value of the i -th parameter;

r_i - the decay rate for the i -th parameter;

t - time.

This model assumes that each parameter independently decays over time according to its decay function.

Let us give an example of software modeling of the predicted level of navigation safety in general terms (Fig. 1).

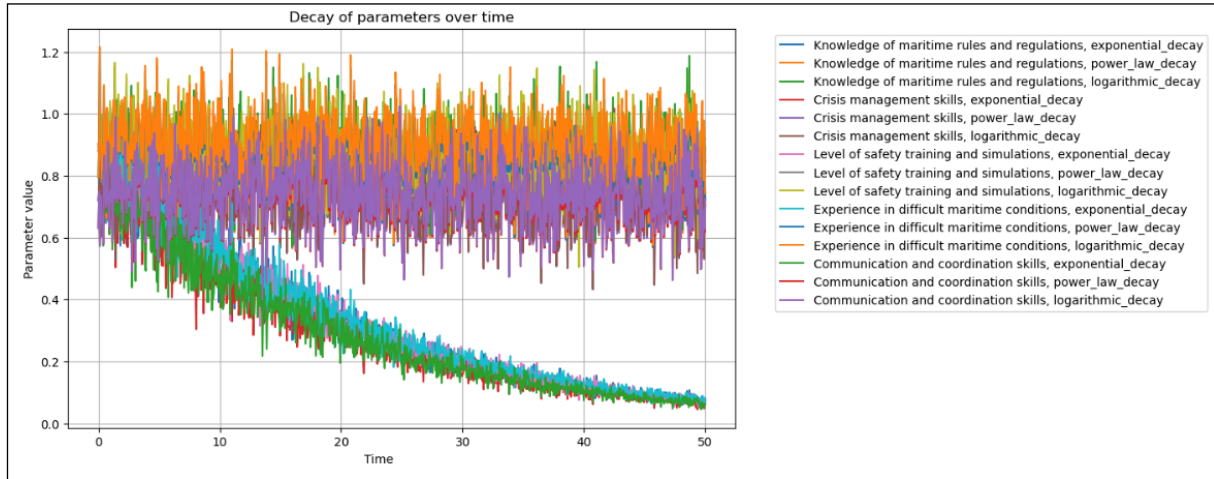


Fig. 1. Modeling the safety of navigation in general

Let's carry out a simulation for the parameter "Safety of navigation" based on the real data of four officers - navigators with similar initial data, but different circumstances that affect the degree of attenuation of the parameter under study (Fig. 2).

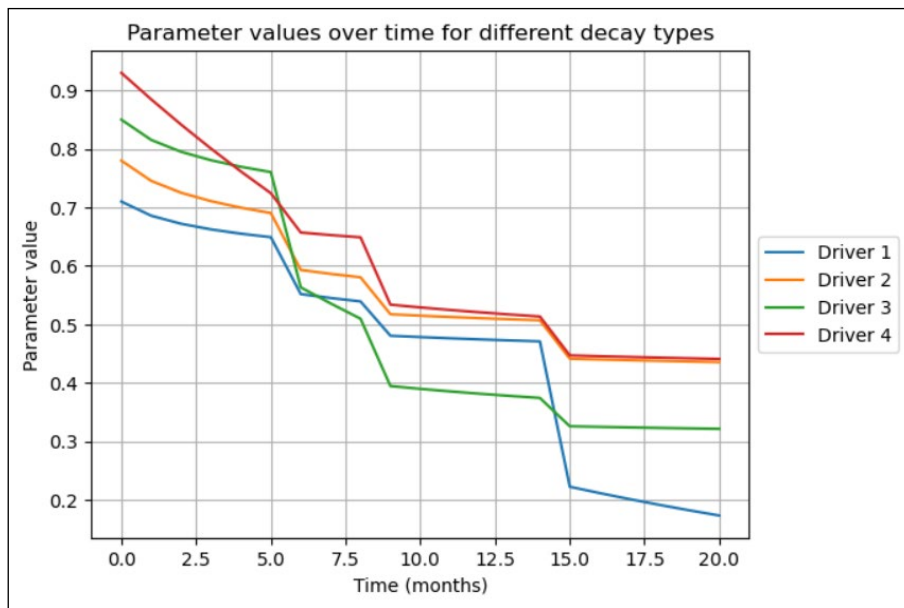


Fig. 2. Simulation graph for the navigation watch safety parameter

This chart and the methodology on which it is based have several strong points when applied to the monitoring of maritime safety (Fig. 3):

Clarity: The chart is easy to interpret and provides a visual representation of how the levels of various safety parameters change over time under different decay conditions. This can help assess the overall trend and track potential problem areas.

Flexibility: The use of different decay functions allows for the modeling of various scenarios, assuming different rates of skill decay. This can be useful when it is necessary to take into account various factors, such as the frequency of training or the occurrence of certain maritime conditions.

Predictive ability: The chart can be used to predict future safety levels based on current data and assumed decay rates. This can be a useful tool for planning training, simulations, and other safety measures.

Personalization: The model parameters can be tailored to a specific navigator or group of navigators, allowing for more accurate and relevant results. For example, various initial skill levels, experience, and individual characteristics can be considered.

Objectivity: The use of quantitative methods and mathematical models in the assessment of safety levels helps reduce subjectivity and the possibility of errors in the evaluation process.

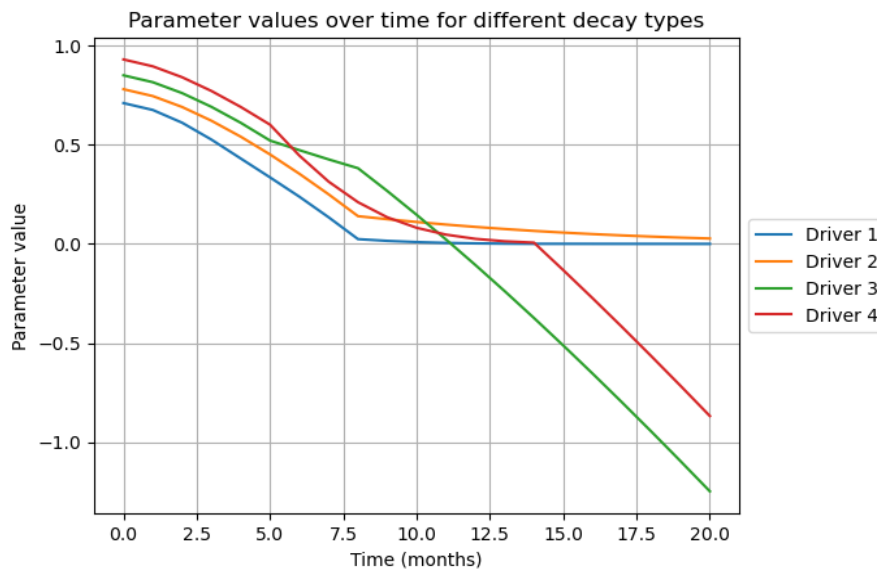


Fig. 3. Modeling based on feedback - parameter recovery

Based on the current task, let's assume that we want to optimize a maritime crew set in order to maximize the average skill level of navigator operators across the entire crew over a given period of time (e.g., 2 years). Let's suppose that the skills of the navigator operators can change over time using decay functions, but we have the ability to influence this process (e.g., through additional training or other support measures), and this influence can be modeled as a control effect in our system.

In this case, our objective function could simply be the sum of the average skill levels of the navigator operators across the entire crew over 2 years. Our task here would be to find the optimal control interventions (in the form of additional training programs, for example). Pontryagin's maximum principle can now be used to find the optimal control that maximizes the objective function [15].

From the perspective of mathematical modeling, numerical methods (specifically, Euler's method) were employed to simulate the dynamics of parameters over time, taking into account different types of damping (exponential, step, and logarithmic). Several parameters ("navigators") are modeled independently from each other with randomly selected types of damping.

This is expressed in the form of a system of differential equations (1):

$$\frac{dy_i}{dt} = -u \cdot k \cdot f(t, y_i, k) \quad (1)$$

where:

y_i - is the value of the i -th parameter (navigator);

t - is the time

u - is the initial control (constant)

k - is the damping coefficient

$f(t, y_i, k)$ - is the damping function, which could be exponential, step, or logarithmic.

Moving towards optimal control, it is advisable to apply the Pontryagin maximum principle, which serves as a tool for finding the optimal safety level trajectory based on navigator data in a dynamic system.

This criterion usually requires defining constraints and a target function. Suppose our target function is to minimize the overall damping of all navigators over a certain period of time (for instance, 20 months, as in the program's algorithm) (Fig. 4). Therefore, we should minimize (2):

$$J = \int_0^{20} (y_1(t) + y_2(t) + y_3(t) + y_4(t))dt, \tag{2}$$

where $y_i(t)$ are the solutions to our system of differential equations, and t from 0 to 20 months.

According to the Pontryagin maximum principle, the unique optimal control $u(t)$ is the one that maximizes the Hamiltonian (3):

$$H = L + \lambda'(t)f(t, y(t), u(t)) \tag{3}$$

where $L = y_1(t) + y_2(t) + y_3(t) + y_4(t)$ - is our target function;

$\lambda(t)$ - is the vector of Pontryagin multipliers, and $f(t, y(t), u(t)) = \frac{dy}{dt}$.

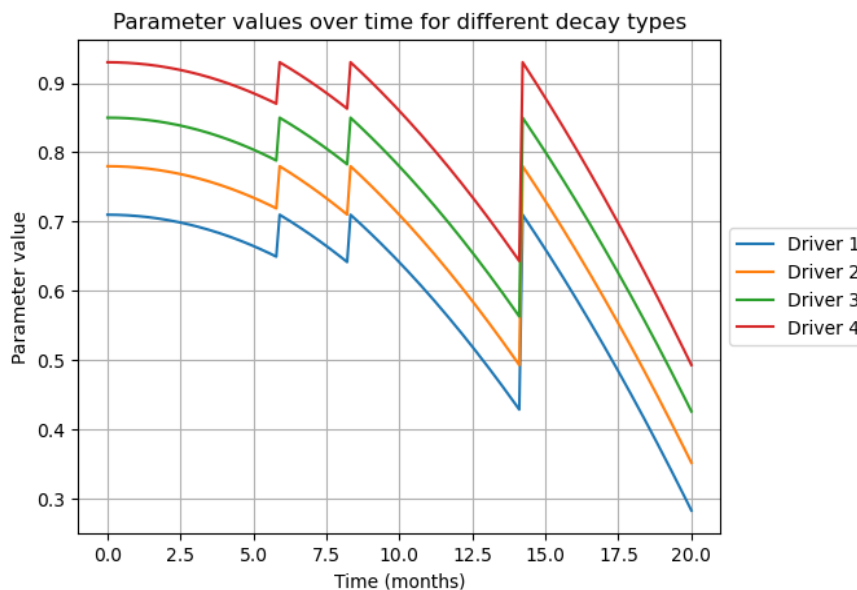


Fig. 4. Graph of the indicator "Safety of navigation" based on optimal control according to the criterion of Pontryagin's maximum

$$\frac{\partial H}{\partial u} = 0 \text{ (necessary condition for maximizing the Hamiltonian concerning control),}$$

$$\frac{dy}{dt} = \frac{\partial H}{\partial \lambda} \text{ (Pontryagin's equation),}$$

$$\frac{d\lambda}{dt} = -\frac{\partial H}{\partial y} \text{ (Pontryagin's coprime).}$$

These conditions will help us define the optimal control $u(t)$, which minimizes the overall damping of navigator parameters. The results of the modeling are presented in the chart based on the calculations of a computer program written in Python.

Step-by-step counteraction to damping allows for reaching a safe level without significant time loss. However, we see that the next wave has a larger damping angle, and already on the fourth stage, the safety level drops sharply. This requires a change in methods of maintaining the safety level at the 3rd and 4th stages.

Thus, the functionality was optimized for the "Safety of navigation" parameter associated with the parameters of the system, to which a step was added that calculates the optimal control at each time step using the Pontryagin maximum principle.

Conclusion. The simulation data exhibits a well-performing model with balanced metrics across various indices. On average, the model correctly classifies 79% of observations, identifies about 78.24% of actual positive instances, and approximately 81.20% of predicted positive results are accurate. The overall F1 score, which balances precision and recall, stands at around 78.54%, signifying a promising multifactorial model at this stage of simulation.

Based on this model, a forecast was made on the extent to which unneeded professional qualities directly influencing navigational safety are diminishing. The forecast indicates that with a mixed type of professional team's expertise fading (Fig. 1), there is a noticeable drop to 54% annually without recovery (Fig. 2). The presence of feedback only slightly reduces the decline of these indices, to 38% (Fig. 3). It is only under constant control based on Pontryagin's maximum principle in an integrated software product's online mode that allows safety levels to be restored synchronously during downtime.

However, it should be considered that the minimum decline is observed during the first two cycles, dropping to 6...8% over six months. Subsequent downtime in the third and fourth cycles leads to a more significant drop and may be catastrophic in the most critical navigation zones, dropping to 32% over six months. The most effective approach was the second cycle within 2.5 months, with full recovery of indices, which can be used as a foundation for application in maritime transport to ensure a sufficient level of navigational safety.

Assessment of the model's long-term effects on career progression and employer satisfaction will yield critical insights for further refinement of the system. Thereby, we can enhance the efficiency of the automated selection and recruitment process, which ultimately contributes to enriched career growth opportunities for operator-navigators and strengthens navigational safety.

REFERENCES

1. Akyuz, E., & Celik, M. (2015). Computer-based human reliability analysis onboard ships. *Procedia-Social and Behavioral Sciences*, 195, 1823-1832. <https://doi.org/10.1016/j.sbspro.2015.06.398>.
2. Lützhöft, M., & Nyce, J. M. (2008). Integration work on the ship's bridge. *Journal of Maritime research*, 5(2), 59-74.
3. Nosov, P., Cherniavskiy, V., Zinchenko, S., Popovych, I., Prokopchuk, Y., & Safonov, M. (2020). Identification of distortion of the navigator's time in model experiment. *Bulletin of University of Karaganda. Instrument and experimental techniques*, 4(100), 57-70. <https://doi.org/10.31489/2020Ph4/57-70>.
4. Hanzu-Pazara, R., Barsan, E., Arsenie, P., Chitoroiu, L., & Raicu, G. (2008). Reducing of maritime accidents caused by human factors using simulators in training process. *Journal of Maritime Research*, 5(1), 3-18.
5. Macrae, C. (2014). Early warnings, weak signals and learning from healthcare disasters. *BMJ quality & safety*, 23(6), 440-445. <http://dx.doi.org/10.1136/bmjqs-2013-002685>.
6. Nazir, S., Øvergård, K. I., & Yang, Z. (2015). Towards effective training for process and maritime industries. *Procedia Manufacturing*, 3, 1519-1526. <https://doi.org/10.1016/j.promfg.2015.07.409>.
7. Salas, E., & Cannon-Bowers, J. A. (2001). The science of training: A decade of progress. *Annual review of psychology*, 52(1), 471-499. <https://doi.org/10.1146/annurev.psych.52.1.471>.
8. Fathi, D. E., Grimstad, A., Johnsen, T. A., Nowak, M. P., & Stålhane, M. (2013, June). Integrated decision support approach for ship design. In *2013 MTS/IEEE OCEANS-Bergen* (pp. 1-8). IEEE. <https://doi.org/10.1109/OCEANS-Bergen.2013.6608103>.
9. Saaty, T. L. (1980). *The Analytic Hierarchy Process*. New York, NY: McGraw-Hill.

10. Hwang, C. L., & Yoon, K. (1981). *Multiple Attribute Decision Making: Methods and Applications*. Berlin, Heidelberg: Springer-Verlag.
11. Breiman, L. (2001). Random forests. *Machine Learning*, 45(1), 5-32. <https://doi.org/10.1023/A:1010933404324>.
12. Kuhn, M., & Johnson, K. (2013). *Applied Predictive Modeling*. New York, NY: Springer.
13. Raschka, S., & Mirjalili, V. (2019). *Python Machine Learning: Machine Learning and Deep Learning with Python, scikit-learn, and TensorFlow 2*. Birmingham: Packt Publishing Ltd. <https://www.packtpub.com/product/python-machine-learning-third-edition/9781789955750>.
14. Géron, A. (2019). *Hands-On Machine Learning with Scikit-Learn, Keras, and TensorFlow: Concepts, Tools, and Techniques to Build Intelligent Systems*. O'Reilly Media.
15. McGregor, C., Glasser, D., & Hildebrandt, D. (1999). The attainable region and pontryagin's maximum principle. *Industrial & engineering chemistry research*, 38(3), 652-659. <https://doi.org/10.1021/ie980380l>.

Ігор Грицук¹, Павло Носов², Олена Дягилева³, Марія Масьонкова⁴

¹Доктор технічних наук, професор, професор кафедри експлуатації суднових енергетичних установок, Херсонська державна морська академія, 73000, Херсон, проспект Ушакова, 20, Україна, ORCID: <https://orcid.org/0000-0001-7065-6820>

²Кандидат технічних наук, доцент, доцент кафедри навігації, Херсонська державна морська академія, 73000, Херсон, проспект Ушакова, 20, Україна, ORCID: <https://orcid.org/0000-0002-5067-9766>

³Кандидат педагогічних наук, доцент, проректор з навчально-методичної роботи, Херсонська державна морська академія, 73000, Херсон, проспект Ушакова, 20, Україна, ORCID: <https://orcid.org/0000-0001-9718-152X>

⁴Аспірант, Херсонська державна морська академія, 73000, Херсон, проспект Ушакова, 20, Україна, ORCID: <https://orcid.org/0000-0003-3741-4066>

Покращення безпеки навігації шляхом створення динамічної моделі дій навігатора в умовах навігаційних ризиків

Це дослідження вирішує складне завдання створення динамічної моделі навігатора, планування його траєкторії досвіду та прийняття рішень в умовах навігаційних ризиків в морській промисловості з використанням автоматизованих систем управління. Запропонована математична модель враховує індивідуальні навички, досвід та особистісні риси, враховуючи непередбачувану динаміку галузі. Дослідження підкреслює важливість адаптивних автоматизованих систем управління, здатних моделювати ситуації навігаційного ризику та визначати відповідні кар'єрні та розвиткові шляхи. Крім того, обговорюється важливість оцінки зовнішніх факторів, таких як економічні, технологічні та регуляторні зміни, а також забезпечення відповідності стандартам галузі, захисту даних і приватності. В роботі також підкреслюється необхідність масштабування і гнучкості, а також інтеграції автоматизованих систем з існуючою організаційною інфраструктурою. У дослідженні робиться висновок, що запропонована модель, оптимізована за параметром "безпека навігації" за допомогою принципу максимуму Понтрягіна, покращує процеси набору, створює всеосяжні професійні профілі для моряків і сприяє розвитку кар'єри. У роботі наводиться припущення про потенціал застосування цієї моделі в інших морських та суміжних професіях, що в кінцевому результаті покращує індивідуальне навчання та оперативну ефективність.

Ключові слова: безпека навігації, автоматизована система, морська галузь, людський фактор, навігаційні ризики, підготовка, динамічна модель.

Olga Petrychenko^{1*}, Maksym Levinskyi², Danylo Prytula³, Alla Vynohradova⁴

¹Doctor of Philosophy, Theory and Structure of a Ship Department, National University "Odessa Maritime Academy, 8, Didrikhson str., Odessa, 65052, Ukraine, ORCID: <https://orcid.org/0000-0002-4893-8204>

²PhD in Automation Control, Associate professor at Theory of Automatic Control and Information Technology Department, Head of Foreign Students Department, National University "Odessa Maritime Academy, 8, Didrikhson str., Odessa, 65052, Ukraine, ORCID: <https://orcid.org/0000-0002-6544-5110>

³Master of Navigation, National University "Odessa Maritime Academy", 8, Didrikhson str., Odessa, 65052, Ukraine, ORCID: <https://orcid.org/0009-0009-6474-1784>

⁴Head of the laboratory of the Ship's handling department, National University "Odessa Maritime Academy, 8, Didrikhson str., Odessa, 65052, Ukraine, ORCID: <https://orcid.org/0009-0007-9406-3203>

*Corresponding author: oapetrychenko@gmail.com

Fuel options for the future: a comparative overview of properties and prospects

As the maritime industry seeks to reduce its impact on the environment, the search for alternative fuel options is becoming increasingly important. Various fuel options are being studied, including biofuels, hydrogen, and ammonia, which are considered to be more environmentally friendly than traditional fuels extracted from the Earth's depths. The choice of fuel depends on various factors, including the size, speed, and distance of the ship, as well as the availability and cost of fuel. In the future, a combination of different fuel options may be necessary to achieve emission reduction goals. This article compares different alternative fuel types for ships, including low-sulfur fuel, LNG, electricity, methanol, hydrogen, and ammonia. Research shows that low-sulfur fuel is expensive but still cheaper than LNG, and the process of transitioning a ship to this type of fuel is relatively simple. LNG is the most expensive type of fuel and requires a complete overhaul of the ship's fuel system, which reduces its profitability. The article provides a table comparing the properties of different fuel types and concludes that methanol is likely to be the most promising alternative fuel in the near future.

Keywords: safe energy policy, ecology, environmental protection, pollution of atmosphere, low sulphur.

Introduction. Environmental pollution has become an increasingly concerning issue in modern times, with human progress being a major contributor. Various sources, including factories, vehicles, airplanes, and ships, emit a significant amount of harmful gases that have a detrimental impact on the environment. To address this, the International Maritime Organization (IMO) has taken steps to regulate air emissions from ships, with an amendment to Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) adopted in 2020. This requires ships to use fuel that contains less than 0.5% of sulfur or utilize a scrubber to clean heavy fuel oil. However, scrubbers are not a complete solution as they simply transfer pollution from the air to the ocean. The biggest challenge is to find an economically viable and environmentally friendly fuel. While very low sulfur fuel oil can reduce sulfur pollution, it still contributes to nitrogen oxides (NO_x) and carbon dioxide (CO₂) emissions. Liquid natural gas (LNG) is a promising option, but its high cost is a concern for ship-owners. Another potential solution is fully electric-powered vessels, but they are only practical in regions where electricity is both cheap and environmentally friendly. Overall, methanol is the most promising alternative fuel due to its ecological benefits and relatively low cost. However, its utilization requires significant attention from ship-owners.

Despite its benefits, methanol as a fuel option has not been widely adopted by ship-owners due to the need for additional attention in handling and utilization. However, ongoing research and development in the field of alternative fuels for ships are leading to new innovations and solutions that could make methanol a more viable option in the future. The shipping industry is also exploring the use of new technologies such as wind-assisted propulsion and hydrogen fuel cells to reduce emissions. However, these technologies are still in the early stages of development and require significant investment and infrastructure.

Reducing air pollution from ships is crucial for protecting the environment and human health. The use of alternative fuels and new technologies can play a significant role in achieving this goal, but further research and development is needed to make these solutions more widely available and economically viable for the shipping industry.

Analysis of recent research and problem statement. Different types of scrubbers exist, including open-loop and closed-loop systems, which operate on similar principles. Open-loop scrubbers draw water from the ship's kingston box and use it to purify the air of sulfur before discharging it overboard [1]. Closed-loop scrubbers work similarly, but the water used for scrubbing is retained on board and discharged as sludge in ports [2]. Hybrid systems are also available, which can use both open and closed-loop cycles.

In order to make a decision regarding the installation of a scrubber on a vessel, a shipowner must carry out a comprehensive analysis [3]. One of the important factors to consider is the age of the vessel. It should also be noted that retrofitting an operational vessel with a scrubber system can result in the vessel being out of commission for a minimum of 30-40 days, leading to substantial loss of profit for the shipowner [4].

Purchasing and using Very Low Sulfur Fuel Oil (VLSFO) is an alternative approach to comply with the IMO 2020 regulations. However, it should be noted that transitioning a vessel from heavy fuel to VLSFO requires a thorough cleaning of the entire fuel system, which results in a prolonged downtime at the berth and loss of profits for the shipowner. Additionally, recent studies have found that VLSFO may produce higher emissions of soot than its predecessor, High Sulfur Fuel Oil (HSFO). This is attributed to the high percentage of aromatic compounds in new mixtures of marine fuels with a sulfur content of 0.50%, which directly contribute to the production of soot [5].

The purpose and tasks of the study. Based on data from ship & bunker's website, the mean global cost of heavy fuel per metric ton was \$520 in October 2021 (Figure 1a), while the price of low-sulfur fuel was \$620 per metric ton (Figure 1b) [6]. In a few years, the difference in the cost of using low-sulfur fuel instead of heavy fuel may outweigh the cost of installing a scrubber, although the calculations were made assuming vessels were operating at low speeds [7]. However, it should be noted that fuel consumption may be twice as high when a vessel is traveling at full speed [8].

Thus, it can be inferred from sources [9, 10] that the benefits of utilizing low-sulfur fuel in lieu of installing a scrubber are not immediately clear. The primary reason being that the conversion process from heavy fuel to low-sulfur oil is both costly and complex. Furthermore, in the long-term, this option is significantly more expensive. Additionally, some research suggests that even low-sulfur fuel may have detrimental effects on the environment. Therefore, it is worthwhile to explore alternative fuels that can be used for shipping [11].

When considering alternative fuels, it is important to evaluate them based on three critical factors: cost-effectiveness, environmental impact, and safety in fuel usage. Among the most promising alternative fuels for shipping are liquefied natural gas, electricity, and methanol. Figure 2 provides a useful comparison of these fuels' characteristics on ships, as of 2021.

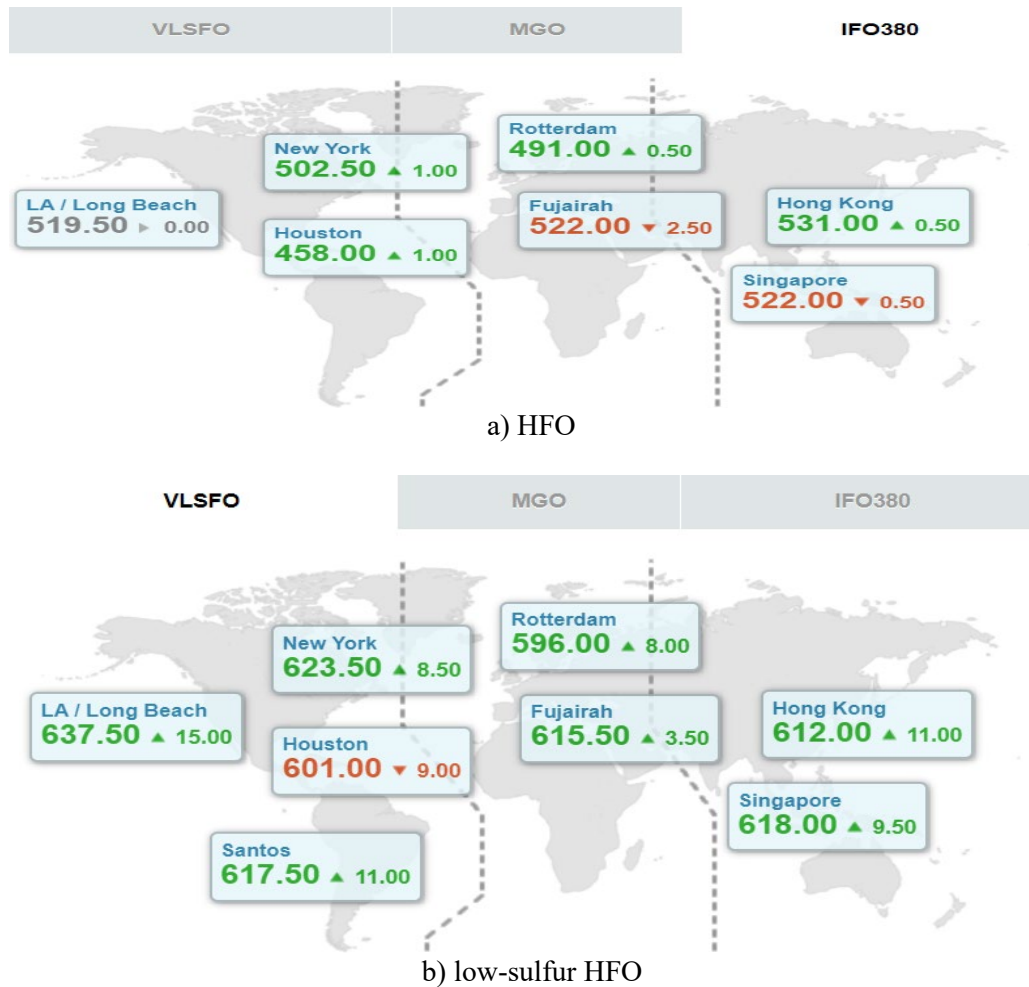


Fig. 1. Fuel prices in different countries

Comparing the prices of low-sulfur fuel and gas can be challenging, as it depends heavily on trends in the global market, which can change rapidly. For example, in February 2021, the energy efficiency price per unit of measure for gas (mmBTU) was \$6.85, while for the same unit of measure for low-sulfur fuel, it was around \$12, indicating that using gas was twice as profitable. The fuel market has experienced significant changes since then, with gas prices increasing threefold compared to February of the same year. While the price of low-sulfur fuel has also increased, it has not increased as much as gas. Currently, gas is 1.5 times more expensive than low-sulfur fuel. Given these circumstances, it is difficult to determine which fuel will be more profitable for future use. The obvious disadvantage of gas usage over low-sulfur fuel is manifested in the following. The cost of installing a gas or two-fuel engine, LNG tanks, relevant pipelines and related equipment can increase the cost of a new vessel by up to 30% compared to a traditional propulsion system. Another disadvantage of LNG is the very time-consuming and expensive re-equipment of marine bunkering terminals [12].

Consideration will now be given to the impact of gas on the environment. Firstly, it should be emphasized that sulfur emissions are markedly reduced, by up to 90%, when utilizing gas as opposed to heavy fuel. Furthermore, natural gas is widely promoted due to its comparatively lower CO₂ emissions relative to coal or oil. However, it is important to note that methane, which comprises a significant component of natural gas, is a greenhouse gas with a potency 25 times greater than that of CO₂ [13]. The overall environmental benefits of liquefied natural gas (LNG) depend on the level of emissions occurring during its production and usage. According to calculations by DNV GL (Det Norske Veritas

and Germanischer Lloyd), a total methane leak rate of 5.5% (incorporating both production and transportation stages, as well as combustion) would result in greenhouse gas emissions from LNG equivalent to those arising from diesel. Consequently, the issue necessitates the implementation of measures to reduce emissions from both production and combustion in engines [14]. Presently, a range of techniques and ideas exist for mitigating these leaks, and their implementation may yield tangible reductions in greenhouse gas emissions by a range of 10-20% when compared to conventional petroleum-based fuels.

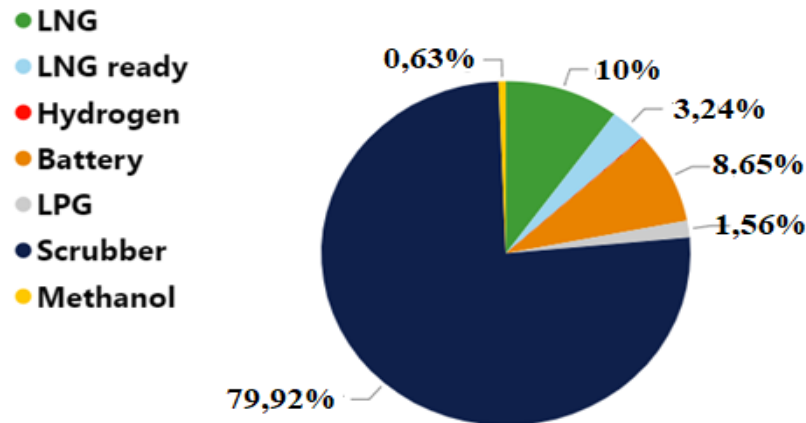


Fig. 2. The total number of vessels operated and under construction that use different types of fuel

It is imperative to consider the environmental impact of utilizing gas as a fuel source in shipping. The reduction in sulfur emissions by up to 90% when using gas, as opposed to heavy fuel, is a significant advantage. Additionally, natural gas has been touted for its relatively lower CO₂ emissions in comparison to coal or oil. However, it is crucial to acknowledge that methane, a major component of natural gas, is a greenhouse gas with a potency 25 times greater than that of CO₂. Therefore, the environmental benefits of liquefied natural gas (LNG) are contingent on the level of emissions occurring during its production and utilization. The total methane leak rate, incorporating both production and transportation stages as well as combustion, is estimated by DNV GL to be 5.5%. Such a leak rate would result in greenhouse gas emissions from LNG equivalent to those emitted from diesel fuel. As such, measures to reduce emissions from both production and combustion are necessary, and a variety of techniques and ideas exist for mitigating these leaks. Implementation of these measures may yield tangible reductions in greenhouse gas emissions of 10-20% when compared to conventional petroleum-based fuels.

Materials and methods of research. When considering the cost-effectiveness of alternative fuels, it is important to not only analyze current market trends but also take into account the long-term cost implications of investing in new propulsion systems and infrastructure. It is also worth noting that environmental regulations, such as the International Maritime Organization's (IMO) sulfur cap, can greatly impact the demand and supply of different types of marine fuels, further affecting their cost-effectiveness. The environmental impact of alternative fuels is another critical factor to consider. As discussed earlier, methanol has the advantage of emitting low levels of sulfur, NO_x, and greenhouse gases during combustion, making it a promising option for reducing marine pollution. However, the production and transportation of methanol also have their own environmental impacts, such as carbon emissions from its production process and potential leaks during transportation. Thus, a comprehensive assessment of the environmental impact of different fuels should take into account the entire supply chain, from production to combustion.

Safety is another important factor to consider when evaluating alternative fuels. While LNG and methanol have been used safely in some vessels, there are still concerns about the risks associated with

their use, such as the potential for leaks or fires. The development of safe and reliable technologies for handling and using alternative fuels is crucial to ensuring their safe implementation.

The choice of alternative fuels for shipping must take into account a variety of factors, including cost-effectiveness, environmental impact, and safety. While LNG, electricity, and methanol are among the most promising options, each has its own advantages and disadvantages that must be carefully weighed. Ultimately, the development and adoption of sustainable and environmentally friendly marine fuels will require continued research, investment, and collaboration among industry stakeholders, policymakers, and researchers.

The issue of whether to use gas or low-sulfur fuel remains a subject of discussion, particularly in terms of cost-effectiveness and eco-friendliness. While gas may be a more affordable option at present, fluctuations in the global market make it difficult to predict which fuel will be more profitable in the long-term. In terms of environmental impact, while gas is known to emit significantly lower levels of sulfur than heavy fuel, the issue of methane leaks must be addressed to fully realize its potential as an eco-friendly alternative.

In addition to the aforementioned criteria of cost-effectiveness, environmental impact, and safety, the selection of alternative marine fuels is influenced by the availability and associated infrastructure for each fuel type. For instance, while liquefied natural gas (LNG) possesses the potential to significantly diminish emissions, its production and transportation infrastructure is still in its nascent stage. On the other hand, electric-powered ships necessitate substantial investments in charging infrastructure and battery technology to become a feasible option for long-haul shipping.

It's important to note that the adoption of alternative fuels in shipping is not only driven by environmental concerns but also by regulatory requirements. The International Maritime Organization's (IMO) regulations, such as the sulfur cap implemented in 2020, are pushing the industry towards cleaner fuels. This has led to a surge in research and development of new fuels, such as biofuels and hydrogen, which have the potential to significantly reduce emissions and meet the IMO's targets for decarbonization.

The shift towards alternative fuels in shipping is a complex and multifaceted issue that requires a holistic approach. While gas and low-sulfur fuel are currently the most popular options, continued research and investment in emerging technologies will be necessary to achieve a sustainable and environmentally friendly future for the shipping industry.

Other alternative fuels are also being considered in the shipping industry. Liquefied natural gas, electricity, and methanol are among the most promising options, and each has its own unique advantages and disadvantages. For example, while LNG has the potential to significantly reduce greenhouse gas emissions, its production and transportation must be carefully managed to avoid methane leaks. Meanwhile, electric-powered vessels produce no direct emissions, but their batteries require frequent recharging, which can limit their range and require significant infrastructure investments.

The shipping industry is exploring a range of options for reducing its environmental impact, including the use of alternative fuels and improved technologies for reducing emissions from existing vessels. By carefully weighing the cost-effectiveness, eco-friendliness, and fuel usage safety of each option, it may be possible to develop a sustainable and profitable model for the shipping industry in the years to come.

Another alternative fuel for vessels is electricity, stored in batteries. However, the potential for emission reductions largely depends on the structure of electricity: in regions with a high level of usage of renewable sources or nuclear energy, emissions of both greenhouse gases and other pollutants will be low (Fig. 3).

Figure 3 shows the carbon intensity of the electricity structure in different countries, expressed in grams of CO₂ equivalent emitted per 1 kWh of electricity produced.

The cost of operation may be low, provided that the price of electricity is competitive with the prices of marine fuel. The main obstacle to the introduction of batteries in transportation is their high capital cost, which exceeds \$ 1,000/kWh. Despite this, using batteries is one of the best long-term solutions for addressing environmental problems, as long as shore-based electricity production can meet or surpass

emissions from conventional fuel-powered ships. significant investment will be required to develop port infrastructure and equip ships with batteries, and the varying electricity prices in different countries may affect the economic feasibility of battery-powered ships. Safety considerations also need to be addressed, and current battery capacity is insufficient for long voyages. At present, electricity is mainly used in hybrid vessels in combination with conventional fuel to reduce emissions and improve efficiency. However, as technology improves and battery capacity increases, using batteries as a standalone fuel for ships could become a viable option in the future.

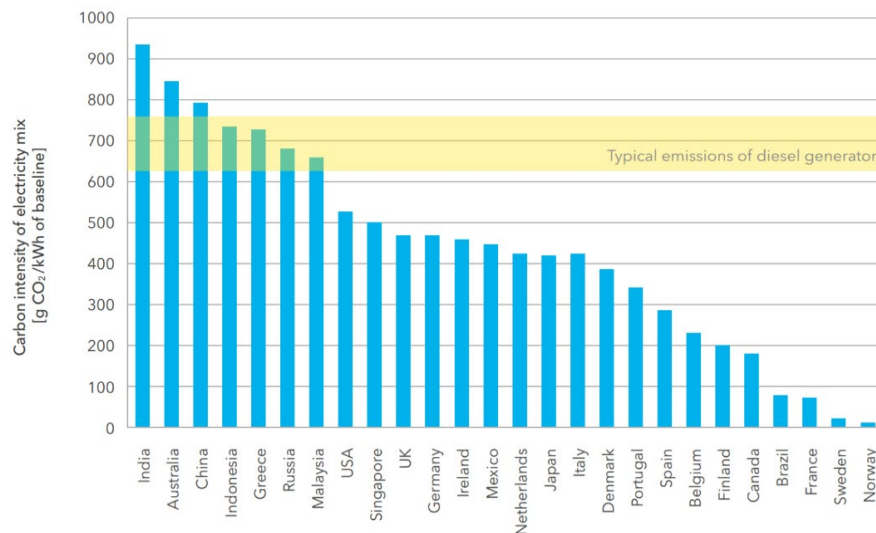


Fig. 3. Specific carbon emissions in electricity production in different countries

In the long run, this is one of the best solutions to environmental problems, provided that the production of electricity on shore will not cover or even exceed the emissions of ships running on conventional fuel [15]. Another important aspect is the financial side of the idea. First of all, a large amount of money should be invested in ports infrastructure and ships equipment. Also, all countries have different electricity prices, so when calling at one port, the ship can save very well compared to the cost of conventional fuel, and in another port, it can cost several times more and exceed the cost of conventional fuel. It is also necessary to pay attention to the development of safe technology for the use of batteries on ships. Another important issue is the fact that now the battery capacity is far from what is needed to conduct long voyages. Nowadays, electricity is used mainly on hybrid vessels in combination with conventional fuel to reduce emissions and increase efficiency. It will take a long time before electricity can be used on ships as a stand-alone fuel.

The use of electricity as a primary fuel source on ships raises concerns regarding the capacity and cost-effectiveness of the necessary battery technology. Currently, battery capacity is insufficient for long voyages, limiting the application of electric power in shipping to hybrid vessels that combine conventional fuel and electricity. The development of battery technology that can meet the energy demands of long voyages is crucial to the adoption of electric power in the shipping industry. The financial aspect of electric power usage is also a significant consideration. Investment in port infrastructure and ship equipment is necessary to enable electric power usage, and the cost of electricity can vary significantly between countries, potentially making it more or less cost-effective compared to conventional fuels in different regions. Ensuring the safety of battery usage on ships is another critical issue that requires attention. While electric power has great potential to reduce emissions and improve efficiency in shipping, it will take significant time and investment to develop the technology and infrastructure necessary for its widespread adoption.

Methanol is an alternative fuel called methyl or wood alcohol, which is a liquid, that means that the existing infrastructure for fuel storage and refueling will require only minor changes for methanol

processing [16], which will require low infrastructure investment costs compared to the large investment required to build liquefied gas terminals or electricity supply systems.

Methanol can be produced from a variety of feedstocks, including natural gas, coal, and biomass. The production of methanol from renewable energy sources such as wind and solar power is also being developed [17]. Methanol is considered a clean fuel due to its low emissions of particulate matter, sulfur oxides, and nitrogen oxides. Methanol also has a higher octane rating than gasoline, which makes it a potential replacement for gasoline in the transportation sector [18].

Methanol is a polar liquid that combines with water, other alcohols, esters, and most organic solvents. This means that methanol, which is released into the environment, will decompose quickly [19]. A large spill will have only local consequences and will decompose in water. Methanol is highly toxic and flammable, which poses safety risks during storage and transport. Methanol also has a lower energy density than conventional fuels, which means that more fuel is required to produce the same amount of energy. In addition, the production of methanol from fossil fuels is a significant source of greenhouse gas emissions, which undermines its status as a clean fuel. The development of renewable methanol production methods could mitigate this issue, but further research is needed to assess the feasibility and scalability of these methods.

The availability of methanol on a large scale is main problem. To be able to supply a large fleet, more methanol has to be produced. To cover 25-30% of the maritime market it is necessary to significantly increase production capacity [20].

In terms of environmental impact during combustion, methanol does not emit sulfur, and the levels of NO_x and greenhouse gases are even lower than in LNG (Fig. 4).

However, the production of methanol can be energy-intensive and may lead to emissions of CO₂ and other pollutants if fossil fuels are used as the primary source of energy. Additionally, the transportation and storage of methanol require specialized infrastructure, which may pose a challenge for widespread adoption.

The safety aspects of methanol as a fuel should also be considered. Methanol is highly flammable and toxic, which requires strict safety protocols for its handling and storage. The risk of leaks and fires must be minimized through appropriate design and operational procedures.

Methanol is considered a promising alternative fuel for shipping, with several pilot projects and demonstration vessels already in operation. Ongoing research and development efforts aim to further improve the cost-effectiveness, environmental performance, and safety of methanol as a marine fuel.

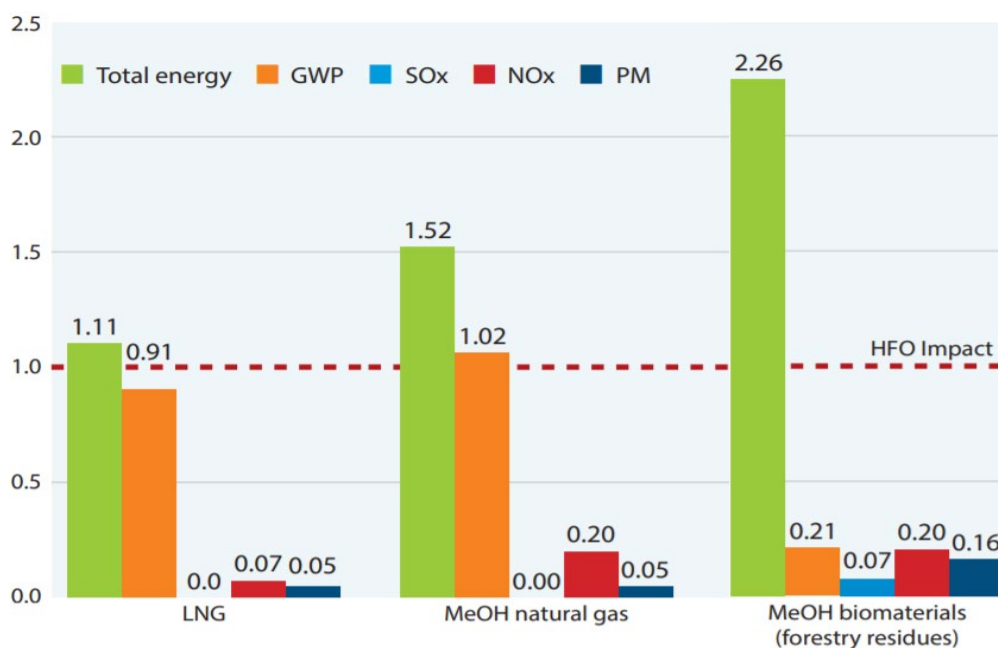


Fig. 4. Comparison of emissions during LNG and methanol production

This makes methanol a highly attractive alternative fuel option for environmentally-conscious industries and governments. The production of methanol is relatively easy and cost-effective, and it does not require a complete overhaul of a ship's fuel system, unlike LNG. As a result, the adoption of methanol as a fuel source has the potential to significantly reduce the shipping industry's carbon footprint and mitigate the negative impacts of climate change. However, further research and development are necessary to address the remaining technical and regulatory challenges associated with the widespread adoption of methanol as a marine fuel.

Methanol is a renewable fuel source that can be produced from a variety of feedstocks, such as natural gas, coal, and even carbon dioxide. This makes it a highly versatile and sustainable alternative to traditional fossil fuels. Moreover, methanol has a high energy density, which means it can be stored and transported more efficiently than some other alternative fuels. It's worth noting that methanol does have some drawbacks. For example, it has a lower energy density than gasoline or diesel, which means that more fuel is needed to achieve the same level of power. Also, the production of methanol requires a significant amount of energy, which can lead to increased greenhouse gas emissions if the energy is not derived from renewable sources.

While methanol may not be a perfect solution to our energy needs, it does offer a promising alternative to traditional fossil fuels, especially in terms of its low environmental impact and potential for renewable production.

Conclusions and prospects for further work in this area. As a conclusion, the general table of an estimation of various properties of all considered kinds of fuel is presented (tab. 1). The table shows that the scrubber is the most profitable in the long run, because paying only several millions the shipowner gets the opportunity to supply the ship with the cheapest fuel, which pays off in just a few years. It is also easy to install on a ship and can be done in most docks around the world. However, the scrubber does not solve the problem of pollution at all and has no long-term prospects taking in consideration that the IMO plans to further increase the requirements for environmental pollution prevention by ships. A heavy fuel spill is a terrible natural disaster that destroys all the flora and fauna nearby.

Table 1. Estimates of various types of fuel parameters

	Scrubber/ heavy fuel	Low sulfur fuel	LNG	Electricity	Methanol
Profitability	+	+/-		+/-	+/-
Ease of installation	+	+	-	-	+
Availability	+	+	+/-	-	-
Environmental impact	-	+/-	+	+/-	+
Safety during accident	-	-	+	-	+
Prospects	-	+/-	+	+/-	+

Low-sulfur fuel is quite expensive, but still cheaper than LNG. For a complete transition of the vessel to this type of fuel requires washing all tanks and systems, however, compared with the installation of systems for other alternative fuels, this is a much easier process. Low-sulfur fuel has been widely adopted as a means to comply with the International Maritime Organization's sulfur emissions regulations. However, the transition to this fuel comes with its own set of challenges. One of the biggest hurdles is the cost, as low-sulfur fuel is more expensive than traditional heavy fuel oil. This has led to concerns about the financial impact on shipping companies, especially during periods of economic downturn.

Another challenge is the need to clean tanks and systems before switching to low-sulfur fuel, to prevent contamination and ensure proper operation. While this is a simpler process compared to installing new infrastructure for other alternative fuels, it still requires significant time and resources.

Despite these challenges, low-sulfur fuel remains a promising option for reducing emissions in the shipping industry. Ongoing research and development efforts are aimed at improving its cost-effectiveness and performance, as well as exploring other alternative fuels with potential benefits for both the environment and the industry as a whole.

Liquefied natural gas today is the most expensive of all fuels compared in this paper. In order to equip a ship with LNG power supply system, the ship's fuel system must be completely redesigned, and it should be borne in mind that LNG occupies a larger volume with the same energy efficiency as other fuels, which further reduces its profitability. Not all ports in the world can supply vessels with gas and it will take some time before LNG bunkering systems will be available everywhere.

The implementation of a liquefied natural gas (LNG) power supply system on a vessel requires a complete redesign of the ship's fuel system, and it should be noted that LNG occupies a larger volume with the same energy efficiency as other fuels, which further diminishes its profitability. Moreover, LNG is presently the most expensive fuel compared to other alternatives, thus making it a less attractive option for commercial shipping. The availability of LNG in ports is another limiting factor, as not all ports are equipped with the necessary infrastructure to supply vessels with gas. The implementation of LNG bunkering systems worldwide will require significant investments in infrastructure and may take some time to be fully realized.

Electricity is a very controversial type of alternative and depends on the place of its production. In some countries, such as Norway, this is the best choice for ships sailing locally, as it is cheap there and electricity generation causes minimal damage to the environment. Electricity itself does not affect the environment during usage.

Continuing the discussion on alternative fuels for shipping, it is important to note that electricity is a complex and location-dependent option. The suitability of this fuel depends on the electricity production method used and its availability at ports. In countries like Norway, which produce electricity from renewable sources, electric-powered ships may offer a cost-effective and environmentally friendly option for local shipping. However, in other countries where electricity is generated primarily from non-renewable sources, electric power may not be a feasible alternative. It should also be noted that the production and disposal of batteries used to store electricity raise environmental concerns. Once in use, however, electric propulsion does not contribute to air pollution or greenhouse gas emissions, making it an attractive option for clean transportation.

Methanol is the most promising but still underestimated type of fuel. It is cheaper than LNG and takes up less space for the same energy efficiency, which makes it more competitive with low-sulfur fuel than gas. To convert a vessel to methanol, shipowner needs to do the same as to convert it to low-sulfur fuel, which is not such a complicated process. Furthermore, methanol is a liquid at room temperature and atmospheric pressure, which simplifies storage and transportation compared to LNG. Methanol is also widely available, as it is a commodity chemical and can be produced from various feedstocks, including natural gas, coal, and biomass. Methanol has a lower greenhouse gas emission profile than conventional fossil fuels, but its production still generates CO₂ emissions. However, the use of renewable energy sources in methanol production, such as biomass and carbon capture and storage (CCS) technologies, can significantly reduce its carbon footprint. Methanol also has a higher octane rating than traditional fuels, which can lead to better engine performance and efficiency. However, methanol is still a relatively new fuel in the shipping industry, and its infrastructure for bunkering and distribution is not yet fully developed, which presents a challenge for its widespread adoption.

Energy sources such as hydrogen and ammonia were also considered during the search and information was analyzed for this report. However, at the moment they cannot compete with the types of fuel described in this work, because their production and price are much higher, they take even more space for storage than LNG, during the accident they pose a great danger to the ship's crew and the environment. Hydrogen and ammonia are energy sources that have been studied for their potential use

as fuels for shipping, but they currently face significant challenges. The production and price of hydrogen and ammonia are higher than other alternative fuels described in this report, making them less competitive. Additionally, the storage of hydrogen and ammonia requires even more space than LNG, which is a significant disadvantage for ships where space is limited. Furthermore, both hydrogen and ammonia pose safety risks during transportation and handling, as they can be highly flammable or toxic in certain conditions, which can endanger both the crew and the environment. Therefore, despite their potential advantages, hydrogen and ammonia remain less feasible options for the shipping industry, at least until technological and infrastructural developments occur.

The table 1 presented in this study provides an overview of various properties of different types of fuels. The most profitable option in the long run is the scrubber, but it does not solve the problem of pollution and has no long-term prospects. Low-sulfur fuel is expensive but still cheaper than LNG, and the process of converting a vessel to this type of fuel is relatively easy. LNG is the most expensive fuel and requires a complete redesign of the ship's fuel system, which reduces its profitability. Electricity is a viable option in some countries, but its effectiveness depends on the place of production. Methanol is the most promising alternative fuel due to its low cost and space requirements, making it competitive with low-sulfur fuel and more attractive than gas. While hydrogen and ammonia were also considered, their production and price are much higher, and they pose a significant danger to the environment during an accident. Thus, methanol is likely to be the most promising alternative fuel in the near future.

REFERENCES

1. Mikosyanchyk, O., Mnatsakanov, R., Zaporozhets, A., & Kostynik, R. (2016). Influence of the nature of boundary lubricating layers on adhesion component of friction coefficient under rolling conditions. *Eastern European Journal of Enterprise Technologies*, 4(1), 24-31. <https://doi.org/10.15587/1729-4061.2016.75857>.
2. Andersson, K., Brynolf, S., Lindgren, F., & Nilsson, L. (2020). Comparison of Alternative Marine Fuels, Part II: Life Cycle Assessment. *Journal of Marine Science and Engineering*, 8(9), 667. <https://doi.org/10.3390/jmse8090667>.
3. Leduc, G., Patrizio, P., Yeh, S., Wetterlund, E., & Dotzauer, E. (2020). Green ammonia as an energy carrier for a decarbonized future: Techno-economic and environmental. *Applied Energy*, 268, 114965. <https://doi.org/10.1016/j.apenergy.2020.114965>.
4. Koirala, R., & Yuan, J. (2020). Evaluating the Energy and Environmental Performance of Alternative Marine Fuels for International Shipping: A Comparative Study. *Journal of Cleaner Production*, 258, 120915. <https://doi.org/10.1016/j.jclepro.2020.120915>.
5. Serbin, S.I., Kozlovskiy, A.V., & Burunsuz, K.S. (2016). Investigations of nonstationary processes in low emissive gas turbine combustor with plasma assistance. *IEEE Transactions on Plasma Science*, 44(12), 2960-2964.
6. Hamrock, B. J., Schmid, S. R., & Jacobson, B. O. (2004). *Fundamental of Fluid Film Lubrication: Second Edition*. Marcel Dekker, Inc.
7. Zablotzky, Yu. V., & Sagin, S. V. (2016). Enhancing Fuel Efficiency and Environmental Specifications of a Marine Diesel When using Fuel Additives. *Indian Journal of Science and Technology*, 9(46), 353-362. doi: <https://doi.org/10.17485/ijst/2016/v9i46/107516>.
8. Leduc, G., Patrizio, P., Yeh, S., Wetterlund, E., & Dotzauer, E. (2020). Green ammonia as an energy carrier for a decarbonized future: Techno-economic and environmental assessment. *Applied Energy*, 268, 114965. <https://doi.org/10.1016/j.apenergy.2020.114965>.
9. Liu, C., Hong, J., Chen, W., & Chen, B. (2020). Alternative Fuels for Shipping: Technological, Economic, and Environmental Assessments. *Energy Policy*, 137, 111143. <https://doi.org/10.1016/j.enpol.2019.111143>.
10. Pechenyuk, A., & Petrychenko, O. (2021). Prediction of Safe Maneuvers in Restricted Waters as Problem of Navigation and Ship Hydrodynamics. *Transport Means - Proceedings of the International Conference, 2021, 2021-October*, (pp. 239-244).
11. Koirala, R., & Yuan, J. (2020). Evaluating the Energy and Environmental Performance of Alternative Marine Fuels for International Shipping: A Comparative Study. *Journal of Cleaner Production*, 258, 120915. <https://doi.org/10.1016/j.jclepro.2020.120915>.
12. Andersson, K., Brynolf, S., Lindgren, F., & Nilsson, L. (2020). Comparison of Alternative Marine Fuels, Part II: Life Cycle Assessment. *Journal of Marine Science and Engineering*, 8(9), 667. <https://doi.org/10.3390/jmse8090667>.
13. Liu, C., Hong, J., Chen, W., & Chen, B. (2020). Alternative Fuels for Shipping: Technological, Economic, and Environmental Assessments. *Energy Policy*, 137, 111143. <https://doi.org/10.1016/j.enpol.2019.111143>.
14. Golikov, V. A., Golikov, V. V., Volyanskaya, Y., Mazur, O., & Onishchenko, O. (2018, June). A simple technique for identifying vessel model parameters. In *IOP Conference Series: Earth and Environmental Science (172(1))*, p. 012010. IOP Publishing. <https://doi.org/10.1088/1755-1315/172/1/012010>.

15. Sagin, S. V., & Kuropyatnyk, O. A. (2018). The Use of Exhaust Gas Recirculation for Ensuring the Environmental Performance of Marine Diesel Engines. *OUR SEA: International Journal of Maritime Science & Technology*, 65(2), 78-86. <https://doi.org/10.17818/NM/2018/2.3>.
16. Sagin, S. V., & Solodovnikov, V. G. (2015). Cavitation treatment of high-viscosity marine fuels for medium-speed diesel engines. *Modern Applied Science*, 9(5), 269-278. <https://doi.org/10.5539/mas.v9n5p269>.
17. Matveev, I. B., Serbin, S. I., & Washcilenko, N. V. (2014). Sewage sludge-to-power. *IEEE Transactions on Plasma Science*, 42(12), 3876-3880.
18. Cherednichenko, O., & Serbin, S. (2018). Analysis of Efficiency of the Ship Propulsion System with Thermochemical Recuperation of Waste Heat. *Journal of Marine Science and Application*, 17(1), 122-130.
19. Sagin, S. V. (2019). Decrease in mechanical losses in high-pressure fuel equipment of marine diesel engines. In *Materials of the International Conference "Scientific research of the SCO countries: synergy and integration". Part 1* (pp. 139-145). Beijing, PRC. doi: <https://doi.org/10.34660/INF.2019.15.36258>
20. Ryzhkov, R. S., & Serbin, S. I. (2015). Experimental Investigations Of Efficiency Of The Turboimpact Breathing Systems Separator For Gas Turbine Installation Of Closed Cycle. *Shipbuilding & Marine Infrastructure*, (2). <https://doi.org/10.15589/smi20150205>.

Ольга Петриченко¹, Максим Левінський², Данило Притула³, Алла Виноградова⁴

¹Кандидат технічних наук, доцент кафедри теорії і устрою судна, Національний університет «Одеська морська академія», 8, вул. Дідріхсона, Одеса, 65052, Україна, ORCID: <https://orcid.org/0000-0002-4893-8204>

²Кандидат технічних наук, доцент кафедри теорії автоматичного управління та обчислювальної техніки, начальник відділу іноземних студентів Національного університету «Одеська морська академія», вул. Дідріхсона, 8, м. Одеса, 65052, Україна, ORCID: <https://orcid.org/0000-0002-6544-5110>

³Магістр судноводіння, Національний університет «Одеська морська академія», 8, вул. Дідріхсона., Одеса, 65052, Україна, ORCID: <https://orcid.org/0009-0009-6474-1784>

⁴Завідувач лабораторії кафедри управління судном, Національний університет «Одеська морська академія», 8, вул. Дідріхсона., Одеса, 65052, Україна, ORCID: <https://orcid.org/0009-0007-9406-3203>

Паливні опції майбутнього: порівняльний огляд властивостей та перспектив

Оскільки морська галузь прагне зменшити свій вплив на довкілля, пошук альтернативних варіантів палива стає все важливішим. Вивчаються різні варіанти палива, включаючи біопаливо, водень та амоніак, які вважаються більш екологічно чистими, ніж традиційні палива, які добуваються з недр Землі. Вибір палива залежить від різних факторів, включаючи розмір, швидкість та дальність корабля, а також від наявності та вартості палива. У майбутньому, для досягнення цілей зменшення викидів, може знадобитися комбінація різних варіантів палива. Ця стаття порівнює різні альтернативні види палива для кораблів, включаючи низькосульфатне паливо, СПГ, електрику, метанол, водень та аміак. Дослідження показує, що низькосульфатне паливо є дорогим, але все ж дешевшим, ніж СПГ, і перехід корабля на цей вид палива - досить простий процес. СПГ є найбільш дорогим видом палива і вимагає повної переробки системи палива судна, що зменшує його прибутковість. У статті надана таблиця, що порівнює властивості різних видів палива, і заключено, що метанол ймовірно буде найбільш перспективним альтернативним паливом в найближчому майбутньому.

Ключові слова: безпечна енергетична політика, екологія, охорона довкілля, забруднення атмосфери, низькосульфатне паливо.

Olena Oliyuk^{1*}, Lesia Kushmar²

¹Associate Professor, Railway Track and Track Facilities Department, State University of Infrastructure and Technologies, Kyrylivska str., 9, Kyiv, 04071, Ukraine, ORCID: <http://orcid.org/0000-0003-3362-8956>

²Candidate of Philological Sciences, Associate Professor, Associate Professor of the Department of Foreign Philology and Translation, State University of Trade and Economics, Kioto str., 19, Kyiv, 02156, Ukraine, ORCID: <http://orcid.org/0000-0003-0407-6267>

*Corresponding author: oliyuk_oa@gsuite.duit.edu.ua

Grapho-analytic method of determining the minimum groove at the pivot root of symmetrical switches

Switches are a barrier place in the track for setting the permissible speeds for trains on the main tracks, as they have special structural devices for branching traffic from the main track to the secondary track. Symmetrical switches have a number of advantages compared to conventional ones: with the same brand with conventional switches, symmetric ones allow significantly higher speeds for the train movement with side tracks; symmetrical switches have a shorter length with the same radii of the transfer curves; it is possible to apply crosspieces with a larger angle than in the conventional switches while preserving the length of the curve and the radius. The specified qualities of single, versatile, symmetrical switches determined their use scope. On the main transport tracks, symmetrical switches are used in sorting parks of the stations, as well as in main tracks when it is necessary to achieve increased speeds of movement on both side tracks. Symmetric switches according to the purpose and design have the significant differences from the most conventional switches, and therefore the study of these designs is important and relevant. Moreover, very few scientific works were devoted to such studies of Ukrainian railways.

Keywords: *symmetric switches, design, minimum groove between the pivot and the frame rail.*

Introduction. The design of symmetric directional switches is significantly different from the design of conventional one-way switches. A complete methodology for designing the parameters of a symmetric switch with curvilinear pivots is needed. At the same time, special attention should be paid to the issues of mutual location of the diverted pivots and frame rails, and determining the dimensions of the groove between them, i.e., so that the wheels of rolling stock do not touch the diverted pivots with the inner side face of the rib. The safety of the movement of wheel pairs on these switches depends on a rational solution to this issue.

Analysis of the latest research and problem statement. Technical issues that need to be solved by Ukrainian railway include the issue of improving the structures of switches and their individual elements [1, 2]. The issues of improving the geometric parameters of switches in order to improve the dynamic interaction of rolling stock and switch elements are given considerable attention abroad [3-5]. At the same time, insufficient attention is paid to the design of symmetric switches. The study and analysis of technical literature [6-12] show that the calculations of symmetrical multi-way switches are given very briefly, in some parts only fragmentarily and, as a rule, with references to the calculation method of ordinary switches that are not completely identical. Furthermore, it applies to the methods of designing structural units of symmetrical switches and the features of their design for various operating conditions, including the methods of determining the actual minimum groove between the frame rail and the diverted pivot.

The purpose and objectives of the research. The purpose of the article is to present a new method of calculations and design of symmetrical switches. The task of the research is to introduce the previously missing calculation of the minimum groove according to one of the two possible cases of the mutual location of the frame rail and the diverted pivot (respectively, the root distance is bigger than the stroke of the shutter – $U_n^0 > Sh_p$ and less – $U_n^0 < Sh_p$).

Research materials and methods. One of the two cases of mutual location of the frame rail and the diverted pivot is when the root distance is smaller than the stroke of the shutter at the switch drive ($U_n^0 < Sh_p$, Fig. 1).

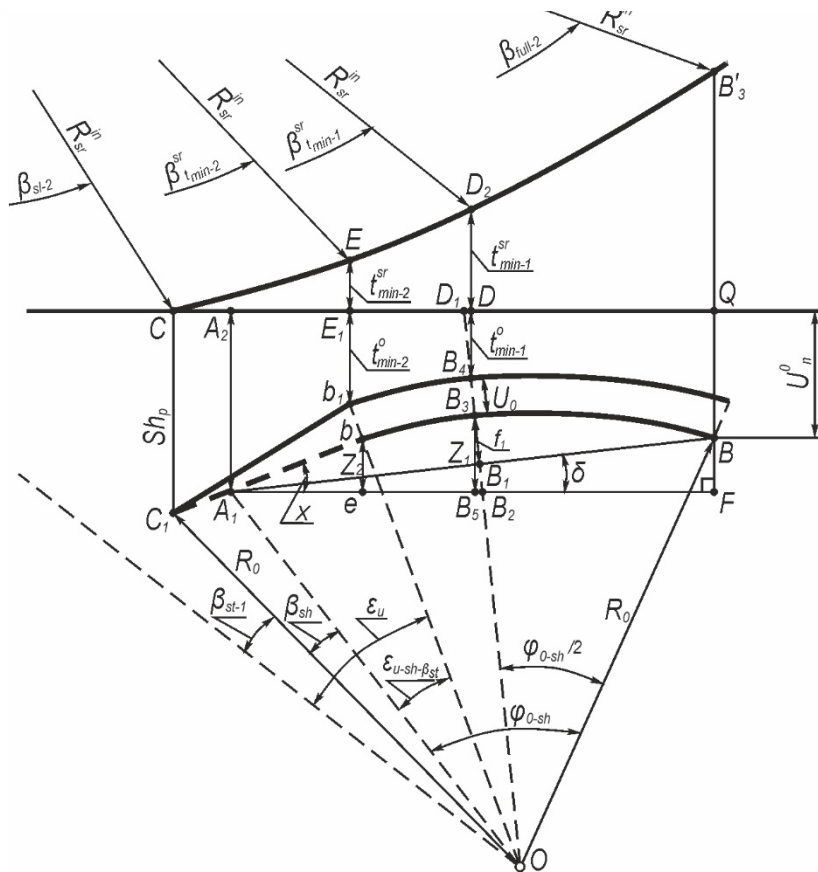


Fig. 1. Mutual arrangement scheme of the frame rail and the diverted pivot at $U_n^0 < Sh_p$

For the scheme, the minimum width of the groove between the frame rail and the pivot is determined between 2 competing sections – against the end of the horizontal groove of the pivot (point b_1), where the distance from the horizontal CQ to the working face of the frame rail (outside the groove of the pivot) will be the smallest (t_{min-2}^{sr}).

To determine the required values, it will be performed auxiliary construction in the scheme (Fig. 1). A chord A_1B between the root of the pivot (point B) and the attachment point of the switch rod to the pivot (in the point A_1) has been drawn.

The maximum arrow of the segment f_1 from the chord A_1B will be located on the perpendicular radius passing through the middle of the chord – the point B_7 . The distance between the points $B_4D_1 = t_1$ has been shown on the continuation of the perpendicular radius against the arrow, but the vertical distance between the points $B_4D = t_{min-1}^o$ will be the minimum vertical distance between the drawn pivot and the calculated horizontal CQ. In this section (against the point B_4), it is need to determine the

minimum distance $DD_2 = t_{mn-1}^{sr}$ from the frame rail to the calculated horizontal CQ . And after that, it is need to determine the total minimum groove between the diverted pivot and the frame rail in the first competing section – against the point B_4 – in the place of maximum pivot bending

$$(t_{min-1})^{vert} = t_{min-1}^0 + t_{min-1}^{sr} \quad (1)$$

The second competing minimum distance between the outer edge of the pivot and the frame rail (Fig. 1) must be determined against the point b_1 (the end of the horizontal groove of the pivot) in the section b_1E_1E

$$(t_{min-2})^{vert} = t_{min-2}^0 + t_{min-2}^{sr} \quad (2)$$

To calculate the minimum distance $b_1E_1 = t_{min-2}^0$ from the diverted pivot to the calculated horizon CQ , it will be performed the following auxiliary constructions in the scheme (Fig. 1):

- draw the radius Obb_1 from the center of the circle to the point b_1 – the end of the sharpener;
- draw also the radii OC_1 and OA_1 ;
- draw the horizontal A_1F to the intersection be and B_3B_5 with the vertical QBF at the root of the pivot;
- draw a chord A_1B and perpendiculars in the sections under consideration from the points b and B_3 to the horizontal A_1F .

The problem is solved in 4 stages.

1 stage. Definition t_{min-1}^0 in the section B_4D .

Find the value Sh_p of the distance between the points A_1 i A_2 using the formula [13, 14]

$$Sh_p = Sh + t'_{sh}, \quad (3)$$

where the thickness of the pivot against the arrow thrust t'_{sh} is determined [13, 14] by the formula

$$t'_{sh} = R_0 (\cos \beta_{st-1} - \cos (\beta_{st-1} + \beta_{sh})), \quad (4)$$

where the angle $\beta_{sh} = \frac{a}{R_0}$, $a=360$ mm [13, 14].

The value of the ordinate $BQ = U_n^0$ in the root of the pivot [13, 14] is defined according to the formula

$$U_n^0 = R_0 (\cos \beta_{st-1} - \cos \beta_{full-1}). \quad (5)$$

After that, it is necessary to compare the values of Sh_p and U_n^0 , in order to be sure of the initial condition in the problem solution according to the scheme of Fig. 1 for the case, when $U_n^0 < Sh_p$.

2. Find some auxiliary values for determining t_{min-1}^0 . Half the length of the chord A_1B marked as $B_1B = A_1B_1$ is determined [13, 14] by the formula

$$B_1B = A_1B_1 = R_0 \cdot \sin \frac{\varphi_{0-sh}}{2}. \quad (6)$$

The whole length of the chord

$$A_1B = B_1B + B_1A_1 = 2R_0 \cdot \sin \frac{\varphi_{0-sh}}{2}. \quad (7)$$

The maximum arrow of the segment from the chord A_1B is found [13, 14] according to the formula

$$f_1 = R_0 - B_1O. \quad (8)$$

The length of the perpendicular to the chord is found by

$$B_1O = R_0 \cdot \cos \frac{\varphi_{0-sh}}{2}. \quad (9)$$

The value of the segment BF is determined by the formula

$$BF = Sh_p - U_n^0. \quad (10)$$

The angle BA_1F marked $\angle \delta$ will be determined by

$$\frac{BF}{A_1B} = \sin \delta. \quad (11)$$

The length of the segment B_1B_2 is determined by

$$B_1B_2 = A_1B_1 \cdot \operatorname{tg} \delta. \quad (12)$$

The distance between the points B_2B_3 is found by

$$B_2B_3 = f_1 + B_1B_2 = f_1 + \left(R_0 \cdot \sin \frac{\varphi_{0-sh}}{2} \right) \cdot \operatorname{tg} \delta. \quad (13)$$

The vertical distance between the points B_3B_5 , marked $B_3B_5 = Z_1$ in Fig. 1 is by

$$Z_1 = B_3B_5 = B_2B_3 \cdot \cos \delta. \quad (14)$$

3. After that, determine the desired $t_{min-1}^0 = B_4D$ value in the section B_4D

$$t_{min-1}^0 = Sh_p - Z_1 - \frac{U_0}{\cos \delta}. \quad (15)$$

For further calculations, find the length of the segment B_4D_1

$$B_4D_1 = \frac{t_{min-1}^0}{\cos \delta}. \quad (16)$$

2 stage. Definition t_{min-2}^0 in the section b_1E_1 .

Find the auxiliary values. The angle OA_1b of the triangle OA_1b (Fig. 1) is defined by

$$\angle OA_1b = \frac{180^\circ - \varepsilon_{u-sh-\beta_{st-1}}}{2} = 90^\circ - \frac{\varepsilon_{u-sh-\beta_{st-1}}}{2}. \quad (17)$$

The angle $\angle bA_1e$, denoted as the angle x , is found by considering two triangles bA_1e i OA_1F

$$\angle x = \angle OA_1b - \angle FA_1O, \quad (18)$$

where

$$\angle FA_1O = \angle BA_1O - \angle \delta = 90^\circ - \frac{\varphi_{0-sh}}{2} - \delta, \quad (19)$$

i.e.

$$\angle x = 90^\circ - \frac{\varepsilon_{u-sh-\beta_{st-1}}}{2} - \left(90^\circ - \frac{\varphi_{0-sh}}{2} - \delta \right) = \frac{\varphi_{0-sh}}{2} + \delta - \frac{\varepsilon_{u-sh-\beta_{st-1}}}{2}. \quad (20)$$

The length of the perpendicular be , lowered from the point b to the horizontal A_1F and marked as $be = Z_2$ in Fig. 1, is determined by

$$Z_2 = A_1b \cdot \sin x. \quad (21)$$

2. After that, determine the desired value t_{min-2}^0 using the formula

$$t_{min-2}^0 = Sh_p - Z_2 - U_0 \cdot \cos x. \quad (22)$$

3 stage. Definition t_{min-1}^{sr} , t_{min-2}^{sr} i U_{sr} .

1. Determine all the abscissas along the calculated horizontal, which are necessary for finding the ordinates in the location of the working frame rail face relative to the horizontal CQ .

It is necessary to determine the abscissas: CE_1 , CD , CQ .

Determine the value CE_1 by the formula [15]

$$CE_1 = \lambda'_v = \sqrt{R_0^2 - (R_0 - B)^2} - A = \sqrt{2R_0B - B^2} - A. \quad (23)$$

Length $CD = 360 \text{ mm} + A_2D$.

$$A_2D = A_1B_3, \quad (24)$$

where

$$\begin{aligned}
 A_1 B_5 &= A_1 B_2 - B_2 B_5; \\
 A_1 B_2 &= \frac{A_1 B_1}{\cos \delta}; \\
 B_2 B_5 &= Z_1 \cdot \operatorname{tg} \delta; \\
 A_1 B_1 &= R_0 \cdot \sin \frac{\varphi_{0-sh}}{2}.
 \end{aligned} \tag{25}$$

Thence

$$A_2 D = A_1 B_5 = \frac{A_1 B_1}{\cos \delta} - Z_1 \cdot \operatorname{tg} \delta = R_0 \frac{\sin \frac{\varphi_{0-sh}}{2}}{\cos \delta} - Z_1 \cdot \operatorname{tg} \delta. \tag{26}$$

The abscissa $CQ = l'_0$ is the projection of the pivot onto the horizontal (Fig. 1) and is determined [15] by the formula

$$l'_0 = R_0 \cdot \sin \beta_{full-1} - R_0 \cdot \sin \beta_{st-1}. \tag{27}$$

So, all necessary abscissas are defined.

2. After determining the abscissas, find the necessary ordinates. The procedure for calculating is.

2.1. The ordinate U_{sr} – from the frame rail to the calculated horizontal CQ is determined by the formula

$$U_{sr} = BQ = R_{sr}^{in} \cdot \cos \beta_{st-2} - R_{sr}^{in} \cdot \cos \beta_{full-2}. \tag{28}$$

2.2. The first sought ordinate t_{min-1}^{sr} is determined by considering the equation of projections relative to the central angle $\beta_{t_{min-1}^{sr}}$. The central angle $\beta_{t_{min-1}^{sr}}$ against the desired ordinate t_{min-1}^{sr} at a point D_2 can be determined by

$$R_{sr}^{in} \cdot \sin \beta_{t_{min-1}^{sr}} - R_{sr}^{in} \cdot \sin \beta_{st-2} = CD. \tag{29}$$

From the formula (29), $\sin \beta_{t_{min-1}^{sr}}$ is determined, and then the angle $\beta_{t_{min-1}^{sr}}$. After that, determine the first sought ordinate t_{min-1}^{sr} in the section DD_2

$$t_{min-1}^{sr} = DD_2 = R_{sr}^{in} \cdot \cos \beta_{st-2} - R_{sr}^{in} \cdot \cos \beta_{t_{min-1}^{sr}}. \tag{30}$$

2.3. The second sought ordinate t_{min-2}^{sr} is determined in a similar way to t_{min-1}^{sr} , considering the equation of projections relative to the central angle $\beta_{t_{min-2}^{sr}}$. The central angle $\beta_{t_{min-2}^{sr}}$ against the desired ordinate t_{min-2}^{sr} at the point E is determined by

$$R_{sr}^{in} \cdot \sin \beta_{t_{min-2}^{sr}} - R_{sr}^{in} \cdot \sin \beta_{st-2} = CE_1. \tag{31}$$

Next, $\sin \beta_{t_{min-2}^{sr}}$ is determined firstly, and then the angle $\beta_{t_{min-2}^{sr}}$ itself by the formula (31).

After that, it is possible to determine the second desired ordinate t_{min-2}^{sr} in the section E_1E

$$t_{min-2}^{sr} = EE_1 = R_{sr}^{in} \cdot \cos \beta_{st-2} - R_{sr}^{in} \cdot \cos \beta_{t_{min-2}^{sr}} \quad (32)$$

4 stage. Determination of the required minimum width values of the gutter between the frame rail and the removed pivot in the calculated sections t_{min-1} and t_{min-2} , and the absolute minimum gutter $t_{min\ min}$.

Solving the problem of determining the minimum values of the gutter width between the frame rail and the diverted pivot for the calculation scheme of Fig. 1 is performed by methods of analytical geometry. For this, in addition to the main calculation scheme (Fig. 1), it must be analyzed additional calculation schemes in Fig. 2 and Fig. 3, which presents a detailed consideration of the grapho-analytical solution to the problem of finding the minimum dimensions of the gutter in the calculated sections B_4D_2 (against the maximum bend of the pivot) and b_1E (against the end of the pivot groove).

The minimum width of the gutter t_{min-1} (vertically) in the zone of maximum pivot bending (in the section B_4DD_2) is defined as the sum of the smallest distances from the calculated horizontal CQ to the diverted pivot, and to the frame rail in the section B_4DD_2 (Fig. 2)

$$(t_{min-1})_{vert} = t_{min-1}^0 + t_{min-1}^{sr} \quad (33)$$

The minimum width of the gutter t_{min-2} (vertically) against the end of the horizontal pivot groove (in the section b_1E_1E) is determined by the same method as the sum of the smallest distances from the calculated horizontal CQ to the diverted pivot, and to the frame rail in the section b_1E_1E (Fig. 3)

$$(t_{min-2})_{vert} = t_{min-2}^0 + t_{min-2}^{sr} \quad (34)$$

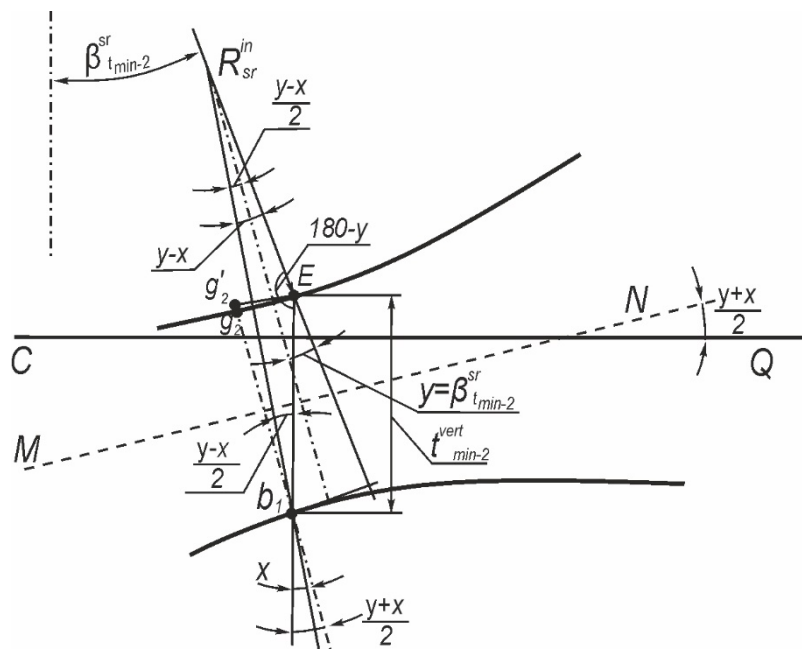


Fig. 2. Diagram for determining the minimum width of the chute t_{min-1} in the zone of maximum tip bending

$$\left. \begin{matrix} (t_{min-})_{norm} \\ (t_{min-2})_{norm} \end{matrix} \right\} \min(t_{min min})^{des}. \quad (37)$$

At the end, it should be compared the actual minimum design groove $t_{min min}^{des}$ with the minimum permissible groove $[t_{min}]_{accep} = 71$ mm [7], and when the inequality $t_{min min}^{des} > [t_{min}]_{accep}$ is fulfilled, it has been concluded that the safety conditions for the movement of wheel pairs are ensured. But, if the specified inequality is not fulfilled, it is need to choose other geometric parameters, first of all, change the length of the pivot, the radius of curvature or the starting angles of the symmetrical switch.

Conclusions. A refined method of designing a symmetric switch with curvilinear pivots has been proposed, which allows obtaining rational dimensional geometric parameters.

A new approach to the design of symmetric switches with multifactor initial conditions allows reducing such switch parameters as: theoretical and practical length, length of frame rail, length of connecting rails, and length of transfer curve.

Reducing the total length of switches will allow wider use in the compressed conditions of the track stations' development.

Optimum geometric parameters of symmetric switches will make it possible to reduce the cost of the construction in general by reducing its metal capacity while preserving the conditions for the safe movement of trains at the set speeds.

REFERENCES

1. Darenskyi O.M. (2008) Z'iednannia i skhreshchennia zaliznychnykh kolii [Connection and crossing of railroad tracks]. Kyiv: UkrDAZT [in Ukrainian].
2. Berezovyi M.I., Bozhko M.P., Mazurenko O.O., & Dorosh A.S. (2016) Elementy koliinoho rozvytku: pryklady ta zadachi [Elements of track development: examples and tasks]. Dnipropetrovsk: DNUZT im. akademika V. Lazariana [in Ukrainian].
3. Klauser, P.E. (1991). Assessing the benefits of Tangential-geometry turnouts. *Railway Track and Struct*, 1, 21-23.
4. Taylor, E.M. (1976). Innovations in frog and switch design. *Bull. Amer. Railway Eng. Assoc.*, 658, 652-664.
5. Plášek, O., Raif, L., Vukušić, I., Salajka, V., & Zelenka, J. (2019). Design of new generation of switches and crossings. Scientific Symposium: Future trends in civil engineering.
6. Danilenko, E.I. (2010). Zaliznychna kolia [Railway track]. Kyiv: Inpres [in Ukrainian].
7. Railway applications. Track. Acceptance of works Part 1: Works on ballasted track. Plain line, switches and crossings (2013). BS EN 13231-1:2013 from 31 May 2013. *The British Standards Institution: Published by BSI Standards Limited*.
8. Esveld, C. (2001). Modern railway track, 2nd editon. *Delft university of Technology*.
9. Ping Wang (2015). Design of High-Speed Railway Turnouts. *China: Southwest Jiao Tong University Press*.
10. Boiko, V., Molchanov, V., & Artiukhovych, T. (2017). Doslidzhennia znosostiikosti strilochnykh perevodiv dlia umov ekspluatatsii kyivskoho metropolitenu [Switch's wear-resistance investigation for operating conditions of kiev underground railway]. *Zbirnyk naukovykh prats Ukrainського derzhavnoho universytetu zaliznychnoho transportu - Collection of scientific papers of the Ukrainian State University of Railway Transport*, 169, 39-47 [in Ukrainian].
11. Xu, J., Wang, P., Wang, L., & Chen, R. (2016). Effects of profile wear on wheel-rail contact conditions and dynamic interaction of vehicle and turnout. *Advances in mechanical Engineering*, 8(1), 1687814015623696. <https://doi.org/10.1177/1687814015623696>.
12. Danilenko, E.I., Orlovsky, A.M., Kurhan, M.B. & Yakovlev V.O., (2012) Instruktisiia z ulashtuvannia ta utrymannia kolii zaliznyts Ukrainy [Instruction on arrangement and maintenance of the railway track of Ukraine CP-0269] Kyiv: TOV «NVP Polihrafservis» [in Ukrainian].
13. Danilenko, E.I., Boyko, V.D., Kurgan, M.B., Tverdomed, V.M., Molchanov, V.M., & Soroka O.O. et al. (2020). Proektuvannia i rozrakhunky konstruksij zaliznychnoi kolii [Design and calculations of railway structures]. Kyiv, *Hi-Tech Press Publ.* [in Ukrainian].
14. Oliinyk, O.A. (2021). Naukovi osnovy proektuvannia symetrychnykh strilochnykh perevodiv za umovamy bezpeky rukh kolis v mezhakh vidvedenykh vistriakiv [Scientific bases of designing of symmetrical turnouts under conditions of safety of movement of wheels within the limits of the allotted points]. *Candidate's thesis. Kyiv: DUIT.* [in Ukrainian].
15. Oliinyk, O.A. (2017). Osoblyvosti proektuvannia i rozrakhunkiv symetrychnykh strilochnykh perevodiv dlia mahistralnogo i promysloвого transportu [Features of design and calculation of symmetrical turnouts for mainline and industrial transport]. *Zbirnyk naukovykh prats UkrDUZT - Collection of scientific works of UkrDUZT*, 169, 54-63 [in Ukrainian].

¹Олійник Олена Андріївна*, ²Кушмар Леся Вікторівна

¹Кандидат технічних наук, доцент кафедри доцент кафедри «Залізнична колія та колійне господарство», Державний університет інфраструктури та технологій, вул. Кирилівська, 9, м. Київ, Україна, 04071, ORCID: <http://orcid.org/0000-0003-3362-8956>

²Кандидат філологічних наук, доцент кафедри «Іноземної філології та перекладу» Державний торговельно-економічний університет, вул. Кіото, 19, м. Київ, Україна, 02156, ORCID: <http://orcid.org/0000-0003-0407-6267>

Графоаналітичний метод визначення мінімального жолобу в корені вістряка симетричного стрілочного переводу

Стрілочні переводи є бар'єрним місцем в колії для призначення допустимих швидкостей руху поїздів по головних коліях, так як вони мають спеціальні конструктивні прилади для відгалуження руху від головної колії на другорядну. Симетричні стрілочні переводи мають ряд переваг порівняно із звичайними: при однаковій марці із звичайними переводами симетричні дозволяють реалізувати суттєво більші швидкості руху поїздів боковими коліями; при однакових радіусах перевідних кривих симетричні переводи мають меншу довжину; при збереженні довжини кривої і радіуса можна застосувати хрестовини з більшим кутом, ніж у звичайному переводі. Указані якості одиночних різносторонніх симетричних стрілочних переводів визначили їх сферу застосування. На коліях магістрального транспорту симетричні стрілочні переводи застосовуються в сортувальних парках станцій, а також в головних коліях коли потрібно досягти підвищених швидкостей руху на обидві бокові колії. Симетричні стрілочні переводи за своїм призначенням і конструкцією мають суттєві відмінності від найбільш розповсюджених звичайних стрілочних переводів, і тому дослідження даних конструкцій є важливими й актуальними. Тим більше, що таким дослідженням на українських залізницях було присвячено зовсім мало наукових праць.

Ключові слова: симетричні стрілочні переводи, проектування, мінімальний жолоб між вістряком і рамною рейкою.

Research of frogs point wear resistance in various conditions for transportation systems: main-line railway and subway

The experience of operating switches shows that load-bearing elements fail for two main reasons: defects and wear. The percentage failure of elements due to one reason or another depends on the operating conditions in which they operate. In this case, the most worn elements of switches are pointers and point frogs and their service life is determined by the amount of tonnage passed through them before reaching the standard values of wear or the appearance defects. The article is devoted to the study of wear resistance of switches operated in various transport systems, namely, mainline transport and subways. The article considers the issues of predicting the standard service life cross elements of typical angles using operational studies for subway conditions and a new theoretical methodology based on the analysis of switches withdrawn from operation after they reach the standard wear values for mainline transport. For analytical calculations, the method of modeling the interaction process and graph-analytical methods were used. As a result of the study, the analytical equations predictive curves for the formation vertical wear as a function of the passed tonnage for the switches point frogs operated on lines of mainline railway transport and the Kyiv subway were established.

Keywords: switch, intensity of traffic, passed tonnage, wear, defects, service life.

Introduction. Switches are complex and special track structures that operate under more difficult and challenging operating conditions than conventional railroad track. At the same time, switches entail technical, economic and operational costs, both in terms of capital expenditures and current maintenance. Therefore, there is a need to properly utilize the service life of switches and rationally predict their service life to plan their replacement.

Analysis of recent research and problem statement. A number of scientific schools have been studying the impact of operational factors and the differences in switch designs that affect the formation of wear and defects in metal elements, and, accordingly, the prediction of their "life cycle". Well-known scientific schools in Soviet Union include the St. Petersburg University of Railways under the leadership of Professors S. Amelin and V. Yakovlev and the VNIIZT (Moscow) scientific school under the leadership of B. E. Gluzberg and M. Putri.

In Ukraine, we can distinguish the scientific school DIIT, whose representatives include such well-known scientists as: M. Frishman, Y. Voloshko, O. Orlovsky and others. Since the late 1990s, the Kyiv Institute of Railway Transport has had a scientific school headed by Professor E. Danilenko, many of whose developments were directly related to the study of the operational characteristics of switches [1].

Different scientific schools have their own approaches to assessing the performance of structures and the impact of operating conditions on the service life of switches.

In particular, scientific developments under the leadership of Professor E. Danilenko take into account the operating conditions for a specific type and angle of switches through a generalized characterization of the track power load [1, 2].

As for foreign studies, they are mainly aimed at studying the life cycle of switches structures to reduce the cost of their design and maintenance; using artificial intelligence to develop an effective

system for early detection of wear of structural elements and prevent the development of switches defects at early stages [3-6].

The purpose and tasks of the study. The aim of the study is to predict the operation of switches under different operating conditions for different transport systems (e.g., mainline railways and subways), as well as to determine the standard service life of switch elements using experimental and theoretical methods.

To achieve this goal, the following was done. For mainline transport, the data set on switches of different types and angles withdrawn from service depending on the operating conditions was analyzed; a methodology was developed to determine the dependence of vertical wear of point frogs based on the data on their withdrawal according to the parameter of acquiring the maximum allowable wear limits and analytical dependencies of predicted wear for areas with different load stresses were established. For subway conditions was analyzed experimental studies of the operation of cross elements (wing rail, crossing wing rail) of typical switches.

Materials and methods of the study. The study of the elements of switches removed from the tracks on mainline railways (stock rail, point tongue, point frog) or switches in general was based on the data of the railways of "Ukrainian Railways" (UZ). We considered the switches (or their elements) of R65 and R50 types of 1/6, 1/9, 1/11, 1/18 angles removed from the tracks, which were operated on main, receiving and sending and other categories of tracks. In just three years (2016-2018), 12879 switches were withdrawn from service, including 9727 due to reaching the maximum wear limit and 3152 due to defects. The distribution of switches elements withdrawn from service (stock rail, point tongue, point frog) by wear and defectiveness is shown in Table 1 and Fig. 1.

Table 1. Quantitative distribution of switches withdrawn from service

Extraction parameter	Deleted item	Quantity of seized items, pcs.	Total number of items removed due to wear and defects	Total seized items
Wear	Stock rail	1412	9727	12879
	Point tongue	5677		
	Point frog	2638		
Defects	Stock rail	390	3152	
	Point tongue	619		
	Point frog	2143		

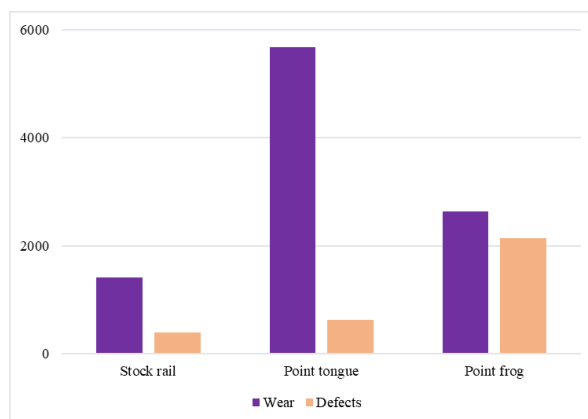


Fig. 1. Distribution of switch elements yield by wear and defects

From the analysis of the yield of switch elements by wear and defects, it can be concluded that the largest yield by wear for switch elements is made up of points - 58%, while crossbars accounted for 27% and frame rails 15% of the total. As for the withdrawn switch elements due to defects, most of them were withdrawn - 68%, while the number of points was 20% and the number of frame rails was 12%. In general, 76% of all switch elements were removed due to wear, and 24% due to defects.

To establish the main regularities of wear formation of switch elements for the Kyiv subway tracks, experimental studies were conducted to determine the vertical wear of switch elements under operating conditions (factors such as speed, load stress, and tonnage passed were taken into account). The study involved switches operated in underground and above-ground sections of the main subway tracks.

Out of the total number of switches operated on the main tracks, 37 switches (73% of the total number) were used for wear resistance studies.

Of these, 22 switches of the project 2497 type P50 of angle 1/9 (73%): Sviatoshyno-Brovarska line - 14 switches (88%); Kurenivsko-Chervonoarmiyska line - 8 switches (50%); Syretsko-Pecherska line - 15 switches of Project 2433 type P65 angle 1/9 (83%).

The selection of switches was performed in such a way that the studied structures differed in terms of the characteristics of the tonnage passed during operation, as well as had different operating conditions (the predominant direction of train movement, different speeds, etc.) The initial data for determining the operating conditions were the operational characteristics of the sections provided by the Service of Track, Tunnel Facilities and Buildings of the Kyiv Metro.

The maximum established speed V , km/h, on the transfers in the forward direction is up to $V_{max} = 80$ km/h, in the lateral direction up to $V_{max} = 40$ km/h.

At the time of the study, the load capacity, million tons per year, of the subway sections was as follows: on the Sviatoshynsko-Brovarska line - 25.23 million tons per year; on the Kurenivsko-Chervonoarmiyska line - 21 million tons per year; on the Syretsko-Pecherska line - 17.1 million tons per year.

The passed tonnage T from the moment of installation to the time of field surveys for P50 crossovers ranged from 13.1 to 133.4 million tons, and for P65 crossovers from 24.6 to 106.2 million tons.

There were 13 and 10 switches with the predominant direction of movement of the P50 and P65 types, respectively, and 9 and 5 switches with the predominant direction of movement were studied, respectively [7].

Service life of switches. The service life of pointers and point frogs is determined by the amount of tonnage passed through the switch until the vertical wear value regulated by [8] is reached or until defects or damage appear regulated by [9] that do not allow further operation of these structures in the track.

There are warranty and standard service lives of switches and crossovers.

The standard service life of pointers and point frogs is determined by the amount of tonnage passed through them - the standard operating time T_n until the value of the regulated vertical wear h_n of the structure the pointer elements (stock rail and point tongue) and the structure of the point frog elements (wing rail and crossing wing rail) for different operating conditions (axial loads, train speeds, load stress, etc.), and they also differ for different types and angles of switches.

The warranty service life of switches and crossovers is determined by the quality of manufacturing of structures at factories (under conditions of technically correct operation) and is set by agreement between the customer and the manufacturer. The warranty periods are measured by the guaranteed minimum tonnage passed through the pointers and point frogs or the guaranteed minimum service life (in years) of these elements in a trouble-free mode and mean that during the warranty period of a pointer or point frog (when operated in the track in accordance with the requirements of [10]) all structural elements must operate without breaks and other defects that disrupt their normal operation, while the dimensions of their vertical wear before the guaranteed minimum tonnage is passed must not exceed the maximum tolerances established by the same instruction.

The standard service life of pointers and point frogs is established by the criterion of reaching the value of their regulated vertical wear.

The warranty service life pointers and point frogs is established by the criterion of accumulation of defects on their structural elements: frame rails and tips (for switches) and crossing wing rails and wing rails (for point frogs).

Defects or damages are considered to be any inconsistencies of structural elements with the available regulatory and technical documentation for them. In particular, elements of switches with wear exceeding the permissible wear specified by the standards are considered defective [8, 10].

The processes and regularities of the formation of vertical wear of the rolling surface of switches' structural elements are well studied and repeatedly described in scientific papers [1, 2, 11, 13, 15]. It has been established that for rigid point frogs made of high manganese steel, the loss of element height during operation (total vertical wear) occurs as a result of several simultaneous processes: due to metal crushing as a result of high contact pressures, due to metal abrasion as a result of impact interaction between the wheels and the rolling surface, and due to structural settling during the period of track stabilization. Fig. 2 shows the graphical dependence of wear (h) on the value of the passed tonnage (T), which sufficiently reliably characterizes the physical nature of the wear phenomenon.

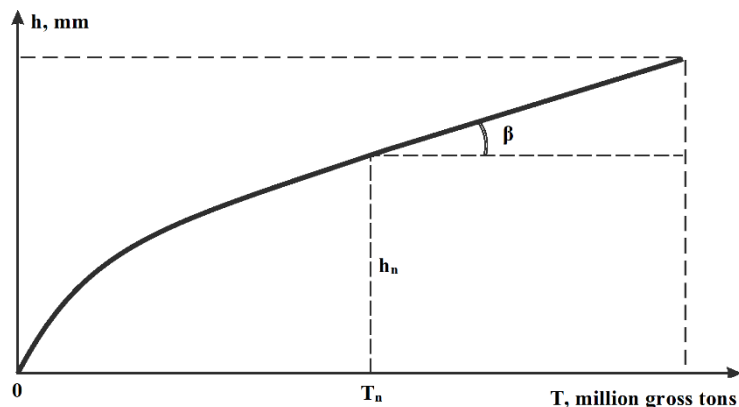


Fig. 2. Dependence of wear on passed tonnage

The formation of vertical wear (Fig. 2) is most closely described by the analytical dependence:

$$h = a \cdot \sqrt{T} + \epsilon \cdot T. \quad (1)$$

In expression (1), denoted:

T - is the tonnage passed through the switch structure element;

a i ϵ – are numerical coefficients that have specific values for each structure, location of the cross section on the cross elements, and operational factors.

Predicting the service life of switches depending on operational factors. In accordance with the methodology [1, 2], the formula for the dependence of wear on the passed tonnage (1) is adopted as the basic one, which allows predicting the standard service life of crossovers T_n depending on the standard wear value h_n and the type of curve from Fig. 2. The specific type of curve $h=f(T)$ (1) is determined by the coefficients "a" and "ε" of equation (1), which are responsible for the crushing and abrasion of metal in the total wear accumulation.

The methodology is based, firstly, on the general laws of the wear kinetics (h) of point frog depending on the passed tonnage (T) of equation (1); secondly, on determining the impact on wear of other operational factors, such as wheel loads P_i (and their spectrum), wheel diameters of rolling stock d_i , train speeds V_i (and their spectrum) and intensity of train traffic.

Using the basic formula (1) and solving it with respect to the value of the passed tonnage T , when substituting a specific value of the wear value h_n , Prof. E. Danilenko obtained a formula that allows predicting the standard service life of point frogs T_n depending on the standard wear value h_n .

$$T_n = \left(\frac{-a + \sqrt{a^2 + 4 \cdot \epsilon \cdot h_n}}{2 \cdot \epsilon} \right)^2, \quad (2)$$

where h_n – is the standard value of vertical wear for the structures under consideration, taken in accordance with [8].

Predicting the wear resistance of point frogs in subways. During the operational observations, when measuring the vertical wear of the rolling surface on the point frogs, we used standard measuring instruments used at the railroad for the current maintenance and inspection of the state of switches, namely "Puteyets" caliper (0.1 mm division price) - for measuring the vertical wear of the rolling surface of the whiskers and crossing wing rails; metal tape measure and metal ruler (1 mm division price) - for breaking down the sections in which wear measurements were performed. Measurements of the vertical wear of the whiskers and crossing wing rails were carried out in the cross-sections defined in [8].

Fig. 3 shows the field marking of cross-sections on the point frogs, which was carried out during the research in the subway tracks, in accordance with the scheme of Fig. 4 of measurements of vertical wear of switch's point frogs of types R50 and R65 of angle 1/9.

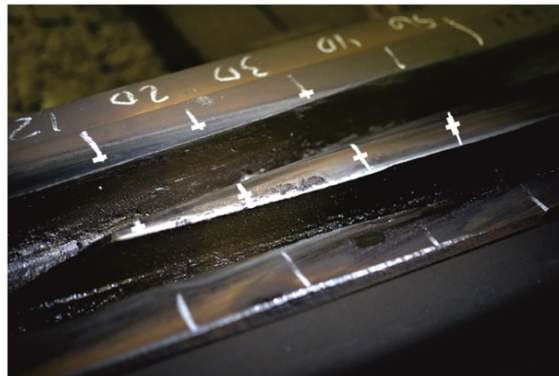


Fig. 3. Marking of cross-sections on point frogs in subway tracks in accordance with the measurement scheme on point frog of types R50 and R65 angle 1/9

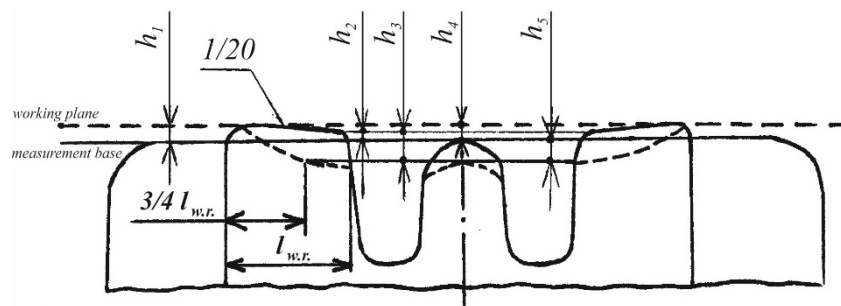


Fig. 4. Scheme for measuring the vertical wear of cross elements

In Fig. 4, we denote:

- h_1 – the design elevation of the wing rail above the design surface along the insertion line, mm;
- h_2 – design elevation at the point of wear measurement on the wing rail relative to the design surface, mm;
- h_3 – the amount of wear on the wing rail, mm;
- h_4 – design lowering of the crossing wing rail relative to the design elevation of the wing rail, mm;
- h_5 – design elevation of the wing rail, mm;
- $l_{w.r.}$ – width of the wing rail in the measured section, mm;
- 1/20 – slope of the wing rail.

According to this methodology, vertical wear was measured on all selected point frogs of switches laid on the tracks of the Kyiv subway for three branches.

The results of the actual values of wear of the wing rails and crossing wing rails at different values of the passed tonnage were processed by mathematical statistics in order to establish an analytical

dependence $h=f(T)$ according to expression (1) and determine the specific coefficients of this dependence. Based on the measurement results, graphical dependence curves were constructed $h=f(T)$ for each group of similar point frogs operating under the same operating conditions.

The approximation of wear curves allows using each specific curve on the projected service life of the cross elements in terms of wear, close to the acquisition of the permissible wear value (h_{permis}), and this allows, in turn, to determine the current value of cross elements wear in any period of operation, characterized by the passed tonnage T_i , as well as to determine or predict the service life of the structure (T_{norm}), both during the initial period of its operation in the track or during the design period of laying the switch, and at any stage of operation before reaching the limit parameters of wear.

Analytical curves of wear of point frogs were determined separately: for point frogs of R50 and R65 types; for whiskers and crossing wing rails; for all standard cross-sections.

The curves in the form (1) were approximated using the Maple software package. As a result, the equations characterizing the formation of vertical wear from $T=0$ to $T=140$ million gross tons for each selected group were obtained.

Taking into account that the wear rates of point frogs in accordance with the Instruction [8] are set by the wear of the crossing wing rails in a cross section of 40 mm, or wear on the wing rails in a cross section against 20 mm of the crossing wing rails, the article presents dependencies $h=f(T)$ for translations of types R50, R65 of 1/9 angles for wing rails and crossing wing rails in these cross sections at the predominant directions of movement (Figs. 5, 6).

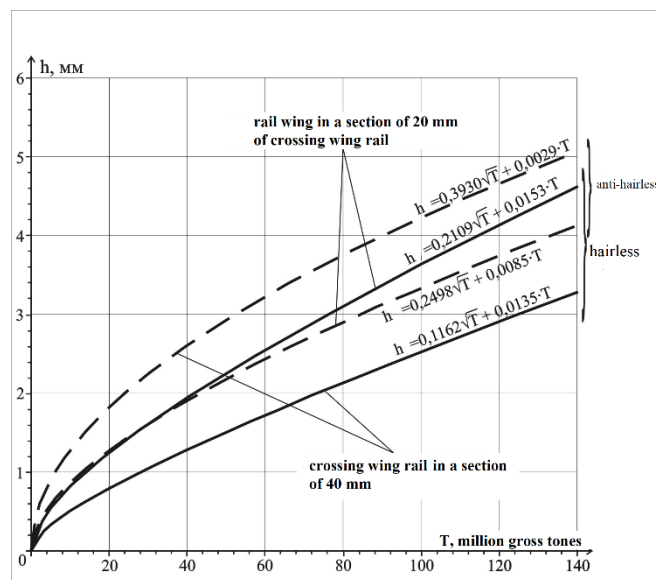


Fig. 5. Analytical dependences of wear crossing wing rails and wing rails of point frogs type R50 angle 1/9 in the main sections

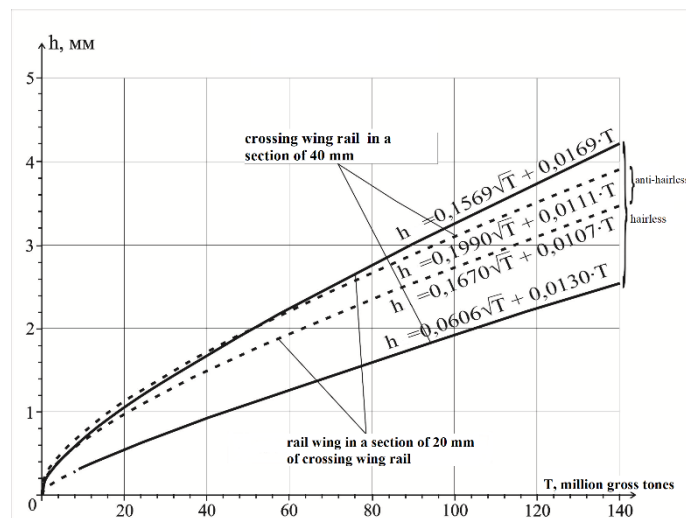


Fig. 6. Analytical dependences of wear crossing wing rails and wing rails of point frogs type R65 angle 1/9 in the main sections

A methodology for determining the service life of switch elements for mainline railroad conditions based on statistical data. In order to obtain objective information about the reliability of a product (in this case, a switch cross elements), statistical data on failures obtained during operation can be used. Having information on failures, it is possible to determine reliability indicators, identify deficiencies in the design of switches and their maintenance, determine the impact of operating conditions on reliability, predict the service life of the structure and, on this basis, take measures to improve track reliability.

Based on the fact that the service life of point frogs is the shortest among the elements of switches, the issue of predicting the service life of point frogs of conventional switches was considered. In this case, for each case of a withdrawn switch or its element, the data on withdrawn from service point frogs of different types and angles in terms of the permissible amount of wear and the presence of defects and for different categories of tracks, which are shown in Table 2, were considered.

Table 2. Quantity of crossing removed due to wear/defects

Elements of point frog	Type of point frog							
	R50				R65			
	1/18	1/11	1/9	1/6	1/18	1/11	1/9	1/6
MAIN TRACK								
Wing rail	-/-	14/8	4/6	-/-	18/10	87/543	63/73	-/-
Crossing wing rail	-/-	32/6	28/24	-/-	18/14	1086/822	327/104	-/-
ARRESTOR TRACK								
Wing rail	-/-	1/4	12/10	-/-	-/-	20/78	60/64	2/1
Crossing wing rail	-/-	20/16	54/36	1/3	-/-	258/137	384/106	15/2
OTHER TRACK								
Wing rail	-/-	-/2	17/3	-/3	-/-	2/4	-/6	-/3
Crossing wing rail	-/-	13/3	10/6	1/3	-/-	13/10	28/4	43/3

The quantitative distribution of extracted switch elements by wear and defects for different categories of tracks is shown in Fig. 7.

The most common types and angles of switches used on the main lines of Ukrainian railways are R65 type 1/11 and 1/9, which account for 94.7% of the total number of switches. Therefore, we consider these types and angles of switches.

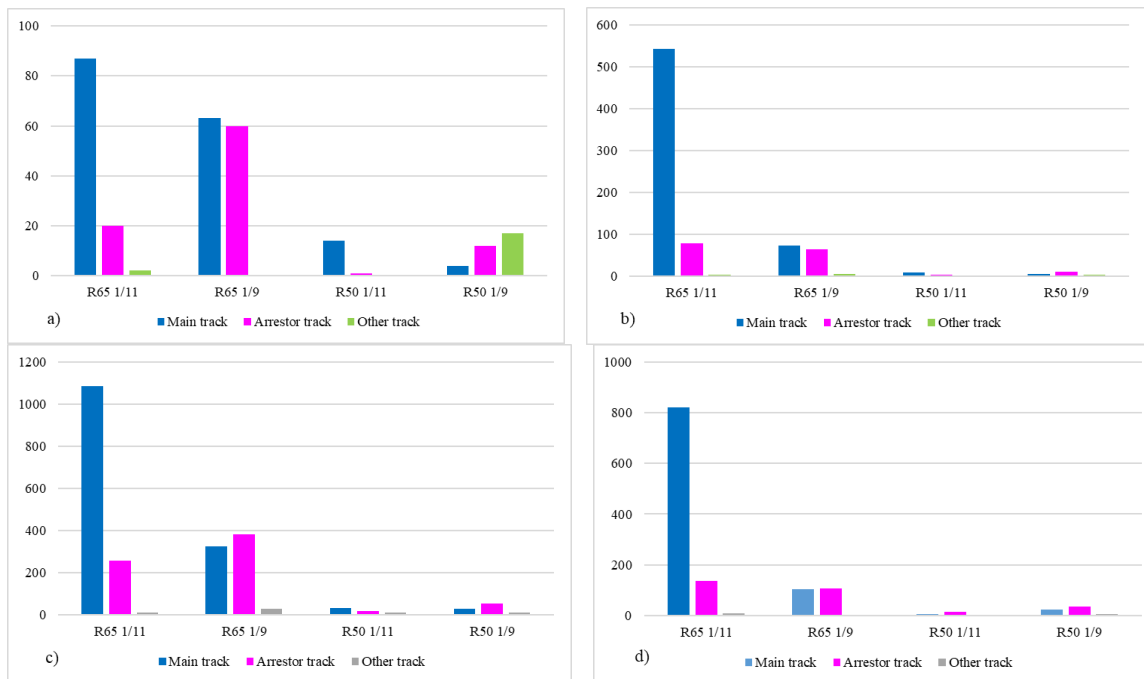


Fig. 7. Extracted point frogs according to wear and defects: a) – wing rail due to wear, b) – wing rail due to defects, c) crossing wing rail due to wear, d) – crossing wing rail due to defects

The distribution of switches within the established categories of tracks according to [13, 14] (by the indicator of load stress) is shown in Table 3 and Fig. 8, with the determined average values of load stress for each of the analyzed groups and the average values of the tonnage passed through the structure before their decommissioning.

Table 3. Distribution of switches within the established categories of tracks by load and tonnage throughput

Type and angles of switches	Gross-load intensity, mln gross ton-kilometers per km per year	Average gross-load intensity, mln gross ton-kilometers per km per year	Passed tonnage, mln gross tones			Quantity of switches, pcs.
			T_{min}	T_{max}	T_{mid}	
R65 1/11	> 80	97,8	51,1	421,4	167,9	11
	50,1-80	57,9	48,0	440,0	193,5	96
	30,1-50	38,7	20,7	482,0	231,1	303
	15,1-30	21,9	30,0	465,3	176,1	426
	5,1-15	10,4	11,5	445,4	159,1	215
	<5	2,7	3,1	209,7	92,0	93
	Total					1144

At the first stage, we analyze the entire data set in each group (in accordance with the established limits of load stress of the sections according to [13, 14]) of the removed cross elements by the vertical wear parameter (h) and determine the average value of the tonnage $T_{mid}^{(n)}$ before removal in each data set for the normalized wear value $h_{mid}^{(n)}$ according to [8], as shown in Fig. 9.

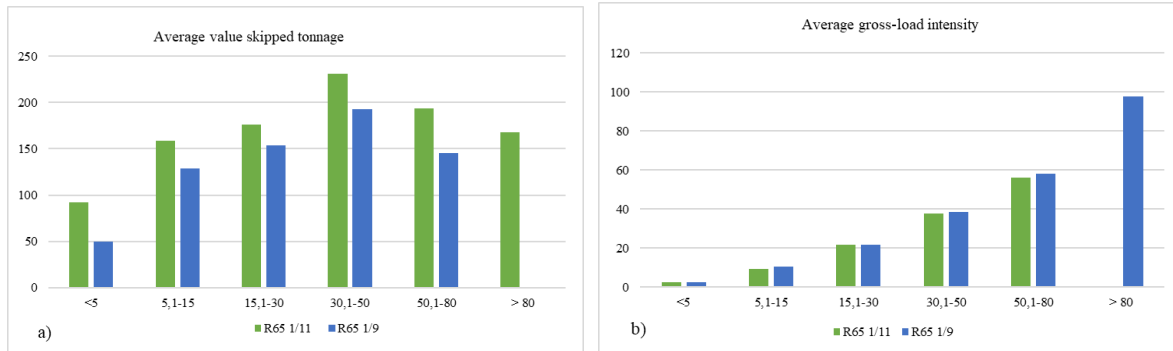


Fig. 8. Average values on switches of type R65 angle 1/11: a) passed tonnage b) gross-load intensity

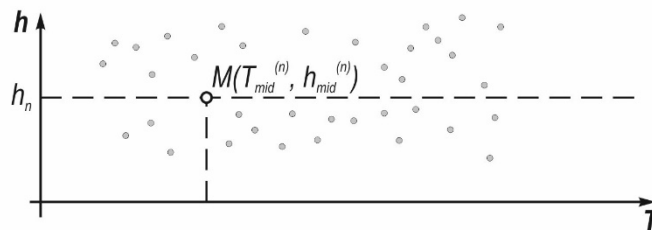


Fig. 9. Determination of average passed tonnage and average wear

The resulting (M) of the average standard tonnage in Fig. 10 is the point through which the analytical curve of the form (1) should pass. This point is different for each specific case, since areas with different load stresses are affected by different operating conditions.

From the analysis of equation (1) and Fig. 2, it follows that the 1st term of the equation ($a\sqrt{T}$) prevails to a greater extent in the area from the initial passed tonnage $T=0$ to the tonnage T_n^{mid} . We determine the forecast curve in the first approximation on the first (curved) section by expression (3), from where we find the coefficient "a1":

$$h_n = a_1 \cdot \sqrt{T_{mid}^{(n)}} \tag{3}$$

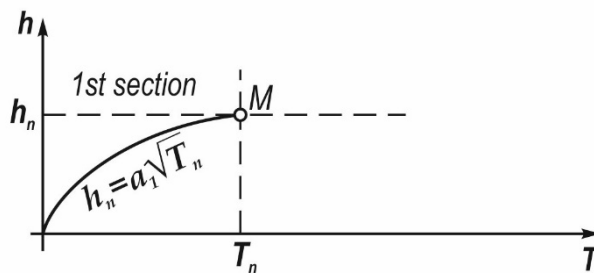


Fig. 10. Initial section of the wear curve

The greater the value of the average tonnage T_n^{mid} , the greater the influence of the second term of equation ($b \cdot T$), so in order to determine the slope of the straight section of the wear curve, we divide the data on the removal of point frogs into three sections: the first section from $T=0$ to T_n^{mid} , the second section from T_n^{mid} to T_2 , the third section from T_2 to $T_2=T_{max}$.

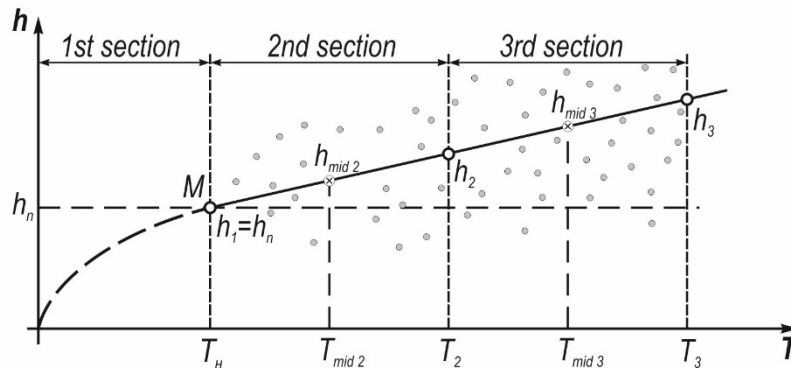


Fig. 11. Determining the slope of the straight section of the wear curve

At the next stage, we consider the area from $T_n = T_n^{mid}$ to $T_3 = T_{max}$. For this section, we determine the average value of the passed tonnage and the corresponding wear value h_2 , at which the point frogs were removed. On Fig. 11, we determine the average wear value h_{mid2} for the second section with coordinates T_{mid2} (Fig. 12); then we similarly determine h_{mid3} the average wear value for the middle of the third section with coordinates T_{mid3} and then connect the points M , h_{mid2} , h_{mid3} and get a straight line.

Next, using the diagram in Fig. 12, we determine the parameters of the line in the range from T_n to T_2 and transform equation (1) to obtain the equation of the straight branch of the wear curve:

$$h = k \cdot T_i + h_0, \quad (4)$$

where h_0 – initial ordinate of the line at tonnage $T=0$;

k – tangent of the slope of the line $k=tg\alpha$, which is determined from the following equation:

$$k = tg\alpha = \epsilon_1 = \frac{h_{mid3} - h_n}{l_2 + l_3 / 2}. \quad (5)$$

The same angle tangent is the coefficient "ε" from the original equation (1), i.e. $k=tg\alpha=\epsilon_1$.

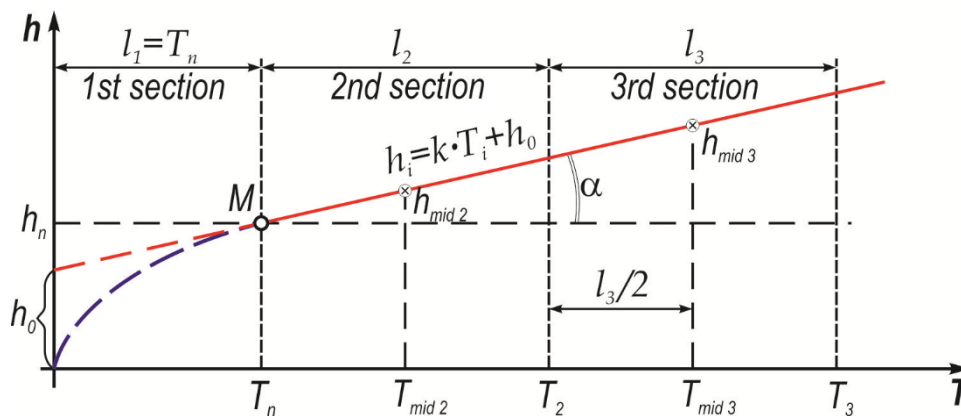


Fig. 12. Scheme for determining the equation of the straight section of the wear curve

Thus, the initial values of the coefficients "a₁" and "ε₁" from the original equation (1) are determined, which further need to be specified according to the following algorithm.

In the first approximation, the ordinate h'_0 is found by the equation:

$$h'_0 = h_n - \epsilon_1 \cdot T_n, \quad (6)$$

where ϵ_1 – is the coefficient of the right-hand side of equation (1), which is determined by equation (5).
The value h_0 is ultimately refined after determining the coefficient " ϵ_2 " by the expression:

$$h_0 = h_0'' = h_n - \epsilon_2 \cdot T_n, \quad (7)$$

where ϵ_2 – is the refined value of the coefficient of the right-hand side of equation (1), which is determined further by expression (14).

Let's move on to clarify the coefficients " a_1 " i " ϵ_1 ".

In the first approximation, the first term $h_n = a_1 \cdot \sqrt{T_n}$ of the general equation (3) is taken into account on the curved section of the wear curve, but in reality, the influence of the second term of the equation must also be taken into account in this section $\epsilon_1 \cdot T_n$. Therefore, it is necessary to determine the coefficient " a " in the second approximation, i.e., " a_2 ", which is determined as follows:

$$a_1 \cdot \sqrt{T_n} = a_2 \cdot \sqrt{T_n} + \epsilon_1 \cdot T_n. \quad (8)$$

From here we find the coefficient " a_2 ":

$$a_2 \cdot \sqrt{T_n} = a_1 \cdot \sqrt{T_n} - \epsilon_1 \cdot T_n, \quad (9)$$

$$a_2 = \frac{a_1 \cdot \sqrt{T_n} - \epsilon_1 \cdot T_n}{\sqrt{T_n}}. \quad (10)$$

On the other straight section of the wear curve, it is also necessary to take into account the influence of the first term of Equation (1). Therefore, first, according to the scheme of Fig. 12, we determine the ordinate h_{mid2} :

$$h_{mid2} = h_n + \epsilon_1 \cdot (T_{mid2} - T_n) \quad (11)$$

and taking into account the first term of equation (1), we rewrite equation (11) for the ordinate h_{mid2} as:

$$h_{mid2} = a_2 \cdot \sqrt{T_{mid2}} + \epsilon_2 \cdot T_{mid2}. \quad (12)$$

By equating expressions (11) and (12), we obtain the following:

$$h_n + \epsilon_1 \cdot (T_{mid2} - T_n) = a_2 \cdot \sqrt{T_{mid2}} + \epsilon_2 \cdot T_{mid2}. \quad (13)$$

Finally, by performing mathematical operations, we get a new refined value of the coefficient ϵ_2 , which is calculated by the equation:

$$\epsilon_2 = \frac{h_n + \epsilon_1 \cdot (T_{mid2} - T_n) - a_2 \cdot \sqrt{T_{mid2}}}{T_{mid2}}. \quad (14)$$

This will be the new refined value of the coefficient θ_2 , which should be used for the original equation of the wear curve (1). Next, it is necessary to consider the third section in the range from T_2 to $T_3=T_{max}$ and finally refine the coefficients " a_3 " and " θ_3 " using the same algorithm as above.

Using this algorithm, we analyzed the entire data set for the removed switches elements and established analytical equations for the predictive curves of vertical wear formation as a function of the passed tonnage for point frogs elements of R65 1/11 switches at different parameters of the load stress of sections (different categories of tracks), which are given in Table 4.

Table 4 – Equations of wear curves for switches point frogs of type R65 of angle 1/11 on reinforced concrete bars under different operating conditions

№ п/ п	Gross-load intensity, mln gross ton-kilometers per km per year	Average gross-load intensity, mln gross ton-kilometers per km per year	Average value of passed tonnage, T mln gross tones for $h_n=6$ mm	Wear curve equation $h=f(T)$
1	More than 80	96,9	168,0	$h = 0,322498 \cdot \sqrt{T} + 0.010833 \cdot T$
2	More than 50 up to 80 inclusive	57,9	194,0	$h = 0,28568 \cdot \sqrt{T} + 0.010417 \cdot T$
3	More than 30 up to 50 inclusive	38,7	231,0	$h = 0,22107 \cdot \sqrt{T} + 0.011429 \cdot T$
4	More than 15 up to 30 inclusive	21,9	176,0	$h = 0,398113 \cdot \sqrt{T} + 0.004082 \cdot T$
5	More than 5 up to 15 inclusive	7,7	159,0	$h = 0,421787 \cdot \sqrt{T} + 0.004286 \cdot T$
6	Up to 5 inclusive	2,7	92,0	$h = 0,56244 \cdot \sqrt{T} + 0.006579 \cdot T$

Conclusions. To conduct the study, we analyzed previous scientific works on the study of the formation of switches wear in various transport systems, namely in the conditions of main-line railways and subways. For the conditions of main-line railways, a new theoretical methodology was developed to establish the dependence of vertical wear for point frogs on the basis of statistical data on their removal obtained during operational observations of the parameter of reaching the maximum permissible wear limits. As a result, analytical dependencies of the predicted wear were established for sections with different load stresses, i.e., for different categories of tracks.

For subway operating conditions, the difference in the operation of switches is mainly in traffic intensity, load stress, and tonnage passed. It was found that the use of previous studies performed for mainline transport is incorrect for subway conditions. Therefore, the operational studies carried out in real conditions made it possible to obtain specific equations characterizing the formation of vertical wear depending on the passed tonnage in the range from $T=0$ to $T=40$ million gross tons for each selected group.

REFERENCES

- Danilenko, E. I., & Karpov, M. I., & Boiko, V. D. (2003) Vyznachennia strokiv sluzhby strilochnykh perevodiv [Determination of the service life of switches]. *Visnyk Dnipropetrovskoho natsionalnoho universytetu zaliznychnoho transportu imeni akademika V. Lazariana*, 2, 138-146. Dnipropetrovsk: DNUZT [in Ukrainian].
- Danilenko, E.I. (2010). Zaliznychna kolia. Ulashtuvannia, proektuvannia i rozrakhunky, vzaïmodiia z rukhomym skladom [Railway track. Arrangement, design and calculations, interaction with rolling stock]. Kyiv: Inpres [in Ukrainian].
- Mundrey, J. S. (2019). Railway Track Engineering. *India, New Delhi: Tata McGraw-Hill Education Private Limited*. Retrieved from <https://www.pdfdrive.com/railway-track-engineering-e158101672.html>
- Nissen, A. (2009). LCC analysis for switches and crossings: a case study from the Swedish Railway Network. *International Journal of COMADEM*, 12(2), 10-19.
- Najeh, T., Lundberg, J., & Kerrouche, A. (2021). Deep-learning and vibration-based system for wear size estimation of railway switches and crossings. *Sensors*, 21(15), 5217. <https://doi.org/10.3390/s21155217>.

6. Ghodrati, B., Ahmadi, A., & Galar, D. (2017). Reliability Analysis of Switches and Crossings: A Case Study in Swedish Railway. *International Journal of Railway Research*, 4(1), 1-12. <https://doi.org/10.22068/IJRR.4.1.1>.
7. Vstanovlennia umov ekspluatatsii reioik i strilochnykh perevodiv na koliaakh Kyivskoho metropolitenu [Establishment of operating conditions for rails and switches on the tracks of the Kyiv subway] (2015). Technical conditions of operation *from 2015*. Kyiv: KP «Kyivskiy metropoliten», [in Ukrainian].
8. Danilenko, E.I., & Orlovsky, A.M., & Kurhan, M.B. & Yakovlev V.O., (2012) Instrukttsiia z ulashtuvannia ta utrymannia kolii zaliznyts Ukrainy [Instruction on arrangement and maintenance of the railway track of Ukraine CP-0269] Kyiv: TOV «NVP Polihrafservis» [in Ukrainian].
9. Danilenko E.I. & Orlovskiy A.M. (2000) Klasyfikatsiia i kataloh defektiv i poskodzhen elementiv strilochnykh perevodiv ta reioik zaliznyts Ukrainy [Classification and catalogue of defects and damages of elements of switches and rails of Ukrainian railways CP-0060]. Dnipropetrovsk: Art-Pres.
10. Verkhnia budova kolii. Strilochni perevody. Pravyla vyznachennia normatyvnykh ta harantiinykh strokiv sluzhby u riznykh ekspluatatsiinykh umovakh [The upper structure of the track. Switches. Rules for determining the normative and warranty service life in different operating conditions.]. (2022). STP 06-041:2022 from 12th January 2022. Kyiv: Standard of Joint Stock Company «Ukrainian Railways» [in Ukrainian].
11. Boiko, V. D., & Molchanov, V. M., & Artiukhovych, T. D. (2017) Doslidzhennia znosostiikosti strilochnykh perevodiv dlia umov ekspluatatsii kyivskoho metropolitenu [Switch's wear-resistance investigation for operating conditions of Kiev underground railway]. *Zbirnyk naukovykh prats Ukrainського derzhavnoho universytetu zaliznychnoho transportu – Collection of scientific works of Ukrainian State University of Railway Transport*, 169, 39-47 [in Ukrainian].
12. Boiko, V. D., & Molchanov, V. M., & Soroka, O. O. (2018) Vstanovlennia normatyviv strokiv sluzhby strilochnykh perevodiv dlia umov ekspluatatsii kyivskoho metropolitenu [Establishment of standards switch's wear-resistance for operating conditions in Kiev underground]. *Zbirnyk naukovykh prats Ukrainського derzhavnoho universytetu zaliznychnoho transportu – Collection of scientific works of Ukrainian State University of Railway Transport*, 178, 59-67 [in Ukrainian].
13. Sporudy transportu. Zaliznytsi kolii 1520 mm. Normy proektuvannia [Transport facilities. Railways of 1520 mm gauge. Design standards]. (2018). DBN V.2.3-19:2018 from 1st April 2018. Kyiv: Derzhavni budivelni normy [in Ukrainian].
14. Sporudy transportu. Klasyfikatsiia, periodychnist pryznachennia ta provedennia planovo-zapobizhnykh remontiv zaliznychnykh kolii [Structures of transport. Classification, frequency of appointment and scheduled preventive maintenance of railway tracks]. (2020). DSTU ISO 9002-2020 from 1st July 2021. Kyiv: Derzhstandart Ukraine [in Ukrainian].
15. Sait zhurnalu «Zaliznychnyi transport Ukrainy» [Site of journal «Railway Transport of Ukraine»]. <http://ztu.1520mm.com/> [in Ukrainian].

УДК 625.1:621.153

Ольга Сорока^{1*}

¹Старший викладач, кафедра залізничної колії та колійного господарства, Державний університет інфраструктури та технологій, вул. Кирилівська, 9, м. Київ, 04071, Україна. ORCID: <https://orcid.org/0000-0002-8746-0805>

* Автор, відповідальний за листування: soroka_oo@gsuite.duit.edu.ua

Дослідження зносостійкості хрестовин в різних умовах експлуатації для транспортних систем: магістральних залізниць та метрополітену

Досвід експлуатації стрілочних переводів показує, що несучі елементи виходять з ладу з двох основних причин: дефекти та знос. Відсоткове співвідношення виходу елементів по тим чи іншим причинам відбувається залежно від умов експлуатації, в яких вони працюють. При цьому найбільше зношуються з елементів стрілочних переводів стрілки та хрестовини, а строк їх служби визначається за кількістю пропущеного по ним тоннажу до досягнення нормативних значень зносу або появи дефектів. Стаття присвячена дослідженню зносостійкості стрілочних переводів, які експлуатуються в різних транспортних системах, а саме: магістрального транспорту та метрополітенів. Розглядаються питання щодо прогнозування нормативних строків служби елементів хрестовин типових марок за допомогою експлуатаційних досліджень для умов метрополітенів та нової теоретичної методики, яка основана на аналізі вилучених з

експлуатації стрілочних переводів по досягненню ними нормативних значень зносу для умов магістрального транспорту. Для аналітичних розрахунків використовувався метод моделювання процесу взаємодії та графоаналітичні методи. В результаті дослідження були встановлені аналітичні рівняння прогнозних кривих формування вертикального зносу, як функції пропущеного тоннажу для хрестовин стрілочних переводів, які експлуатуються в головних коліях магістрального транспорту залізниць та Київського метрополітену.

Ключові слова: стрілочний перевід, вантажонапруженість, пропущений тоннаж, знос, дефекти, строки служби

Valerii Samsonkin¹, Iryna Biziuk^{2*}

¹Doctor of technical science, Full Professor The department of process control traffic State University of Infrastructure and Technology Ogienska str. 19, Kyiv, 03049, Ukraine, ORCID: <https://orcid.org/0000-0002-1521-2263>.

²Iryna Biziuk, Senior Lecturer at computer and control systems department, Ukrainian State University of Railway Transport Feuerbach Square 7, 61050, Kharkiv, Ukraine, ORCID: <https://orcid.org/0000-0002-6458-5701>

*Corresponding author: iryna.biziuk1@gmail.com

Development of the concept of simulation modeling of the ecological situation based on the theory of self-organization

The article is devoted to the development of a concept of simulation of the environmental situation based on the theory of self-organization. The trend of increasing temperature and sea level due to an increase in the level of greenhouse gases in the Earth's atmosphere is global. This indicates the need to predict the development of the environmental situation in order to inform the population about possible disasters for preparing people's responses, resettlement planning, psychological adaptation. To predict the environmental situation as a result of accidents and disasters, including in rail transport, an analysis apparatus for possible situations is proposed with the aim of developing recommendations for their prevention. An environmental simulation model based on the theory of self-organization was chosen as the apparatus of research. It is based on the processes of mutually agreed relations, as a result of changes in two species of wildlife (object and environment), leading to the formation of a certain orderliness of these relations. Interaction of this kind occurs in the direction of achieving the existing equilibrium state or the formation of a new balance.

Keywords: simulation model, environmental situation, theory of self-organization, expert assessment, equilibrium state, knowledge base.

Introduction. To predict the environmental situation as a result of accidents and disasters, and not least in railway transport, a theoretical study of possible situations and means of their prevention is proposed using a simulation software model built on the basis of the theory of self-organization.

Justification of relevance. The 26th Conference of the UN Framework Convention on Climate Change (COC-26) was held in October-November 2021 [1].

It was called "the last chance to agree on measures that will slow down the process of global warming on the planet." Currently, 197 countries and one intergovernmental association - the European Union - are parties to the Convention.

This is the largest conference in this field in recent years. If in the zero years of the 21st century the world was faced with climate change, today it lives in an emergency mode. The decade of 2009-2019 became the hottest since the beginning of keeping relevant statistics.

According to the Paris Agreement, its participants agreed to update their plans for reducing greenhouse gas emissions every five years. However, this was not fully implemented.

The UK is pushing for a deal that would "make lignite and coal a thing of the past" and proposes to phase out internal combustion engine cars by 2040. Another direction of investment should be the work to prevent deforestation on Earth. The US and China have already pledged to become climate neutral by mid-century.

Most of the responsibility for greenhouse gas emissions lies with the rich, industrialized countries of the world.

More and more of the world's industrialized nations are committing to transform their economies in such a way that they become carbon-neutral in the next 10-30 years. But if CO₂ emissions stabilize in Europe and North America, they continue to grow in Asia and Africa. Fig. 1 shows how intensive the economic turnaround in these regions must be in order to achieve the goal of climate neutrality.

But the absolute amount of CO₂ emissions is not the only important indicator. After all, the population of the planet is growing, especially on the Asian continent, and the increase in the number of its inhabitants means an increase in consumed resources. If we correlate CO₂ emissions with the population, it turns out (Fig. 2) that the ranking of countries with the vast majority of emissions is led by the USA, Australia, Russia, Saudi Arabia, Oman, Qatar and Mongolia.

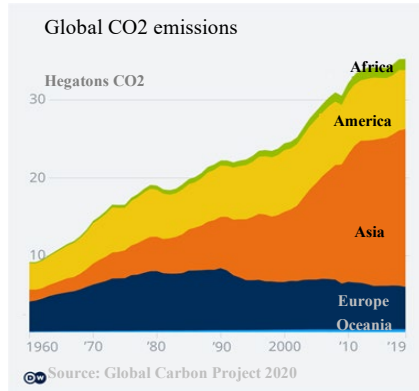


Fig. 1. Global CO₂ emissions

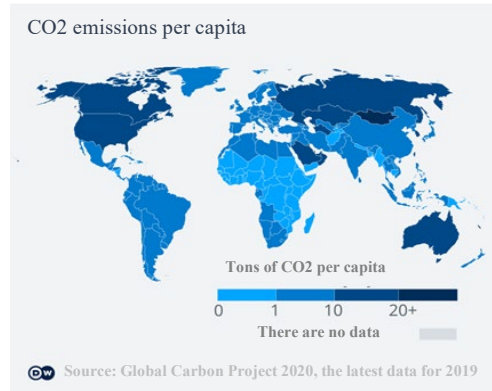


Fig. 2. CO₂ emissions per capita

The economic power of the state and CO₂ emissions are closely related (Fig. 3), so it is not surprising that the industrial sector is responsible for the largest share of the total volume of greenhouse gases (35%).

Deforestation has been steadily increasing over the past two decades. The first places according to this indicator are occupied by Russia, Brazil and the USA. However, compared to the period of 1990-2000, the pace of this phenomenon has somewhat slowed down. (Fig. 4). Deforestation is problematic not only because it releases CO₂ previously stored in soil and trees into the atmosphere: forests and soil are powerful sinks of carbon from the atmosphere, making them a critical tool in the fight against climate change.

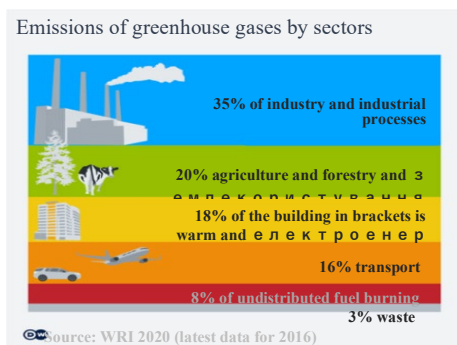


Fig. 3. Emissions of greenhouse gases

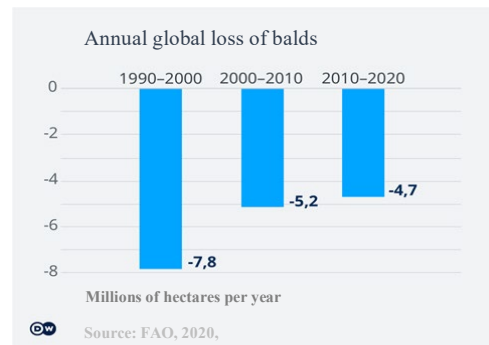


Fig. 4. Annual global loss of bald spots

Since the beginning of the industrialization era, CO₂ emissions from burning fossil fuels have continued to rise. At first, this was a big problem: from every ton of CO₂ produced by humans, carbon dioxide was absorbed by natural "carbon sinks" - forests and oceans. However, later on, man began to

produce much more CO₂ and other greenhouse gases than the amount that the planet's ecosystems could naturally absorb. As a result, the amount of CO₂ that remains "locked" in the atmosphere is steadily increasing (see the red area on the graph - Fig. 5).

The increase in the amount of CO₂ in the Earth's atmosphere creates a kind of greenhouse effect: sunlight and heat penetrate inside, but cannot go back out. Thus, the planet is getting warmer. Compared to the average indicators of the 20th century, the global temperature rose by one degree Celsius - it increased especially intensively during the last five years (Fig. 6).

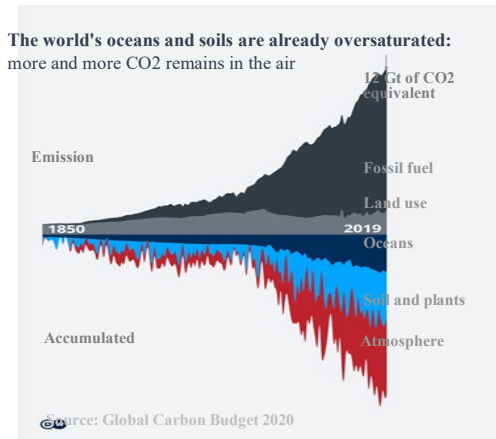


Fig. 5. Concentration of greenhouse gases

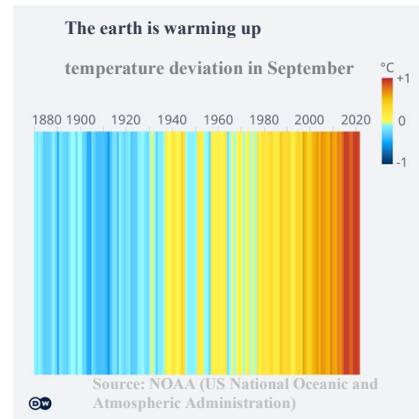


Fig. 6. Gradient of warming of the Earth's surface

A warming of one degree on the global average means radical changes at the local level. Warming is calculated from temperature deviations across the planet – extreme heat and extreme cold balance each other in different places.

Among the most obvious consequences of rising temperatures is a rise in the level of the world's oceans, as the melting of glaciers and ice in the mountains increases the amount of water.

According to NOAA - the US state agency for climate research - over the last 140 years, the average level of the world ocean has risen by almost 25 cm. A third of this increase has occurred in the last 25 years. The rise in the level is observed all over the world, but this process is especially fast in the Arctic, where the temperature is rising much faster than in other regions. Even more, it accelerates the property of water to expand when heated.

Formulation of the problem. The analysis shows that the tendency to increase the temperature and level of the World Ocean due to the increase in the level of greenhouse gases in the Earth's atmosphere has a global character. However, the implementation of the trend has regional features [2,3]. This indicates the need to forecast the development of the ecological situation in certain regions in order to inform the population about possible cataclysms for the preparation of people's response, resettlement planning, and psychological adaptation[4-7].

Various models (including ecological ones) built on the basis of the theory of self-organization are an effective research apparatus for solving forecasting tasks [8-10].

Types of models of ecological relationships. The basis of the proposed model is the processes of mutually determined relations as a result of the change of two species (sets) of living nature and, which lead to the formation of a certain orderliness of these relations [11].

At the same time, two assumptions were made:

a) each element has a field of interaction, within which changes are made to system-forming relationships;

b) system-forming relations of steel, for which a continuous compensatory flow is necessary.

This process can proceed to a certain limit, as it approaches the limit of the activity of the 1st set. This is due to the presence of the substance and energy necessary for existence in the incoming flow of the environment and the state of the 2nd set, which functions due to the results of the 1st set. Interaction of this kind occurs in the direction of achieving the existing equilibrium state or forming a new equilibrium.

At the heart of the process of inclusion or exit from the active state of elements are competitive relationships that are revealed; in intensifying their activities and suppressing competitors [6, 12].

The interaction of two sets can be described by a system of differential equations with respect to their number

$$\begin{cases} \frac{dN_1}{dt} = (\lambda_1 - \mu_1 \cdot N_1 - \nu_1 \cdot N_2) \cdot N_1; \\ \frac{dN_2}{dt} = (\lambda_2 - \mu_2 \cdot N_2 - \nu_2 \cdot N_1) \cdot N_2, \end{cases} \quad (1)$$

where the coefficients:

in the 1st set of elements with the previous properties:

- promotes the growth of elements;
- prevents the growth of similar elements;
- prevents the growth of elements of the 2nd set;

in the 2nd set of new elements:

- promotes the growth of elements,
- hinders the growth of similar elements,
- hinders the growth of the elements of the 1st set.

By changing the values of the parameters of the initial set of elements, all possible forms of relationships between two sets can be described by nine equations that reflect the sequence of transition from one state to another, generating a certain cycle in the phase space.

Competing relationships were considered for two sets of elements located in the same environment. Without violating generality, these considerations can be extended to the case of n sets.

The resulting system is a Volterra model of the "competition" type [13, 14].

Naturally, assumptions are made regarding the integrality of solutions and restrictions.

Questions arise: are such interactions possible, or will elements with new qualitative characteristics be replaced by the previous ones? If possible, in what proportion can they exist?

Let us analyze solutions (1) from the point of view of finding equilibrium stationary solutions with an analysis of the stability of these solutions. This system does not have direct analytical solution methods, however, it can be fully characterized using the phase space method on the plane in coordinates (N_1, N_2) .

The equilibrium stationary state is realized when

$$\frac{dN_1}{dt} = \frac{dN_2}{dt} = 0. \quad (2)$$

Then from (1)

$$\begin{cases} (\lambda_1 - \mu_1 \cdot N_1 - \nu_1 \cdot N_2) \cdot N_1 = 0, \\ (\lambda_2 - \mu_2 \cdot N_2 - \nu_2 \cdot N_1) \cdot N_2 = 0, \end{cases} \quad (3)$$

All cases of invariant conditions of the process ($\lambda_1, \lambda_2, \mu_1, \mu_2, \nu_1, \nu_2 = const$) can be obtained analytically. In the general case, invariance leads to the dominance of that process, which will have a larger ratio of the "increase in activity" coefficient to the "energy consumption" coefficient.

The effect of competing relations, arising as a result of self-limitation in the process of increasing the number of elements of the same type, can lead, depending on current conditions, either to the complete displacement of some elements by others, or to an equilibrium state with different quantitative ratios.

Of particular interest are the equilibrium states. They are largely determined by the behavior of the coefficients λ_i, μ_i, ν_i , and the stability of equilibrium relations will generally depend on their constancy. Let us assume that each element from a homogeneous population is in a certain state of active functioning or recovery. Consequently, such a state will already affect their non-equivalence with respect to any process, and affect the value of competing coefficients.

In this case, the manifestation of two opposite forms of competing relations is possible:

a) "positive" - when the achievement of a dominant position is carried out by increasing the activity of the elements of each of the sets. This leads to a faster consumption of the potential reserve, and if the required result is not achieved during the time interval of increased activity, then the dominant position is lost;

b) "negative" - when the preservation of a dominant position is achieved by actively reducing the possibility of a competing system.

In practice, these forms are analogues of positive and negative feedback.

In real conditions, both mechanisms of competitive relationships are used with the predominance of the type that allows minimizing the energy expenditure to achieve a dominant position. The adequacy of adaptive activity plays a significant role in maintaining the dominant position. When it coincides, the dominant is strengthened, and competitors are even more suppressed, and when it does not match, the dominant is weakened, and now the competing set occupies a dominant position.

Such a periodic change in the dominant position affects the value of the coefficients of intra- and inter-group competition, and, consequently, leads to a change in the equilibrium state of their numbers. This change will carry out fluctuations in a certain area, the boundaries and stability of which will depend on the change in the indicated coefficients.

According to the theory of similarity and dimensionality of H. Galileo, mathematical equations follow values or ratios. And operate with the terms: "how many times", %, trend. This more obviously characterizes the results, because absolute numbers can be converted to a dimensionless form, that is, when the variables of the equations take a value less than one, and strictly speaking - in modulus less than one. There are purely rational explanations for this. When it comes to simulation statistics, it is better to move from absolute values to relative values.

To convert the equation with the absolute variable X to the dimensionless form x , we use the formula:

$$x = \frac{X - X_{\min}}{X_{\max} - X_{\min}}, \quad (4)$$

where X_{\max} and X_{\min} the maximum and minimum value of X , respectively.

We will show the procedure for transforming the model "Competition: mutually suppressive competition (-,-)" (the first model into a dimensionless form. We define the dimensionless variables of the mathematical model (1) for N_1 and N_2 , respectively, (4):

$$n_1 = \frac{N_1 - N_{1\min}}{N_{1\max} - N_{1\min}}, \quad n_2 = \frac{N_2 - N_{2\min}}{N_{2\max} - N_{2\min}}. \quad (5)$$

Assume without loss of generality $N_{1\min} = N_{2\min} = 0$ and $N_{1\max} = N_{2\max} = N_{\max}$.

Then the formula (5) will have the form

$$n_1 = \frac{N_1}{N_{\max}}; \quad n_2 = \frac{N_2}{N_{\max}} \tag{6}$$

From (6) it is obvious that $n_1, n_2 \in [0,1]$ and

$$N_1 = n_1 \cdot N_{\max}, \quad N_2 = n_2 \cdot N_{\max}, \tag{7}$$

Substituting (7) into the equation for model 1, we obtain

$$\begin{cases} \frac{d(n_1 \cdot N_{\max})}{dt} = (\lambda_1 - \mu_1 \cdot n_1 \cdot N_{\max} - \nu_1 \cdot n_2 \cdot N_{\max}) \cdot n_1 \cdot N_{\max}; \\ \frac{d(n_2 \cdot N_{\max})}{dt} = (\lambda_2 - \mu_2 \cdot n_2 \cdot N_{\max} - \nu_2 \cdot n_1 \cdot N_{\max}) \cdot n_2 \cdot N_{\max}. \end{cases} \tag{8}$$

By making simple transformations and labeling

$$\mu_i \cdot N_{\max} = \mu'_i, \quad \nu_i \cdot N_{\max} = \nu'_i, \quad (i=1,2). \tag{9}$$

We will get the mathematical model "Competition: mutually overwhelming competition (-,-)" in dimensionless form

Carrying out similar transformations with all other options of interaction models from table.1, after transforming them into a dimensionless form, we will obtain mathematical models of interaction in a dimensionless form, as shown in table.1.

We present in Table 1 a list of models of different modes of interaction of two self-organizing sets, with an indication of the effect of the number of one species on the rate of change in the number of another.

Table 1. Types of self-organized models of joint interaction in dimensionless form

Type of interaction	Influence		Mathematical model
	2nd species on the 1st	1st species on the 2nd	
1	2	3	4
1. Competition: mutually superior competition	—	—	$\begin{cases} \frac{dn_1}{dt} = (\lambda_1 - \mu'_1 n_1 - \nu'_1 n_2) n_1; \\ \frac{dn_2}{dt} = (\lambda_2 - \mu'_2 n_2 - \nu'_2 n_1) n_2. \end{cases}$
2. Amensalism: one-sided dominant competition	—	0	$\begin{cases} \frac{dn_1}{dt} = (\lambda_1 - \mu'_1 n_1 - \nu'_1 n_2) n_1; \\ \frac{dn_2}{dt} = (\lambda_2 - \mu'_2 n_2) n_2. \end{cases}$

Continued table. 1.

1	2	3	4
3. Parasitism (predation): "request - satisfaction"	–	+	$\begin{cases} \frac{dn_1}{dt} = (\lambda_1 - v_1' n_2) n_1; \\ \frac{dn_2}{dt} = (-\lambda_2 + v_2' n_1) n_2. \end{cases}$
4. Commensalism: one-sided positive competition	0	+	$\begin{cases} \frac{dn_1}{dt} = (\lambda_1 - \mu_1' n_1) n_1; \\ \frac{dn_2}{dt} = (\lambda_2 - \mu_2' n_2 + v_2' n_1) n_2. \end{cases}$
5. Neutralism: balance	0	0	$\begin{cases} \frac{dn_1}{dt} = (\lambda_1 - \mu_1' n_1) n_1; \\ \frac{dn_2}{dt} = (\lambda_2 - \mu_2' n_2) n_2. \end{cases}$
6. Amensalism: one-sided dominant competition	0	–	$\begin{cases} \frac{dn_1}{dt} = (\lambda_1 - \mu_1' n_1) n_1; \\ \frac{dn_2}{dt} = (\lambda_2 - \mu_2' n_2 - v_2' n_1) n_2. \end{cases}$
7. Parasitism (predation): Batesian mimicry	+	–	$\begin{cases} \frac{dn_1}{dt} = (-\lambda_1 + v_1' n_2) n_1; \\ \frac{dn_2}{dt} = (\lambda_2 - v_2' n_1) n_2. \end{cases}$
8. Commensalism: one-sided positive competition	+	0	$\begin{cases} \frac{dn_1}{dt} = (\lambda_1 - \mu_1' n_1 + v_1' n_2) n_1; \\ \frac{dn_2}{dt} = (\lambda_2 - \mu_2' n_2) n_2. \end{cases}$
9. Mutualism: joint positive activity	+	+	$\begin{cases} \frac{dn_1}{dt} = (\lambda_1 - \mu_1' n_1 + v_1' n_2) n_1; \\ \frac{dn_2}{dt} = (\lambda_2 - \mu_2' n_2 + v_2' n_1) n_2. \end{cases}$

The concept of computer simulation of the interaction of two sets.

For a set of two interacting sets, four levels of simulation modeling complexity are proposed, which are described in Table 2.

Algorithms of the model. Figures 7-10 show the generalized algorithms that form the basis of the process modeling system under study. The method proposed by the authors was called SRS (Selective Rapid Scan). The sequence of actions is described in Table 2.

Table 2. Levels of simulation modeling of a self-organizing ecological community from two sets

Level	Essence of modeling
Level 1	<p><i>Partial debugging (3-4 models).</i></p> <p>The need for a level is to adjust the values of the coefficients of the models. The starting model is not important here.</p> <p>The task of this stage is to model situations for different ratios of coefficient values by changing them and obtaining a numerical solution of the corresponding equation - to make sure of the correctness of the results of the implementation of a separate model under certain conditions, to make a transition from one model to another [15]. For this, it is enough to use 3-4 models from Table 1. Model1 modeling sequence is formed. Values and ratios of model coefficients are worked out. A depot is introduced in Model1. The simulation results are analyzed.</p>
Level 2	<p><i>Debugging is complete according to a fixed sequence of model activation.</i></p> <p>The starting model and one of the variants of the activation sequence are selected. All nine models from Table 1 must be activated. The Level1 sequence is taken as the initial sequence. The simulation results are analyzed, and the numerical characteristics of the models are adjusted.</p>
Level 3	<p><i>Formation of the modeling complex</i></p> <p>The starting model is changed and 3-4 activation sequences of all nine models from Table 1 are generated. One of the modeling options is with Level2. The main task is to check the performance of the modeling complex and its verification. Description of the simulation complex and development of instructions for the user (experimenter).</p>
Level 4	<p><i>Adequacy check</i></p> <p>The complex is being adapted to real conditions. For this, it is desirable to choose a real, investigated and well-described case of violation of environmental safety. It can be a catastrophe or a transport accident with damage to the natural environment. The process of eliminating the consequences of a disaster or accident is recorded. An accident is simulated and the process dynamics are compared with real data.</p>

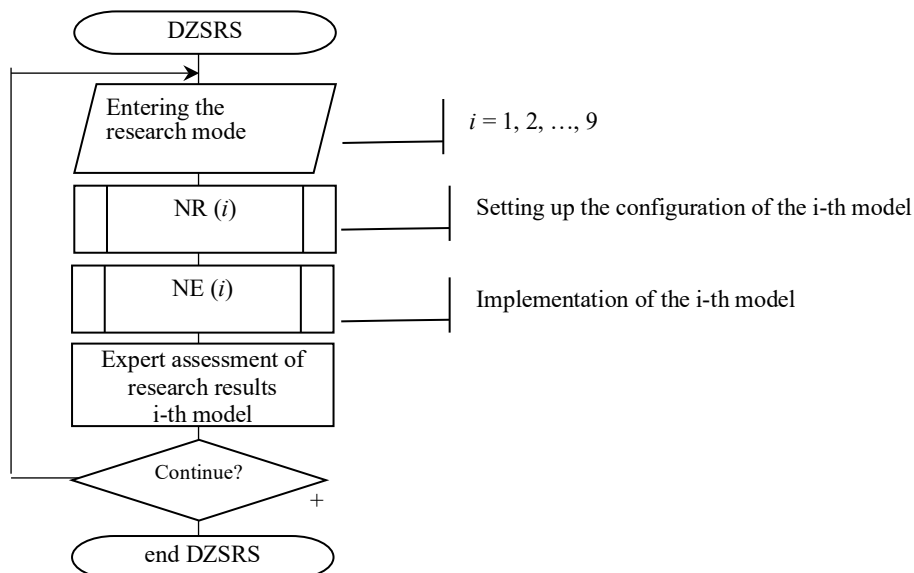


Fig. 7. Manager of the software complex

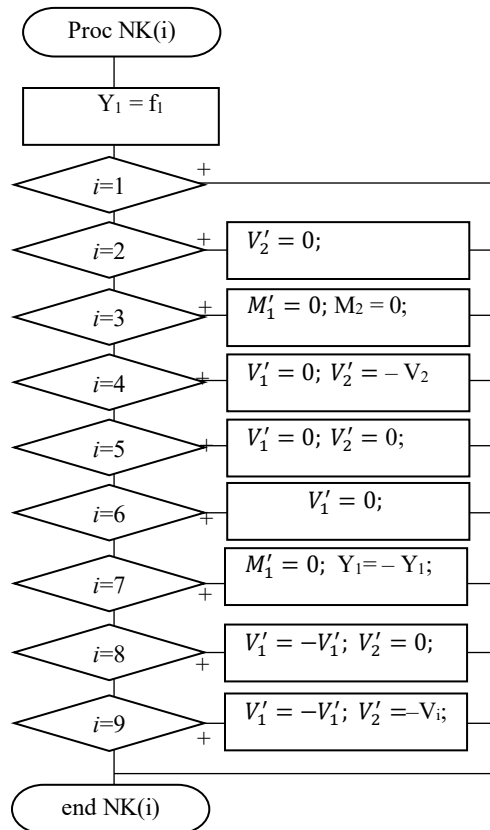


Fig. 8. Model configuration settings (transition implementation algorithm)

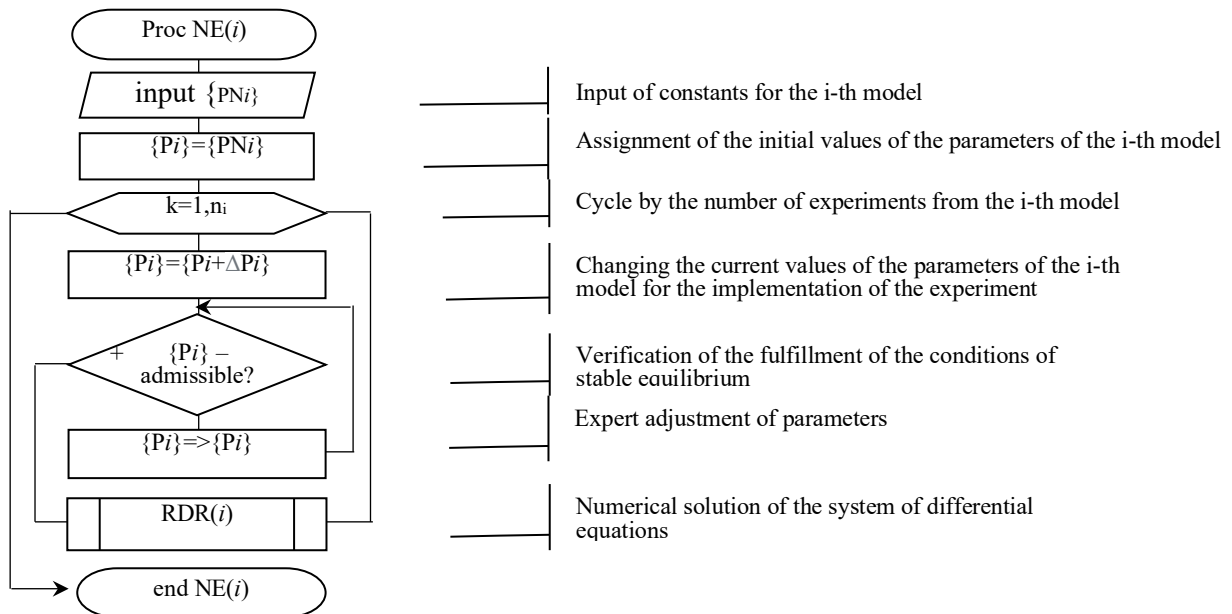


Fig. 9. Implementation of the study of the i-th model (general case)

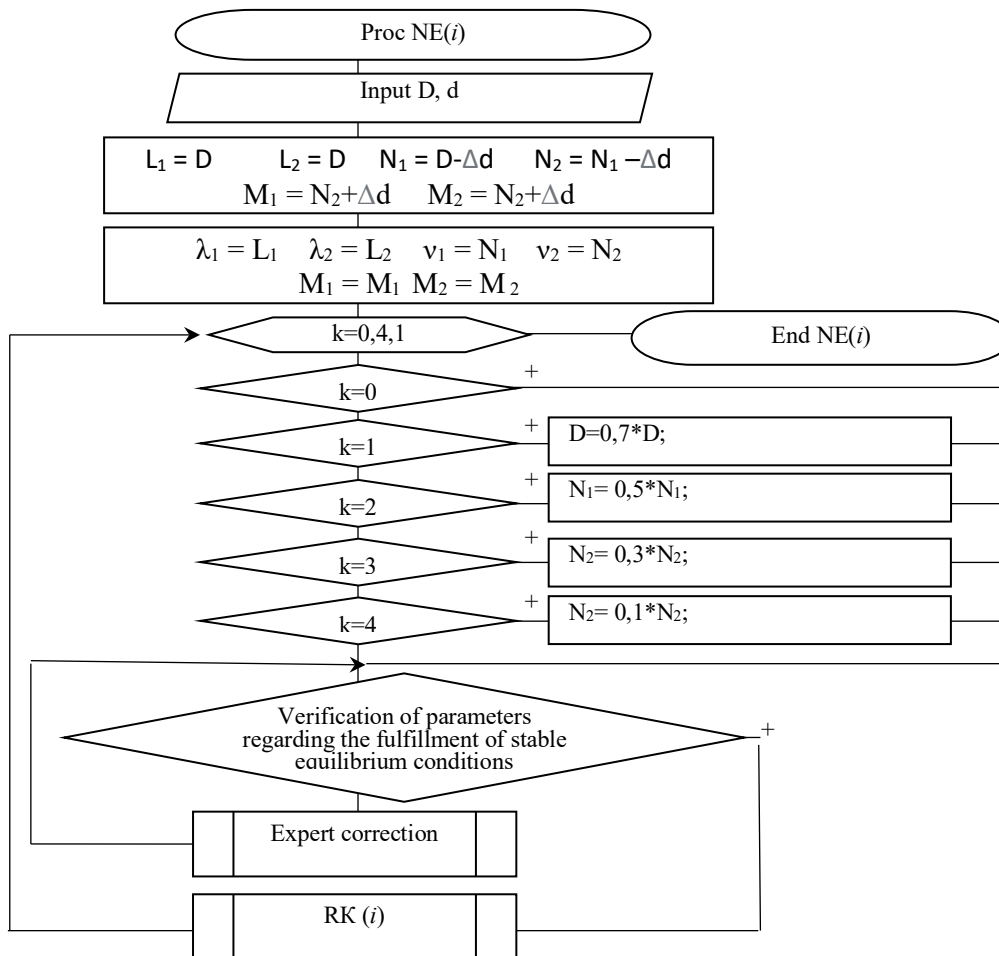


Fig. 10. Implementation of the studio of the i -th model (general time)

Conclusions. Note:

- conditions of competition arise in the process of self-organization;
- competitive relations lead to dismemberment of the initial complex of multiparametric system-forming relations into groups with a more simplified variation, but with a more significant manifestation of certain indicators in them;
- as a result of the principle of isomorphism, the preservation of equipotential states leads to the sequential activation of the elements of the system, and therefore to the continuous change of their state and the limits of this change.

We choose a real investigated and well-described case of an accident on railway transport with damage to the natural environment. This definitely leads to a violation of environmental safety.

The consequences of this case are recorded. Anomalous process is described by means and terms embedded in the modeling system. Scenarios predicted with the help of expert evaluation are played out.

The obtained results regarding the dynamics and consequences of the processes are compared with real data. In this way, the knowledge base is filled with certain information, the use of which will allow preventing unforeseen life situations in the future.

REFERENCES

1. Munich Security Conference (2022) Proceedings of the 17-19 February 2022 UN Climate Change Conference [in German]. <https://securityconference.org/publikationen/munich-security-report/>.

2. Chub, I.A. Novozhilova, M.V., & Melezhyk, R.S. (2018). Simulation of urban engineering infrastructure as a source of man-made emergency. *Collection of scientific works*, 27, 169-174. *Problems of emergency situations*. [in Ukrainian]. <http://repositsc.nuczu.edu.ua/handle/123456789/8472>.
3. Komarnytsky, I. M., & Bublik, M. I. (2018). Assessment of technogenic losses and analysis of approaches to their calculation in global and regional aspects. [in Ukrainian]. *Access mode: vlp.com.ua/files/21_31.pdf (Date of application: 07.03.2018)*.
4. Yatsenyo, E. (2021) Environmental policy of Ukraine: goals, directions and tools of implementation. *Article from 16 September 2021*. [in Ukrainian]. <https://ecopolitic.com.ua/ua/news/ekologichna-politika-ukraini-cili-napryami-ta-instrumenti-realizacii/>
5. Shramovich, V. (2023). Devastated lands. What will be the nature of Ukraine after the war? *BBC News Ukraine*. https://www.bbc.com/ukrainian/extra/mwu5sxghvc/ukraine_war_damaged_nature.
6. Peterson, E. R., & Laudicina, P. A. (2016). From Globalization to Islandization. Council Perspective. // Global Business Policy Council. *Research Report*. <https://www.kearney.com/web/global-business-policy-council/article/-/insights/from-globalization-to-islandization>.
7. Krasnobokyi, Yu.M., Tkachenko, I.A. & Ilnitska, K.S. (2022). Self-organization in climate formation on the planets of the solar system. *Scientific notes. Series: Pedagogical sciences*, 208, 161-166. <https://doi.org/10.36550/2415-7988-2023-1-208-161-166>. [in Ukrainian]
8. Mykytyn, H.V. (2016). Systemic, regulatory and complex models of information technology protection. *Bulletin of the National University "Lviv Polytechnic"*. – Ser.: *Automation, measurement and control*. – Lviv: *Publication of NU" Lviv Polytechnic*, 695, 126-132. <https://science.lpnu.ua/sites/default/files/journal-paper/2017/jun/3775/mykytynhv.pdf>. [in Ukrainian].
9. Ruzych, R.I. (2014). Processes of self-organization in biogeocenosis. *Bukovynian Mathematical Journal*, 2(2), 2-3. [in Ukrainian].
10. Samsonkin, V., & Feldman, A. (2018). Applying of activities management based on self-learning. *EUREKA: Physics and Engineering*, (1), 29-38. <https://doi.org/10.21303/2461-4262.2018.00530>.
11. Samsonkin, V., & Goretzkyi, O. (2019, May). Control Technology of Railway Traffic Safety: A System Approach and Digitalization. In *International Conference TRANSBALICA: Transportation Science and Technology* (pp. 633-638). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-38666-5_66.
12. Forrest-Owen, O. (2016). Mathematical Modelling and it's Applications in Biology, Ecology and Population Study. *University of Chester, United Kingdom*, 124. <http://hdl.handle.net/10034/620506>.
13. Zagvoyska, L. D. (2014). Theoretical approaches to modeling the dynamics of ecological and economic systems. *Modeling of regional economy*, 2, 85-102. [in Ukrainian].
14. Coperlios, R. J. (2014). Methodology of scientific knowledge of complexity: diversity of options. *Humanitarian studies*, 21, 67-75. [in Ukrainian]. file:///C:/Users/Windows-10/Downloads/gums_2014_21_11.pdf.
15. Pospelov, B. B. Andronov, V. A., & Rybka, E. A. (2017). Algorithms and devices for optimal forecasting and detection of emergency situations in the event of unknown loss functions. *Emergency problems*, 25, 85-93. [in Ukrainian].

Валерій Самсонкін¹, Ірина Бізюк²

¹ Самсонкін Валерій Миколайович, доктор технічних наук, професор кафедри управління процесами перевезень Державного університету інфраструктури та технологій, вул. Огієнка, 19, м. Київ, 03049, Україна, ORCID: <https://orcid.org/0000-0002-1521-2263>.

² Бізюк Ірина Григорівна, старший викладач кафедри обчислювальної техніки та систем управління Українського державного університету залізничного транспорту, пл. Фейєрбаха, 7, м. Харків, 61050, Україна, ORCID: <https://orcid.org/0000-0002-6458-5701>.

Розробка концепції імітаційного моделювання екологічної ситуації на основі теорії самоорганізації

Стаття присвячена розробці концепції моделювання екологічної ситуації на основі теорії самоорганізації. Тенденція до підвищення температури та рівня моря через збільшення рівня парникових газів в атмосфері Землі є глобальною. Це свідчить про необхідність прогнозування розвитку екологічної ситуації з метою інформування населення про можливі катастрофи для підготовки людей до реагування, планування переселення, психологічної адаптації. Для прогнозування екологічної ситуації внаслідок аварій і катастроф, у тому числі на залізничному транспорті, запропоновано апарат аналізу можливих ситуацій з метою розробки рекомендацій щодо їх запобігання. В якості апарату дослідження обрано імітаційну модель навколишнього середовища на основі теорії самоорганізації. В його основі лежать процеси взаємоузгоджених відносин, що виникають в результаті зміни двох видів живої природи (об'єкта і середовища),

що призводить до формування певної впорядкованості цих відносин. Взаємодія такого роду відбувається в напрямку досягнення існуючого стану рівноваги або формування нового балансу.

Ключові слова: імітаційна модель, екологічна ситуація, теорія самоорганізації, експертне оцінювання, рівноважний стан, база знань.

¹**Oleksandr Gertsy***

¹Assistant professor, Automation and Computer-Integrated Transport Technologies Department, State University of Infrastructure and Technology, 9, Kyrylivska str., Kyiv, Ukraine, 04071, Ukraine, ORCID: <https://orcid.org/0000-0002-8634-5880>

*Corresponding author: gertsy_ua@gsuite.duit.edu.ua

Models of criterion evaluation of the image processing systems effectiveness

The criteria used to evaluate the effectiveness of image processing systems are investigated in the article. The requirements for performance criteria are analyzed. Private criteria which are used for image processing systems are selected and justified. Such parameters as performance, system cost, hardware costs characterize the system itself and depend on its specific type. It was shown that the information capacity, the probability of completing the task, and the accuracy of the image processing algorithm are the main criteria that characterize the quality of the processing method. It is shown that such a reliability criterion as normalized root mean square error best meets the requirements of efficiency criteria. Criteria models that are based on the normalized root mean square error in relation to discrete images have been studied. The simulation results and obtained dependences of cost functions on the speed of system information processing are given. The methodology for choosing a generalized criterion, which characterizes not only the information processing system, but also the methods used to implement this system was found. We obtained a generalized cost criterion, which arguments are the accuracy of system operation, speed of operation, and cost advantages.

Keywords: *Efficiency criterion, image processing, normalized root mean square error.*

Introduction. Synthesis of any system, in particular a image processing system, should begin with choosing and justifying the criteria for evaluation of efficiency, quality and optimization. At the same time, it is necessary to choose a criterion that would allow synthesizing an optimal process and a system regarding the most important indicators of quality efficiency. These indicators should in the first place include the following:

- Problem solving probability or system reliability;
- Information capacity;
- Speed;
- Volume and weight, complexity and cost;
- Accuracy of work and controllability of the system itself;
- Noise immunity.

In addition to these requirements, the criterion should possess certain constructability in order to easily evaluate its numerical value, which would allow calculating the efficiency of not only the process, device and the system itself in its proximity to potential perfection, but also comparatively similar devices, processes and systems in cumulation.

Propositions and consequences formulated in this research allows deriving a generalized functional-statistical efficiency evaluation criterion that satisfies all above-mentioned requirements. Main properties of the generalized criterion and particular criteria derived from the general, based on the maximum total utility at minimum cost are also described.

Analysis of recent research and problem statement. The concept of quality efficiency and optimality occupies an important place in theories about information systems in general and image processing systems, as well as for evaluating of information processing methods used in these systems.

The efficiency of the system can be considered as the benefit received as a result of its use, attributed to the costs of its development and operation E_s [1].

Criteria are used to evaluate efficiency. A criterion is an indicator or a measure of the effectiveness of the quality and optimality of the system. Criteria can be private or general.

We have to deal with the justification and selection of performance evaluation and optimization criteria at all stages of system modeling. The difficulty of this task lies in the fact that for complex systems it is not possible to choose a single criterion for evaluating efficiency and optimality [2-4]. Therefore, it is necessary to solve the problem of multi-criteria ranking or optimization, the main thing in this is the choice and justification of the compromise principle, that is, the generalized scalar criterion.

When choosing criteria, it is necessary to take into account a lot of requirements [1, 5, 6]:

- the criterion should directly characterize efficiency, reflect objective reality;
- the criterion must have a physical interpretation;
- the criterion should be simple and easy to calculate;
- the value of the criterion must be within certain limits, for example $0 \leq E_s \leq 1$, that means that the criterion of an inefficient system is equal to zero, and the criterion of an ideal system is equal to one;
- the criterion shouldn't have dimensionality, that is, it should be normalized;
- the criterion must be theoretical, that is, formulated in the form of a law;
- the criterion should be heuristic, that is, it should allow to accumulate experience, develop intuition;
- the criterion should characterize the best and worst systems within its limits.

The purpose and tasks of the study. The goal is to determine a generalized criterion that would allow for optimal image processing in terms of the most important performance indicators. It is necessary to define a specific algorithm of criteria for evaluating efficiency, quality and optimization.

Using this algorithm, we can solve different problems. There are: building mathematical model of image processing system, building model of system functioning, development and optimization of the image processing system functioning algorithm, system synthesis and analysis, selection of system implementation elements, alignment of systems elements between each other as well as evaluation of image processing system efficiency, quality and optimization.

Selection and justification of private criteria. The first stage of solving the problem is the selection of a set of private criteria that characterize the system quite accurately. Let's consider the image processing system as an object. The method allows you to highlight the image on a halftone object in real time [7].

We can identify the following private criteria that characterize this specific system:

1. system speed or time consumption;
2. system functionality;
3. information capacity of the system;
4. accuracy of system operation;
5. the probability of system task performance;
6. cost of system implementing;
7. hardware costs used for system implementation;

Let's consider the necessity, possibility and sufficiency of using each of the above criteria to assess the quality and optimality of this system.

1. Speed is the time taken by the system to execute a given image processing algorithm. The type of mathematical model of this criterion will depend on the specific type of system. When implementing the algorithm with a sequential system, the speed of operation is calculated in the following way:

$$T(x, y, z, t) = \sum_{k=1}^L \sum_{j=1}^M \sum_{i=1}^N T(x_i, y_j, z_k, t) + \sum_{k=1}^L T(z_k, t),$$

where $T(x_i, y_j, z_k, t)$ - preprocessing time;

$T(z_k, t)$ - feature selection time;

M and N - the number of rows and columns of the image;

L - the number of discretization levels.

When implementing the algorithm with a parallel system, the speed will be calculated as:

$$T(x, y, z, t) = \sum_{k=1}^L T(z_k, t) + T_0,$$

where T_0 - preprocessing time.

2. The functionality of this method should have:

a) the possibility of work with halftone images of different brightness gradations;

b) invariance of the method to affine transformations (rotation, scale change).

3. The criterion of the information capacity of the system [8, 9] can be considered as the ability of the system to issue the maximum amount of received information about the image of the object after its processing:

$$I_{\max}(x, y, t) = \sum_{i=1}^N \sum_{j=1}^M I_{\max_{i,j}}(t),$$

where $I_{\max_{i,j}}$ - the maximum amount of information for i, j image pixels.

4. The accuracy of the system can be considered as: 1) the accuracy of the method implemented by the system and 2) as the accuracy of the system equipment. The accuracy of the method is most characterized by the probability of an erroneous decision [9]. A similar problem is considered in [10] which consists in the fact that it's necessary to determine whether the received signal at each pixel of the image is useful or noise. The following errors may occur: 1) the decision is made that signal is useful when it's noisy; 2) the signal is useful, but it's decided that it belongs to noise. The first error is an error of the first kind or "false alarm". The second is an error of the second kind or "missing signal". The amount of errors of the first and second kind is estimated by the conditional probabilities α and β of false decisions about the presence of a useful signal when in reality it is absent and about the absence of a signal when it really is. The probability of a wrong decision on one pixel is:

$$P_{i,j} = q_{i,j} \alpha_{i,j} + p_{i,j} \beta_{i,j},$$

where $q_{i,j}$ i $p_{i,j}$ - a priority probabilities of the absence and presence of a useful signal on i, j pixels.

The total probability of a false decision for the entire image will be:

$$P_{er} = \sum_{i=1}^N \sum_{j=1}^M q_{i,j} \alpha_{i,j} + p_{i,j} \beta_{i,j}$$

Another criterion that reflects accuracy is the probability of recovery.

A lot of attention was paid to the construction and development of a system of quantitative measures of the accuracy of monochrome images restoration. It is indicated in [11] that adequate accuracy measures should be consistent with the results of subjective evaluations for a wide class of images,

without requiring super complicated calculations. In addition, it is desirable for these measures to have a simple analytical form – then they could be applied as optimality criteria in the optimization or selection of image processing system parameters. The specified requirements are fully consistent with the general requirements for the criteria formulated earlier. Quantitative measures of accuracy of monochrome images restoration can be divided into two groups: single and paired. A single measure is a number that is compared to an image based on an analysis of its structure. A paired measure is a numerical result of a mutual comparison of two images, for example, a reference and a real one.

As a criterion of efficiency and optimality of the method we can take the root mean square error of correction [12].

Let's say $U=\{F(i, j)\}$ - ideal picture, and $i=1, \dots, M, j=1, \dots, N$ - coordinates of image elements, M and N - the number of line elements and lines in the frame. The image we observe $V = \{\tilde{F}(x, y)\}$, which was formed as a result of system processing according to a given algorithm of some initial image. The quality of the algorithm will be better in accordance with the match of ideal and resulting image, therefore it is necessary to determine the "closeness of the images".

It is convenient to start with the quadratic measure of closeness - the Euclidean distance [1, 11]. The square of the Euclidean distance between the images is the square of their difference:

$$\|\Delta\|^2 = \sum_{i=1}^N \sum_{j=1}^M \Delta^2(x, y), \quad (1)$$

where the difference image is

$$\Delta(x, y) = V(x, y) - U(x, y) \quad (2)$$

To obtain a measure of the corrective transformation quality for some set of initial images as a whole, which would not depend on the implementation of the disturbance, it is convenient to take the mathematical expectation of the value $\|\Delta\|^2$ (1). By averaging it both over the set of initial images and over different realizations of the obstacle, we obtain the following value:

$$\varepsilon^2 = \langle \|\Delta\|^2 \rangle = \sum_{i=1}^N \sum_{j=1}^M \varepsilon^2(x, y) \quad (3)$$

where $\varepsilon^2(x, y) = \langle (V(x, y) - U(x, y))^2 \rangle$, is called root mean square correction error (RMSE).

It can be used as a criterion for the optimality of the correction. The best image is considered to be the one for which the RMSE is minimal. However, such a criterion does not meet the requirement of variability within defined limits, as there are difficulties in establishing its upper limit.

One of the reliability criteria is the normalized root mean square error (NRMSE) [12, 13].

$$NRMSE = \frac{\sum_{i=1}^N \sum_{j=1}^M [\nu\{F(i, j)\} - \nu\{\tilde{F}(i, j)\}]^2}{\sum_{i=1}^N \sum_{j=1}^M [\nu\{F(i, j)\}]^2}, \quad (4)$$

where $\nu\{\cdot\}$ - a certain (possibly non-linear) operator;

$F(i, j)$ - ideal discrete image, $\tilde{F}(i, j)$ - the image under study.

The most common fidelity criteria, which are based on estimates of normalized root mean square errors (NRMSE) for discrete images are listed in Table 1.

Table 1. Accuracy criteria based on NRMSE f or discrete images

1	Without transformation	$NRMSE = \frac{\sum_{i=1}^N \sum_{j=1}^M [F(i, j) - \tilde{F}(i, j)]^2}{\sum_{i=1}^N \sum_{j=1}^M [F(i, j)]^2}$
2	With transformation by decomposition elements Degree law Logarithmic law	$NRMSE = \frac{\sum_{i=1}^N \sum_{j=1}^M [G(i, j) - \tilde{G}(i, j)]^2}{\sum_{i=1}^N \sum_{j=1}^M [G(i, j)]^2}$ $G(i, j) = [F(i, j)]^v$ $G(i, j) = R_1 \log_b [R_2 + R_3 F(i, j)]$
3	With the Laplace transform	$NRMSE = \frac{\sum_{i=1}^N \sum_{j=1}^M [G(i, j) - \tilde{G}(i, j)]^2}{\sum_{i=1}^N \sum_{j=1}^M [G(i, j)]^2},$ <p>where</p> $G(i, j) = F(i+1, j) + F(i-1, j) + F(i, j+1) + F(i, j-1) - 4F(i, j)$
4	With the use of convolution	$NRMSE = \frac{\sum_{i=1}^N \sum_{j=1}^M [G(i, j) - \tilde{G}(i, j)]^2}{\sum_{i=1}^N \sum_{j=1}^M [G(i, j)]^2},$ <p>where $G(i, j) = [F(x, y) \cdot H(x, y)]^\delta (x - i\Delta x, y - j\Delta y)$</p>

Another common accuracy criterion is the peak root mean square error (PRMSE), which is determined by the ratio

$$PRMSE = \frac{1}{N \cdot M} \frac{\sum_{i=1}^N \sum_{j=1}^M [G(i, j) - \tilde{G}(i, j)]^2}{A^2}, \quad (5)$$

where $G(i, j)$ - a transformed image that meets the definition given in Table 1, and number A is equal to the maximum value $G(i, j)$.

It is also convenient to consider the root-mean-square error as a signal-to-noise ratio:

$$(S/N)_n = -10\lg(NRMSE),$$

$$\text{or } (S/N)_p = -10\lg(PRMSE)$$

Selection of a generalized criterion. To form a generalized criterion, it is necessary to choose such a private criteria that characterize not only the image processing system, but also the way implemented by this system.

Performance, cost of the system, hardware costs characterize the system itself and depend on its specific type, only indirectly on the method. Evaluation according to the "functional capabilities" criterion is complicated due to the complexity of the mathematical formalization of this criterion. Therefore, the criteria that characterize the quality of the method are the information capacity, the probability of completing the task, and the accuracy of the image processing algorithm.

To derive a generalized criterion, let's consider the concept of a real and ideal system [14]. A real system is understood as a system that processes and outputs information according to a given algorithm, chosen under the condition of obtaining the maximum amount of information about the image.

A potential or ideal information system is understood as a system that works in the same way as a real one, what is more, it completely removes uncertainty from the object and the system itself. Based on that, the generalized criterion can be represented as [14]:

$$E(t, \tau) = \frac{E_r(t, \tau)}{E_p(t, \tau)}, \quad (6)$$

where $E_r(t, \tau)$ - efficiency of the real system;

$E_p(t, \tau)$ - efficiency of the potential (ideal) system.

Effectiveness of real and potential systems, can be defined as:

$$E_p(t, \tau) = \frac{B_{\max}}{C_{\min}}, \quad (7)$$

where B_{\max} - maximum benefit;

C_{\min} - minimal costs.

$$E_r(t, \tau) = \frac{B_r}{C_{\Sigma}}, \quad (8)$$

where B_r - real benefit;

C_{Σ} - total costs.

The benefit can be based on any of the previously discussed criteria. Thus, the efficiency of the system according to the information criterion, in relation to the system under consideration, can be estimated by the following expressions:

$$E_r = \frac{I_r(x, y, t)}{C_{\Sigma}} = \frac{\sum_{i=1}^N \sum_{j=1}^M I_{r, i, j}}{C_{\Sigma}} \quad (9)$$

$$E_p = \frac{I_{\max}(x, y, t)}{C_{\min}} = \frac{\sum_{i=1}^N \sum_{j=1}^M I_{\max i, j} | p_{i, j} = 0,5}{C_{\min}} \quad (10)$$

Respectively:

$$E_{I,S} = \frac{\sum_{i=1}^N \sum_{j=1}^M I_{\max i, j} \cdot C_{\min}}{C_{\Sigma} \cdot \sum_{i=1}^N \sum_{j=1}^M I_{\max i, j} | p_{i, j} = 0,5} \quad (11)$$

The defined complexity is the derivation of a generalized criterion, if the accuracy of restoration is considered as its argument. It is difficult to determine the efficiency separately for real and ideal systems, for example, relating the normalized root mean square error to costs, as it includes the concept of parameters of ideal and real systems [15]. However, NRMSE has the highest priority for the evaluation of the effectiveness of this type of system. The advantages of this criterion are listed below:

The criterion reflects objective reality and characterizes efficiency.

The criterion has a physical interpretation. This is the normalized root mean square error of image filtering and restoration.

The criterion is statistical, since its arguments are random values or their probabilistic characteristics.

The criterion is not difficult to calculate and can be calculated using appropriate programs.

The criterion has defined limits $0 \leq E_{\text{NRMSE}} \leq E_{\text{NRMSE}}^{\max}$, where E_{NRMSE}^{\max} - specific limit value calculated for a specific type of images for which optimization is performed. At the same time, the more effective the algorithm, the smaller the error, and the closer E_{NRMSE} to zero.

The criterion is normalized.

The main disadvantage of such a criterion is that it doesn't take into account equipment costs. To evaluate according to the cost criterion, it is necessary to know the costs of development, production and operation of the system, as well as the costs associated with the fulfillment of speed requirements. Generalized total costs can be determined by the expression:

$$C_{\Sigma}(t) = C_D(t) + C_M(t) + C_E(t) + \Delta C_T(t) \quad (12)$$

where C_D , C_M , C_E - the cost of development, production, and operation of the system; ΔC_T - additional costs to obtain the required speed.

$$\Delta C_T = K_T T, \quad (13)$$

where K_T - specific coefficient that solves the dimensionality problem.

The minimum costs are:

$$C_{\min}(t) = C_D(t) + C_M(t) + C_E(t) + \Delta C_T(t) \quad (14)$$

According to the cost criterion efficiency can be presented:

$$E_C = \frac{C_{\min}}{C_{\Sigma}} \quad (15)$$

The criterion varies within:

$$0 \leq E_c \leq 1,$$

At the same time, when E_c is close to 0, the system is inefficient, when E_c is close to 1 – the system is potentially efficient.

The main disadvantage of the cost criterion is its one-sidedness, it means that only costs are taken into account.

Based on the above criteria and their properties, it is possible to formulate the main requirement of system optimality: the optimal system is the one where the normalized root mean square error is minimal at the same costs and given speed.

However, the following requirement will be more convenient: the optimal system is the one for which the cost criterion is maximal at a given NRMSE and a given speed.

Then the cost criterion will be represented by the formula:

$$E_c = \frac{C_D(t) + C_M(t) + C_E(t)}{C_D(t) + C_M(t) + C_E(t) + \Delta C_T(t) + \Delta C_{NRMSE}(t)} \quad (16)$$

where $\Delta C_{NRMSE}(t)$ - the cost of additional costs to achieve the required accuracy.

$$\Delta C_{NRMSE} = K_{NRMSE} \cdot NRMSE,$$

where K_{NRMSE} - the coefficient that solves the dimension problem.

If talk about efficiency E_c in this problem [16], we mean some functionality of the speed of processing of requests V_g and processing reliability, which is expressed in terms of errors of the first and second kind with the corresponding probabilities P_I and P_{II} [9,12]:

$$E = \psi(V_g, P_I, P_{II})$$

The cost is calculated by the formula:

$$C = a_1 V_{inf} + a_0.$$

1. With restrictions on the duration of the system channel with guaranteed quality of task performance: $t_d < T_{max}$, when $t_d > T_{max}$ $C = a_2 \cdot V_{inf}$, where a_1 and a_2 - weighting factors selected experimentally, based on the results of analysis of the system processing state.

If $a_1 > a_0$, where the coefficient a_i is determined by the method of expert assessments based on the results of statistical data processing, then, in this case, a linear dependence is proposed as a first approximation (Fig. 1).

The task of choosing a breaking point is subjective, so let's consider another cost function: $C = a_{12} \cdot V_{inf} + a_0$. Coefficient a_{12} is selected from the condition $a_1 \cdot V_{max} + a_0 = a_{12} \cdot (V_{max})^2$ **OR** $a_{12} = a_1 / V_{max}$.

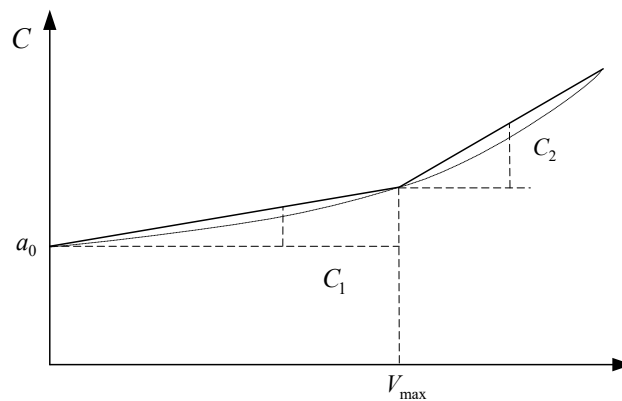


Fig. 1. Dependence with guaranteed quality of processing

2. Alternative - the quality of the data processing is not guaranteed [16].

$$C = a_3 V_{inf} + a_{03}$$

Ensuring data processing is the task of the operator. In this case, we will also focus on the linear dependence as a first approximation, but with a different coefficient and breaking point (Fig. 2), and on the quadratic dependence, where a_{32} is chosen for the same reasons as a_{12} .

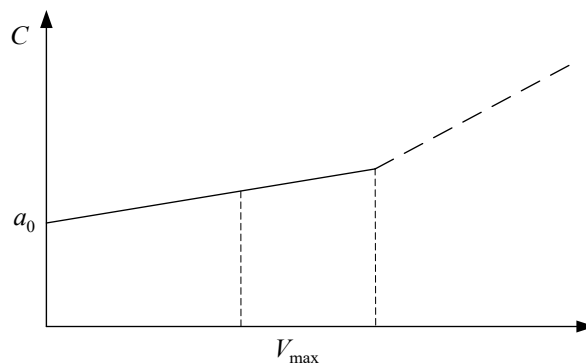


Fig. 2. Dependence of the cost of the data processing mode in the system

Quadratic cost functions are widely used in the analysis and synthesis of large systems, including information and computing and control systems.

3. Force majeure (maximum computing resources), quality of processing is maximum, while cost is the second priority. It is necessary to ensure the guaranteed volume of the system channel - $V_{chan} \geq V_{inf}$.

When determining the required volume of the system channels, the volume of processed information is approximately 10-100 times less in a full-time situation than when an out-of-hours situation occurs. Then, the value increases according to the law $C_{max} = (1 - e^{-a_4 V_{inf}})$, and the graph looks in the next way (Fig. 3)

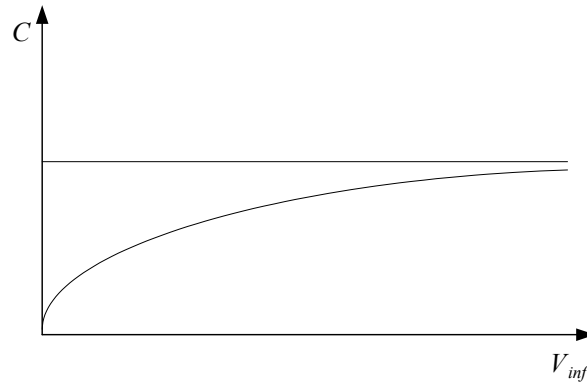


Fig. 3. Dependence of the cost on the quality of information in a "soft" force majeure situation

In some cases, the value of information is an absolute priority. Therefore, it is advisable to choose the information function of the species as a cost function: $C = a_{42} \cdot \log_2(1 + V_{inf})$, $V_{inf} > 0$ (Fig. 4).

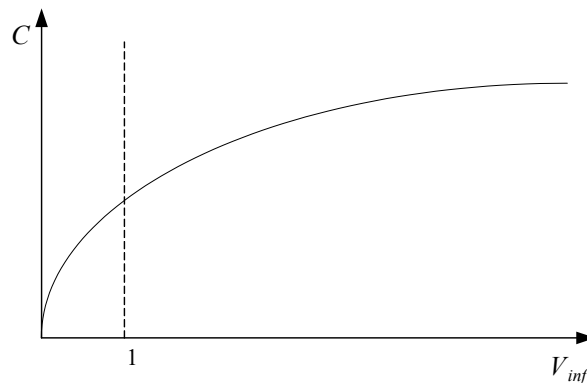


Fig. 4. Dependence of the cost on the quality of information in a "hard" force majeure situation

Thus, it is necessary to choose the appropriate cost functions proposed above to optimize the time of image acquisition and its processing in various situations [17-20].

Criterion application algorithm for the image processing system. For this system, there are X options that differ in their technical implementation and algorithm that they implement.

1. The cost of developing, manufacturing and operating the system is calculated (C_D , C_M , C_E). Moreover, the cost of production includes hardware costs. It should be taken into account that for each of the X systems the parameter C_M will be different.

2. The speed T of each of X systems is calculated. We choose Y options from them that satisfy the condition $T_Y \leq 20ms$, that is, they work in real time [21, 22]. Systems that do not meet this requirement should be refined or rejected.

3. L experiments are conducted for each of the Y selected systems. Next step – to determine the mathematical expectation for each element of the investigated systems. Knowing values of the signal on each element of the reference image, according to the formulas from the table 1 or by the formula (6) we can define NRMSE for each system. By setting defined values $NRMSE_{max}$ we compare the obtained results. When performing the inequality $NRMSE_Y^L \leq NRMSE_{max}$ a subset Z is formed.

4. For systems included in the subset Z the value criterion is calculated according to the formula (16). The closer the obtained value is to 1, the more efficient the system.

Conclusions. The process of control and management of complex informaciologic objects can be considered as the process of formation and regulation of physically independent or interconnected

processes occurring simultaneously or with some time shift. In this case a technical system for control and management of image processing should be considered as a multidimensional complex system.

The obtained efficiency criterion is generalized, its arguments are the accuracy of system operation, speed of operation, and cost savings. The criterion is statistical, since all parameters are random values or their statistical characteristics. Relatively simple criterion is being calculated and it meets the requirement $0 \leq E_c \leq 1$. The closer the value is to one, the more efficient the system. Since the criterion includes indicators of accuracy and speed, it allows to accumulate experience as a result of application for systems with different accuracy and speed. The simulation results and obtained dependences of cost functions on the speed of information processing in the system are given.

Thus, the generalized cost criterion meets all the requirements for optimization and quality criteria, therefore it's suitable for evaluating the effectiveness of image processing systems.

REFERENCES

1. Kuzmin, I.V., Trotsychn, I.V., Kuzmin, A.I., Kedrus, V.O., & Lubchik, V.R. (2009). Osnovy teorii infocii ta coduvannya. [Fundamentals of Information Theory and encrypting]. In: *Kuzmin I.V. (eds.) Teaching book. Khmelnytskyi National University, Khmelnytskyi*. [in Ukrainian].
2. Zwirowicz-Rutkowska, A. (2017). A multi-criteria method for assessment of spatial data infrastructure effectiveness. *Earth Science Informatics*, volume 10, 369–382. <https://doi.org/10.1007/s12145-017-0292-8>.
3. Fernandez, E., Navarro, J., Covantes, E., & Rodriguez, J. (2017). Analysis of the effectiveness of the theseus multi-criteria sorting method: theoretical remarks and experimental evidence. *Journal of the Spanish Society of Statistics and Operations*, volume 25, 314–339. <https://doi.org/10.1007/s11750-016-0433-0>.
4. Jamróz, D. (2020). The examination of the effect of the criterion for neural network's learning on the effectiveness of the qualitative analysis of multidimensional data. *Knowl Inf Syst*, 62, 3263–3289. <https://doi.org/10.1007/s10115-020-01441-8>.
5. Xu, L., & Yang, J.-B. (2001). Introduction to multi-criteria decision making and the evidential reasoning approach. *Manchester School of Management, Manchester*, 23.
6. Kuzmin I.V., Golyachenko A.O., Kilivnik V.S., et al. (2015). Matematychnye modelyuvannya protsesiv upravlinnya okhoronoyu zdorov'ya. [Mathematical modeling of health management]. *Ternopil: Lileya*, 96. [in Ukrainian].
7. Hochbaum, D.S., Lyu, C., & Bertelli, E. (2013). Evaluating performance of image segmentation criteria and techniques. *EURO Journal on Computational Optimization*, 1, 155–180. <https://doi.org/10.1007/s13675-012-0002-8>.
8. Kuzmin, I.V., & Rudyk, S.L. (2014). Entropy and information of control, chaos and catastrophes. *1st International Scientific-Practical Conference Problems of Infocommunications, Science and Technology (PIC S&T-2014)*. IEEE, 15-16. <https://doi.org/10.1109/INFOCOMMST.2014.6992282>.
9. Kuzmin, I.V., Robotko, S.F., & Rudyk, S.L. (2015). Definition of the period of control for the condition of technical means of infocommunication systems in MRP II manufacturing execution systems. *2nd International Scientific-Practical Conference Problems of Infocommunications Science and Technology (PIC S&T-2015)*. IEEE, 12–14. <https://doi.org/10.1109/INFOCOMMST.2015.7357255>.
10. Russ, J.C. (2016). The Image Processing Handbook. *CRC Press, 7th edition*.
11. Gonzalez, R.C., & Woods, R.E. (2017). Digital Image Processing. *Pearson, New York, 4 editions*.
12. James, G., Witten, D., Hastie, T., & Tibshirani, R. (2013). An Introduction to Statistical Learning - with Applications in R. *Springer, New York*.
13. Otto, S.A., Kadin, M., Casini, M., Torres, M.A., & Blenckner, T. (2018). A quantitative framework for selecting and validating food web indicators. *Ecological Indicators*, 84, 619-631, <https://doi.org/10.1016/j.ecolind.2017.05.045>.
14. Kuzmin, I.V., Rudyk, S.L., Gertsy, A.A. & Seleznova, R.V. (2017). Principles of construction of applied cybernetic systems. *4th International Scientific-Practical Conference Problems of Infocommunications Science and Technology (PIC S&T-2017)*. IEEE, 237–240. <https://doi.org/10.1109/INFOCOMMST.2017.8246387>.
15. Menegaz, H. M. T. Ishihara, J. Y., Borges, G. A. & Vargas, A. N. (2015). A Systematization of the Unscented Kalman Filter Theory. *IEEE Transactions on Automatic Control*, 60(10), 2583-2598. <https://doi.org/10.1109/TAC.2015.2404511>.
16. Gertsy, A.A. (2015). Kriterialna ocinka yakosti funkcionuvannya multiservisnyh merezh [Criterial evaluation of the quality of functioning of multi-service networks]. *Collection of scientific works of the State University of Economics and Technology of Transport "Transport Systems and Technologies"*, 26-27, 206-215. [in Ukrainian]
17. Gertsy, A.A., & Botvin, M.M. (2018). Analiz grafichnyh formativ ta algoritmiv koduvannya cifrovyyh zobrazen. [Analysys of graphic formats and algorithms of coding of digital images]. *Collection of Scientific Papers of the State University of Infrastructure and Technologies "Transport Systems and Technologies"*, 32(2), 102-112. [in Ukrainian] <https://doi.org/10.32703/2617-9040-2018-32-2-102-112>.
18. Vedantam, R., Lawrence-Zitnick, C., & Parikh, D. (2015). Cider: Consensus-based image description evaluation. *Proceedings of the IEEE conference on computer vision and pattern recognition*, 4566–4575. <https://doi.org/10.1109/CVPR.2015.7299087>.

19. Jamroz, D (2014) Application of multidimensional data visualization in creation of pattern recognition systems. In *Man-Machine Interactions* 3, 242, 443–450. Springer International Publishing. https://doi.org/10.1007/978-3-319-02309-0_48.
20. Wang, Z., Wang ,E., & Zhu, Y. (2020). Image segmentation evaluation: a survey of methods. *Artif Intell Rev*, volume 53, 5637–5674. <https://doi.org/10.1007/s10462-020-09830-9>.
21. Timchenko, L. I., Kokriatskaia, N. I., Pavlov, S. V., Stepaniuk, D. S., Kutaev, Y. F., Kotyra, A., Sagymbai, A., & Abdihanov, A. (2020, October). Q-processors for real-time image processing. In *Photonics Applications in Astronomy, Communications, Industry, and High Energy Physics Experiments 2020* (Vol. 11581, pp. 116-123). SPIE. <https://doi.org/10.1117/12.2580230>.
22. Orazayeva, A., Wójcik, W., Pavlov, S., Tymchenko, L., Kokriatska, N., Tverdomed, V., Tussupov, J., Abdikerimova, G., V., & Semenova, L. (2022, December). Biomedical image segmentation method based on contour preparation. In *Photonics Applications in Astronomy, Communications, Industry, and High Energy Physics Experiments 2022* (Vol. 12476, pp. 21-26). SPIE. <https://doi.org/10.1117/12.2657929>.

¹Олександр Герцій

¹Доцент, Кафедра Автоматизація та комп'ютерно-інтегровані технології транспорту, Державний університет інфраструктури та технологій, вул. Кирилівська, 9, м. Київ, 04071, Україна, ORCID: <https://orcid.org/0000-0002-8634-5880>

Моделі критеріальної оцінки ефективності систем обробки зображень

В статті досліджуються критерії, які застосовуються для оцінки ефективності систем обробки зображень. Проаналізовані вимоги, які пред'являються до критеріїв ефективності. Проведено вибір і обґрунтування приватних критеріїв, які застосовуються для систем обробки зображень. Такі параметри як швидкодія, вартість системи, апаратурні витрати характеризують в більшій мірі саму систему і залежать від її конкретного виду. Показано, що критеріями, які характеризують якість методу обробки являються інформаційна здатність, імовірність виконання задачі, точність алгоритму оброблення зображень. Показано, що такий критерій вірності як нормована середньоквадратична помилка найбільше відповідає вимогам до критеріїв ефективності. Досліджені моделі критеріїв ефективності, які основані на нормованій середньоквадратичній помилці стосовно дискретних зображень. Приведені результати моделювання і отримані залежності функцій вартості від швидкості обробки інформації в системі. Наведено методику вибору узагальненого критерію, якій характеризує не лише систему обробки інформації, а й методи, що застосовуються для реалізації цієї системи. Одержано узагальнений критерій вартості, аргументами якого є точність роботи системи, швидкодія, вартісні витрати. Запропоновано алгоритм застосування узагальненого критерію для системи обробки зображення.

Ключові слова: Критерій ефективності, система обробки зображень, нормована середньоквадратична помилка.

UDC 656.614.2

Iuliia Mykhailova¹, Anastasiya Steba^{2*}, Galina Silvanskaya³, Marina Vil'shaniuk⁴

¹Assistant professor, Fleet operation and shipping technology Department, Odesa national maritime university, 34, Mechnikova str., Odesa, 65029, Ukraine ORCID: <https://orcid.org/0000-0002-4882-7803>

²Senior Lecturer, Fleet operation and shipping technology Department, Odesa national maritime university, 34, Mechnikova str., Odesa, 65029, Ukraine ORCID: <https://orcid.org/0009-0005-5777-9785>

³Assistant professor, Fleet operation and shipping technology Department, Odesa national maritime university, 34, Mechnikova str., Odesa, 65029, Ukraine ORCID: <https://orcid.org/0000-0002-1272-8029>

⁴Senior Lecturer, Fleet operation and shipping technology Department, Odesa national maritime university, 34, Mechnikova str., Odesa, 65029, Ukraine ORCID: <https://orcid.org/0000-0001-5396-6691>

*Corresponding author: steba.anastasiya@gmail.com

Commercial and legal conditions for the organization of sea passenger transportation

This article explores current trends and prospects in passenger cruise ship chartering. In light of events in recent years, including the global COVID-19 pandemic, the cruise industry has faced serious challenges, prompting companies to look for new approaches to support their operations. The article examines different chartering models, including long-term and short-term agreements, as well as the possibility of sharing vessels between operators. Two organizational and legal forms of operation of marine passenger ships are considered in more detail: liner and cruise. Formalized and provided a schematic representation of the process of interaction of the participants of sea passenger transportation in various forms of ship operation. The interaction schemes of the shipowner, the charterer and the managing agent are described. The interaction technology of the participants in the passenger transportation process is considered in the context of the types of ship charter contracts. Differences in technological processes of interaction of participants in the process of organization and provision of sea passenger transportation, distribution of responsibilities, risks, costs and income in the organization of sea passenger transportation according to various schemes of interaction of participants are given.

Keywords: *passenger transportation, shipping companies, sea transportation contract, ship rental, charter.*

Introduction. At the stage of market instability, under current circumstances, Ukraine is unable to build and purchase marine passenger ships for the organization of passenger transportation. However, taking into account the logistical and tourist potential, this issue remains promising. Creation of own network of maritime passenger communications is absolutely necessary. Otherwise, this free segment of the market will be occupied by foreign capital. The small fleet of domestic shipowners, working sporadically, with separate voyages, on the Greek and Italian routes, will also not hold their positions in the long run. Therefore, the need to develop and revive cruise routes in the Black Sea region remains relevant. For the effective organization of the process of sea transportation of passengers, it is important

to have a clear understanding of the conditions of interaction of the participants in this process, which determines the relevance of this study.

Analysis of recent research and problem statement. With the development of international contacts, shipping enterprises of Ukraine entered shipping market. However, the problems of the development of the activity of shipping enterprises, as before, remain complex and multifaceted and require a comprehensive and professional approach, both from the state and from the side of the shipping enterprises themselves. Analysis of the operating conditions of shipping companies during the transition to market relations and internal aspects of activity allows to formulate a strategy for ensuring the sustainable functioning of shipping enterprises.

The study of theoretical and practical of and foreign scientists, such as V.V. Basevych, M.N. Bilenkyi, B.V. Burkinskyi, S.V. Glebov, Sh.M. Gurevich, B.A. Ridota, L.K. Kendall, O.A. Kybalchich, M.I. Kotlubai, A.M. Kotlubai, M.E. Lynskyi, G.S. Makhurenko, I.V. Morozova, H.P. Pylypenko, M.G. Lyokhovy, M.Ya. Postan, N.T. Primachev, N.I. Savin, V.I. Chekalovets, J. Codsmann, A. Dessler, A. Lawrence, T. Plisley and many others [2, 3, 4].

The domestic authors, including M.E. Lynsky, V.S. Petukhov, N.T. Primachev, A.N. Tymoshchuk et al.

It is necessary to note the absence of scientific research in the domestic literature in this field for a long period of time. Modern problems of the development of maritime passenger transportation are considered in the works of B.A. Lynskyi, V.V. Markov, S.I. Rylov, A.A. Siomin et al [10, 13]. But, despite the detailed study of individual areas of development shipping market in scientific research by domestic scientists, there is no systematic knowledge in the field of functioning of Ukrainian shipping companies on the cruise shipping market in modern conditions.

The efficiency of transport management can be increased only by using the experience of generations and the achievements that already exist, which is a necessary condition for survival in the competition. Studying the theory allows to determine the principles of construction of the transport system, categories and types of transport, historical patterns of the construction of transport systems, classification schemes of the world transport market.

The existing scientific works and articles highlight the current problems and directions of development of the maritime passenger transport industry, carried out by scientists of the transport industry, such as A.V. Selivanov, V.G. Boyko, M.P. Gerasymenko, S.V. Malska, I.M. Pisarevskyi, E.V. Stetsyuk, F.I. Khmil, A.A. Zaitsev, V.V. Panin, I.A. Golubkova – works on regional transportation.

In particular, V.V. Panin considers the prospects and development of integrated transport and logistics systems of the Dniepro basin, the Danube and the Black Sea as a component of the transport system of Ukraine. The imperfect legacy of the Soviet Union in the form of outdated infrastructure, together with a morally outdated management system, outdated technologies and pricing led to a significant decrease in the efficiency of the transport system of Ukraine as a whole, and in particular to an increase in the transportation price, a decrease in traffic flows, and unprofitable logistics. The main problem of V.V. Panin considers the absence of a systematic approach in state regulation of the transportation system. V.V. Panin considers the Danube region as an optimal transit channel Dnipro-Danube, Black Sea-Volgodon-Bosphorus. Such systems worked in the Black Sea Maritime Shipping, on the Danube River, nowadays such systems work in the USA, Canada, Great Britain, Germany and France.

In the works of V.V. Selivanov illuminated the tourist aspect of passenger transportation. The involvement of travel companies in the carrier business and the use of existing developments would allow the development of the passenger transportation market, including such different types as ferry transportation, coastal transportation, short-distance transportation, and segment cruise shipping. The articles consider the passenger transport market and its interaction with other markets - the transport market as a whole, the shipping market, the entertainment and recreation industry market, the tourism market, and the cruise charter market (cruise tonnage charter).

I.A. Golubkova emphasizes systematization in shipping, substantiates the principles of world shipping, presents a set of tools for the development of regional cruises and the shipping business as a whole [5].

In our opinion, the most detailed and essential description of the development processes of cruise tourism is revealed in the works of M.B. Birzhakov V.I. and Nikiforova, in which scientists consider the conditions for the emergence of cruises and their evolution from a historical perspective, systematize the principles of organizing cruise routes, analyze the geography of cruise activity and the features of ships intended for cruising. The authors pay attention not only to the process of serving tourists on board the ship, but also to the system of realization and promotion of the cruise tourist product, the problems of embarking and disembarking passengers in seaports [6, 14]. At the same time, despite a rather detailed description of the processes of the cruise industry, the works of scientists do not present an economic interpretation of indicators that assess the level of development of the studied processes in the context of a comprehensive analysis of their constituent elements [11].

The transport component is undoubtedly an important part of the tourist business, but other aspects should be taken into account - primarily organizational and social, due to the fact that cruise transportation is undoubtedly a complex business. The problems of insufficient attention to these aspects have a negative impact on the development of maritime passenger transport as a whole and on the decrease in demand for cruise transport services.

The aim and objectives of the research. The purpose of the work is to consider and formalize the commercial and legal conditions of interaction of the participants in the process of organizing sea transportation of passengers. To achieve the aim, the following objectives are set:

Consider the organizational and legal conditions for the operation of marine passenger ships.

Formalize and provide a schematic representation of the process of interaction of participants in maritime passenger transportation in various forms of ship operation.

Consider the interaction technology of the participants in the passenger transportation process in the context of types of ship charter contracts.

Research materials and methods. The world market of maritime passenger shipping is divided into the market of liner transportation and cruise shipping according to the form of organization (Fig. 1) [12].

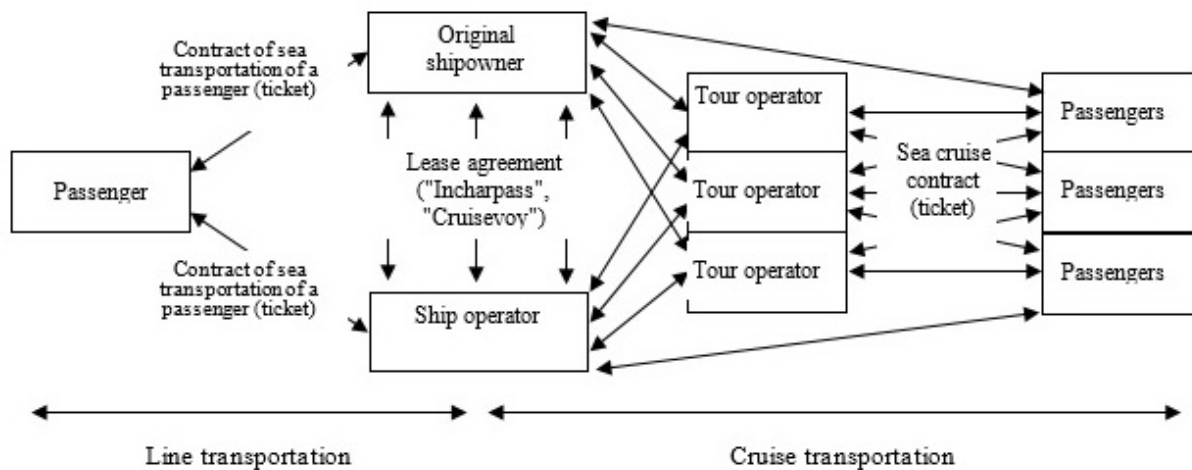


Fig. 1. Organizational and commercial provision of sea passenger transportation

Customers of passenger sea transport services are:

- individual passengers who buy tickets for linear transportation and cruises and thereby conclude contracts for sea transportation and maritime transport cruise;
- tourist organizations that charter passenger ships for the organization of cruises or book tickets for linear transportation (organizers) (Fig. 1).

Counterparts are companies engaged in ship agency, ticket and cruise ticket sales, organization of excursions and outings, etc.

The operation of the passenger fleet is associated with two organizational forms - ship operations - linear navigation and cruise voyages.

These two forms of work also determined the commercial nature of the use of passenger ships [1]. Thus, in the practice of global passenger shipping, depending on the form of the organization, two schemes of commercial interaction of the shipowner, operator and passengers are distinguished (Fig. 2):

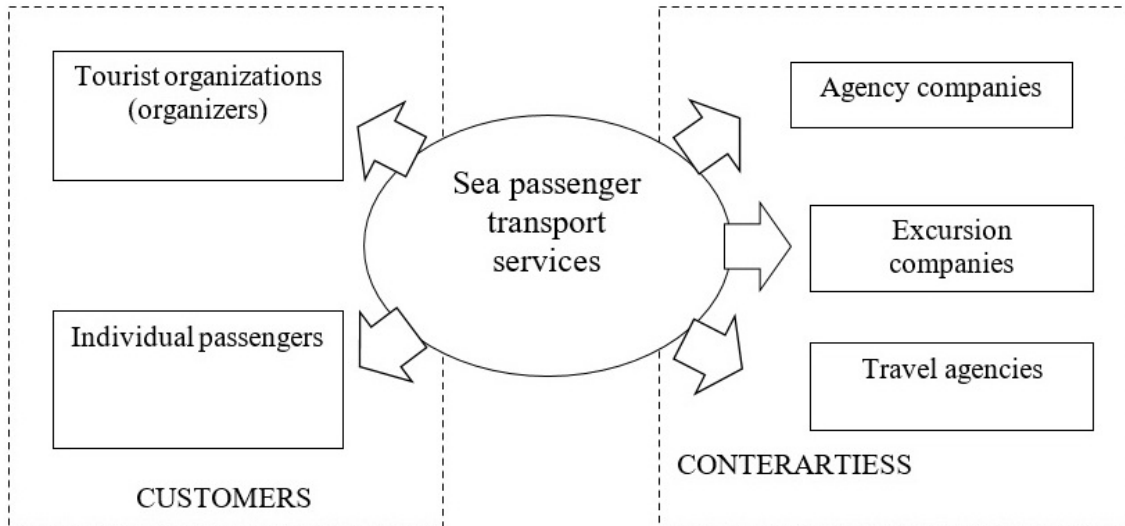


Fig. 2. Customers and counterparties of marine passenger transport services

1) if the shipowner is the organizer of transportation. The tariff rate is set in advance unilaterally by the shipowner and is valid for a fairly long period of time. It can be used by any customer who wants to use the shipping company's services. In the field of passenger shipping, tariff rates are applied on local, cabotage and international lines, as well as in cruise shipping when cruises are organized by shipping companies.

2) if the transportation is organized by a tour operator. Then the shipowner receives a fee for renting the ship under the condition of a time or bareboat charter, and the operator sets passenger tariffs for transportation. The rental rate when using charter contracts is established in each individual case as a result of the agreement between the shipowner and the charterer and is fixed in the charter contract. When organizing transportation on a ship chartered by it, the charterer (tour operator) sets passenger tariffs by which it sells tickets directly to the passenger (tourist).

During the performance of linear transportation, the maritime contract is valid transportation of passengers, which is considered concluded after the purchase of a travel ticket.

When organizing cruises on chartered vessels, two types of contracts apply:

- a sea cruise contract, which acts as a cruise ticket and regulates the relationship between the charterer as the cruise organizer, who carries out this cruise, and the tourist;
- the lease agreement, which regulates the interaction between the shipowner and charterer

The basis of the contract for chartering a passenger ship is the interest of the shipowner and the travel company to preserve its commercial prestige and competitiveness in the market. Therefore, both parties place on each other the obligation of high-quality passenger service in the field of competence of the ship or travel company: omissions of one party undermine the reputation of the other, since the passenger perceives the cruise as a single enterprise.

The charterer's income is generated from the sale of cruise tickets and is directly proportional to the number of passengers involved. Thus, the risk of unprofitability of the cruise rests entirely with the

charterer (operator). The shipowner's income consists of the rent, as well as the profit from the provision of paid services (above those that it is obliged to provide to the passenger for free) and trade on board the ship (kiosks, bars, restaurants).

When organizing cruises at the risk of the shipowner, it bears all costs related to the execution of cruises and receives full income from the sale of tickets or vouchers for such voyages. Travel agencies and other intermediary organizations are involved in advertising and distribution of tickets, for which the shipowner pays them a commission, which is calculated as a percentage of the amount for which the tickets are sold.

In the second case, when the charterer assumes the risks related to the organization of the cruise, it is provided with a passenger ship for rent for the duration of the cruise. Let's consider the establishment of such a form of relationship between the shipowner and the charterer as a chartering operation of a passenger ship.

The process of concluding a freight agreement is carried out with the help of conditional and firm offers (offers). A conditional offer is given to several shipowners in order to find out the demand in the market, to find out the availability of free tonnage, to call for its offer. Only after that, the most suitable shipowner is given a firm offer valid for a certain period of time. Its acceptance means the conclusion of a freight agreement. However, full acceptance of such an offer is an extremely rare phenomenon due to differences in the parties' positions on a number of conditions (usually, the main one is the rental rate). Therefore, the party that received the offer issues its counteroffer. This process of exchange of offers and counteroffers continues until the interests of both parties converge (as a result, a freight agreement is concluded) or the negotiations are terminated (in case of impossibility of reaching an agreement) and the search for new counterparties. In some cases, when the charterer has a clear intention to charter a specific ship of a certain shipowner, the chartering process begins with a firm offer.

The concluded agreement is drawn up with a charter. The broker, taking part in its implementation, not only provides qualified assistance in the process of negotiations and convergence of the parties' positions, but also draws up the charter and in some cases monitors its implementation. For this, it receives a brokerage fee, the amount of which is set as a percentage of the freight amount.

In the practice of passenger shipping, depending on the form of transport organizations, the following types of charters are distinguished:

- time charter
- voyage charter;
- bareboat charter.

Time charter for passenger vessels. When chartering passenger vessels for time charter, a pro forma code-named "Incharpass" (Passenger Charter Party), issued in 1967 by the Institute of Freight Brokers of Great Britain (Institute of Chartered Shipbrokers). In many respects, the pro forma is similar to the usual terms of a time charter contract, but it sufficiently takes into account the specifics of the execution of cruise voyages and passenger transportation.

The characteristics of the ship are not stipulated in detail in the contract, since it is a specific ship, well known to the charterer, but the shipowner hands over to the charterer a number of mandatory appendices to the contract relating to the "passenger characteristics" of the ship, namely:

Appendix 1 (Description of the Vessel), which contains information about: passenger quarters of the ship; capacity of cargo compartments intended for the storage of passenger luggage; volumes of fresh water taken on board; capacities of lifeboats and rafts; the number of seats in restaurants and salons; characteristics of air conditioning systems and duck tranquilizers.

Appendix 2 (Vessel's Passenger Accommodation Plan) contains a plan-diagram of passenger spaces. All premises indicated in the plan-scheme must be made available to the charterer.

Appendix 3 (Services that Be Provided by Owners) contains: services that the shipowner undertakes to provide to passengers to ensure their rest and treatment, with the obligation to maintain devices in a condition suitable for effective operation during operation; services that the shipowner provides to passengers on board the ship free of charge (first aid, games, swimming pool, etc.); a list of paid services that the shipowner must provide on board the ship (communication services, special household services,

showing movies, etc.). The hours of operation of establishments on board the ship are agreed with the charterer, in turn the shipowner must provide them with a sufficient range of food, drinks and other provisions. The charterer has the right to independently and at its own expense organize the entertainment of passengers on board, however, the nature of the entertainment on board must be agreed with the shipowner or captain.

Appendix 4 (Inventory) is a form of inventory information and contains: equipment; adaptation; games, slot machines, etc., the assortment of which is specified by the parties upon delivery and upon return of the ship from the time charter.

Appendix 5 (Owner's Standard Form of Passenger Ticket) contains a typical passenger ticket form developed by the shipowner and the charterer. This form must be approved by the Mutual Insurance Company (To be Approved by Owner's P&I Association) and recognized by the contract concluded between the charterer and the passenger (Embodied in Charterer's Contract with Passenger).

The schedule of the route with the ports of call and the time of arrival and departure of the ship at each port is also a mandatory appendix to the contract. The specifics of chartering a ship for one or more voyages allow to accurately determine the total term of the ship's lease, which simplifies the planning of the ship's operation and the lease calculations.

The length of the route, the duration and the ports of call are agreed upon in the time charter, so the shipowner's income, expenses and profit during the normal course of the voyage are certain values known in advance.

The chartering contract of a passenger ship stipulates the procedure for resolving disputed issues, terminating the contract, indemnifying damages, regulating the accounting of acts of unforeseen circumstances and force majeure.

Let's consider the main commercial and legal conditions of the specified contract. They can be reduced to six main groups.

1. Ship. The shipowner provides the charterer with a passenger ship, specifying in the contract its passenger capacity, broken down by individual classes. A plan for the placement of passenger cabins is attached to the contract, the seaworthiness of the ship and the obligation of the shipowner to maintain it in proper technical condition are specifically stipulated.

The pro forma, in addition to the general requirements for the shipowner regarding the seaworthiness of the ship, contains requirements for cleaning living and other spaces used by passengers. The entire space and capacity of the ship is transferred to the charterer, except for the premises for the captain, command staff, crew, supplies, inventory, bunker, provisions and equipment.

2. The period of the ship's stay with the charterer and regulation of its work. The charterer charters the ship for a certain period, which is calculated per day. The start and end times of this period, as well as the number of voyages, are precisely marked. A characteristic feature of this contract is the presence of an agreed schedule, which firmly defines the rules of the ship's movement in single or consecutive voyages. This schedule is attached to the contract and is part of it. It should be noted that the contract states that the ship is provided to the charterer for the organization of passenger transportation, i.e., the purpose of its work is clearly and unambiguously defined.

3. Distribution of costs between the shipowner and the charterer. Services provided on board the ship. The expenses related to the execution of voyages between the shipowner and the charterer are distributed according to the principle of assigning fixed costs to the shipowner, and variable costs to the charterer. It is worth noting that the mode of operation when renting a passenger ship and the ports of call are regulated by the schedule. Therefore, the shipowner can accurately calculate fuel costs, port ship fees in advance and more logically assign them to the permanent category.

Among the variable costs attributable to the charterer, in particular, the following articles should be noted:

- port fees for boarding and disembarking passengers, transit fees, payment of ship's raid service, fees for boarding and disembarking passengers at ports of embarkation and disembarkation, as well as possible fees for transit passengers at planned ports of call;

- payment of the difference between the actual amount of port fees and the amount of these fees, calculated according to preferential tariffs, in the event that the shipowner loses the right to benefits in this field, granted to passenger ships, as a result of the charterer embarking or disembarking passengers at intermediate ports of call;

- payment of vessels of the port of call, which deliver passengers from the raid to the shore and back in case of a raid parking of the ship in those ports where the approach of the ship to the pier is impossible for technical reasons (shallow depths, short length of the pier, etc.). If, during the voyage, the ship cannot be docked or will not be accepted at one of the scheduled ports of call, due to force majeure circumstances (weather conditions, quarantine, etc.), which will cause raid operations regarding the boarding and disembarking of passengers or will force, by mutual agreement, to replace scheduled port of call to another with higher rates of port fees, then all additional costs must be distributed between the shipowners and the charterer in equal shares on a parity basis;

- expenses for shore excursion service for passengers;

- voyage advertising and other similar expenses.

Costs for the purchase of fuel and lubricants for the ship, galley and electric lighting are borne by the charterer, fuel for motor lifeboats is provided by the shipowner. This condition does not in any way affect the commercial conditions of the lease, but pursues only the strengthening of the shipowner's responsibility for the condition of the lifesaving equipment.

The contract stipulates in detail the types of services that must be provided to passengers on board the ship during the voyage at the expense of the shipowner, the charterer or personally paid for by the passengers. The organization of leisure and entertainment of passengers on board the ship is carried out by the charterer (in agreement with the captain of the ship). Medical assistance on board the ship is provided free of charge.

If extraordinary expenses arise during the voyage as a result of force majeure or government orders, they are usually shared equally between the shipowner and the charterer.

4. Rental rate and payment procedure. the rental rate is stipulated in the charter in the form of a rate for the ship or a kind of " lump sum " payment for the term of the ship's lease. At the same time, the entire passenger capacity fixed in the contract is taken into account, without taking into account its actual use. The rental fee is set for each day, since the duration of the voyage is precisely determined, the total rental amount is known in advance. Rent is paid in advance for the agreed term, and in case of delay in payment, the shipowner cannot withdraw the ship from the voyage, but can charge a penalty on the amount of payment for each day of delay in the amount established by the contract.

The shipowner guarantees the execution of the voyage in exact accordance with the schedule and is responsible for any delays, if they are not related to the fault or omissions of the charterer. The charterer can unilaterally consider the voyage completed and demand the return of unearned rent if the ship is out of service for more than three consecutive days. In the event of the ship's loss or the impossibility of continuing the voyage due to force majeure or other reasons beyond the control of the shipowner and the charterer, the ship's charter fee is paid until the actual termination of the voyage.

The currency of payment must be specified. When chartering vessels, the currency of the charterer's country is used. In the latter case, clearing may be used.

The contract provides payment terms, penalties for non-compliance, names of operator banks. In some cases, when chartering ships by charterers from other countries, the shipowner is provided with a bank guarantee.

5. Meals for passengers. Special attention is paid to the regulation of passenger meals, bar maintenance and provision of drinks, protocol events and presentations. In addition, the number of meals and the daily cost of the passengers' ration, which the shipowner has no right to reduce, are agreed in the contract. At the end of the voyage, the shipowner's expenses for passenger meals are compensated by the charterer, based on the actual number of passengers on board.

Charterers pay the cost of meals additionally, based on the actual number of passengers on board. The contract establishes a daily rate per passenger and, based on it, a part of the cost of passenger meals

is paid by the charterer to the shipowner in advance, and the final calculation is made after the voyage is completed.

6. Legal principles. Here, first of all, it should be noted the regulation of issues related to the termination of the contract, which may arise in the event of unforeseen circumstances that do not depend on the shipowner and the charterer, such as: war, blockade, delay of the ship by the order of the authorities in ports of call, orders of governments, damage to the ship's hull or machinery. In this case, the freight is charged only for the number of actual days of the ship's stay with the charterer.

In separate articles of the contract, the procedure for its termination at the initiative of the shipowner or charterer and the penalties associated with this, as a rule, are determined (covering the actual losses of the other party). Issues related to the possible termination of the voyage due to the ship's accident, which cannot be eliminated within a three-day period, are discussed separately. In this connection, the obligation of the shipowner to compensate the charterer for part of the rental fee for the remaining unused days is established. Issues of lien law are not touched upon here.

One of the articles of the charter envisages the mandatory entry of the chartered ship into the Mutual Insurance Club. At the same time, the payment of the specified commercial transaction belongs to the charterer.

Although the ship is chartered with the shipowner's crew, this charter has certain elements of a bareboat charter. In particular, the charterer has the right to paint the ship's hull and superstructures in other colors, to put its emblem on the chimney, and to fly under its company's flag during the lease period.

All claims of passengers regarding the program, organization and conduct of the cruise are regulated by the charterer. The presence of representatives of a tourist or cruise company on board a passenger liner and 24-hour work with passengers requires the regulation of labor issues and the ship's relations with the border and emigration authorities. Usually, the charterer, if this is provided for by the ship's article (The Vessel's Article), pays the crew overtime (Overtime), and the shipowner – enters in the ship's documents mandatory representatives of the charterer (tourist company, etc.) as "personnel hired overtime" ("... be signed it as supernumeraries in the Vessel's Articles").

Voyage charter for passenger ships. "Cruisevoy" is the pro forma voyage charter for passenger vessels. This standard document is intended for wide use by companies - cruise fleet operators and charterers - travel firms that organize sea cruises. **"Cruisevoy" allows a cruise ship, with an agreed route and voyage schedule, to be chartered by several different charterers or tour operators at once.** At the same time, each of them acts as a charterer of the corresponding quota of the ship's passenger capacity on behalf of its customers on a proportional basis.

"Cruisevoy" foresees the need for long-term planning of the work of tour operators involved in the organization of short-term cruises. At the same time, planning is expected no later than a year before the expected start of the cruise. The pro forma contains equal conditions for termination and termination of the contract when circumstances prevent the cruise, delay or interrupt the voyage.

The pro forma provides charterers with a complete description of the ship, the equipment on board and the intended cruise route, enabling the charterer to conduct effective marketing to customers. Particular emphasis is placed on ensuring that charterers are fully aware of the time constraints required for embarking/disembarking passengers and loading/unloading baggage, in order to avoid disruption to the overall cruise programme. This circumstance is important in cases where several tour operators work on the same cruise ship, each of which ensures the embarkation/disembarkation of its passengers in different ports during the same voyage.

Among all the new charter proformas recently developed by BIMCO, Cruisevoy is characterized by such a format that embodies standard approaches to the composition and placement of various information, including the rental rate, full name and other characteristics of the parties to the contract. 5 appendices have been developed to the pro forma, containing detailed information about the cruise route, a description of the living quarters, catering facilities, types of payments, as well as a sample passenger ticket.

Bareboat charter for passenger ships. Bareboat charter is a contract under which the shipowner leases the ship to the charterer for a certain period of time without the crew and the ship's supplies for a fee. The pro forma used to conclude a bareboat charter agreement is called "Barecon-89". In this agreement, the charterer accepts wider rights to use the ship than under the terms of a time charter. It fully controls its operation and the shipowner does not interfere in the issue of operation. The ship can be operated under the flag of the charterer's country, which has the right to rename it.

Thus, under the terms of a bareboat charter, the charterer becomes the owner of the ship for the duration of the contract and can use it at its discretion, while it bears almost the entire commercial risk of operating the ship. The owner of the ship for its use by the charterer usually receives a fixed monthly rent specified in the contract, regardless of the commercial performance of the ship.

The charterer of a ship under a bareboat charter becomes a temporary shipowner, since such a contract gives legal title to the owner of the ship, regardless of whether it owns the ship or uses it on another legal basis. A bareboat charter is a "legal basis" for operating a ship on its own behalf, and only within the framework of this contract does the party that accepts the ship become its shipowner.

A bareboat charter, unlike a voyage charter or a time charter, does not provide for a detailed distribution of the obligations and costs of the parties regarding the maintenance and commercial operation of the ship, as well as the execution of voyages. The commercial conditions of a bareboat charter are very simple and boil down to the following: protection of the rights of the ship owner; insurance of property and other risks; financial settlements of the parties. The shipowner pays for fuel and engine oil on board, as well as all unpacked seats and ship's supplies.

The rights of the charterer for the use of the ship are defined very broadly, since the ship is transferred to its possession and under its full control. However, there are some restrictions related to the preservation of the legal and physical property rights of the shipowner:

- the charterer may not use the ship for illegal transportation, which may lead to confiscation of the ship;
- the ship should not be operated in areas of high latitudes and other areas not covered by normal CASCO insurance.

Maintenance and operation of the ship is carried out at the expense of the charterer in full compliance with the requirements of international conventions, classification societies and rules of technical operation. The shipowner has the right to monitor the condition of the ship, the conditions of its operation and maintenance, compliance with classification requirements regarding the periodicity of docking, cleaning and painting of the hull. The shipowner carries out such control with the help of surveyor inspections of the ship, which can be carried out at any time and in any port of call of the ship. If it is found that the charterer operates the ship in violation of technical rules or classification requirements, does not carry out timely repairs, docking and measures to maintain the ship's class, the shipowner has the right, after an appropriate warning, to withdraw the ship from operation without prejudice to its other requirements regarding the bareboat charter (except for the case of subsequent repurchase of the ship by the charterer). If, during the bareboat charter period, international or national regulations require the ship to be modernized or equipped with some additional equipment, the charterer must do so at its own expense, however, if the amount of the charterer's expenses for these measures exceeds 5% of the actual value of the ship, this may serve as a basis for review of rent or other expense regulation incurred by the charterer.

Payment for the lease of the ship in the bareboat charter is made in advance for the agreed period of the future operation of the ship. In the event of non-payment of rent within 7 consecutive days, the shipowner has the right to withdraw the ship from the bareboat charter without prejudice to its other claims against it (with the exception of the option of the contract with the subsequent purchase of the ship).

Under the conditions when the shipowner concludes sea transportation contracts on its behalf as a carrier, insurance of its property interests and liability risks is its voluntary decision. In a bareboat charter, risk insurance becomes a contractual condition, but most often this duty is entrusted to the charterer, who must insure: property risks of the shipowner on the widest terms of CASCO insurance

coverage; risks of liability of the shipowner to third parties; carrier (charterer) liability risks. In connection with the fact that the liability of the charterer as a bareboat shipowner or carrier may lead to the seizure of the ship, which in turn will create a threat to the preservation of the right of ownership. According to the terms of the Vageson-89 pro forma, property insurance of the ship against maritime and military risks can be carried out both at the expense of the charterer and at the expense of the owner of the ship, which is reflected in the amount of the rental fee, respectively.

Other bareboat charter conditions include the following:

- the charterer cannot pledge the ship or allow its detention or arrest as a result of its actions. In any case, the detained (arrested) ship must be released immediately at the expense of the charterer. Regarding the impossibility of bailing the ship, the charterer must place a warning on the bulkhead of the running room: "This ship is the property of..., the ship is leased from..., and under the terms of the bareboat charter, neither the charterer nor the captain has the right and is not authorized to carry out or allow any lien on the ship to be exercised";
- the reward for the rescue received by the ship as a result of a successful rescue operation belongs to the charterer; the costs of repairing damage to the ship received during the rescue operation, as well as other costs, are also charged to its account;
- any bills of lading or other transport documents signed on behalf of the charterer shall fully release the shipowner from any liability;
- in case of requisition (temporary seizure) of the ship by state authorities for a reward, such reward belongs to the charterer, and it must pay the shipowner the full rent for the entire period of requisition. In case of confiscation of the ship by the competent authority with loss of ownership of the ship, the bareboat charter is considered terminated;
- the war clause and the arbitration clause are of the nature usual for contracts of charter.
- bareboat charter in practice, along with fulfilling the function of a ship charter contract, it is used as an option for purchasing a ship on credit.

Thus, the bareboat charter provides for two options for ending the contract:

1. returning the ship to the owner;
2. redemption of the ship by the charterer (Fig. 3).

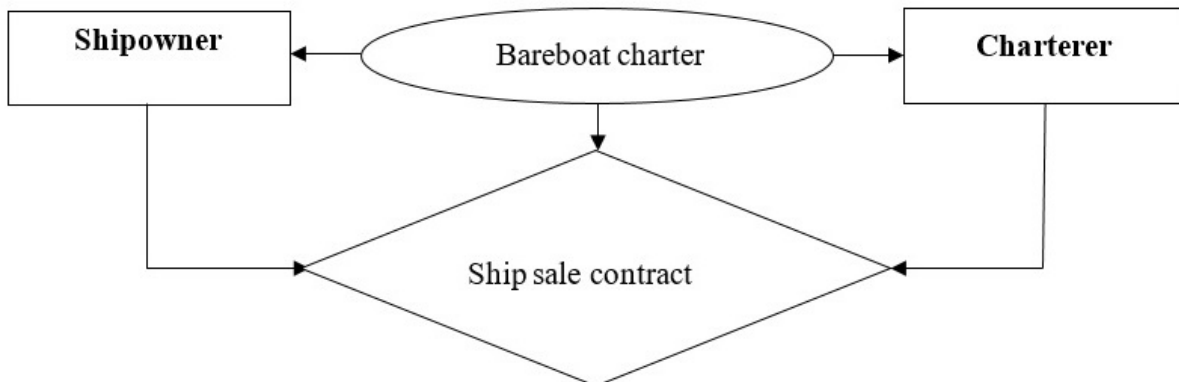


Fig. 3. Commercial relations of the parties in the form of a bareboat charter

The agreement on the purchase of the ship by the charterer after the end of the lease period is reduced to the following items:

1. an agreement on the future purchase of the ship must be reached at the time of concluding the bareboat charter.
2. The charterer has the right to redeem the leased ship if it has fully fulfilled its obligations regarding the bareboat charter.
3. The shipowner-seller guarantees that the ship is free of liens and other debts.

4. All expenses related to the removal of the ship from the registry of the home port shall be borne by the shipowner.

5. All expenses related to the registration of the ship after its purchase are borne by the charterer-buyer.

6. The charterer must settle all labor relations with the crew and other legal issues related to the change of ownership.

Agreement on ship management. The emergence of operating companies became another stage in the development of forms of organization and management of sea passenger transportation. In modern world practice, there are many companies that are separate from shipownership and specialize in ship management (ship management) or transportation organization.

Ship management (Ship Management) is a form of ship operation caused by the practice of separating the functions of shipownership from the function of professional management (management), when all work with agents-managers is based on the requirement of achieving the optimal economic effect through joint commercial activity as participants in the logistics transport chain.

A company specializing in ship management concludes a ship management agreement with the shipowner, in other words, a ship management contract, which is not a ship charter contract for a voyage or time, but an agreement for the performance of a wide range of management services. It should be noted that the traditional delivery of ships built or under construction to long-term bareboat or time charter has justified itself and is currently justified.

But the optimal solution for the results and prospects for the future turned out to be the concentration in the hands of the investor-shipowner (holding company, joint-stock company, financial and industrial group) of solving the following issues: investments, ensuring the quality of services, attracting capital, credit control, insurance. However, the operation of ships, marketing, chartering, issues of the technical condition of the fleet, provision of food, fuel supply, management of freight issues, crewing, reporting, etc., are advisable to be transferred to the management of highly qualified specialists – agent-managers.

Currently, in maritime transport, the separation of the function of ownership of ships from the function of their professional management has already affected more than 25% of the total number of the world merchant fleet and received its legal form in the standard agreement on ship management developed by BIMCO in 1998 under the code name "Shipman-98" (Standart Ship Management Agreement Code Name "Shipman-98"), on the basis of which the relationship between the shipowner and the managing agent is determined.

According to the ship management agreement, the agent-manager undertakes on behalf of the shipowner-principal and at its expense:

- to ensure a reasonable practice of ship operation management;
- to expand the interests of the shipowner in all aspects of transportation.

As a rule, the following functions are included in the scope of services provided under the ship management contract to the ship operator:

- crewing of the ship;
- ship maintenance;
- commercial operation of the ship;
- bunkering and other types of ship supply;
- accounting;
- ship insurance organization;
- other services, for example, conducting claim and lawsuit work.

All revenues from the operation of the ship go to the account of the shipowner, and the agent-manager is compensated for all expenses related to the operation of the ship, and the established remuneration agreement is paid (Fig. 4) [15].

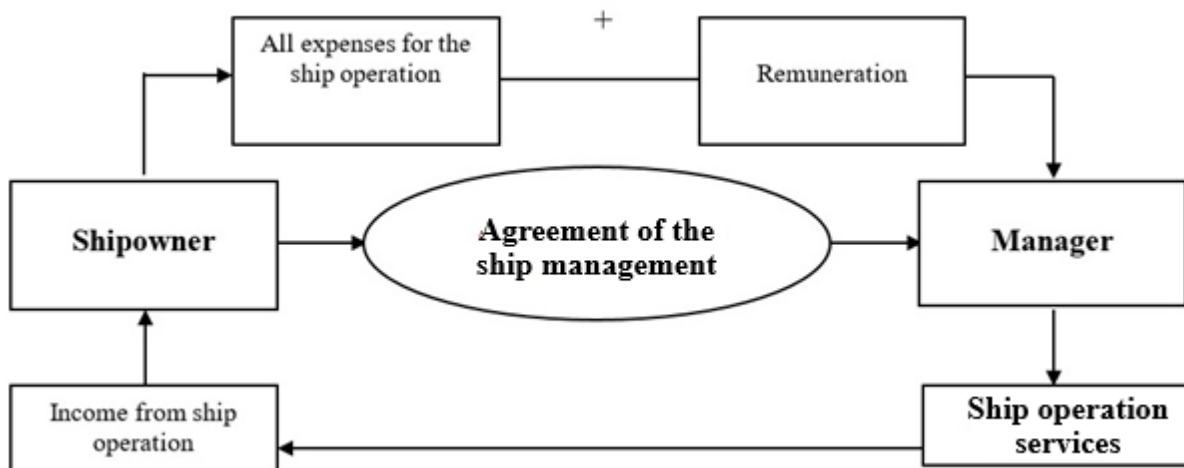


Fig. 4. Commercial terms of the ship management agreement

The manager may be assigned to supply the ship with provisions and fuel, but the choice of quality must be prescribed by the shipowner depending on the ship's operating conditions.

The main obligation of the shipowner is to pay the annual management fee in advance monthly payments, that is, in the form of prepayment, starting with the first payment, which is usually made immediately after the conclusion of the contract. Management remuneration is subject to annual review. It can be revised both upwards and downwards. If the ship is decommissioned for more than three months, the shipowner has the right to raise the issue of a corresponding reduction of the management fee for a period exceeding this period, but this period ends no later than one month before the return of the ship to operation. In addition, the shipowner must reimburse, at the request of the manager, all costs reasonably incurred by it under the terms of the contract of ship management, with the exception of office maintenance costs. In particular, postage and other communication costs, as well as travel expenses, are subject to reimbursement.

The manager's fee is an annual lump sum **payable in equal** quarterly advance installments. At the same time, the first payment is made at the beginning of the term of the agreement, and subsequent payments are made once every three months.

Very important is the condition that the shipowner must pay the manager a fee within three months after the termination of the agreement for reasons that are not related to the manager's failure to fulfill its duties or due to the death or sale of the ship. This condition also applies to the financial support of the ship's crew hired by the manager. Financial planning is carried out by drawing up an agreed estimate, which is valid for the first year of the agreement. The manager must submit the next estimate to the shipowner three months before the end of the current estimate. The shipowner is obliged to notify the manager of the acceptance and approval of the new annual estimate within one month from the date of submission of the draft estimate. If such notification is not received, the manager has the right to consider the estimate accepted.

The manager also prepares and presents to the shipowner an estimate of working capital, which is necessary for the operation of the ship. The estimate is updated every month, and the manager, based on it, asks the shipowner in writing about the allocation of funds for the next month. Funds must be available to the manager within 10 days after the shipowner receives the corresponding request. The manager must provide the shipowner with a comparative analysis of the ship's actual costs and those approved by the budget in the form required by the shipowner and at a frequency agreed by the parties, and by default – monthly.

The manager prepares and directs to the shipowner the calculation of the ship's need for working capital with the right of monthly clarification. Guided by the annual estimate and calculation of working capital, the manager asks the shipowner every month to transfer to it the funds necessary for the

operation of the ship, including covering unplanned expenses: for emergency repairs, additional insurance premiums, fuel and food.

Issues of general management are regulated as follows:

1. The manager undertakes to settle any claim related to its activities, as well as to inform the shipowner of any event known to it that may cause claims and disputes concerning third parties.

2. The shipowner has the right to give instructions to the manager to initiate or deny cases in court, to file lawsuits or to take other procedural actions in connection with the cases entrusted to the manager under this agreement.

3. The manager is given the authority to engage legal, technical or other experts.

4. The shipowner ensures that any necessary guarantee letter, subscription or other legal security is issued to the manager.

5. The shipowner undertakes to reimburse the manager for any expenses incurred by it in the performance of its obligations, while it has the right to conduct an audit of the manager's activities, but only in mutually agreed terms.

The operator can be authorized to sell and buy the ship.

The agreement considers in detail the procedure for terminating its effect, protecting both the interests of the principal - the shipowner and its agent-manager.

The ship management contract is close in its legal nature to the agency contract. The actions of the manager create, change or terminate the rights and obligations of the shipowner, therefore, all risks remain with the shipowner.

If the manager acts on behalf, then two types of relationships are formed in relations with third parties:

- internal agency relations – "agent-principal" relations;
- external relations formed between the agent and third parties, as well as between the principal and third parties in those legal systems that allow it.

The court management contract is valid until it is canceled by one of the parties. The contract enters into force on the day indicated in box 4 of part I of the pro forma. After the expiration of the period specified in box 17, each of the parties has the right to withdraw from the contract by notifying the other party about it in two months.

The pro forma "Shipman-98" is not without certain shortcomings, however, it is successfully used for the organization of the commercial operation of the ship by a third-party operator, as well as for the organization of the internal management of the ship.

Conclusions. The paper examines and formalizes the commercial and legal conditions of interaction of the participants in the process of organizing sea transportation of passengers. To achieve the goal, the following tasks were set and solved:

1. The organizational and legal conditions for the operation of marine passenger ships are considered.
2. The schematic representation of the process of interaction of sea passenger transportation participants in various forms of ship operation is formalized and provided.
3. The technology of interaction of the participants in the process of transporting passengers in the context of types of contractual relationships is considered.

The further development of the shipping business in Ukraine is a complex and multifaceted problem and requires a comprehensive and professional approach, both from the state and from individual enterprises, in particular, shipping companies. The study confirms the importance of further study and systematization of the technical, economic and social conditions of the organization of sea passenger transportation.

REFERENCES

1. Kirillov, Yu. I. (2012). Anti-crisis ways to extend the life cycle of a vessel in commercial shipping. *Collection of scientific papers SWorld*, 1 (1), 35-38.
2. Berrio, L. (2019). Strategic modelling of passenger transport in waterways: the case of the Magdalena River. *Transport*, 34(2), 215-224. <https://doi.org/10.3846/transport.2019.8943>.

3. Qian, B.-Yi., & Shuai, B. (2014). Revenue Management for Dedicated Passenger Line Based on Passenger Preference Order. *Information Technology Journal*, 13, 2152-2158. <https://doi.org/10.3923/itj.2014.2152.2158>.
4. Qiu, B., Jin, Y., Lv, L., & Jin, Z. (2010). An Optimization Model and Heuristic Algorithm for the Ro-Ro Ship Loading. In *ICLEM 2010: Logistics For Sustained Economic Development: Infrastructure, Information, Integration* (pp. 2827-2835). [https://doi.org/10.1061/41139\(387\)396](https://doi.org/10.1061/41139(387)396).
5. Naletina, D., Ačkar, I., Vuletić, A., Petljak, K., & Štulec, I. (2018). Development opportunities of liner maritime passenger traffic in the Republic of Croatia. *Economic and Social Changes: Facts, Trends, Forecast*, 11(5), 182-197. <https://doi.org/10.15838/esc.2018.5.59.12>.
6. Vyskupaitis, A. (2003). Efficiency estimation of transport companies' activity. *Transport*, 18(2), 61-65. <https://doi.org/10.3846/16483840.2003.10414067>.
7. Zhang, S., Li, Y., Yuan, H., & Sun, D. (2019). An alternative benchmarking tool for operational energy efficiency of ships and its policy implications. *Journal of Cleaner Production*, 240, 118223. <https://doi.org/10.1016/j.jclepro.2019.118223>.
8. Lupták, V., Drozdziel, P., Stopka, O., Stopková, M., & Rybicka, I. (2019). Approach methodology for comprehensive assessing the public passenger transport timetable performances at a regional scale. *Sustainability*, 11(13), 3532. <https://doi.org/10.3390/su11133532>.
9. Leurent, F. (2011). Transport capacity constraints on the mass transit system: a systemic analysis. *European Transport Research Review*, 3(1), 11-21. <https://doi.org/10.1007/s12544-011-0046-5>.
10. Matviyenko, M.V., Navrozova, Yu.O., & Sherbina, V.V. (2010). Osnovi ekonomiki morskogo transportu: Navch. Posibn. Odesa: ONMU. <https://doi.org/10.31375/966-7716-61-9-2019>. [in Ukrainian].
11. Nesimko, O.D. (2014). Osoblivosti dogovoru morsk'ogo charteru [Peculiarities of the sea charter contract]. *Visnik Natsional'nogo universitetu «Lviv's'ka politekhnika»*. Seriya: Iuridichni nauki – Series of Legal Sciences of Visnyk of Lviv Polytechnic National University, 807, 180-186. [in Ukrainian].
12. Mihajlova, Yu. V., Steba, A.A., & Navrozova, Yu.O (2022). Osoblyvosti orhanizatsii kruiznykh perevezen pasazhyriv na yakhtakh [Peculiarities of the organization of cruise transportation of passengers on yachts]. *Visnyk Pryazovskoho Derzhavnogo Tekhnichnoho Universytetu. Seriya: Tekhnichni nauky - Bulletin of the Azov State Technical University. Series: Technical sciences*, 45, 126-134. <https://doi.org/10.31498/2225-6733.45.2022.276272>. [in Ukrainian].
13. Nezdoimov, S.G. (2022). Suchasnyy rozvytok infrastrukturi mizhnarodnogo kruiznogo rynku [Modern in-frastructure development of the international cruise market]. *Naukovii visnik Odes'kogo natsional'nogo ekonomichnogo universitetu – Scientific Bulletin of the Odessa National Economic University*, 3-4, 107-112. <https://doi.org/10.32680/2409-9260-2022-3-4-292-293-107-113>. [in Ukrainian].
14. Chaikovskiy, I.V. (2019). Zastosuvannia optymizatsiinykh metodiv v kontroli ta analizi roboty flotu [Application of optimization methods in the control and analysis of fleet operation]. *Transportni systemy ta tekhnologii perevezen - Transport systems and transport technologies*, 17, 76-79. <https://doi.org/10.15802/tstt2019/178219>. [in Ukrainian].
15. Tzannatos, E. S. (2005). Technical reliability of the Greek coastal passenger fleet. *Marine Policy*, 29(1), 85–92. <https://doi.org/10.1016/j.marpol.2004.04.001>.

Юлія Михайлова¹, Анастасія Стеба², Галина Сільванська³, Марина Вільшанюк⁴

¹ Доцент кафедри «Експлуатації флоту та технології морських перевезень», Одеський національний морський університет, вул. Мечникова, 34, Одеса, 65029, Україна, ORCID: <https://orcid.org/0000-0002-4882-7803>.

² Старший викладач кафедри «Експлуатації флоту та технології морських перевезень», Одеський національний морський університет, вул. Мечникова, 34, Одеса, 65029, Україна, ORCID: <https://orcid.org/0009-0005-5777-9785>.

³ Доцент кафедри «Експлуатації флоту та технології морських перевезень», Одеського національного морського університету, 65029, м. Одеса, вул. Мечникова, 34, ORCID: <https://orcid.org/0000-0002-1272-8029>

⁴ Старший викладач кафедри «Експлуатації флоту та технології морських перевезень», Одеський національний морський університет, 65029, м. Одеса, вул. Мечникова, 34, ORCID: <https://orcid.org/0000-0001-5396-6691>

Комерційно-правові умови організації морських пасажирських перевезень

Ця стаття досліджує сучасні тенденції та перспективи фрахтування пасажирських круїзних суден. У світлі подій останніх років, включаючи глобальну пандемію COVID-19, круїзна індустрія зіткнулася з серйозними викликами, що підштовхнуло компанії до пошуку нових

підходів підтримки своєї діяльності. Фрахтування круїзних суден стає все більш привабливим варіантом для круїзних операторів, дозволяючи їм скоротити витрати і гнучко адаптуватися до попиту, що змінюється, на круїзні подорожі. В статті розглядаються різні моделі фрахтування, включаючи довгострокові та короткострокові угоди, а також можливість спільного використання суден між операторами. Докладно аналізуються переваги та ризики фрахтування круїзних суден, включаючи економічні, операційні та юридичні аспекти. Більш деталізовано розглянуто дві організаційно правові форми роботи морських пасажирських суден: лінійну та круїзну. Формалізовано та надано схематичне відображення процесу взаємодії учасників морських пасажирських перевезень при різних формах роботи суден. Описано схеми взаємодії судновласника, фрахтувальника та агента-менеджера. Розглянуто технологію взаємодії учасників процесу перевезення пасажирів в контексті видів договорів фрахтування судном. Наведено відмінності у технологічних процесах взаємодії учасників процесу організації та забезпечення морських пасажирських перевезень, розподілі відповідальності, ризиків, витрат та доходів при організації морських пасажирських перевезень за різними схемами взаємодії учасників.

Ключові слова: пасажирські перевезення, судноплавні компанії, договір морського перевезення, оренда судна, чартер.

UDC 004.4, 004.6, 004.8, 004.9

Kostiantyn Tkachenko¹, Olha Tkachenko^{2*}, Oleksandr Tkachenko³

¹ Assistant professor, Information Technologies Department, State University of Infrastructure and Technologies, 9, Kyrylivska str., Kyiv, 04071, Ukraine, ORCID: <https://orcid.org/0000-0003-0549-3396>.

² Assistant professor, Information Technologies Department, State University of Infrastructure and Technologies, 9, Kyrylivska str., Kyiv, 04071, Ukraine, ORCID: <https://orcid.org/0000-0003-1800-618X>.

³ Assistant professor, Information Technologies Department, State University of Infrastructure and Technologies, 9, Kyrylivska str., Kyiv, 04071, Ukraine, ORCID: <http://orcid.org/0000-0001-6911-2770>.

*Corresponding author: oitkachen@gmail.com

Modeling of transport infrastructure: ontological approach

The article deals with current problems of ontological modeling of processes of design, construction and operation of buildings and structures in transport infrastructure. Such modeling involves use of standards and classifiers adopted in Europe and harmonized within BIM (Building Information Modeling) and EULYNX (European railway technology alliance). Multi-level ontological model of transport infrastructure is proposed. This model contributes to formation of understanding of essence of subject area, which is the field of transport infrastructure (transport repair enterprises, transport facilities (bridges, tunnels, tracks), transport depots, stations, etc.). Proposed model contributes to presentation of knowledge in form that is convenient for their processing in intelligent systems, ensuring intellectualization and digitization of processes in transport infrastructure. Proposed ontological approach ensures multiple use of knowledge and existing ontologies, allows the use of modern technologies (in particular, semantic ones), when objects of subject area correspond to their reflections in multi-level ontological model. Ontological approach to modeling of transport infrastructure makes it possible to move to automatic management of these objects and corresponding processes in systems that ensure intellectualization and digitalization of transport and transport infrastructure. Developed multi-level ontological model is planned to be supplemented with new components, imposing appropriate restrictions.

Keywords: modeling, ontology, multilevel ontological model, transport infrastructure.

Introduction. Currently, the development of information systems and technologies (as well as intelligent systems and information systems with elements of intellectualization) leads to large-scale automation and the use of artificial intelligence in various fields of human activity. The use of knowledge-based systems improves efficiency:

- information interaction of systems (including those working in different subject areas (SA));
- information support for certain types of activities of individual users, enterprises or industries as whole;
- simplifies and transfers the work of enterprises to new level of informatization and intellectualization.

The development of any such system begins, first of all, with description of SA within which it will operate. To describe SA, two approaches are mainly used: ER-modeling and modeling using the construction of an ontological description. In this paper, we consider method based on the construction of ontologies and allowing one to build deeper formal description of SA at the conceptual level.

Analysis of recent research and problem statement. In the 1990s, innovative applications in architecture, engineering, and construction (AEC) emerged, leading to the emergence of: CAD systems that enable the processing of graphic information; 3D models of buildings and structures (including railway infrastructure); new information possibilities (for example, calculation of physical characteristics, unit costs) [33, 34].

All this contributed to the emergence of methodology that is known as Building Information Modeling (BIM) [1, 2, 23,]. BIM processes are well defined for new buildings and railway infrastructure structures (hereinafter referred to as structures), and most of the existing structures are not maintained, repaired or rebuilt. Possible solution to the problem of increasing the efficiency of the AEC is to use knowledge management and an ontological approach [32, 35].

The use of Industry Foundation Classes (IFC) [3, 4] and other standard ontologies at all stages of the life cycle of structure prevents the loss of information and facilitates the transfer of the maintenance process from one participant in the life cycle of railway infrastructure structure to another.

The purpose and tasks of the research. The purpose of the article is to discuss problems related to the management of objects and processes of transport infrastructure (in particular, their design, construction and operation), as well as possible methods of solving them using modern technologies of intellectualization and digitization and multi-level ontological modeling of the corresponding SA.

Materials and methods of research.

The semantic and ontological enrichment of building models can contribute to more optimal storage and access to data, providing means for structuring, storing and visualizing information. Information resources of intelligent systems using BIM and the ontological approach provide information support for the tasks solved in it in the field of design, construction and operation of buildings and structures of the railway infrastructure. In particular, one of the types of information resources are classifiers that provide data representation taking into the account the ontological approach and effective information interaction between system components.

Standards and classifiers contain information about objects (components, information and control flows, etc.), which determines their use in modeling the corresponding SA.

This article describes the method of linking information resources on the example of classifiers to the ontology of SA for the formation of deeper and more detailed conceptualization model of SA [5, 6]. Ontologies make it possible to formalize SA (in the article, such SA is the infrastructure of the railway transport) with the help of an appropriate conceptual scheme.

The ontology is defined in the knowledge representation language, which defines the formal semantics, which provides the possibility of clear interpretation of the ontology in the corresponding intellectual system. The ontology represents SA at the conceptual level with the help of concept classes and their relations. The ontology of SA can be defined as:

$$O^d = \langle C, A, R, D \rangle,$$

where C is the set of SA classes, A is the set of attributes of these classes, R is the partial order relation on the set of classes, $R \subseteq C \times C$, D is the set of domains of admissible values of the attributes of the SA objects. Classes are defined by the triple $\langle d_i, F(d_i), V(d_i) \rangle$, where d_i is the name of the class, $F(d_i) = \{f_{ij}\}$ is the set of attributes of the class, $V(d_i) = \{v_{iq}\}$ is the scope of the class, v_{iq} – objects with features $F(d_i)$. Let $B(F(d_i)) = \{\emptyset, 2^{F(d_i)}\}$ be the content Boolean of the feature set $F(d_i)$ of some class d_i , where $2^{F(d_i)}$ – the set of all subsets of the content $F(d_i)$. The elements of the Boolean form partially ordered set by the inclusion of its elements – the lattice $(B(F(d_i)), \leq, \wedge, \vee)$.

Any element $F(d_i) \in B(F(d_i))$, $H \in [1, 2^{F(d_i)}]$, of the resulting lattice is considered to be the content of some class d_i^H , generalizing the concept of d_i if $F(d_i^H) \subseteq F(d_i)$. The lattice $K(d_i) = (B(F(d_i)), \leq, \wedge, \vee)$ of all content subsets of the initial class d_i is called the conceptual “framework” of the SA ontology. The conceptual “framework” of the SA ontology is necessary structure containing the initial class d_i .

Conceptual modeling with the help of ontologies provides, in particular: semantically deep representation of SA:

- rich formal semantics, reflection of complex axiomatic information due to logical notations;
- solving various problems simultaneously: description of SA as such;
- development on the basis of the formed ontologies of information and intellectual systems.

The use of ontological modeling makes it possible to formalize SA with the help of more accurate conceptual representation, as well as to apply it in intelligent systems to improve the efficiency of processes in the field of designing transport infrastructure facilities. To build ontologies, a lot of software tools have been developed that provide the user with graphical interface for building ontologies. The most popular is Protege [7, 8] ontology editor. Ontological modeling SA goes through several stages:

- defining the scope and scope of ontologies; definition of the main terms of ontologies;
- definition of classes and their hierarchy;
- definition of properties of classes and relations.

For the description of SA, an approach is proposed, which consists in the fact that certain areas of the SA can be described using existing information resources, such as standards and classifiers, operating in the SA under consideration. In other words, the ontology of SA can be extended by ontologically linking ontology classes with standards and classifiers.

Depending on the level of approval, there are the following categories of standards and classifiers: international (regional); national (including Ukrainian); intersectoral; industry; systemic. Thus, we can say that the standards and classifiers present systematized descriptions of SA objects, in which the names of objects have certain codes.

The presented ontology, supplemented by the classifiers described above, can be used to intellectualize the processes of design, construction and maintenance of transport infrastructure facilities, including: to develop an intelligent decision support system for designers when choosing the appropriate BIM standards and classifiers and to control the design (construction) processes or support, depending on the classes of problems to be solved), systems for introducing national characteristics into pan-European standards and classifiers, systems for collecting and analyzing statistical data on the activities of objects of SA.

To link standards and classifiers to the ontology of SA, you need to perform the following actions:

- Representation of the ontology in machine-interpretable form (translation of the ontology into OWL-format [9, 10]).
- Creation and filling of database of pan-European, national and industry standards and classifiers (pan-European, national, intersectoral and industry).
- Selection of standard/classifier for binding to specific ontology.
- Selection of the name of the standard/classifier from its meta description.
- Semantic analysis of standard/classifier by its name (search using semantic analysis by the name of standard/classifier for semantically identical object in the ontology).
- Linking standard/classifier to an ontology object, which is performed using the following sequence of steps: creation of an object in the ontology corresponding to the given standard/classifier; extraction of metadata from the standard/classifier; record of metadata of the standard/classifier in the properties of object created in the ontology.
- The choice of an object in the ontology, the most suitable of the proposed options.

The use of the proposed methodology for expanding the ontological description of SA of an intelligent system facilitates the work of analysts in developing formal description of SA for the subsequent development of the corresponding intelligent system and helps to build models of SA at deeper conceptual level. Standards and classifiers are an important component of intelligent systems and contain variety of information to describe SA. The proposed methodology can be useful in the development of intelligent (information with elements of intellectualization) systems, decision support systems, expert systems based on knowledge bases and requiring broad conceptual descriptions of SA.

When designing and building structures, BIM models are developed at the top level (metaontology) and should reflect the “current” situation. "Designed" BIM-models must be adjusted when creating "built" models. In the ontological modeling, it should be taken into the account that many data become available only after the construction stage, since they refer to specific structure in specific place and have specific properties.

Missing, outdated or unstructured information about the construction can lead to inefficient project management (for the construction or maintenance of transport infrastructure facilities); inadequate process results and wasted time; increased maintenance costs; modernization or restoration of processes and properties of SA objects. The semantic models are most often considered as IFC models [11, 12]. The semantic model of SA is model that includes semantic information that describes the meaning of its specific physical objects [6].

Different models of structures and buildings with large amount of external data are available on railways and their infrastructure facilities, which necessitates distributed data management, as well as the development of semantic and ontological approach for the railway industry and its infrastructure.

One of the main limitations of IFC is the lack of mechanisms for extending the semantics of the model. BuildingSMART [13] is developed on the basis of IFC and is based on ontologies of the construction and infrastructure sectors. Semantic technologies provide the transformation of information about the IFC model into semantically extended ontological model represented using the language OWL [14]). OWL is used as an integrator of all necessary ontologies. This is how EULYNX, the European railway technology alliance [15], is developing, which, in particular, must take into the account the following factors:

1. Transition to the phase of readiness for the implementation of such technologies of the digital economy as ontological methods that improve the possibility of accurate calculations in the life cycle (infrastructures and rolling stock of railways).

2. The need to take into the account the capabilities of information / intelligent systems in transport.

3. The need to predict the development of railways and related infrastructure. It is predicted that global rail transport will double by 2050, which leads to increased competition for freight traffic and passengers, i.e. creation of new transport landscape [16, 17]. Ontologies and formalized ontological and semantic languages play decisive role in this process to ensure the interoperability of the stages of design and operation of railway systems. EULYNX uses formal ontological methods that are needed in high-tech industries, but unfortunately not widely used in railway infrastructure.

General transport ontologies. Studies on the ontology of railway transport and its infrastructure in Great Britain and Denmark [18-23] have shown how ontologies can facilitate: access to information resources and their integration; generating responses to queries. Ontologies support the application of the “build once” approach to application development by protecting software from changes to real (physical) transport systems [21, 22].

System engineering is an approach to the implementation of systems (information, intellectual) in transport that meets the needs, goals and objectives of users. Railway transport ontologies have common components (fragments, elements) [12], in particular, ontologies of its infrastructure and vehicles. Digitalization and intellectualization of the transport sector determines the use of engineering, software and BIM-ontologies. The ontological approach provides an opportunity to work with finite set of formalized concepts and set of formalized relationships between them, which allows you to accumulate knowledge and use it in practice to get better results. With the development of BIM-ontologies, it became possible to create knowledge management system.

BIM-ontology is source of information because it generates and manages the data created during the life cycle of structure. This source of information can be transformed into knowledge using data mining methods and technologies. Ontologies of transport and railway infrastructures are closely related to IFC buildibgSMART and their extensions [12]. The IFC Rail standard does not include railway bridges, tunnels, stations and depots (this is separately developed component of the corresponding domain in the general ontology).

Knowledge in modern systems (intellectual, informational with elements of intellectualization) can be explicit and represent existing knowledge (facts) or obtained using logical inference (reasoning) from existing knowledge. All this is the justification for the need to form formal information knowledge models that represent the knowledge base of buildings and structures of the railway infrastructure.

In Semantic Web [24] technology, ontologies are part of semantic models that represent the key concepts of each domain, their properties and relationships. Domain ontologies use certain concepts in the fundamental meta-domain, ontologies of time and space, and spatial and temporal reasoning.

Meta-domain ontologies, domain ontologies in the use of open BIM and their relationship [25, 26]:

- Meta-Domain Ontologies and Rules (Time Ontology + Rule Sets; Spatial Ontology + Rule Sets).
- Domain Ontologies and Rules (Occupant Ontology + Rule Sets; Equipment Ontology + Rule Sets; Building Ontology + Rule Sets; Weather Ontology + Rule Sets; FDD Ontology + Rule Sets).

Multi-level ontological model, which is the basis for the intellectualization of the processes of design, construction and operation of buildings and structures of transport infrastructure, in real time, involves its modification. The construction of multilevel ontological model of considered SA involves the following steps:

- Formalized description of levels and constituent components of multilevel ontology
- Formalized description of metaontology.
- Formalization of theoretical models of knowledge engineering.
- Formalization of ontology axioms (axioms of identification, planning, calculations).

Objects in this multilevel ontological model are systematized according to the functional feature of their properties included in the class hierarchy. Model components define the structure of the corresponding intelligent system that supports the design, construction and operation processes.

The used multilevel ontological model describes the construction of formal system models of the SA related to the formalization of the tasks of designing, constructing and operating transport infrastructure facilities, taking into the account existing BIM-models. The development and formalization of multilevel ontology presupposes formal representation and conceptualization of knowledge about SA. Such representation involves description of the totality of objects (and corresponding concepts), knowledge about them and the relationship between them.

The functional completeness of multi-level ontological model of SA implies not so much complete reflection of the properties of SA objects, but only the fixation of those properties that are necessary and sufficient for solving the problems of designing, building and operating transport infrastructure facilities. In [25, 26], the connection of decisions made on the basis of the ontological approach (in particular, BIM-ontologies, IFC, engineering ontology described in terms of SysML [11, 28]) is shown.

This takes into the account that EULYNX uses the SysML system modeling language to model functional requirements. System development based on the Model-Based Transport Ontology Engineering (MBSE) standard is systems engineering methodology that focuses on the creation and use of domain models as the primary means of information exchange between engineers [27].

The MBSE takes into the account the results of the practical application of computer simulation, to bridge the gaps between the specification of the system model and the corresponding software. Using MBSE increases the likelihood of “getting it right” the first time, as all the necessary information is connected to single model. When adapting proven solutions based on integrated engineering ontologies (SysML) [28] and ontologies developed with OWL/RDF [5, 22], the following steps are performed:

- Choice of an ontology editor (in particular, Protégé).
- Formation of OWL-statements
- Building model of transformations.
- Building output machines with OWL-tools .
- Formation of SysML engineering ontologies.
- Building transformation model.
- Obtaining new knowledge by users (system).

This organization of engineering processes allows:

- Use the context of systems engineering to identify problems (arising at different stages of the design life cycle of intelligent systems in the field of transport or infrastructure; stages of design, construction and / or operation of structures, etc. using appropriate intelligent systems).

- Based on the identified problems, build models (semantic, ontological) of decision support.
- Use SysML tools and models in specific engineering domains.
- Reduce system development time by integrating cross-domain model.

Ontologies built on the basis of SysML contribute to the visualization of the system description, making different views on systems more structured and formal. SysML can also be used as method of communication between the system designer and various stakeholders [25, 26]. Models help at all stages of the system life cycle (from requirements gathering and design to testing and validation):

1. Modeling has advantages in collecting system requirements, as it can detect, among other things, problems such as:

- Requirements are incorrect, but they are not found.
- The requirements are correct, but incomprehensible to the user.
- The requirements are specified correctly, but not in formal language, which makes them difficult to interpret and understand.

SysML can solve these problems by providing way to clearly and hierarchically organize requirements through relationship types (such as "satisfy" or "infer" for example). It also helps in checking and testing the completeness of the requirements.

2. Modeling has the advantage of improving design quality because it removes ambiguity, provides deeper understanding of the system, and reflects relationships between system components. All this reduces design errors.

3. Possibility of creation on the basis of SysM development tools of tools for check and validation of models.

4. Process modeling using SysML facilitates effective communication with stakeholders about system behavior, generating test cases, and/or finding system bugs.

Comprehensive ontological models in engineering design reduce development time, increase data reliability, and make applications more flexible while ensuring security systems.

The purpose of the application of ontologies is to create set of digital tools to improve the basic indicators of EULYNX railways, such as, for example, their capacity, integration with trains and other elements of engineering and technical support. EULYNX pays great attention to Shift2Rail [29]. Shift2Rail has an excellent digital organization of the initiative in the form of linked websites.

Modeling in EULYNX is one of the MBSE processes. Since simulation plays an important role in the project, EULYNX has formed cluster for this called *Modeling and Testing*. This cluster is responsible, in particular, for:

- creation and testing of SysML models for each subsystem of the corresponding intelligent system;
- documentation of processes during the creation of models and / or their interpretation.

Modeling uses, in particular:

- The modeling standard that provides project guidance for MBSE.
- Interpretation rules explaining the implementation in the project of requirements based on model.
- The systems engineering process, which is described at its top level for the EULYNX project.
- Change and configuration management, describing the necessary activities to model harmonization processes and take into the account the specifications of different countries.

For each subsystem in EULYNX, from the lists of functions that are supported by different information models, requirements specification is created, which is reflected in documents such as:

- interface definitions for each interface type (SCI, SDI);
- interface specifications;
- requirements specifications (these documents contain the relevant models).

In EULYNX, the interface is described at the protocol level, consisting of [15]: application layer; safety/retransmission and redundancy layer; transport layer; network layer; data link and physical layer.

EULYNX defines an interface specification: for an SCI interface, the application layer from the interface protocol. EULYNX defines the structure of subsystems and their associated environments, in particular:

- related subsystems that transmit information about the environment;
- exchange of information with other subsystems using the appropriate interface.

After that, EULYNX defines the behavior of the subsystem that implements its interface, i.e. describes the essential states of the subsystem (main states of the subsystem, its interface, transitions between states). Ontological modeling allows you to get information about:

- commands and messages between the subsystem and other subsystems, such as blocking or maintenance;
- situation, state and time of subsystem initialization;
- the situation, state and time of operational operation and start-up by other subsystems or achievement of operating time limits;
- the occurrence of an error. EULYNX defines the workflow, collects feedback on the current process and the current situation.

ProRail is an information model that provides an analysis of the situation in EULYNX from simulation point of view. In the modeling and testing cluster, decision is made on the types of diagrams and the necessary changes. One of the reasons for this is that models are first created in the cluster, and then, when the simulation is completed, they are checked by equipment suppliers (through appropriate feedback). The review of models is performed within the respective cluster. Model validation is not always transparent to other developers.

Information gathering is necessary to effectively use event data to provide insight, identify bottlenecks, anticipate problems, capture rule violations, recommend countermeasures, and optimize the life cycle processes of buildings and transport infrastructure structures [30]. Common trend at AEC is the intellectualization and digitalization of processes, as well as the use of domain knowledge.

BIM-ontologies encompass all of these research innovations and facilitate their implementation. BIM is based on many technologies such as CAD, CAC, PIM innovations, these innovations precede the concept of BIM. BIM-specifications are set of responses to social and corporate needs driven by today's building processes [30].

The ontological model for integration and the associated ontological process are the basis of the ontological approach to the intellectualization and digitalization of transport and its infrastructure. Nowadays, many algorithms, mathematical models and other data methodologies have been developed to solve the problems of intellectualization and digitalization of transport [31], in particular, the use of:

- neural networks and fuzzy logic to predict, for example, potential failures in the railway network;
- mathematical models for intelligent maintenance using machine learning methods;
- generation algorithms and hierarchical network models for schedule optimization;
- combinations of unified modeling languages and Petri nets in the design of structures, their construction and subsequent operation;
- Bayesian network models to improve railway infrastructure maintenance strategies.

Conclusions. The ontological approach to the design of information and intelligent systems in the transport sector helps to build effective digital cooperation through the ontology of the relevant standards and classifiers operating in the considered SA.

If it is necessary to develop standards for digitalization and intellectualization of the processes of design, construction, operation of buildings and structures of the infrastructure of the railway, then the basis for this is the structural description common with BIM-ontologies or IFC Rail.

Ontological models covering end-to-end processes in railway transport and related infrastructure are playing an increasingly important role. Such models are the basis for intelligent technologies used for the design, construction and operation of buildings and structures of the railway transport infrastructure.

REFERENCES

1. Krijnen, T., Tamke, M., Thomsen, M.R., Gengnagel, C., Faircloth, B., & Scheurer, F. (2015). Assessing Implicit Knowledge in BIM Models with Machine Learning. *Proceedings of The Symposium on Modelling Behaviour: Design Modelling (2015)*. Springer: Cham, Switzerland. 397–406.
2. Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Models (BIM) for existing buildings – literature review and future needs. *Automation in Construction*, 38, 109–127. <https://doi.org/10.1016/j.autcon.2013.10.023>
3. Buruzs, A., Miloš, Š.c, Blank-Landeshammer, B., & Zucker, G. (2022). IFC BIM Model Enrichment with Space Function Information Using Graph Neural Networks. *Energies*, 15, 2937. <https://doi.org/10.3390/en15082937>
4. Lilis, G. N., Giannakis, G. I., & Rovas, D. V. (2017). Automatic generation of second-level space boundary topology from IFC geometry inputs. *Automation in Construction*, 76, 108–124.
5. Tkachenko, O., Tkachenko, K., & Tkachenko, O. (2020). Designing complex intelligent systems on the basis of ontological models. *Proceedings of The Third International Workshop on Computer Modeling and Intelligent Systems (CMIS-2020)*, 266–277.
6. Tkachenko, O., & Tkachenko, O. (2022). Modeling of management of intelligent systems in transport. *Transport systems and technologies*, 39, 252–261. <https://doi.org/10.32703/2617-9040-2022-39-24>
7. Lytvyn, V.V., Pasichnyk, V.V., & Yatsyshyn, YU.V. (2020). Intelektual'ni systemy. [Intelligent systems]. L'viv: "Novyy Svit – 2000" ["New World – 2000"]. 406. [In Ukrainian].
8. Hladun, A.YA., & Rohushyna YU.V. (2016). Semantychni tekhnolohiyi: pryntsyipy ta praktyky. [Semantic technologies: principles and practices]. Kyiv: TOV VD "ADEF-Ukrayina". [Kyiv: "ADEF-Ukraine" LLC]. 308. [In Ukrainian].
9. Basyuk, T.M., & Lytvyn, V.V. (2020). Movy opysu ontolohiy. [Ontology description languages]. L'viv: Vydavnytstvo L'vivskoyi politekhniki. [Lviv: Publishing House of Lviv Polytechnic]. 276. [In Ukrainian].
10. Hladun, A.YA., & Khala, K.O. (2019). Vykorystannya ontolohichnykh modeley dlya formalizovanoho otsynuyannya znan'. [The use of ontological models for formalized knowledge assessment]. *Komp'yuterni zasoby, merezhi ta systemy – Computer facilities, networks and systems*, 23(18), 5–10. [In Ukrainian].
11. Bryde, D., Broquetas, M., Volm, J.M. (2013). The project benefits of Building Information Modeling (BIM). *International Journal of Project Management*, 31, 971–980.
12. Nuttens, T. (2018). Using BIM models for the design of large rail infrastructure projects: key factors for a successful implementation. *International Journal of Sustainable Development and Planning*, 13(1), 73–83. <https://doi.org/10.2495/SDP-V13-N1-73-83>
13. Matthijs van de Riet, M.H. (2016). Semantic model enrichment for BIM-enabled risk-based operation and maintenance. A case study approach with Industry Foundation Classes. *Nederland: Eindhoven University of Technology*. 164.
14. Dovhyi, S.O., Velichko, V.YU., Hloba, L.S., Stryzhak, O.YE., Andrushchenko, T.I., Hal'chenko, S.A., Honchar, A.V., Hulyayev K.D., Kudlyak V.M., Lyashuk K.V., Palahin O.V., Petrenko M.H., Popova M.A., Sydorenko V.I., Slyusarenko O.O., Stus, D.V., & Ternovoy, M.YU. (2013). Komp'yuterni ontolohiyi ta yikh vykorystannya u navchal'nomu protsesi. Teoriya i praktyka. [Computer ontologies and their use in the educational process. Theory and practice]. Kyiv: Instytut obdarovanoyi dytyny. [Kyiv: Institute of the Gifted Child]. 310. [In Ukrainian].
15. Bouwman, M., Van der Wal, D., Luttik, B., Stoelinga, M., & Rensink, A. (2023). A Case in Point: Verification and Testing of a EULYNX Interface. *Formal Aspects of Computing*, 35(1), 1–38. <https://doi.org/10.1145/3528207>
16. Trach, I.A., Petruk, V.H., Ishchenko, V.A., & Turchyk, P.M. (2016). Vplyv transportnoyi infrastruktury na ekolohichnu bezpeku teriofauny. [The influence of transport infrastructure on the ecological safety of theriofauna]. *Naukovi pratsi Vinnyts'koho Natsional'noho tekhnolohichnoho universytetu – Scientific works of the Vinnytsia National Technical University*, 3, 1–5. [In Ukrainian].
17. Kupriyanovsky, V. (2017). Digital sharing economy: technologies, platforms and libraries in industry, construction, transport, and logistics. *International Journal of Open Information Technologies*, 5 (6), 56–75.
18. Rozenberg, E. (2018). Digital Railway: from Concept to Reality. *Railway equipment*, 7, 20–24.
19. PAS 280: 2018. (2018). Through-life engineering services – Adding business value through a common framework – Guide. *The British International Journal of Open Information Technologies*, 6(11), 1–94.
20. Amatsari, J.S. (2016). Towards BIM for Asset Management in Dutch road infrastructure projects .A study of the perspectives of the client and contractor for the municipality of Rotterdam/Netherlands. Rotterdam: Delft University of Technology. 118.
21. Research Programme Engineering. Ontology-based data management for the GB rail industry Feasibility study. (2014). Rail safety and standards board LTD. 256.
22. Tutchter, J., Easton, J., Roberts, C. (2017). Enabling Data Integration in the Rail Industry Using RDF and OWL – the RaCoOn Ontolog. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems. Part A: Civil Engineering*, 3(2). <https://doi.org/10.1061/AJRUA6.0000859>
23. Gigante, A., & Barrera, A. (2017). LOD BIM Element specification for Railway Turnout Systems Risk Mitigation using the Information Delivery. *IOP Conference Series: Materials Science and Engineering*, 245–262.
24. Lan, G., Liu, T., Wang, X., Pan, X., & Huang, Z. (2022). A semantic web technology index. *Scientific Report*, 12, 3672. <https://doi.org/10.1038/s41598-022-07615-4>

25. Takim, R., Harris, M., & Nawawi, A.H. (2013). Building Information Modeling (BIM): A new paradigm for quality of life within Architectural, Engineering and Construction (AEC) industry. *Procedia. Social and Behavioral Sciences*, 101, 23-32. <https://doi.org/10.1016/j.sbspro.2013.07.175>
26. Trach, R.V. (2017). Informatysyne modelyuvannya v budivnytstvi (BIM-tekhnolohiyi): sutnist', etapy rozvytku ta perspektyvy rozvytku. [Information modeling in construction (BIM technologies): essence, stages of development and development prospects]. *Hlobal'ni ta natsional'ni problemy ekonomiky – Global and national problems of economics*, 16, 490–495. [In Ukrainian].
27. Quentin, W., Gouyon, D., Boudau, S., & Levrat, E. (2019). Capitalization and Reuse with Patterns in a Model-Based Systems Engineering (MBSE) Framework. In 2019 International Symposium on *Systems Engineering (ISSE)*, 1–8. <https://doi.org/10.1019/ISSE46696.2019.8984571>.
28. Bonnet, S., Voirin, J.-L., Exertier, D., & Normand, V. (2016). Not (Strictly) Relying on SysML for MBSE: Language, Tooling and Development Perspectives: The Arcadia/Capella Rationale." In 2016 Annual IEEE Systems Conference (SysCon), 1-6. <https://doi.org/10.1016/SYSCON.2016.7490559>.
29. The European Railway Sector Proposal for the development of the general strategic priorities defined in the Shift2Rail Master Plan in the Shift2Rail Programme under the European Union's H2020. Brussels: Framework Programme for Research and Innovation, 571.
30. Benjamin, H. (2017). Ontology Base Requirement Management For Project Standardization System Engineering For Infrastructure Using Semantic Web Technologies.. Eindhoven: Eindhoven University of Technology. 236.
31. Zhu, J., Chong, H. Y., Zhao, H., Wu, J., Tan, Y., & Xu, H. (2022). The Application of Graph in BIM/GIS Integration. *Buildings*, 12(12), 2162.. <https://doi.org/10.3390/buildings12122162>
32. Shynkarenko, V., & Zhuchyy, L. (2022). Ontologichnyy analiz prydatnosti zaliznychnykh kolyi dlya zabezpechennya vysokoshvydkoho rukhu poyizdiv. [Ontological analysis of the suitability of railway tracks to ensure high-speed train movement]. *Komp'yuterni systemy ta informatysyni tekhnolohiyi – Computer Systems and Information Technologies*. (3), 11–21. <https://doi.org/10.31891/csit-2022-3-2>
33. Lee, S., & Ha, M. (2013). Customer interactive building information modeling for apartment unit design. *Automation in Construction*. 35, 424-430.
34. Krijnen, T., Tamke, M., Thomsen, M.R., Gengnagel, C., Faircloth, B., & Scheurer, F. (2015). Assessing Implicit Knowledge in BIM Models with Machine Learning. In *Modelling Behaviour. Design Modelling Symposium*. Springer: Cham, Switzerland. 397–406.
35. Sacks, R., Ma, L., Borrmann, A., Daum, S., & Kattel, U. (2017). Semantic Enrichment for Building Information Modeling: Procedure for Compiling Inference Rules and Operators for Complex Geometry. *Journal of Computing in Civil Engineering*. 31, 04017062.

Костянтин Ткаченко¹, Ольга Ткаченко², Олександр Ткаченко³

¹ Доцент, Кафедра інформаційних технологій, Державний університет інфраструктури та технологій, вул. Кирилівська, 9, м. Київ, 04071, Україна, ORCID: <https://orcid.org/0000-0003-0549-3396>.

² Доцент, Кафедра інформаційних технологій, Державний університет інфраструктури та технологій, вул. Кирилівська, 9, м. Київ, 04071, Україна, ORCID: <https://orcid.org/0000-0003-1800-618X>.

³ Доцент, Кафедра інформаційних технологій, Державний університет інфраструктури та технологій, вул. Кирилівська, 9, м. Київ, 04071, Україна, ORCID: <http://orcid.org/0000-0001-6911-2770>.

Моделювання транспортної інфраструктури: онтологічний підхід

У статті розглядаються актуальні проблеми онтологічного моделювання процесів проєктування, будівництва та експлуатації будівель і споруд транспортної інфраструктури. Таке моделювання передбачає використання стандартів і класифікаторів, прийнятих в Європі та гармонізованих в межах BIM (Building Information Modeling) та EULYNX (the European railway technology alliance). Запропонована багаторівнева онтологічна модель транспортної інфраструктури. Ця модель сприяє формуванню розуміння сутностей предметної області, якою є сфера транспортної інфраструктури (транспортні ремонтні підприємства, споруди транспортного призначення (мости, тунелі, колії), транспортні депо, вокзали, тощо). Запропонована модель сприяє представленню знань у вигляді, який є зручним для їх обробки у інтелектуальних системах, забезпечуючи інтелектуалізацію та цифровізацію процесів в транспортній інфраструктурі. Запропонований онтологічний підхід забезпечує багаторазове використання знань та існуючих онтологій, дозволяє використовувати сучасні технології (зокрема, семантичні), коли об'єктам предметної області відповідають свої відображення у багаторівневій

онтологічній моделі. Онтологічний підхід до моделювання транспортної інфраструктури дозволяє перейти до автоматичного управління цими об'єктами та відповідними процесами в системах, які забезпечують інтелектуалізацію і цифровізацію транспорту і транспортної інфраструктури. Розроблену багаторівневу онтологічну модель планується доповнювати новими складовими, наклавши відповідні обмеження.

Ключові слова: моделювання, онтологія, багаторівнева онтологічна модель, транспортна інфраструктура.

UDC 629.463.66

Andrii Sulym^{1*}, Pavlo Khozia², Andrii Strynzh³, Yurii Pavlenko⁴, Serhii Stolietov⁵

¹Deputy Director for Scientific Work, State Enterprise "Ukrainian Scientific Railway Car Building Research Institute", 33, I. Pryhodka Str., Kremenchuk, 39621, Ukraine. ORCID: <https://orcid.org/0000-0001-8144-8971>

²Head of the Research Laboratory, Research Laboratory of Experimental Studies of Railway Technics, State Enterprise "Ukrainian Scientific Railway Car Building Research Institute", 33, I. Pryhodka Str., Kremenchuk, 39621, Ukraine. ORCID: <https://orcid.org/0000-0001-8948-6032>

³Head of the Research Laboratory, Research Laboratory of Feight and Special Purpose Railway Vehicles, State Enterprise "Ukrainian Scientific Railway Car Building Research Institute", 33, I. Pryhodka Str., Kremenchuk, 39621, Ukraine. ", ORCID: <https://orcid.org/0000-0003-3743-7006>

⁴Head of the Research Laboratory, Research Laboratory of Running gears, Passenger, Tailer, Traction, Self-propelled and Light Rail Vehicles, State Enterprise "Ukrainian Scientific Railway Car Building Research Institute", 33, I. Pryhodka Str., Kremenchuk, 39621, Ukraine. ", ORCID: <https://orcid.org/0000-0001-8612-3228>

⁵Head of the research group, Research Laboratory of Experimental Studies of Railway Technics, ORCID: <https://orcid.org/0000-0001-8819-2534>

*Corresponding author: sulim1.ua@gmail.com

Improvements to the procedure for determination of the residual lifetime of railway vehicles

Existing research concerning the extension of the service life of various types of railway vehicles and assessing its remaining lifetime has been reviewed and analyzed. It has been established that the vast majority of studies relate to the assessment of the residual lifetime of various types of railway rolling stock based on the results of technical diagnostics and routine tests, as well as the assessment of corrosion wear of supporting elements and vehicles bodies. At the same time, little attention has been paid to the issue of improving existing programs and procedures of complex technical diagnostics.

It was determined that the set of diagnostics operations for the extension of the service life includes routine tests of a test sample and examination of the technical condition of the metal structure of each railway vehicle for mechanical and corrosive damage. It is proposed to make changes to the existing current programs and procedures in such key sections as: terminology, objects of technical diagnostics and tests, selection of a test sample for routine tests, execution order and methods of technical diagnostics and routine tests, data processing and evaluation of results. A comprehensive approach for assessing the residual lifetime of railway vehicles is also proposed.

Keywords: *railway vehicles, residual lifetime, routine tests, rolling stock, technical diagnostics.*

Introduction. In recent years, the operating fleet of railway rolling stock has aged significantly. The operation of life-expired railway vehicles involves an increased risk related to ensuring the necessary level of safety in railway traffic. At the same time, decommissioning of railway rolling stock that has served out its lifetime will lead to a sharp decrease in the operating fleet that result into significant problems in railway traffic. Therefore, one of the possible ways to ensure a stable high level of railway traffic safety and prevent a sharp reduction of the operating fleet is to extend the service life of railway vehicles that have served the designated service life guaranteed by the manufacturer.

In this work, it is proposed to continue research in such an important and relevant focus area as the extension of the service life (life cycle) of various types of railway vehicles.

Analysis of recent research and problem statement. The issues of extending the service life of various types of railway vehicles and assessing its residual lifetime have been constantly discussed recently, which indicates their importance and relevance.

Publications [1-8] deal with the extension of the service life and assessment of the residual lifetime of passenger cars. Thus, in paper [1], the residual lifetime of the passenger car body structure was evaluated under operating loads corresponding to 10-year operation. Based on the results of static tests and impact endurance tests with a high degree of reliability, the new service lifetime of the passenger car was confirmed. In work [2], the residual lifetime of a passenger car body structure with corrosion centers of the center sill was assessed. In work [3], the strength of load-bearing structures of passenger cars was studied based on experimental static and shock strength tests, endurance tests under action of longitudinal forces. The assessment and forecasting of the compliance of the wagon bodies for the specified next period have been performed. During scheduled repairs, special attention should be paid to the condition of the side sill and supports. In the study [4], an analysis of the residual lifetime of passenger compartment and open seating cars was performed. In the publication [5] technical condition of passenger cars bodies was considered and their wear was analyzed. Research [6] is aimed at improving the technical diagnostics technique of passenger cars taking into account the features of structural elements damage during operation. In article [7], it is proposed to improve the existing methodology based on the results of scientific and experimental research on determining the maximum service life of passenger cars and bogies. In the article [8], an analysis of the technical condition of the frame elements of passenger cars was performed and the dependence of corrosion wear was obtained.

Works [9-16] focus on research of the service life extension and assessment of the residual lifetime of mainline freight cars. Corrosion wear of load-bearing metal structures of freight cars was studied in [9]. Damage to the load-bearing metal structures of open wagons taking into account corrosive wear is considered. The rate of corrosion wear of elements of load-bearing metal structures and bodies of open wagons models 12-532 and 12-757 was determined. The work [10] deals with the determination of the remaining lifetime of 12-532 model open wagons and the possibility of continuing their operation within Ukraine for more than one and a half years. The article [11] describes the process of carrying out routine type and life tests of the model 19-752 grain wagon. Based on the results of the tests, the residual lifetime of the load-bearing metal structure of the grain wagon was estimated. In work [12], an assessment of the residual lifetime of the load-bearing metal structures of reference wagons and the UVZ-9M bogie operated on the railways of Ukraine, was performed. It has been found that during the technical diagnosis of railcar calibration wagons, it is necessary to pay special attention to the places where the design modifications of the base car were performed. The article [13] addresses the research on corrosion damage of structural elements of open wagons and the effect of cargoes transported in wagons on the speed of corrosion processes. The average speed of corrosion processes of structural elements of open wagons was determined. The publication [14] deals with a study of the residual lifetime of the load-bearing metal structures of hopper-dozer wagons and dump cars (dumpers) based on the results of technical diagnostics and typical tests. Articles [15] give the results of a technical inspection and routine life tests on the cyclic durability of the structural elements of hopper wagons for pellets transportation.

Papers [16-20] address the research on the service life extension and the assessment of the residual lifetime of traction and multiple unit railway vehicles. In article [16] durability and extension of the service life of load-bearing structures of traction and multiple unit rolling stock of railways of Ukraine are considered. The article [17] focuses on the study of the lifetime of the load-bearing structures of the 2TE10 series diesel locomotive, which are under operation at JSC "Ukrzaliznytsia", regarding the possibility of their further safe operation within an extended service lifetime of at least 20 years, including integrated retrofitting. In the article [18], an assessment of the possibility of further safe operation of ChME3 shunting diesel locomotives was performed. The possibility of extending the service life of diesel locomotives of the CHME3 series for at least 6 years has been determined. Article [19] deals with the assessment of the technical condition of the load-bearing structures of VL60 electric locomotives and the expediency of their future operation. The articles [20] give the results of scientific

and experimental studies of the technical condition and residual lifetime of the metal structures of the bodies of metro cars of the model 81-717/714, which served out the designated service life.

The analysis of existing studies [1-20] made it possible to establish that the vast majority of them relate to the assessment of the residual lifetime of various types of railway rolling stock based on the results of technical diagnostics and typical routine tests [1-5, 10-12, 14-20] and research corrosion wear of elements of supporting metal structures and bodies of railway vehicles [8-10, 13]. At the same time, insufficient attention has been paid to the issue of improving existing programs and methods of a complex of diagnostic operations. This issue is considered in works [6, 7] and relate only to passenger cars.

Taking into account the above-mentioned, this article proposes to improve the existing procedure for determining the residual lifetime of railway vehicles by developing appropriate changes to the current programs and methods on the basis of the experience of extending their service life.

The purpose of the study is to improve the procedure for determining the residual lifetime of railway vehicles based on the accumulated experience of carrying out its technical diagnostics and the results of typical routine tests.

Material and methods of research. Currently, the extension of the service life of various types of railway vehicles is carried out on the basis of current programs and methods developed by specialized organizations and agreed with the relevant departments of JSC "Ukrzaliznytsia" in accordance with the established procedure. At the same time, a specialized institution is an institution that has been granted the right to carry out technical diagnostics work for the extension of the service life of railway vehicles by the Wagon Management Commission of the Council on Railway Transport of the Commonwealth Member States. The current programs and methods of conducting a complex of diagnostic operations in order to extend the service life of railway rolling stock must be constantly reviewed and supplemented by making appropriate changes. To begin with, one should describe the point of the existing procedure for extending the service life of railway rolling stock in a simplified form.

The main criterion for the possibility of extending the service life of railway rolling stock is its residual lifetime (or the possibility of its renovation), which is assessed by carrying out a set of diagnostic operations by a specialized institution in accordance with approved programs and methods. Based on the results of the complex diagnostic operations of the railway rolling stock, the specialized institution issues a technical decision regarding the possibility of extending the service life.

Comprehensive diagnostics operations to extend the service life of freight cars intended for operation on main railway lines are performed in accordance with the requirements of the current Order [21]; passenger cars - in accordance with the requirements of the methodology [22]; locomotives, multiple unit and special purpose railway vehicles - in accordance with the requirements [23-25] or other valid regulatory documents.

The set of diagnostic operations to extend the service life includes:

- examination of the technical condition of the metal structure body, bogie frames and beam bolsters (for freight cars, running gear diagnosis is not performed) of each railway vehicle using methods and means of non-destructive testing;
- carrying out routine strength and life tests of bodies samples of various types of railway rolling stock, fatigue bench tests of frames and beam bolster samples (diagnostics of the running gears is not performed for freight cars).

Interchangeable units and elements of bodies and bogies are subject to maintenance and repair in the prescribed manner for these units within the terms, according to the technical documentation for their operation, and are not included in the list of technical diagnostics works.

The task of inspecting the technical condition of railway vehicle is to identify damage and malfunctions of their metal structures, as well as to determine the actual thicknesses of the main load-bearing elements of the bodies, frames and bolster beams of the bogies. Inspection of the

technical condition of metal structures of each railway vehicle is carried out in the following sequence:

- receiving an application for diagnostics;
- studying the operating conditions of the rolling stock by analyzing the design and technical and operational documentation (passport, repair logs), the nature, scope, term and quality of repairs, obtaining data on average daily mileage, transported cargo (for freight rolling stock) using the databases of the Main information and computing center (GIOC) of JSC "Ukrzaliznytsia";
- identification of the railway vehicle model and the year of its manufacture;
- examination of the technical condition of metal structures by the visual-optical method in order to determine the places of mechanical damage and deformations, their nature and geometric parameters;
- detection of defects in the elements of vehicle metal structures that cannot be detected by the visual-optical method or other methods of non-destructive testing;
- determination of the degree of corrosion damage to the main bearing elements of vehicle metal structures;
- photo/video recording of malfunctions and non-compliance with technical requirements;
- filling in the "Sheet of the technical condition of the railway vehicle";
- comparative analysis of the results of the actual measured thicknesses of metal construction elements;
- preparation of a technical decision according to the established procedure and form.

The process of measuring the thickness of elements of the load-bearing structure of freight and passenger cars by the specialists of SE "UkrNDIV" is shown in fig. 1.

According to the results of technical diagnostics, railway vehicles may be excluded from the inventory park if there is significant mechanical and (or) corrosion damage. Freight wagons are excluded from the inventory fleet in the presence of at least one of the malfunctions of the load-bearing structure, which are listed in clause 6.2 of the rules [26]. Passenger cars are excluded from the inventory if there is one of the malfunctions of a mechanical or corrosion nature, which are listed in Appendix D of the methodology [22] and rules [27]. Motorcars and other traction rolling stock are excluded from the inventory park according to the instructions [28, 29] or other valid regulatory and technical documents.

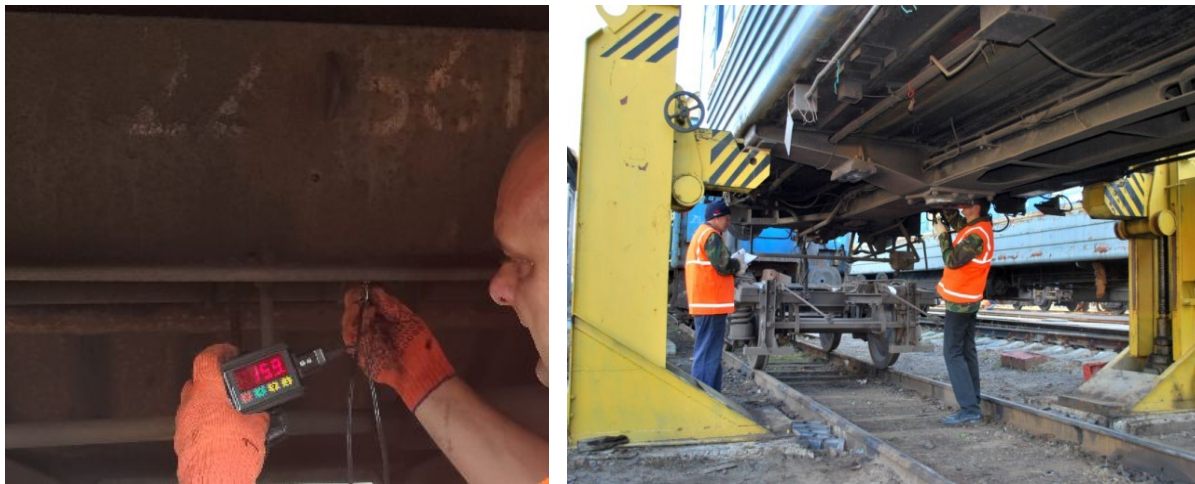


Fig. 1. Measurement of the thickness of the frame elements of the supporting structure of the freight (a) and passenger (b) cars

The criteria for evaluating the possibility of extending the service life of wagons based on the results of the technical condition inspection are established based on the following basic prerequisites:

- mechanical and corrosion damage at the time of the inspection is not extreme and during the period for which the operation of the wagon continues, it should not reach the limit values and go beyond the

limits at which the wagon is subject to exclusion from the inventory. At the same time, the assessment of the degree of further damage development is considered for the most affecting unfavorable coincidence of factors during the new designated operating period;

- mechanical and corrosive damage at the time of inspection, which are eliminated during the repair process, are qualified depending on their type, location, nature of development, size and other factors, as well as the possibility of their elimination during this or that type of repair. At the same time, mechanical and corrosion damage must be eliminated in accordance with the current rules for the repair of railway rolling stock, welding and surfacing instructions, and the established repair technology. For the main load-bearing elements of metal structures of the bogie body, frames and bolster beams, repeated repair of fatigue cracks is not allowed;

- the reasonability of repairing damaged wagons is determined depending on the technical possibility of recovering the necessary load-bearing capacity of the metal structures of the bogie body, frames and bolster beams, as well as the scope of necessary repair work.

The task of the routine tests is to study the strength of a sample of the body of a specific type of railway vehicles, samples of bogie frames and bolster beams (running gear diagnostics for freight cars is not carried out) and to determine the maximum period of continued operation of rolling stock of this type. At the same time, the following types of tests are included in the scope of routine tests: static strength tests under the action of vertical loads; impact tests; impact endurance tests; fatigue bench tests (not for freight cars).

Samples of bodies for routine tests are taken from the batch of railway vehicles, which are subject to diagnostics in the current year (rolling stock that has served the appointed term), in the process of examining their technical condition. Sampling is carried out by experts who perform an examination of the technical condition of rolling stock, in the presence of a representative of its owner. Samples should have the greatest service life (service life, mileage), the most characteristic maximum allowable damage, including repaired, minimum thicknesses of the main bearing elements (if possible).

The main task of static strength tests is to study the stressed state of the metal structure of a car body sample of a specific type that has served the specified term, with the actual thicknesses of elements under calculated static load, as well as to establish the fact that its metal structure has lost its resistance to such loads. During static load tests, the stresses and deformations that occur at the check points of the load-bearing elements of the body structure under the given load modes are determined. Check points are selected in the most heavily loaded areas of the metal structure, which are expertly established on the basis of preliminary calculations, the results of previously performed experimental studies, and the accumulated experience of inspecting wagons.

Static strength tests from vertical load are performed in the following sequence:

- preparation of vehicles for testing (selection of strain gauges, preparation of places for installation of strain gauges on metal construction elements of a vehicle; gluing of strain gauges; installation of connecting cables);

- weighing of railway vehicles containers;

- registration of deformations (stresses) in selected locations of metal construction elements of railway vehicles in empty mode using measuring equipment;

- loading to the nominal carrying capacity (for freight cars); loading to the maximum passenger capacity and equipping with water and coal (for passenger cars); complete locomotive servicing;

- weighing of loaded/equipped vehicles;

- registration of deformations (stresses) in selected locations of metal construction elements of railway vehicles in a loaded state and (or) fully equipped with measuring equipment;

- inspection of railway vehicle metal construction.

The conditioned railway vehicles with selected and glued strain gauges on the elements of its metal structure for static tests is shown in fig. 2.

The purpose of the shock load tests is to study the stress state and strength of the metal structure of a sample of a vehicle body of a specific type with the actual thicknesses of the elements when impacting the vehicle auto-coupling with a given force and speed.



Fig. 2. Railway vehicles conditioned for static tests

The purpose of the impact endurance tests is to experimentally check the durability of the metal structure of a sample of a specific type vehicle body with actual (after the intended period of operation) thicknesses of elements under specified shock load modes, which are equivalent in terms of destructive effect to the loading of the car by operational longitudinal dynamic forces. When carrying out impact endurance tests the following indicators are determined: impact force on the coupling; number of impacts; the presence of permanent deformations, damage from impact loads in the inspected elements of the body. At the same time, it is allowed to assess the durability of the load-bearing elements of the body structure of the passenger car and the locomotive by the fatigue resistance factor, which is calculated based on the results of dynamic and strength tests in accordance with the requirements of the "Standard for the calculation and design of new and modernized railway cars of MPS gauge 1520 mm (non-self-propelled) » [30] and RD 24.050.37 [31]. During dynamic strength tests, dynamic stresses in the main load-bearing elements of the body structure which occur during the movement of wagons at different speeds, up to the design one, on specific sections of the railway track of the corresponding design and current condition are determined and evaluated. During dynamic strength tests, in accordance with the requirements [31], such indicators as the natural frequency of the main vertical bending oscillations of the body and the fatigue resistance factor of the main bearing elements of the body are determined.

Impact endurance tests are carried out in the following sequence:

- a vehicle is equipped with a special auto-coupling dynamometer, static load pre-graded up to 400 tons;
- loading to the nominal carrying capacity (for freight cars); loading to the maximum passenger capacity and provision with water and coal (for passenger cars); complete servicing (for locomotives);
- weighing of loaded/equipped vehicles;
- location of railway vehicles on the test site with a shunting hump test stand with a buffer stop, equipped with a self-coupling device, and preparation of a striker, the weight of which must be no less than the weight of the test car. At the same time, it is allowed to use a railway locomotive instead of a shunting hump test stand, and instead of a railway stop - a formation of several wagons, the total weight of which is at least 300 tons;
- direct impact test;
- measurement of stresses, rolling speed of the tank car with the aid of measuring equipment;
- inspection of the metal structure of the rolling stock is performed after every 3-5 impacts.

The process of carrying out shock endurance tests using a locomotive and an experimental coupling as a railway stop is shown in Fig. 3.

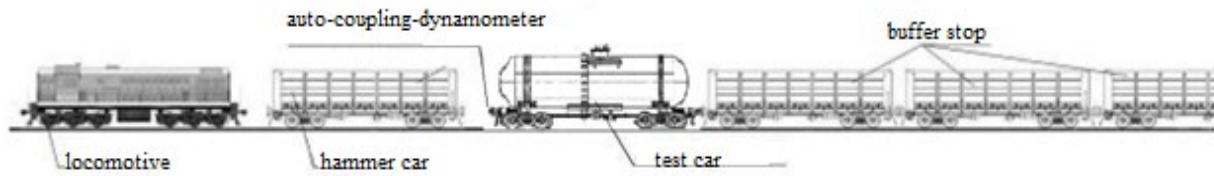


Fig. 3. Scheme of impact endurance tests

The purpose of fatigue bench tests is to experimentally assess the fatigue strength of bogie frames and bolster beams. The following indicators are determined and monitored during the fatigue tests of bogie frames and bolster beams:

- the number of load cycles before the appearance of macrocracks of a 10 mm to 50 mm length, which are detected visually, as well as the number of cycles before destruction;
- the nature of fatigue cracks development when testing and the type of fatigue failure.

Specific test equipment, i.e., test stands, hydraulic pulsator machines, etc. is used to carry out routine fatigue tests. During routine fatigue tests of bogie frames and bolster beams of passenger cars and locomotives, it is possible to use a specialized test stand of type 2CO (Fig. 4).

Therefore, the possibility of extending the service life of each railway vehicle is based on the results of its technical diagnostics and routine tests in order to determine its residual lifetime. At the same time, the main criterion for assessing corrosion wear is the minimum thickness of the elements, which must be at least the minimum set value; mechanical damage, that is deformations, fractures, cracks of the load-bearing elements of the metal structure, which can be eliminated during the prescribed type of repair, are minimally determined by size.



Fig. 4. Appearance of the 2CO test stand

In order to improve the procedure for determining the residual lifetime of railway rolling stock, it is proposed to make the following changes to the existing current programs and methods.

First, it is proposed to make changes in the wording of the term specialized institution. The need to make changes to this term is due to the armed aggression of the Russian Federation and, accordingly, the actual impossibility of Ukrainian institutions to obtain the right to carry out work on technical

diagnostics of railway rolling stock from the Council of Railway Transport of the Commonwealth Member States. The following wording of the term specialized institution is proposed - an institution that has a scientific and technical base and is accredited by the National Accreditation Agency of Ukraine for the right to perform work on technical diagnostics of railway rolling stock.

Secondly, in the near future, it is necessary to supplement the existing methods and provisions with new models of railway rolling stock, whose designated service life guaranteed by the manufacturer ends, taking into account their design features and the results of routine tests.

Thirdly, during routine tests, one should consider the possibility of replacing impact endurance tests with wedge tests and dynamic-strength tests provided that there is a satisfactory convergence of the tests results.

Fourth, review the approach to recording corrosion damage. At present, corrosion damage to load-bearing structures and bodies is recorded during technical diagnostics of railway rolling stock that has served the appointed term. At the same time, under the existing approach, it is assumed that the rate of corrosion of the main load-bearing elements is uniform. In fact, the results of many existing studies show that corrosion processes have a non-linear nature. Therefore, to increase the accuracy of determining the residual lifetime of railway rolling stock, it is necessary to monitor corrosion processes during its life cycle.

In the future, it is proposed to monitor the corrosion processes of load-bearing elements and bogies (with the exception of freight cars) during their operation within the time limits guaranteed by the manufacturer during scheduled repairs of railway rolling stock, with the entry of the check results into the database of the Main information computational center. It is suggested to record the thicknesses of load-bearing elements and bogies (with the exception of freight cars) before and after scheduled repairs of railway vehicles.

According to this approach, the value of the residual lifetime is proposed to be determined through the thinning coefficient according to formula (1):

$$T_{res.} = T_{des.} \cdot \lambda_{\Delta t}(t), \quad (1)$$

where - $T_{des.}$ is the designated service life of the railway vehicle, years;

$\lambda_{\Delta t}(t)$ is the dependence of the thinning coefficient on the time of operation of the car.

The thinning coefficient at a specified time period is determined by formula (2):

$$\lambda_{\Delta t} = \frac{t_{act.}}{t_{nom.}}, \quad (2)$$

where $t_{nom.}$ is the nominal thickness of the element, mm, is determined by the results of measuring the element in places not affected by corrosion, or by horizontal dimensions. Horizontal dimensions, as a safety margin, are taken with a positive tolerance;

$t_{act.}$ is the actual thickness of the structural element according to the measurement results, mm;

At the same time, the actual fatigue limit value, taking into account the service life, can be determined by expression (3):

$$\sigma_{a,N}^{act.} = \frac{\sigma_{a,N}}{\lambda_{\Delta h}}, \quad (3)$$

where $\sigma_{a,N}$ is the calculated limit of endurance under a symmetrical stress cycle, brought to the test base, obtained on the basis of bench vibration tests of supporting elements.

It is proposed to explain the determination of the value of the residual lifetime due to the thinning factor according to the dependence shown in Fig. 5.

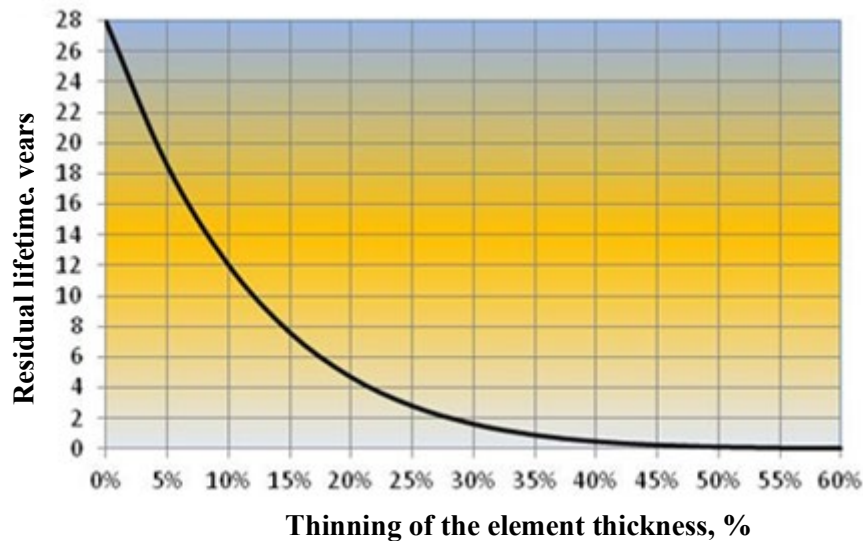


Fig. 5. Dependence of the residual lifetime on the amount of corrosion wear

So, for example, with a 30-year service life and 15% thinning of the supporting element at the time of diagnostics, the residual lifetime of the structure will be 8 years.

The dependence $\lambda_{\Delta t}(t)$ can be exponential, power, polynomial and is determined experimentally on the basis of a significant amount of accumulated research data based on the results of technical diagnostics of railway rolling stock.

Fifth, one should review the procedure for selecting a test sample for routine tests. It should be taken into account that routine tests results will be distributed to the entire batch of railway vehicles of this type, subject to diagnostics. So correctly selected samples for routine tests directly depend on the validity of their results and, accordingly, the term of service extension.

It is suggested that the content of the section "Sample selection for routine tests" should be reworded, taking into account the gained experience, experimental studies, as well as the recommendations formulated in the work [32]. This paper proposes its own algorithm for selecting samples of passenger cars and bogies for routine tests, which is based on the most characteristic mechanical and corrosive damage identified based on the results of an examination of the technical condition of all vehicles that underwent technical diagnostics during the year preceding the year in which the routine tests are scheduled.

This section is proposed in the following wording:

Body samples for routine tests are selected from the batch of railway vehicles, which are subject to diagnosis in the current year (rolling stock that has served the appointed term), in the process of examining their technical condition. The selection of samples is carried out by specialists who carry out an examination of the technical condition of rolling stock, in the presence of a representative of its owner. Samples should have the greatest performance (service life, mileage), the most characteristic maximum allowable damage, including repaired, minimum thickness of the main bearing elements. Samples for routine tests are selected by specialists based on a comprehensive analysis using the GIOC database of mechanical and corrosion damage, calculations of the reliability indicators of load-bearing structures, as well as a result of direct technical diagnostics of the selected vehicles with the longest operating time, maximum, but permissible damage of a mechanical and corrosion nature.

Sixth, in the programs and methods, it is proposed to determine the reliability indicators for each object of diagnostics using the GIOTS database, which will allow to take into account the structural and

technological features of each rolling stock, to expand the possibilities for a comprehensive analysis of the feasibility of extending its service life beyond that set by the manufacturer.

At the same time, as part of the work on technical diagnostics of railway rolling stock, it is proposed to determine the reliability indicators using the database of the Main information computational Center upon request, taking into account the KZhA classification of the railway vehicles. In this case, unplanned uncoupling of rolling stock is analyzed depending on the fault code. The analysis period is from the moment the railway vehicle is put into operation until its technical diagnosis. Malfunctions (failures) are formed and subsequently analyzed for separate time periods (intervals). Time periods are established on the basis of planned maintenance intervals according to the consideration of technical documentation for a specific type of rolling stock.

The processing of the results of the determination of reliability indicators can be presented in the form of a computational process, the input of which is the following data: the period of operation of the vehicle (T , years), the number of the same type of inspected (N_i , pcs) and damaged (n_i , pcs) elements in the i -th interval. The main reliability indicators that are determined are the following:

- the frequency of occurrence of a malfunction in the i -th interval

$$q_i = \frac{n_i}{N_i} \quad (4)$$

- the accumulated interval frequency of malfunction in the i -th interval

$$r_i = \sum_{k=1}^i q_k = \sum_{k=1}^i \frac{n_k}{N_k} \quad (5)$$

- the empirical probability of element failure during the i -th service life

$$R_i^* = \exp\left(-\sum_{k=1}^i \frac{n_k}{N_k}\right) \quad (6)$$

- the empirical probability of the element working in good condition during the i -th service life:

$$Q_i^* = 1 - \exp(-r_i) = 1 - \exp\left(-\sum_{k=1}^i \frac{n_k}{N_k}\right) \quad (7)$$

- density of damages (failures)

$$f(t) = \lambda \exp\left(-\sum_{k=1}^i \frac{n_k}{N_k}\right) \quad (8)$$

- average working time before failure

$$T_{cp} = \frac{1}{\lambda}; \quad (9)$$

- gamma percentage resource

$$T_{\gamma} = \frac{1}{\lambda} \left(-\ln \frac{\gamma}{100} \right); \quad (10)$$

- failure flow parameter

$$\omega = \frac{\Omega(t_p)}{t_p}, \quad (11)$$

where $\Omega(t_p)$ is the average specific number of failures of rolling stock, its nodes or systems during the estimated period of operation;

t_p is the average mileage of the car during the estimated period of operation before the first depot repair (in years, thousand km of mileage, etc.).

It should be noted that formulas (4)-(11) are given for the exponential distribution law. This distribution is uniparametric and is a partial case of the Weibull distribution, in which the failure rate is a constant value. Under conditions of subordination to another theoretical law of failure distribution (Rayleigh distribution, Weibull distribution, gamma distribution, etc.), formulas are used to determine reliability indicators, which are considered in detail in papers [33, 34].

Seventh, the approach to the criteria for evaluating the residual lifetime should be reviewed. Currently, the residual lifetime of railway rolling stock is determined based on the results of routine tests and technical diagnostics. At the same time, the new service life is based on the expert assessment of specialists of a specialized institution, which cannot exceed the limit established by the results of routine tests.

The authors suggest evaluating the residual lifetime of railway vehicles based on its complex minimum value. This comprehensive indicator of residual lifetime assessment will take into account the results of routine tests, expert assessment of specialists based on the results of technical diagnostics, research of corrosion processes due to the thinning factor, calculated reliability indicators. In a simplified mathematical form, the complex criterion for evaluating the residual lifetime can be presented in the following form:

$$T_{res.} = \left(\begin{array}{c} T_{res.}(\lambda_{\Delta t}(t)) \\ T_{res.}(n) \\ T_{res.}(Q_i^*) \end{array} \right) \rightarrow \min \quad (12)$$

where $T_{res.}(\lambda_{\Delta t}(t))$ is the residual lifetime determined by the results of technical diagnostics of corrosion processes due to the thinning factor;

$T_{res.}(n)$ is estimate of the residual lifetime based on the results of data processing of routine tests;

$T_{res.}(Q_i^*)$ is the residual lifetime determined based on the results of calculations of reliability indicators.

The proposed comprehensive approach to the assessment of the residual lifetime of the railway rolling stock will allow to increase the descriptiveness and accuracy of the results of such an assessment, to determine this indicator more reasonably, which will generally increase the safety of railway transportation.

Thus, this article proposes seven key directions for improving the procedure for determining the residual lifetime of railway rolling stock, which are aimed mainly at improving the safety of railway transportation and preventing a sharp reduction in the operating fleet.

Conclusions.

1 The whole point of current programs and methods of extending the service life of railway rolling stock is given. It was determined that the complex of diagnostic operations for the extension of the service life and the assessment of the residual lifetime includes routine tests on the experimental sample

and the examination of the technical condition of the metal structure of each vehicle for mechanical and corrosion damage. At the same time, the experimental sample for routine tests must have the longest operating time, the greatest characteristic maximum permissible damage, including those removed, minimum thickness of the main supporting elements (if possible). The limit period of continued operation is determined by the results of routine tests. The possibility of extending the service life of each railway vehicle is determined based on the results of its technical diagnostics, taking into account the marginal residual lifetime of the metal structure.

2. It is proposed to make seven key changes and additions to existing current programs and methods of extending the service life of railway rolling stock. These changes and additions primarily relate to terminology, sample selection for control tests, processes and methods of technical diagnostics and control tests, data processing and evaluation of results. The main differences concern the control of corrosion processes, the additional determination of the reliability indicators of the load-bearing elements of metal structures, the application of a comprehensive approach to the assessment of the residual resource of railway rolling stock.

Further efforts should be directed to the introduction of proposed changes and additions to the current programs and methods of extending the service life of railway rolling stock in order to further coordinate them with the relevant structures in the established order.

REFERENCES

1. Miamlin, S.V., Reidemeister, O.H., & Kalashnyk, V.O. (2015). Naukovo-tehnicne obhruntuvannia prodovzhennia terminu sluzhby pasazhyrskykh vahoniv pislia KVR [Scientific and technical justification for extending the service life of passenger cars after overhaul]. *Vahonnyi park – Car fleet*, 11-12(104-105), 4-7. [in Ukrainian].
2. Miamlin, S.V., Reidemeister, O.H., Pulariia, A.L., & Kalashnyk, V.O. (2015). Obhruntuvannia prodovzhennia terminu sluzhby pasazhyrskykh vahoniv iz oseredkamy korozii khrebtovoi balky [Justification of the extension of the service life of passenger cars with corrosion pit of the centre sill]. *Nauka ta prohres transportu. Visnyk Dnipropetrovskoho natsionalnoho universytetu zaliznychnoho transportu - Science and progress of transport. Bulletin of the Dnipropetrovsk National University of Railway Transport*, 5(59), 132-140. [in Ukrainian].
3. Myamlin, S.V., Reidemeister, O.H., Pulariia, A.L., & Kalashnyk, V.O. (2015). Development of recommendations for extending the useful life of passenger cars. *Nauka ta prohres transportu. Visnyk Dnipropetrovskoho natsionalnoho universytetu zaliznychnoho transportu - Science and progress of transport. Bulletin of the Dnipropetrovsk National University of Railway Transport*, 6 (60), 118-126. <https://doi.org/10.15802/stp2015/57096>. [in Ukrainian].
4. Shykunov, O.A., Reidemeister, O.H., Anofriiev, V.H., Kyrylchuk, O.A., & Doniev, O.A. (2012). Doslidzhennia hranychnoho stanu pasazhyrskykh vahoniv [Study of the limit state of passenger cars]. *Vahonnyi park - Car fleet*, 12(69), 4-6 [in Ukrainian].
5. Martynov, I.E., Trufanova, A.V., Pavlenko, Yu.S., & Serhiienko, M.O. (2018). Analiz tekhnichnoho stanu pasazhyrskykh vahoniv [Analysis of the technical state of passenger cars]. *Visnyk Natsionalnoho tekhnichnoho universytetu «KhPI». Zbirnyk naukovykh prats. Serii: Novi rishennia v suchasnykh tekhnolohiiakh. Transportne mashynobuduvannia - Bulletin of the National Technical University "KhPI". Collection of scientific works. Series: New solutions in modern technologies. Transport engineering*, 45(1321), 41-46. Kharkiv: NTU «KhPI» [in Ukrainian].
6. Radkevych, M.M., Saponova, S.Iu., Braikovska, N.S., & Tkachenko, V.P. (2021). Udoskonalennia metodyky tekhnichnoho diahnostuvannia pasazhyrskykh vahoniv [Improvement of the technique of technical diagnostics of passenger cars]. *Zbirnyk naukovykh prats DUIT. Serii «Transportni systemy i tekhnolohii» - Collection of scientific papers DUIT. "Transport systems and technologies" series*, 38, 80-87. <https://doi.org/10.32703/2617-9040-2021-38-80-7>. [in Ukrainian].
7. Yezhov, Yu.V., Pavlenko, Yu.S., & Voitenko, O.I. (2018). Udoskonalennia diiuchoi systemy prodovzhennia terminu ekspluatatsii pasazhyrskykh vahoniv [Improvement of the current system of extending the service life of passenger cars]. *Zbirnyk naukovykh prats «Reikovy rukhomyi sklad» - Collection of scientific works "Railbound Rolling Stock"*, 17, 46–50.
8. Martynov, I.E., Trufanova, A.V., & Serhiienko, M.O. (2019). Do pytan prohnozuvannia zalyshkovoho resursu ram pasazhyrskykh vahoniv [To the issues of predicting the residual lifetime of passenger cars frames]. *Zbirnyk naukovykh prats DUIT. Serii «Transportni systemy i tekhnolohii» -Collection of scientific papers DUIT. "Transport systems and technologies" series*, 34, 144-154. <https://doi.org/10.32703/2617-9040-2019-34-1-12>. [in Ukrainian].
9. Bulich, D.I., Saponova, S.Yu., Tkachenko, V.P., & Kosheh, O.O. (2020). Doslidzhennia koroziiinoho znosu nesuchykh metalevykh konstrukttsii vantazhnykh vahoniv pid chas provedennia zakhodiv shchodo prodovzhennia terminu sluzhby [Study of corrosion wear of load-bearing metal structures of freight cars while extending the service lifetime]. *Zbirnyk naukovykh prats DUIT. Serii «Transportni systemy i tekhnolohii» - Collection of scientific papers DUIT. "Transport systems and technologies" series*, 36, 43-53. <https://doi.org/10.32703/2617-9040-2020-36-5>. [in Ukrainian].

10. Fomin, O.V., Prokopenko, P.M., Burlutskiy, O.V., & Fomina, A.M. (2019). Kontroliv vyprovuvanniavantaznohovahona z metoiuotsinkyzalyshkovohoresursunesuchykhkonstruktsii [Routine tests of a freight car to assess the residual lifetime of the load-bearing structures]. *Vchenizapysky TNU im. V.I. Vernadskoho. Serii: tekhnichninauky - Scientific notes of TNU named after V.I. Vernadskiy. Series: technical sciences.* (Vol. 30(69), Part 2, Iss. 3), (pp. 177-182). <https://doi.org/10.32838/2663-5941/2019.3-2/31>. [in Ukrainian].
11. Fomin, O.V., Prokopenko, P.M., Shvets, A.O., Lakhai, O.I., & Sviderskiy, R.V. (2019). Vyznachennia zalyshkovoho resursu nesuchoi zdatnosti bazovoi konstruktsii vahona-zernovoza z proterminovanyim strokom sluzhby [Determination of the residual resource of the load-bearing capacity of the basic design of the grain wagon with an extended service lifetime]. *Visnyk sertyfikatsii zaliznychnoho transportu - Bulletin of railway transport certification*, 05(57), 5-18. [in Ukrainian].
12. Fomin, O.V., Prokopenko, P.M., Horbunov, M.I., & Sova, S.S. (2019). Osoblyvosti vyznachennia zalyshkovoho resursu vahonopovirochnykh vahoniv z terminom sluzhby, yakyy perevyshehuie pryznacheniy [Peculiarities of determining the residual lifetime of wagon-loading wagons with a service life that exceeds the intended one]. *Zbirnyk naukovykh prats DUIT. Serii «Transportni systemy i tekhnolohii» - Collection of scientific papers DUIT. "Transport systems and technologies" series*, 34, 95-105. <https://doi.org/10.32703/2617-9040-2019-34-1-8>. [in Ukrainian].
13. Fedosov-Nikonov, D.V., Strynzha, A.M., Shamshei, D.O., Poluliakh, V.M., Fedorov, V.V., & Shushmarchenko, V.O. (2019). Doslidzhennia koroziiinykh poshkodzen elementiv vahoniv pid chas tekhnichnoho diahnostuvannia [Study of corrosion damage of wagon elements under technical diagnostics]. *Visnyk Skhidnoukrainskoho natsionalnoho universytetu imeni Volodymyra Dalia - Bulletin of the Eastern Ukrainian National University named after Volodymyr Dahl*, 3(251), 181-185. [in Ukrainian].
14. Koshel, O.O., Sapronova, S.Iu., Bulich, D.I., & Tkachenko, V.P. (2020). Vyznachennia zalyshkovoho resursu nesuchykh metalevykh konstruktsii vahoniv khoper-dozatoriv (samoskydiv) na osnovi rezultativ tekhnichnoho diahnostuvannia ta typovykh vyprovuvan [Determination of the residual lifetime of the load-bearing metal structures of hopper-doser wagons (dumpers) based on the results of technical diagnostics and typical tests]. *Zbirnyk naukovykh prats DUIT. Serii «Transportni systemy i tekhnolohii» - Collection of scientific papers DUIT. "Transport systems and technologies" series*, 35, 14-23. <https://doi.org/10.32703/2617-9040-2020-35-2>. [in Ukrainian].
15. Ilchyshyn, V.V., Strynzha, A.M., & Fedosov-Nikonov, D.V. (2016). Obstezhennia tekhnichnoho stanu ta kontrolni vyprovuvannia vantaznykh vahoniv [Examination of the technical condition and routine tests of freight cars]. *Zbirnyk naukovykh prats «Reikovi rukhomiy sklad» - Collection of scientific works "Railbound Rolling Stock"*, 13, 49-51 [in Ukrainian].
16. Horobets, V.L., & Bondariiev, O.M. (2015). Doslidzhennia pytan mitsnosti ta podovzhennia terminu sluzhby nesuchykh konstruktsii tiahovoho ta motorvahonnoho rukhomoho skladu zaliznyts Ukrainy [Study of issues of durability and service life extension of load-bearing structures of traction and rolling stock of railways of Ukraine]. *Lokomotyv-inform - Locomotive-inform*, 9-10, 4-11 [in Ukrainian].
17. Leonets, V.A., Kara, S.V., & Prokopenko, P.M. (2019). Otsinka zalyshkovoho resursu nesuchykh konstruktsii teplovoziv serii 2TE10 ta vyznachennia mozhlyvosti prodovzhennia terminu yikh ekspluatatsii [Assessment of the residual lifetime of the load-bearing structures of the 2TE10 series diesel locomotives and determination of the possibility of extending their service life]. *Zaliznychnyi transport Ukrainy - Railway transport of Ukraine*, 4, 19-28. <https://doi.org/10.34029/2311-4061-2019-133-4-19-28>. [in Ukrainian].
18. Kara, S.V., Petrenko, V.O., Prokopenko, P.M., & Hordiienko, T.M. (2019). Doslidzhennia nesuchykh konstruktsii teplovoziv serii ChME3 ta vyznachennia mozhlyvosti prodovzhennia terminu yikh ekspluatatsii [Study of the load-bearing structures of the ChME3 series diesel locomotives and determination of the possibility of extending their service lifetime]. *Zaliznychnyi transport Ukrainy - Railway transport of Ukraine*, 3, 9-13. <https://doi.org/10.34029/2311-4061-2019-131-2-09-13>. [in Ukrainian].
19. Tyshchyshyn, O.I., & Hupalov, M.V. (2020). Otsinka tekhnichnoho stanu nesuchykh konstruktsii elektrovoziv VL60 ta dotsilnosti yikh ekspluatatsii u podalshomu [Assessment of the technical condition of the load-bearing structures of VL60 electric locomotives and the feasibility of their future operation]. *Zaliznychnyi transport Ukrainy - Railway transport of Ukraine*, 4, 22-31. <https://doi.org/10.34029/2311-4061-2020-137-22-31>. [in Ukrainian].
20. Yezhov, Yu.V., Pavlenko, Yu.S., Voitenko, O.I., & Poluliakh, S.M. (2018). Doslidzhennia tekhnichnoho stanu nesuchykh metalokonstruktsii kuzoviv vahoniv metropolitenu modelei 81-717/714 ta yikh modyfikatsii [Research of the technical condition of the load-bearing metal structures of the bodies of metro cars models 81-717/714 and their modifications]. *Zbirnyk naukovykh prats «Reikovi rukhomiy sklad» - Collection of scientific works "Railbound Rolling Stock"*, 17, 22-28 [in Ukrainian].
21. Poriadok provedennia kompleksu diahnostychnykh, remontnykh ta reiestratsiinykh operatsii, spriamovanykh na prodovzhennia stroku ekspluatatsii vantaznykh vahoniv (krim vantaznykh vahoniv pidpriemstv tekhnolohichnoho zaliznychnoho transportu, shcho pryznacheniy dlia peremishchennia vantazhiv u vyrobnychykh tsiliakh v mezhakh terytorii takykh pidpriemstv), ustanovlenoho vyrobnykom, strokiv prodovzhennia ekspluatatsii. [The procedure for carrying out a complex of diagnostic, repair and registration operations aimed at extending the period of operation of freight wagons (except for freight wagons of technological railway transport enterprises, which are intended for the movement of goods for production purposes within the territory of such enterprises), established by the manufacturer, the period of operation extension]. *Nakaz Mininfrastruktury № 647 vid 30.11. 2021 - Order of the Ministry of Infrastructure No. 647 from 2021, November 30.* (2022, January 1). URL: <https://zakon.rada.gov.ua/laws/show/z1677-21#Text>. [in Ukrainian].

22. *Metodyka tekhnichnoho diahnostuvannia pasazhyrskykh vahoniv, shcho vysluzhyly pryznachenyi termin, z metoiu yoho prodovzhennia* [Procedure for technical diagnostics of passenger cars with expired service lifetime, with the aim of extending it]. Nakaz Ukrzaliznytsi № 304-Ts (2008, June 25) - Order of Ukrzaliznytsia dated June 25, 2008. *TsL 0070*. Kyiv: Neskinchedzherelo [in Ukrainian].

23. Polozhennia pro orhanizatsiiu robit shchodo prodovzhennia pryznachenoho terminu sluzhby tiahovoho rukhomoho skladu Ukrzaliznytsi (ram vizkiv, holovnykh ram kuzoviv i nesuchykh kuzoviv). [Provisions on the organization of works regarding the extension of the designated service lifetime of traction rolling stock of Ukrzaliznytsia (bogie frames, main body frames and wagon body bearing structures)]. (2002). *VND 32.007.123-03-2002*. Kyiv: Ministerstvo transportu Ukrainy [in Ukrainian].

24. Tekhnichne diahnostuvannia ta otsinka zalyshkovoho resursu nesuchykh konstrukttsii teplovoziv z metoiu podovzhennia yikh terminu sluzhby. *Metodyka diahnostuvannia*. [Technical diagnosis and assessment of the residual lifetime of the load-bearing structures of diesel locomotives with the aim of extending their service life. Methodology of diagnosis]. (2018). *M 4.1.00740*. Kremenchuk: SE «UkrNDIV» [in Ukrainian].

25. *Metodyka tekhnichnoho diahnostuvannia vahoniv metropolitenu, shcho vysluzhyly pryznachenyi termin, z metoiu yoho prodovzhennia* [Methodology of technical diagnostics of metro cars that have served the designated lifetime, with the aim of extending it]. (2011). Kremenchuk, SE "UkrNDIV" [in Ukrainian].

26. Pravyly vykliuchennia vantazhnykh vahoniv iz inventarnoho parku. Vvedeno na pidstavi nakazu Ukrzaliznytsi vid 11.05.2005 № 151-TsZ (zi zminamy ta dopovnenniamy zhidno do nakazu vid 26.12.2006 № 532) [Rules for excluding freight wagons from the inventory fleet. Introduced on the basis of the order of Ukrzaliznytsia dated 11.05.2005 No. 151-CZ (with changes and additions according to the appendix to the order No. 532 dated 2006, December 26)]. (2005). *TsV 0063*. Kyiv: MinisterstvotransportuiviazkuUkrainy [in Ukrainian].

27. Pravyly vykliuchennia pasazhyrskykh vahoniv iz inventarnoho parku. Vvedeno na pidstavi nakazu Ukrzaliznytsi vid 28.12.2007 № 635-Ts. (2008). *TsL 0069*. Kyiv: Neskinchene dzherelo [in Ukrainian].

28. Instrukttsiia pro poriadok vykliuchennia z inventariu zaliznyts tiahovoho rukhomoho skladu. Vvedeno na pidstavi nakazu Ukrzaliznytsi vid 15.02.1995 (zi zminamy ta dopovnenniamy zhidno dodatku do nakazu Ukrzaliznytsi vid 16.02.1995) [Instruction on the procedure for excluding traction rolling stock from railway inventory. Entered on the basis of the order of Ukrzaliznytsia dated 15.02.1995 (with changes and additions according to the appendix to the order of Ukrzaliznytsia dated 1995, February 16)]. *TsT 0002*. Kyiv: Ministerstvo transport Ukrainy [in Ukrainian].

29. Instrukttsiia pro poriadok vykliuchennia z inventarnoho parku ta spysannia elektrorukhomoho skladu metropolitenu. Nakaz № 347-N. 2015. [Instructions on the procedure for exclusion from the inventory and decommissioning of electric rolling stock of the metro. Order No. 347-N]. (2015, October 6). Kyiv: Komunalne pidpriemstvo «Kyivskiy metropoliten» [in Ukrainian].

30. Normy dlya rascheta i proektirovaniya novykh i moderniziruemykh vagonov zheleznykh dorog MPS kolei 1520 mm (nesamohodnykh). Norms for the calculation and design of new and modernized railway vehicles of Ministry of Railways of 1520 mm gauge (non-self-propelled). (1996). Moscow: GosNIIV – VNIIZHT [in Russian].

31. Vagony gruzovoyei passazhirskie. Metody ispytaniy na prochnost' i hodovyekachestva [Freight and passenger cars. Test methods for strength and riding qualities]. (1995). *RD 24.050.37-95*. M.: GosNIIV [in Russian].

32. Yezhov, Yu.V., & Pavlenko, Yu.S. (2018). Alhorytm vidboru zrazka pasazhyrskoho vahona lokomotyvnoi tiahly dlia kontrolnykh vyprobuvan [Algorithm for selecting a sample of a locomotive traction passenger car for control tests]. *Zbirnyk naukovykh prats «Reikovy rukhomiy sklad» - Collection of scientific works "Railbound Rolling Stock"*, 17, 62–70 [in Ukrainian].

33. Vodiannikov, Yu.Ia., Fedosov-Nikonov, D.V., Strynzha, A.M., & Poluliakh, V.M. (2022). Alhorytm vyznachennia pokaznykiv nadiinosti odynyts rukhomoho skladu zaliznyts za rezultatamy tekhnichnoho diahnostuvannia v ekspluatatsii [Algorithm for determining the reliability indicators of railway rolling stock units based on the results of technical diagnostics under operation]. *Zbirnyk naukovykh prats «Reikovy rukhomiy sklad» - Collection of scientific works "Railbound Rolling Stock"*, 24, 47–60. <https://doi.org/10.47675/2304-6309-2022-24-47-60>. [in Ukrainian].

34. Vodiannikov, Yu.Ia., Sulym, A.O., Khozia, P.O., Stolietov, S.O., Melnyk, O.O., & Lashkevych, I.M. (2023). Pasazhyrski vahony. Diahnostuvannia. Zalyshkovy resurs. Nadiinist. [Passenger cars. Diagnostics. Remaining lifetime. Reliability]. *Monograph. Kremenchuk: SE "UkrNDIV"*. [in Ukrainian].

Андрій Сулим^{1*}, Павло Хозя², Андрій Стринжа³, Юрій Павленко⁴, Сергій Столетов⁵

¹Заступник директора з наукової роботи, Державне підприємство «Український науково-дослідний інститут вагонобудування», вул. І. Приходька, 33, м. Кременчук, 39621, Україна. ORCID: <https://orcid.org/0000-0001-8144-8971>

²Завідувач науково-дослідної лабораторії, Науково-дослідна лабораторія експериментальних досліджень залізничної техніки, Державне підприємство «Український науково-дослідний інститут вагонобудування», вул. І. Приходька, 33, м. Кременчук, 39621, Україна. ORCID: <https://orcid.org/0000-0001-8948-6032>

³Завідувач науково-дослідної лабораторії, Науково-дослідна лабораторія вантажного та спеціального

рухомого складу, Державне підприємство «Український науково-дослідний інститут вагонобудування», вул. І. Приходька, 33, м. Кременчук, 39621, Україна. ORCID: <https://orcid.org/0000-0003-3743-7006>

⁴Завідувач науково-дослідної лабораторії, Науково-дослідна лабораторія ходових частин, пасажирського, причіпного, тягового, самохідного та міського рейкового рухомого складу, Державне підприємство «Український науково-дослідний інститут вагонобудування», вул. І. Приходька, 33, м. Кременчук, 39621, Україна. ORCID: <https://orcid.org/0000-0001-8612-3228>

⁵Завідувач науково-дослідної групи, Науково-дослідна лабораторія експериментальних досліджень залізничної техніки, Державне підприємство «Український науково-дослідний інститут вагонобудування», вул. І. Приходька, 33, м. Кременчук, 39621, Україна. ORCID: <https://orcid.org/0000-0001-8819-2534>

* Автор, відповідальний за листування: sulim1.ua@gmail.com

Удосконалення процедури визначення залишкового ресурсу залізничного рухомого складу

Обґрунтовано необхідність продовження строку експлуатації залізничного рухомого складу, що виступив призначений термін служби гарантований заводом-виробником, з метою запобігання різкому скороченню експлуатаційного парку. Розглянуто та проаналізовано існуючі дослідження в напрямку продовження строку служби різного типу залізничного рухомого складу та оцінки його залишкового ресурсу. Встановлено, що переважна більшість досліджень стосується оцінки залишкового ресурсу різного типу залізничного рухомого складу на підставі результатів технічного діагностування та типових контрольних випробувань, а також оцінці корозійного зносу елементів несучої конструкції та кузовів залізничного рухомого складу. При цьому питанню удосконалення існуючих програм та методик комплексу діагностичних операцій приділено недостатньо уваги. Наведено основну сутність чинних програм та методик продовження строку експлуатації залізничного рухомого складу різного типу. Визначено, що комплекс діагностичних операцій з продовження строку експлуатації включає проведення контрольних випробувань на дослідному зразку та обстеження технічного стану металоконструкції кожного рухомого складу на наявність пошкоджень механічного та корозійного характеру. Запропоновано в існуючі чинні програми та методики внести зміни за такими ключовими розділами як: термінологія, об'єкти технічного діагностування та випробувань, відбір дослідного зразка для контрольних випробувань, порядок та методи технічного діагностування та контрольних випробувань, обробка даних та оцінка результатів. Також запропоновано комплексний підхід для оцінки залишкового ресурсу залізничного рухомого складу, який дозволить підвищити інформативність та точність результатів такої оцінки, а також більш обґрунтовано визначати цей показник.

Ключові слова: залізничний транспорт, залишковий ресурс, контрольні випробування, рухомий склад, технічне діагностування.

UDC 656.073.28

Olha Shulika¹, Oleksandra Orda^{2*}, Natalia Potaman³, Yurii Yashchuk⁴

¹Associate professor, Department Transport Technologies, Kharkiv National Automobile and Highway University, 25, Yaroslava Mudroho str., Kharkiv, 61002, Ukraine, ORCID: <https://orcid.org/0000-0002-1912-1115>

²Associate professor, Department Transport Technologies, Kharkiv National Automobile and Highway University, Str. Yaroslava Mudroho 25, Kharkiv, 61002, Ukraine, ORCID: <https://orcid.org/0000-0002-7213-8469>

³Associate professor, Department Transport Technologies, Kharkiv National Automobile and Highway University, 25, Yaroslava Mudroho str., Kharkiv, 61002, Ukraine, ORCID: <https://orcid.org/0000-0002-9545-5002>

⁴Postgraduate of the Department Operational work management, Ukrainian State University of Railway Transport, 7, Feuerbach sq., Kharkiv, 61050, Ukraine, ORCID: <https://orcid.org/0009-0006-1985-1181>

* Corresponding author: kost.alexandra@gmail.com

Developing an efficient road-based batch freight delivery technology for intercity connections with a focus on resource conservation

In this paper, we propose the solution of the scientific and applied problem of batch freight delivery in the intercity by road in terms of system's limited resource of the system due to the development of long-distance freight delivery technology in terms of resource savings and the observation of the established level of reliability of the freight delivery functioning of the logistics system (FDLS). For certain parameters of cargo flow with limited resources of the transport market entities involved in the delivery process, the formation of a resource-saving delivery technology allows maximising the effect of the functioning of the system of delivery of consignment cargo by road in intercity traffic.

To solve the problem, we used methods of mathematical modelling, a systematic approach, optimization methods (functions of many variables), the provisions of probability theory and mathematical statistics, methods of regression analysis.

For the given operating conditions of the developed logistics system, the rational technology of long-distance batch freight delivery has been determined in terms of resource savings. It will reduce overall costs by 13.9% for the given level of the readiness of FDLS.

Keyword: road transport, resource savings, delivery, batch freight, readiness factor

Introduction. The events of the armed conflict on the territory of Ukraine led to massive disruptions in the movement of road and rail transport. Extraordinary disruptions were observed both on the roads of the country's eastern border, most of which were destroyed or occupied, and on the roads of the western border, which were used by refugees to travel to neighbouring EU countries [1]. The trucking industry has taken on a huge burden due to the blockade of the sea ports and the closure of airspace. The recovery of logistics supply chains for goods under the influence of various risks is slow. According to the developed national program "Expansion and Integration of Logistics with the EU" within the framework of the Recovery Plan of Ukraine, one of the priority areas is the development of road transport, which, in our opinion, can be achieved using a balanced approach that responds to the future projected growth and changes in demand for transportation services, promoting economic development, improving the quality of life of the population and efficient use of resources. Therefore, the task of developing transport and technological delivery schemes in which delivery resources will be minimal is

of particular relevance to achieve a balance between marketing requirements and logistics capabilities. It will allow FDLS to make extra profit and distribute it between participants in the delivery process according to their contribution.

It is known that the bulk of the demand for long-distance transportation in Ukraine is occupied by batch freight transportation [2]. Modern road transport conditions dictate the need to find efficient resource- and energy-saving freight delivery technologies that provide high quality customer service and cost-effective road transport.

Currently, the issue of resource savings has not been fully explored in Ukraine. There is no forecast of further development of resource savings in the context of the world economy. This makes it impossible to formulate a state resource savings policy, to develop appropriate regional and state strategic plans for development, and to promote resource savings in Ukraine. Additionally, the issue of resource-saving technologies and the development of computerization will remain a question without improving information technology in road transport, which contributes to reducing of problematic indicators of the transport market.

Today's realities require freight owners to look constantly for new, progressive ways to improve their performance. The extensive experience of developed foreign countries testifies to the necessity of introduction of scientifically grounded approaches to planning and organization of freight delivery in the intercity connection with the use of logistics delivery systems. Within these systems for logistics services and freight owners there is a possibility of operative planning of freight delivery with the maximization of resource efficiency of the delivery process participants.

Therefore, the question of the formation of technology of long-distance batch freight delivery by road in terms of resource savings is relevant and needs further research.

Analysis of recent research and problem statement. The research of the theoretical and practical aspects of increasing the efficiency of long-distance freight delivery was carried out by many scientists, such as B. Anikin, S. Artemyev, D. Bauersoks, V. Belyaev, O. Velmozhin, A. Vorkut, A. Gorev, M. Goryaev, O. Goryainov, V. Gudkov, O. Kalinichenko, I. Levitsky, L. Mirotin, Ye. Nagorny, V. Naumov, V. Nefedov, N. Potaman, M. Pravdin, A. Smekhov, A. Chebotaev, N. Shramenko, O. Shulika, and other scientists.

The task of increasing the efficiency of FDLS in intercity connection can be solved both by updating the technical base and by increasing the efficiency of technological solutions, taking into account resource savings. Insufficient working capital for the acquisition of new rolling stock and historically formed transport and technological delivery schemes do not provide optimal costs and time for long-distance freight transportation. In market conditions, when planning production capacities and implementing transport services, it is necessary to align the logistical goals of the production system with the marketing needs of consumers - freight owners.

The issues of the development of approaches and models aimed at the implementation of resource-saving technologies were addressed by both foreign scientists [2-14] and domestic scientists and scientists from the near-outlands, among whom Ye. Aloshinsky, V. Bobrovsky, V. Gubenko, M. Danko, D. Lomotko, V. Mironenko, Ye. Nagorny, V. Naumov, V. Negri, R. Khabutdinov, N. Shramenko etc.

In [2-4], it is observed that traditional competitive barriers between participants in the logistics supply chain are mitigated to create mutually beneficial relationships. It leads to an increase of information flows, reduction of uncertainty, and a more profitable supply chain. An important aspect in the development of technologies for the implementation of logistics chains is to take into account the principles of "green" logistics [11, 12]. That means reducing the environmental impact of logistical operations. Scientists have stated that the main direction of increasing the efficiency of transport system operation in conditions of fuel and energy deficit [6-10] is the development of resource-saving technologies [9, 13, 14].

Today, scientists are deeply analysing the problem of the so-called "last mile" [15]. Last Mile Logistics is the least efficient step in the supply chain, accounting for up to 28% of total shipping costs. New innovative Industry 4.0 technologies and organizational strategies make it possible to create a real-time planning optimization model focusing on energy efficiency of operations, development of

management systems for information and advertising activities of cargo owners, etc. [2]. In the traditional supply chain, increasing energy efficiency is focused on the level of individual parts of the value chain. Industry 4.0 technologies allow you to create hyper communication logistics solutions that aim to reduce energy consumption and reach economically globally.

Regarding the practical aspect of the issue, it can be noted that at present most manufacturers are actively involved in developing variants of their products delivery to final consumers or coordinating them with freight forwarding companies, since the competitiveness of manufacturers depends on the efficiency of delivery. Today, companies that compete solely on the basis of product specifications, sooner or later, find themselves in a disadvantageous situation compared to firms that strengthen their market position, improving the quality of service for freight owners and carriers. In this process, an important role belongs to an effectively organized integrated logistics service, which should be implemented not only at the level of the individual enterprise, but also be a process that unites all participants of the delivery process. Therefore, at the current stage of the long-distance transportation market development, it is advisable to develop new innovative resource-saving technologies to improve and optimize the co-operation and interaction of the long-distance transportation market actors.

In the study [16] four sets of measures have been proposed to introduce a system of long-distance shipping system, taking into account the resource savings. These four types of measures are developed to support economic, social and environmental goals to achieve sustainability. The first set of measures is related to material infrastructure: linear (refers to interconnections) or nodal (refers to areas that may be reserved for freight operations, such as terminals). The second set of measures is related to the intangible infrastructure, which includes road information systems, freight exchange systems, route optimization services, other information services via the Internet and centralized traffic planning (intelligent transport systems). The third set of measures concerns equipment including rules relating to the loading, traction and transportation of new low emission vehicles. The last set of measures is related to traffic management, namely the definition of regulatory rules (such as access time, heavy-duty vehicle network, maximum stopping time, etc.). In long-distance freight transportation by road, the most common are two transport and technological schemes: direct delivery scheme (first scheme) and terminal delivery scheme (second scheme).

The main advantage of the first scheme is direct door-to-door freight delivery. The disadvantage of this is that the collection and transportation of freights inefficiently used the mileage and load of the car, and the load of goods and paperwork in each enterprise associated with considerable time. Often, such an organization requires additional loadings. These further increases downtime and impedes freight delivery. This scheme is used mainly for intra-regional freight transportation.

The second scheme (terminal delivery scheme) consists in the delivery of freights with their transshipment at the terminal only at the point of departure or destination. In the latter case, the freight from the consignor is loaded directly into the vehicle intended for intercity transportation.

The main purpose of the terminal system in the service of freight owners is to take into account their interests in ensuring a full and high quality processing of freights with the rational use of transport and warehouse resources. Thus, in this research, the terminal system was adopted as a modern resource-saving technology for the batch freight delivery. When choosing the best variant of resource-efficient freight delivery technology, the most important parameters are time and cost [17], their correlation in different terms forms the sum of logistics costs associated with the organization of such technologies.

Having analysed the scientific research in the direction of development of resource-saving technologies of cargo delivery, we can note the following. Among the priority areas for improving batch freight delivery, most researchers point to the formation of rational freight delivery technologies, taking into account resource saving and determining the rational amount of resources in the operation of systems of different levels based on the use of logistics principles. Thus, for certain parameters of freight traffic with limited resources of transport market entities involved in the delivery process, the formation of resource-saving delivery technology will maximize the effect of the functioning of the batch freight delivery system by road in the intercity direction.

Purpose and objectives of the study. The aim of the work is to increase the efficiency of cargo delivery on the basis of resource saving and compliance with the established level of reliability of the logistics system of cargo delivery (FDLS) by road transport.

To achieve this purpose, the following tasks need to be solved:

to carry out theoretical studies of the issue of increasing the efficiency of organization of the technological process of delivery of consignment cargo in intercity connections, taking into account the condition of resource conservation

to develop a mathematical model of the process of delivery of consignment cargoes by alternative technologies in intercity connections, taking into account the condition of resource saving

to carry out experimental studies on the selection of a rational technology for the delivery of consignments in intercity connections, taking into account the condition of resource conservation

to determine the optimal areas for the effective use of certain technologies for the delivery of consignment cargo in intercity connections

Materials and methods of the study. The object of research is the technological process of batch freight delivery in the intercity road connection. Direct delivery and terminal delivery systems are considered as alternative delivery schemes (Fig. 1).

The subject of research includes four main participants: consignor (CR), consignee (CE), carrier and terminal. Each participant has an internal structure. The nature and properties of the object of study were revealed between participants and internal communication structures.

The managed object of this system is the market of freight forwarding services (FFM), and terminal services. It consists of the totality of transport and forwarding companies (FFC), terminals (T) that form the offer for long distance batch freight delivery and exist on FFM, and the totality of freight owners (FO) that make up the demand for delivery. FFM is influenced by many external factors, including the economic performance of FFM participants, the road network, etc. (external factors).

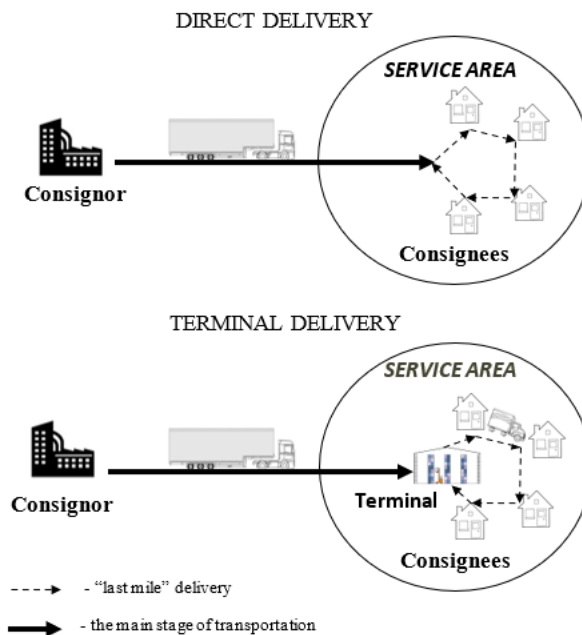


Fig. 1. Direct and terminal delivery systems for batch freight in the intercity connection

The process of rendering freight forwarding services in FDLS can be represented in the form of a contour of the functional connections of the formation of technology of batch freight delivery in the intercity connection by road in terms of resource savings (Fig. 2).

The consumer subsystem is formed by freight owners according to the characteristics determined by the complex of necessary feasibility services. Demand for delivery is formed by the flows of FO' requests. The operating parameter of a CR is the manufacturer's processing capacity (PC , t/h). The parameters of the FO request flow are: the volume for the request (Q , t), the distance of delivery (l , km) and the delivery density of the points of delivery in the territory of the service area (λ , km⁻²).

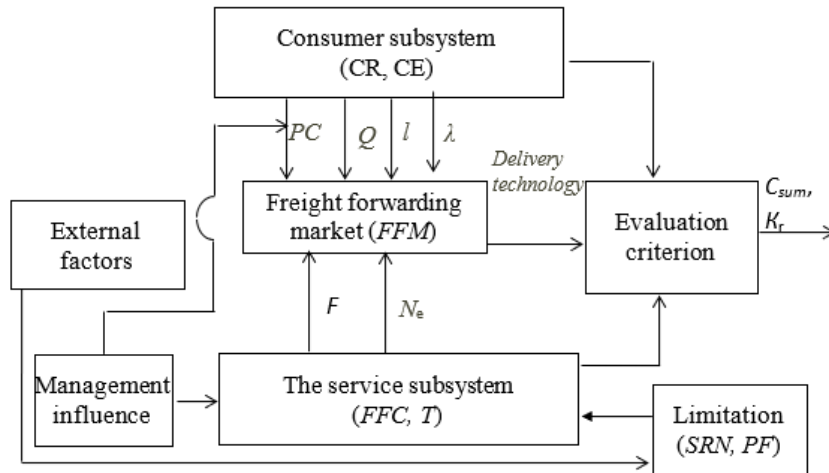


Fig. 2. Functional link contours for the formation of batch freight delivery in intercity connection by road in terms of resource savings

Freight forwarding enterprises and terminals form a service subsystem with controlled parameters, which is the amount of labor resources, dispatchers at a freight forwarding enterprise (N_d , person) and the service area (F , km²).

The limitation system takes into account the production facilities (PF) of the service system and the limitations caused by the parameters of the street-road network (SRN).

In this research, to select a rational transport and technological scheme for the batch freight delivery in long distance, the overall cost of freight delivery (C_{sum}) and the readiness factor (K_r) were taken as the criterion of efficiency.

Cost reduction is achieved through the formation of resource-saving technology for the batch freight delivery in long distance. Reducing the overall cost of delivery is an important means of reducing tariffs and thus attracting additional customers. In this case, the use of resource-saving technologies involves ensuring the reliability of freight delivery. Thus, the target function is as follows

$$\begin{cases} C_{sum} = f(Q, l, F, \lambda, PC, N_d) \rightarrow \min; \\ K_r = f(Q, l, F, \lambda, PC, N_d) \rightarrow 1. \end{cases} \quad (1)$$

The total cost of long-distance freight delivery is calculated by the formula

$$C_{sum} = C_{FO} + C_C + C_{FF} + C_T + C_{fc}, \quad (2)$$

where C_{FO} – costs of FO operations, UAH;

C_C – carrier transportation costs, UAH;

C_{FF} – forwarding operations costs, UAH;

C_T – costs for processing and storage of freight at the terminal, UAH;

C_{fc} – capital freezing, UAH.

The article suggested that the service area has the shape of a circle (Fig. 1), where one terminal operates, located in the conditional centre of the service area. The system of restrictions and assumptions is as follows

$$\left\{ \begin{array}{l} 0,4 \leq \gamma_s \leq 1; \\ Q \leq q; \\ 1 \leq Q \leq 5; \\ 50 \leq l \leq 1800; \\ 0,5 \leq \beta \leq 1; \\ 13,5 \leq F \leq 350; \\ 1 \leq N_d \leq 5; \\ 5 \leq PC \leq 100; \\ 0,1 \leq \lambda \leq 2, \end{array} \right. \quad (3)$$

where γ_s – an automobile load factor;

q - automobile carrying capacity rated, t;

β – the mileage utilisation factor;

The costs of FO operations are calculated according to the formula.

$$C_{FO} = Q \cdot \left(\frac{C_L^{CR}}{PC} + \tau_{UL}^{CE} \cdot C_{UL}^{CE} \right), \quad (4)$$

where C_L^{CR} – unit costs of loading 1 ton at the CR, UAH/h;

τ_{UL}^{CE} – time for unloading of 1 t of cargo at the CE, h/t;

C_{UL}^{CE} – unit costs of unloading 1 ton at the CE, UAH/(t·h).

For direct delivery, carrier's costs are defined as follows

$$C_C^D = Q \cdot \left[\frac{l}{q^D \cdot \gamma^D \cdot \beta^D} \cdot \left(C_{zm}^D + \frac{C_{post}^D}{V_t} \right) + C_{post}^D \cdot \left(\frac{1}{PC} + \tau_{UL}^{CE} \right) \right], \quad (5)$$

where C_{zm}^D, C_{post}^D – the variable and constant component of transportation cost, UAH/km and UAH/h;

V_t – the average technical vehicle speed, km/h.

For the terminal delivery system, transportation costs consist of the costs of the main stage of transportation and transportation costs to the customers in the service area [17]. They are defined as follows

$$C_C^T = Q \cdot \left[\frac{l - \sqrt{\frac{F}{\pi}}}{q^D \cdot \gamma^D \cdot \beta^D} \cdot \left(C_{zm}^D + \frac{C_{post}^D}{V_t} \right) + C_{post}^D \cdot \left(\frac{1}{PC} + \tau_{UL}^{CE} \right) \right] +$$

$$+ Q \cdot \left[\left(\frac{4}{3} \cdot \sqrt{\frac{F}{\pi}} + \frac{4}{5} \cdot \left(\frac{q^{lm} \cdot \gamma^{lm}}{Q} - 1 \right) \cdot \frac{1}{\sqrt{\lambda}} \right) \cdot \frac{Q \cdot F \cdot \lambda}{q^{lm} \cdot \gamma^{lm}} \cdot (a_{zm} + \epsilon_{zm} \cdot q^{lm}) + \right.$$

$$\left. \left(\frac{4}{3} \cdot \sqrt{\frac{F}{\pi}} + \frac{4}{5} \cdot \left(\frac{q^{lm} \cdot \gamma^{lm}}{Q} - 1 \right) \cdot \frac{1}{\sqrt{\lambda}} \right) \cdot \frac{Q \cdot F \cdot \lambda}{q^{lm} \cdot \gamma^{lm} \cdot V_t^{lm}} + 2 \cdot \tau_{L(UL)} \cdot q^{lm} \cdot \gamma^{lm} \right] \times$$

$$\left. \left(a_{post} + \epsilon_{post} \cdot q^{lm} \right) \cdot \frac{1}{Q \cdot F \cdot \lambda} \right], \quad (6)$$

where q^{lm} – rated carrying capacity of “last mile” automobile, t ;

γ^{lm} – a load factor of “last mile” automobile;

a_{zm}, ϵ_{zm} – coefficients of the regression model of the dependence of the variable component of transportation cost on the automobile’s carrying capacity [17];

V_t^{lm} – medium technical vehicle speed during “last mile” transportation, km/h ;

$\tau_{L(UL)}$ – time to load (unload) 1 ton of freight at the terminal, h/t ;

$a_{post}, \epsilon_{post}$ - coefficients of the regression model of the dependence of the constant component of the cost of transportation on the automobile’s carrying capacity [17].

Forwarding operations costs are determined by the formula

$$C_{FF} = D \cdot \delta + \frac{C_{kom} \cdot t^{obs}}{T} + \frac{C_{or} \cdot q}{Q} + \frac{C_{zv}}{N_r} + q \cdot C_{1h}^d \cdot (t_{supr}^{1t} \cdot N_d), \quad (7)$$

where D – the income of FFC from servicing of freight owner’s request, UAH;

δ – the share of the costs of the dispatcher’s salary (depends on the specific FFC, on average $\delta = 0.1$);

C_{kom}, C_{or}, C_{zv} – costs for utility bills, rent of FFC’s premises, payment of communication services, UAH/time period;

t^{obs} – service time of the freight owner’s request, h ;

T – the total operating time of the dispatcher for a month, h /time period;

C_{1h}^d – unit costs for 1 hour work of dispatchers, UAH/hour;

t_{supr}^{1t} – specific time to accompany the cargo owner's request, h/t .

Costs for processing and storage of freight at the terminal

$$C_E = Q \cdot (t_1 \cdot C_1 + N_t \cdot (C_2^{1t} + C_3^{1t} + C_4^{1t} + C_5^{1t}) +$$

$$+ (2 \cdot \tau_{L(UL)} + \tau_{per}) \cdot C_{LUM}^{1t \cdot h} \cdot N_{LUM} + t_{st} \cdot C_{st}^{1t \cdot h}) + Q \cdot t_s \cdot C_s^{1t \cdot h}, \quad (8)$$

where t_1 – reception time of 1 ton of freight, h ;

C_1 – reception costs of 1 ton of freight, UAH/(t·h);

C_2, C_3, C_4, C_5 - unit costs of the terminal's employee's work to check the integrity of the freight packaging in the automobile; receiving and stacking freight in the reception area at the terminal; moving the freight unit to the departure area; check of cargo and documents before departure, UAH/t;

N_t – the number of terminal workers involved in the handling of freight at the terminal, person;

τ_{per} – specific time to move a freight unit to the departure zone, h/T;

$C_{LUM}^{1t\cdot h}$ $C_{LUM}^{1t\cdot h}$ – unit costs of 1 hour of loading and unloading mechanism (LUM), UAH/(t·h);

N_{LUM} – the number of LUM involved in the handling of freight at the terminal, units;

t_{st} – storage time of the freight at the terminal, h;

$C_{st}^{1t\cdot h}$ – the cost of storing 1 ton of freight at the terminal for 1 hour, UAH/(t·h).

Costs of freezing capital is calculated by the formula

$$C_{fc} = Q \cdot \frac{C_t \cdot H_p}{36500} \cdot t_p \cdot \left(\frac{1}{2} + \frac{R_s}{Q} \right), \quad (9)$$

where C_t – the cost of 1 ton of freight, UAH/t;

H_p – internal rate of return, %

t_p – time between two consecutive deliveries, days;

R_s – insurance stock, t.

Thus, optimisation of total costs will allow us to choose rational resource-saving technology of batch freight delivery in long distance while ensuring the established level of reliability of freight delivery system, which requires the use of resource-saving technologies.

The main task of ensuring the reliability of freight delivery is the complete exclusion or minimisation of losses of the participants of the transport process in the freight delivery from the freight forming to the freight absorbing points. For customers of transport services, high reliability of freight delivery means coordination of working parameters in all participants of transport process and absence of delays, as well as losses or damage of cargo. Considering that the logistics system of the transport service consists of logistical links – participants of the process, it is necessary to ensure that the above requirements are met for all participants of the transport process.

State Union standard 51006-96 “Transport services. Terms and definitions” gives the following definition: ‘the reliability of transport services is the totality of the characteristics of the transport services that determines their provision of them to consumers in specified volumes and quality for a specified time’. In this research, reliability is proposed to be determined by the method using the readiness factor.

The readiness factor is the probability that the logistics system of the transport service with the logistics chains of all components of the process included in it will be working condition at any time. Namely, this coefficient assesses the potential of the logistics links or the logistics system of batch freight delivery in long distance

$$K_r = (1 - p_f), \quad (10)$$

where p_f – the probability that the logistic link of the system (logistic system) will find itself in a state of failure at any point in time.

In this work, the forwarder is a key link in the logistics system, organizes and coordinates the entire delivery process. Therefore, as part of the task, it is necessary to determine the readiness factor of FFC as a key link in the logistics system of the batch freight delivery.

In queuing systems (the specificity of FFC operation allows them to be considered from the point of view of queuing systems), in which requests for elementary operations arrive at random times or are serviced at random intervals, the appearance of queues is a failure of the production process. For a large number of service channels (operators), the system suffers losses due to possible long downtime. With a small number of service channels, system losses cause accumulated queues.

By a flow of events is understood a sequence of homogeneous events that occur one after the other at some random time (for example, the flow of calls received by dispatchers, the flow of failures, etc.). The flow is characterised by intensity (λ) – the frequency of occurrence of the event or the average number of events entering the queueing system (QS) per unit of time.

The effectiveness of QS with failures is determined as follows.

Absolute bandwidth is an indicator that shows the average number of requests served per unit of time. It is calculated by the formula

$$A = \frac{\lambda \cdot \mu}{\lambda + \mu}, \quad (11)$$

where λ – the intensity of the request flow, units/h;

μ – the intensity of the service flow, units / h.

The intensity of the service flow is the inverse of the average service time

$$\mu = \frac{1}{t^{obs}}. \quad (12)$$

Relative bandwidth is an indicator that characterises the average proportion of requests received and served by the system

$$B = \frac{\mu}{\lambda + \mu}. \quad (13)$$

Failure probability - a value that characterises the probability that a request will leave the queuing system unsupported. It indicates the proportion of request s that will be denied a service

$$P_f = \frac{\lambda}{\lambda + \mu}. \quad (14)$$

Average number of channels used (for multichannel system). This parameter is calculated as follows

$$\bar{k} = \frac{A}{\mu}. \quad (15)$$

Channel load intensity (or reduced flow rate) is also an indicator that expresses the average number of requests that exceeds the average service time of a single request. It is calculated by the formula

$$P = \frac{\lambda}{\mu}. \quad (16)$$

In multichannel QS with limit probabilities, formulas are used for the limit probabilities of a state. The probability of a QS failure is the marginal probability that all n channels of the system will be occupied

$$P_f = \frac{P^n}{n!}, \tag{17}$$

$$P_0 = (1 + p + \frac{p^2}{2!} + \dots + \frac{p^n}{n!}). \tag{18}$$

$$\begin{cases} P_1 = p \cdot p_0; \\ P_2 = \frac{p^2}{2!} \cdot p_0; \\ \dots\dots\dots \\ P_n = \frac{p^n}{n!} \cdot p_0. \end{cases} \tag{19}$$

The relative throughput (the probability that the request will be served) is determined

$$Q = 1 - P_{\text{bid}} = 1 - \frac{p^n}{n!} \cdot p_0. \tag{20}$$

The absolute throughput is calculated

$$A = \lambda \cdot Q. \tag{21}$$

For the QMS, the discipline of service is important. It determines the order of selection of requests from among the received and the order of their distribution among the free channels. On this basis, the request servicing can be organised according to the principles of the order of receipt: in the order of receipt (from the beginning) or vice versa, those who received at the end (from the end) are serviced with priority of service (first, the most important requests are served).

The concept of organising the technological process of batch freight delivery in the intercity connection by road in terms of resource savings can be represented in the form of a diagram (Fig. 3).

Thus, the developed theoretical studies will allow the organization of the technological process of batch freight delivery in the intercity connection.

Pilot studies are planned in three stages.

At the first stage of the experiment information is collected on the parameters that affect the batch freight delivery in the intercity connection. On the basis of them, the values of the model parameters that are random in nature are determined.

At the second stage of the experiment, by conducting a full-factor experiment taking into account the modelling of request flow parameters and the limited resources of the transport market entities, rational resource-saving technologies of batch freight delivery in the intercity connection (according to the chosen efficiency criterion) under various operating conditions are determined and their reliability is evaluated.

At the third stage, a regression analysis is performed to determine regression models of the dependence of total costs on the parameters of request flow of transport services and the amount of resources of transport market entities. In the next step, the optimal areas for the use of certain technologies of batch freight delivery technologies are determined in the inter-city connection. That is,

the intervals of the input parameters of the model are determined at which the value of the efficiency criterion is optimal.

Thus, a mathematical model has been developed for alternative technologies of batch freight delivery. It is possible to conduct experimental studies to determine resource-saving delivery technology under specified operating conditions.

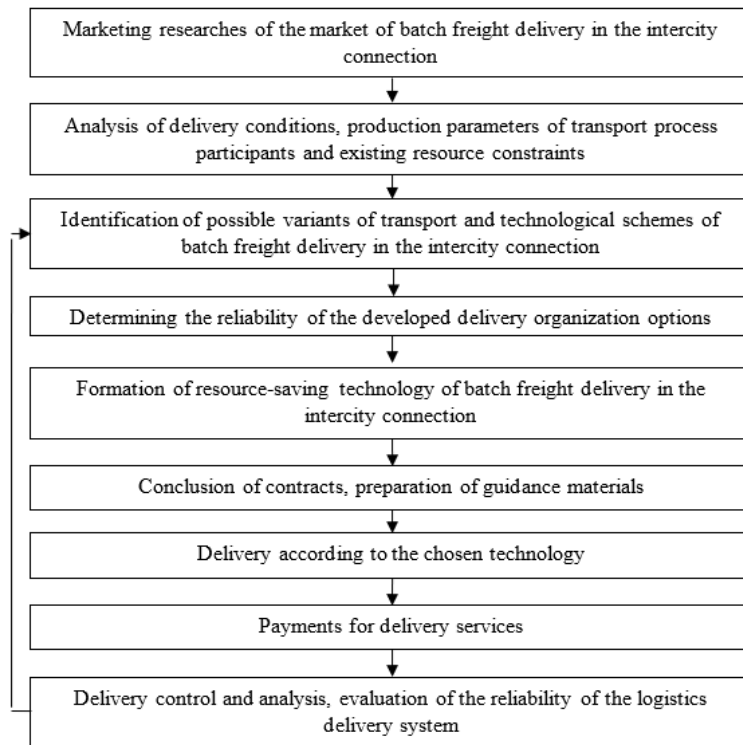


Fig. 3. Organisation of the technological process of batch freight delivery in the intercity connection by road in terms of resource savings

Given the number of parameters that affect the end result and recommendations for the requirements for the plans, the study used the plan of a full-factorial experiment, which as a result of which determines the value of the parameters of the state of the object with all possible combinations of levels of variation of parameters.

The ranges of variation of each parameter involved in the experiment are given in Table. 1.

Based on the developed of the full-scale experiment, taking into account the variation of factors in the experimental calculations, indicating the maximum and minimum values of the arguments, the values of the total cost of delivery for two delivery schemes (direct and terminal) for 64 series of experiments were obtained. The obtained data are the basis for applying the regression analysis toolkit.

Table 1. Levels of variation of input factors

The value of the input factors	The level of variation of the factor	
	The minimum value	The maximum value
$X_1 - F, \text{ km}^2$	13,5	350
$X_2 - Q, \text{ t}$	1	5
$X_3 - l, \text{ km}$	50	1800

$X_4 - \lambda, \text{ km}^2$	0,1	2
$X_5 - PC, \text{ t/h}$	5	100
$X_6 - N_d, \text{ person.}$	1	5

The functional dependence of the total costs of batch freight delivery on the parameters of the request flow and technological parameters of the participants of the delivery process is carried out in the following sequence: formation of alternative hypotheses about the type of regression model; determination of coefficients of regression models according to the proposed alternative hypotheses; estimation of adequacy of the obtained regression models and selection of the most adequate one.

The functions of the MS Excel analysis package (Data Analysis - Regression) were used as the main tool for determining the coefficients of regression models when processing the results of experimental studies.

Testing the hypotheses about the form of regression models showed that the highest values of the coefficient of determination are characterized by a linear model for direct delivery (C_{sum}^1) and exponential for terminal delivery (C_{sum}^2):

$$C_{sum}^1 = 22,58227 + 18,86497 \cdot Q + 9,03902 \cdot l - 0.37956 \cdot PC, \quad (22)$$

$$C_{sum}^2 = 95,51644 \cdot 1,008185^F \cdot 1,770343^Q \cdot 1,000503^l \cdot 2,304923^\lambda \cdot 1,01766^{N_d}. \quad (23)$$

Testing the model for the possibility of its practical application is carried out according to the criteria of accuracy, reliability and adequacy. All parameters must be performed simultaneously. Inconsistency with one of the criteria means the absence of a model at all.

The accuracy is estimated by the value of the correlation coefficient r , the determination coefficient r^2 , the calculations of which are given in Table 2.

Table 2. Model accuracy check

Criterion	Critical value	Estimated value	
		For the direct delivery	For the terminal delivery
Correlation coefficient	$> 0,7$	0,87	0,97
Determination factor	$> 0,5$	0,99994	0,901646

The reliability and adequacy of the model is estimated by the value of the Fisher F test, the calculated values are shown in Table 3.

Table 3 Checking the reliability and adequacy of the model

Critical value		Estimated value	
		For the direct delivery	For the terminal delivery
Fisher's test, F	$F > F_t$	1661340	87,1
The significance of the criterion F	$< 0,05$	$1,7 \cdot 10^{-147}$	$7,26 \cdot 10^{-27}$

The results show that the models can be used to choose a rational delivery system. Thus, the results obtained are the basis for performing the analysis of the influence of factors on the efficiency of consignment delivery in long distance, taking into account the reliability of the freight forwarding enterprise. The degree of influence on the total cost of consignment delivery by a certain delivery technology of such factors as the consignment volume for the request, the service area, delivery distance,

the density of the points of delivery in the territory of the service area and the number of dispatchers (at a fixed position at the average level of other factors) is graphically shown in Fig. 4–8.

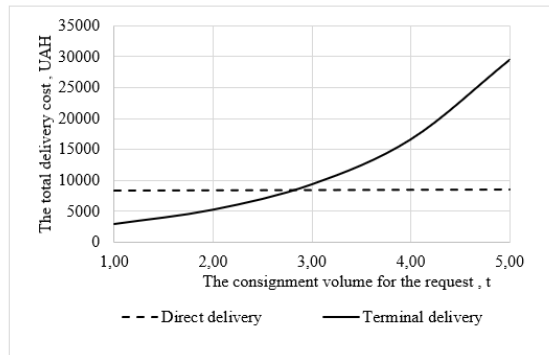


Fig. 4. Graph of the total cost dependence on the volume for the request

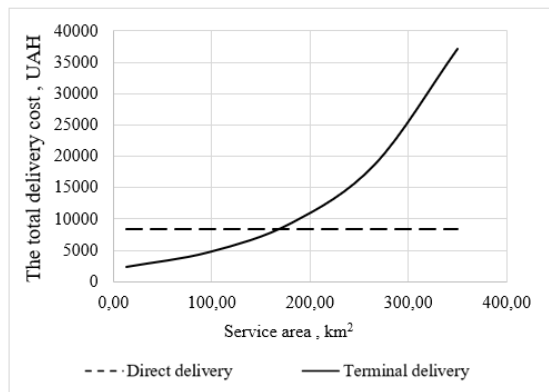


Fig. 5. Graph of the total cost dependence on service area

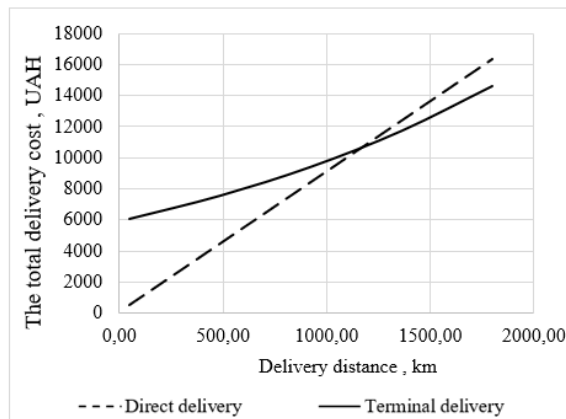


Fig. 6. Graph of the total cost dependence on delivery distance

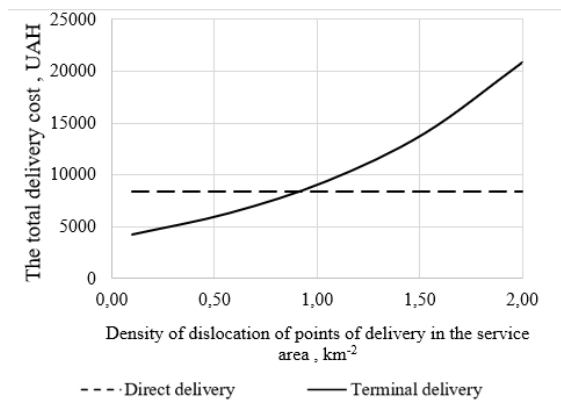


Fig. 7. Graph of the total cost dependence on the density of delivery dislocation of points in the service area at a fixed position at the average level of other factors

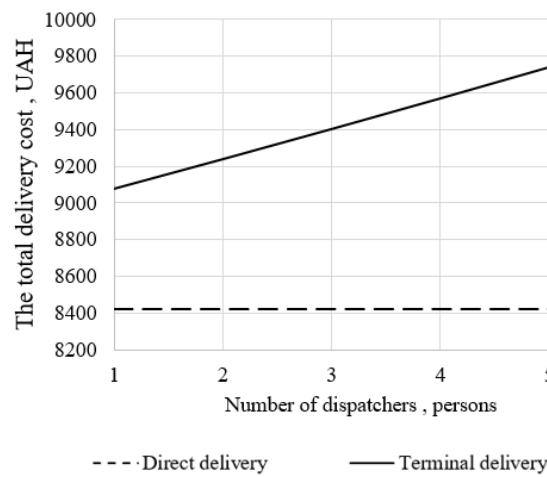


Fig. 8. Graph of the total cost dependence on the number of dispatchers at fixed position on average of other factors

Determine the effectiveness of QS with refusals by formulas (11) – (21) for the following conditions of work of dispatchers LLC “Deliveri”™: duration of processing – 15 minutes, the intensity of request receipt – 8 units/h for one dispatcher.

Intensity of service flow

$$\mu = \frac{60}{15} = 4 \text{ units/h.}$$

Relative bandwidth (the average proportion of requests received and served by the system)

$$B = \frac{4}{4 + 8} = 0,33,$$

$$p_f = \frac{8}{8 + 4} = 0,67..$$

Absolute bandwidth

$$A = \frac{8 \cdot 4}{8 + 4} = 2,67.$$

Thus, on average, the dispatcher will process almost 3 requests per hour.

Similarly, we calculate the main characteristics of queuing systems for 2, 3, 4 dispatchers and summarize them in Table 4.

Table 4. Main characteristics of service requests in the warehouse depending on the number of posts

Indicator	Number of dispatchers, persons		
	1	2	3
Relative bandwidth (B)	0,33	0,8	1,31
Absolute throughput (A)	2,67	6,4	10,48

The schedule of dependence of readiness factor on the number of dispatchers is shown in fig. 9.



Fig. 9. Schedule of readiness factor on the number of dispatchers

This means that, if optimality is met (satisfaction with an average of 10 requests at least 8 requests for cargo delivery ($K_f = 0,8$), an average of two dispatchers is optimal.

For the considered ranges of the values of the transport request parameters:

- at the consignment volume for the request up to 2.81 t (Fig. 4), terminal delivery is more resource-saving and direct delivery is more than 2.81 t;
- at service area up to 169 km² (Fig. 5), resource delivery is terminal delivery, and over 169 km² – direct delivery;
- at delivery distance up to 1172 km (Fig. 6), resource delivery is direct delivery, and over 1172 km – terminal delivery;
- at the density of the deployment of points of delivery in the territory of service up to 0.95 km² (Fig. 7), resource delivery is terminal delivery, and more than 0.95 km² – direct delivery;
- the number of dispatchers (Fig. 8) affects the total costs only at the terminal system in this formulation of the problem, so the optimal number of dispatchers at the normative value of the coefficient of readiness for the terminal delivery system was 2 persons.

Introduction to the production of innovations allows to obtain effect and increase efficiency.

The effect associated with the total cost of delivery, is determined by the following formula

$$E = C_{sum}^{rs} - C_{sum}^b \tag{24}$$

where C_{sum}^{rs} – the total cost of freight delivery using resource-saving delivery technology, UAH/request;
 C_{sum}^b – the total cost of basic freight delivery technology, UAH/request.

Efficiency (E_f) when implementing resource-saving delivery technology is calculated

$$E_f = \frac{E}{C_{sum}^{rs}} \cdot 100\%. \quad (25)$$

There are three dispatchers at the Delivery LLC in the Kharkiv branch. The transit terminal is one in the city. Other offices for collecting and transporting requests around the city. The Kharkov area is 350 km². For the consignment volume 3.0 tons delivery distance is 675 km. LLC Delivery uses a terminal system for batch freight delivery. The total costs of the company in this case (C_{sum}^b) are 7040 UAH. Total costs proposed in the work (including the optimal number of dispatchers – two)

$$C_{sum}^{rs} = 22,58227 + 18,86497 \cdot 3 + 9.03902 \cdot 657 - 0.37956 \cdot 52,5 = 6179 \text{ UAH.},$$

$$E = 7040 - 6179 = 861 \text{ UAH},$$

$$E_f = \frac{861}{6179} \cdot 100\% = 13,9\%.$$

The economic effect of the implemented measures is $E = 861$ UAH.

When using direct batch freight delivery in intercity connection, total costs can be reduced by 13.9 %.

Conclusions. In this paper, we propose the solution to the scientific and applied problem of batch freight delivery in the intercity road connection in terms of system's limited resource due to the formation of technology of long-distance freight delivery in terms of resource savings and observing the established level of reliability of the functioning of the logistics system of freight delivery.

After analysing scientific research in the direction of developing resource-saving technologies of freight delivery, it can be noted the next. Among the priority areas for improving the process of batch freight delivery, most researchers highlight the formation of rational technologies of freight delivery in terms of resource savings and determining a rational amount of resources when functioning systems of various levels based on the use of logistics principles.

In the research of freight delivery in long distance, two transport and technological scheme were considered as alternatives. The first technology involves direct freight delivery from consignor to consignee, and the second - a terminal delivery system.

Considering that the criterion of effectiveness in the study is justified the use of the total cost of delivery and readiness factor, for the considered ranges of the values of the transport request parameters: at the consignment volume for the request up to 2.81 t (Fig. 4), terminal delivery is more resource-saving and direct delivery is more than 2.81 t; at service area up to 169 km² (Fig. 5), resource delivery is terminal delivery, and over 169 km² – direct delivery; at delivery distance up to 1172 km (Fig. 6), resource delivery is direct delivery, and over 1172 km – terminal delivery; at the density of the deployment of points of delivery in the territory of service up to 0.95 km⁻² (Fig. 7), resource delivery is terminal delivery, and more than 0.95 km⁻² – direct delivery; the number of dispatchers (Fig. 8) affects the total costs only at the terminal system in this formulation of the problem, so the optimal number of dispatchers at the normative value of the coefficient of readiness for the terminal delivery system was 2 persons.

The economic effect of the implemented measures may be 861 UAH. When using direct delivery in the intercity connection for a request with specified parameters, it is possible to reduce total costs by 13.9%. Reducing the total cost of batch freight delivery due to the choice of resource saving technology will allow FDLS to receive additional income and distribute it among the participants in the delivery process according to their contribution.

REFERENCES

1. Butko, T.V., Horsin, Th., & Yashchuk, Yu.I. (2022) Orhanizatsiia podorozhei pasazhyriv na osnovi tekhnolohii ryzyk-menedzhmentu z vykorystanniam kraudsorsynhovykh danykh pro trafik. *Collection of abstracts of the III International Scientific and Technical Conference Intelligent Transport Technologies*, 14-16. [in Ukrainian].
2. Naumov, V., Shulika, O., Orda, O., Vasiutina, H., Bauer, M., & Oliskevych, M. (2022) Shaping the Optimal Technology for Servicing the Long-Distance Deliveries of Packaged Cargo by Road Transport. *Sustainability*, 14 (12), 7283 <https://doi.org/10.3390/su14127283>.
3. Marchi, B., Zaroni, S., Ferretti, I., & Zavanella, L.E. (2018) Stimulating investments in energy efficiency through supply chain integration. *Energies*. 11, 4, 858.
4. Marchi, B., & Zaroni, S. (2017) Supply chain management for improved energy efficiency: Review and opportunities. *Energies*, 10 (10), 1618.
5. Maloni, M.J., & Benton, W.C. (1997) Supply chain partnerships: Opportunities for operations research. *European Journal of Operational Research*, 101, 3, 419-429.
6. Wang, Y. (2004) Low-Carbon Logistics and Sustained Economic Cycle for Manufacturing Engineering. *Applied Mechanics and Materials*, 264 – 267.
7. Zhang, D.P., & Hua, X. Y. (2003) International Experience and Enlightenment of Energy Saving and Emission Reduction in Logistics Industry. *Advanced Materials Research*, 734 – 737.
8. Zhang, D.P., & Hua, X.Y. (2014) Research on Energy Saving and Emission Reduction Countermeasures for China's Logistics Industry. *Advanced Materials Research*, 1925-1928, 734-737.
9. Malak, R.C., Adam, M., Waltemode, S., & Aurich, J.C. (2014) Lifecycle Oriented Assessment of Resource Efficiency in the Commercial Vehicle Industry. *Advanced Materials Research*. 907, 475 – 487.
10. Zhang, L., Zhang, Y., He, Y.H., & You, X.R. (2013) The Behavior Strategy in Energy Saving and Emission Reduction of Transportation. *Advanced Materials Research*. 718 – 720.
11. Zou, X., Zhao, W., Zhang, & T.T. (2015) Study of Green Logistics Technology to Manufacturing Based on Green Supply Chain Theory. *Advanced Materials Research*, 2438-2442, 1073 – 1076.
12. Nowak, S., & Grabara, J. (2015) Green Logistics and its Solutions in Polish Companies. *Applied Mechanics and Materials*, 708, 65-69.
13. Lomotko, D. V., & Mkrtychian, D. I. (2006) Optymizatsiia systemy dostavky vantazhiv na osnovi mnozhyny kryteriiv resursoberihaiuchykh pidkhodiv. *Eastern-European Journal of Enterprise Technologies*, 3(2), 6 – 9. [in Ukrainian]
14. Potaman, N.V., Shulika, O.O., & Orda, O.O. (2021) Modeliuvannia marshrutnoi merezhi dostavky shvydkopsuvnykh vantazhiv u rehionalnomu spoluchenni za dopomohoiu merezh Petri. *Municipal economy of cities. Series: Engineering science and architecture*, 4, (164), 240-245. [in Ukrainian] <https://doi.org/10.33042/2522-1809-2021-4-164-240-245>.
15. Bányai, T. (2018) Real-time decision making in first mile and last mile logistics: How smart scheduling affects energy efficiency of hyperconnected supply chain solutions. *Energies*, 11 (7), 1833.
16. Russo, F. A. (2010) Classification of city logistics measures and connected impacts. *Procedia-Social and Behavioral Sciences*, 2, 6355 – 6365.
17. Pavlenko, O. V., Kalinichenko, O. P., & Nefodov, V. M. (2018) Metodyka formuvannia resursoberihaiuchoi tekhnolohii dostavky vantazhiv transportno-lohistychnym tsentrom. *Municipal economy of cities. Series: Engineering science and architecture*, 142, 96 – 102. [in Ukrainian]

Ольга Шуліка¹, Олександра Орда², Наталія Потаман³, Юрій Ящук⁴

¹ Кандидат технічних наук, доцент, доцент кафедри «Транспортні технології», Харківський національний автомобільно-дорожній університет, вул. Ярослава Мудрого, 25, м. Харків, 61002, Україна, ORCID: <https://orcid.org/0000-0002-1912-1115>.

² Кандидат технічних наук, доцент, доцент кафедри «Транспортні технології», Харківський національний автомобільно-дорожній університет, вул. Ярослава Мудрого, 25, м. Харків, 61002, Україна, ORCID: <https://orcid.org/0000-0002-7213-8469>

³ Кандидат технічних наук, доцент, доцент кафедри «Транспортні технології», Харківський національний автомобільно-дорожній університет, вул. Ярослава Мудрого, 25, м. Харків, 61002, Україна, ORCID: <https://orcid.org/0000-0002-9545-5002>.

⁴Аспірант кафедри «Управління експлуатаційною роботою», Український державний університет залізничного транспорту, пл.Фейєрбаха, 7, м. Харків, 61050, Україна, ORCID: <https://orcid.org/0009-0006-1985-1181>.

Розробка ефективної технології доставки партійних вантажів автомобільним транспортом у міжміському сполученні з урахуванням умови ресурсозбереження

Логістичні рішення з відновлення та розвитку галузі автомобільних перевезень вантажів потребують застосування ефективних інструментів, що дозволять забезпечити гнучкість логістичним ланцюгам постачань, в умовах змінного попиту на транспортні послуги, сприяючи економічному відновленню та розвитку, підвищенню якості життя населення, ефективному використанню ресурсів. В роботі вирішена науково-прикладна задача підвищення ефективності функціонування логістичної системи доставки партійних вантажів автомобільним транспортом у міжміському сполученні в умовах розподілу обмеженого ресурсу системи за рахунок формування технології доставки вантажів на умовах ресурсозбереження та дотримання встановленого рівня надійності функціонування логістичної системи доставки вантажів автомобільним транспортом. В дослідженні для вирішення поставленої задачі використані методи математичного моделювання, системний підхід, методи оптимізації (функції багатьох змінних), положення теорії ймовірності та математичної статистики, методи регресійного аналізу. Для заданих умов функціонування розробленої логістичної системи визначено раціональну технологію доставки партійних вантажів у міжміському сполученні з урахуванням умови ресурсозбереження, що дозволить на 13,9% зменшити загальні витрати при заданому рівні готовності логістичної системи доставки вантажів.

Ключові слова: *автомобільний транспорт, ресурсозбереження, доставка, партійні вантажі, коефіцієнт готовності*

UDC 629.4.072

Svitlana Sapronova^{1*}, Viktor Tkachenko², Nadiya Braykovska³, Ivan Kulbovskiy⁴

¹Professor, Department of Wagons and Wagon Management, State University of Infrastructure and Technologies, 9 Kyrylivska St., Kyiv, 04071, Ukraine. <https://orcid.org/0000-0002-1482-1665>

²Professor, Department of Electromechanics and Railway Rolling Stock, State University of Infrastructure and Technologies, 9 Kyrylivska St., Kyiv, 04071, Ukraine. <https://orcid.org/0000-0002-5513-2436>

³Professor, Department of Wagons and Wagon Management, State University of Infrastructure and Technologies, 9 Kyrylivska St., Kyiv, 04071, Ukraine. <https://orcid.org/0000-0003-1556-4020>

⁴Associate professor, Department of Automation and Computer-Integrated Transport Technologies, State University of Infrastructure and Technologies, 9 Kyrylivska St., Kyiv, 04071, Ukraine. <https://orcid.org/0000-0002-5329-3842>

Author responsible for correspondence: doc.sapronova@gmail.com

Study of guiding vehicle by railway track

The analysis of scientific publications related to the guiding of wheelsets of railway rolling stock along the rail track has been carried out. It is stated that for a valid simulation of the guiding of wheelsets by a rail track, an accurate description of the contact forces of adhesion is necessary. It was found that the flange wheel-rail contact exists only in combination with the angle of attack and in the presence of a lateral cohesive force. A scheme of power interaction of a wheelset with rails with a ridge contact of one of the wheels has been developed. The force contact interaction of a wheel and a rail is a process that is difficult to describe and, at the same time, very important for studying the dynamics of the frictional interaction of vehicles and track and the guiding of vehicles by the rail track. In the general case, the contact of the wheel with the rail occurs in two contact zones: on the rolling surface and on the flange. Simplified, the contact is considered as a two-point contact. The considered force factors cannot be unambiguously attributed to guiding factors or factors of resistance to movement. Specific values and guiding of forces and moments depend on the position of the wheelset relative to the rail track. It is argued that the longitudinal and transverse slips of the wheelsets cause resistance to movement and are overcome by guiding forces.

Key words: *guiding vehicle by railway track, wheelset, rolling stock, flange reactions, contact adhesion forces.*

Introduction. In the initial period of railway development, the issues of wheel-rail adhesion were considered exclusively in connection with the traction qualities of the rolling stock.

A large number of studies have been devoted to increasing the maximum traction force for adhesion. Their main goal is a more complete implementation of the propulsion function in a wheel-rail system. However, the problem of wheel-rail adhesion is much deeper than his analysis in terms of traction. Wheel-rail adhesion must be considered comprehensively, taking into account the full picture of the horizontal forces of interaction between the vehicle and the track. In particular, it should be taken into account that the horizontal components of the contact forces determine the horizontal dynamics of the vehicle. And in this sense, it would be appropriate not to single out, as separate problems, longitudinal phenomena associated with cohesive qualities, but transverse ones associated with horizontal transverse dynamics.

It is necessary to consider these phenomena jointly within the framework of full horizontal dynamics. Attempts to treat the issues of longitudinal and transverse cohesion as separate from each other, or at best as partially related, often lead to errors in the results of studies. For example, constructive

improvements in dynamic performance can lead to a deterioration in other indicators: an increase in resistance to movement; increasing the intensity of wear of rolling surfaces of wheels, etc.

Analysis of recent research and problem statement. The monograph by H. Heyman can be considered the first fundamental study of the direction of carriages by a rail track. Heyman noted that the deviation of the movement of wheelsets from the trajectory of pure rolling can only be observed in the form of sliding. According to him, the main reason for longitudinal slips in wheel-rail contacts is the rigid connection of the wheels in the wheelset through the axle.

When driving in curved sections of the track of a large radius, due to the conical shape of the wheels in the wheelset, the guiding forces between the wheel flanges and the rails are reduced. But, in curves of medium and small radius, the taper of the rolling surfaces is not sufficient, which causes the wheels to slip in the longitudinal direction. Longitudinal sliding forces cause an increase in the misalignment of the wheelset axis relative to the track axis and, as a result, an increase in the angle of attack of the wheels on the rail heads. An increase in the angles of attack is the cause of an increase in transverse reactions in wheel-rail contacts and additional resistance to movement. An indirect confirmation of this is the characteristic screech when the crew moves in curves. The results of studying this phenomenon are given in the article [1].

The authors of the article [3] used the theory of closed power circuits to describe the three-point contact of the wheelset with the rails. The article notes that in the system of contacting the wheelset with the rails there is a closed power circuit with nodal points in the main and flanges contacts. The characteristic for closed power circuits in wheel-rail contacts is parasitic sliding, which is the cause of additional power losses and wears on the rolling surface of wheels and rails. Wheelsets and rail together form separate closed power circuits. The contacts of the wheels with the rails are the nodal points in the power circuits “rail–wheel–axis–wheel–rail–sleeper”. Parasitic power flows can occur in interaxle closed power circuits of bogies. Parasitic power circulation in closed power circuits can reach significant values and is the cause of additional resistance to the movement of vehicles. The authors classify this resistance as “kinematic resistance to motion”.

When driving in tangent track, due to the horizontal irregularities of the rails and the conical shape of the wheel tread surfaces, intense self-oscillations of wheel sets hunting can occur with periodic contact of the flange of the right and left wheels of the wheelsets with the rails [3]. At a high speed of movement, the transverse loads on the rails increase and can reach significant values [4, 5]. This leads to intensive wear of the wheel flanges, increased resistance to movement and creates a risk of loss of stability.

Railway rolling stock belongs to a subgroup of land vehicles that are guided by guide rails. The rails provide vertical support for the vehicles and guide the wheelsets along the trajectory. Large values of interaction forces in the wheel-rail contacts can lead to the destruction of track components [6, 7, 8].

Therefore, an accurate description of the contact forces in the wheel-rail system is necessary for theoretical studies of the guiding wheelsets by the rail track.

When considering the process of guiding vehicle by railway track, ensuring stability against derailment of wheelsets is the most important task.

As is known, the criterion for the tendency of a wheelset to derail is the ratio between the lateral and vertical loads in the flange wheel-rail contact. This ratio proposed by *Nadal* has been refined many times, for example, in the studies of such scientists as *Shabana* [9], *Weinstock* [10], *Ohno* [11] and others.

The forces acting in wheel-rail contacts in the horizontal plane have a complex structure.

In Shahzamanian Sichani's dissertation [12] a new method is proposed which results in more accurate contact patch and pressure distribution estimation while maintaining the same computational efficiency. The experience gained through this Licentiate work illuminates future research directions among which, improving tangential contact results and treating conformal contacts are given higher priority. The dissertation also provides an analysis of the main types of derailment of rail crews. Three of them are related to the characteristics of the rail track, and two are related to the shape of the wheel and rail profile. It has been confirmed that the angle of inclination of the wheel flange is the main geometric

parameter that affects the probability of derailment of vehicles.

Results of experimental studies of experimental investigation of transient traction characteristics in rolling-sliding wheel-rail contacts under dry-wet conditions are given in the article [13].

The authors of the study [14] provide statistical data and analyze the causes of large-scale railway accidents. The importance of ridge contact studies as the main safety factor is emphasized. As a quicker method, authors propose to estimate the derailment coefficient from analytically calculated lateral and vertical wheel loads, based on analytic equations and measured data. This paper describes the equations used, shows how the derailment coefficient is calculated, and compares it with the results achieved by measurements.

The paper [15] proposes a mathematical model for assessing safety by derailment of a wheelset. Loads in the wheel-rail contact take into account centrifugal forces, rail irregularities and deformations of the spring suspension of a railway vehicle. A method was proposed for calculating the critical safety factor, taking into account the angle of attack of the wheel on the rail and the equivalent coefficient of friction. This study of traffic safety and comfort is based on the results of numerical simulation of a nonlinear model of the movement of railway rolling stock along a straight track. Traffic safety is investigated in accordance with the UIC 518 code: through the ratio of the transverse Y to vertical Q forces at the point of contact of the wheel with the rail. The lateral and vertical accelerations of the vehicle body to which a passenger of a railway vehicle is subjected are used to assess ride comfort in accordance with the ISO 2631-1 standard. The influence of various parameters of the "railway transport - way" system on traffic safety and traffic comfort is analyzed.

It is believed that the coefficient of friction in contact between the wheel flange and the rail has a strong influence on the derailment of wheelsets. However, the coefficient of friction varies greatly depending on the condition of the wheel-rail contact, atmospheric conditions, speed, etc. It is also considered that the direct measurement of the coefficient of friction is very difficult. The authors of the article [16] managed to obtain data on the derailment of wheels during the practical operation of electric trains. The experiments were carried out on a curved section of the track with a radius of 100–110 m. Such quantities as the derailment coefficient, the angle of attack of the wheel on the rail, and the separation of the wheel from the rail were measured. As a result of the experiments, it was found that reducing the coefficient of friction in the contact between the flange and the wheel (lubrication) is an effective means of reducing the derailment coefficient according to the Nadal criterion.

The purpose and tasks of the study. The purpose of the study is to refine the mathematical description of wheel-rail reactions based on the scheme of three-point contacting of wheelsets and rail track.

Therefore, the following tasks were set: analysis of scientific research on the guiding vehicle by railway track; study of kinematics and dynamics of wheel-rail contact; mathematical description of contact forces and adhesion forces in a wheel-rail system.

Materials and methods of research. As a rule, many scientists use a two-point wheel-rail contact model when modeling the interaction of vehicles with a rail track. However, in fact, it is correct to consider the complex picture of the contact of the wheelset with the rail track, and not the individual wheel with the rail. This approach was substantiated by the co-authors of this article in [17].

It is a typical case when the flange contact is combined with of the angle attack and the flange friction force. The following shows a picture of the force interaction of the wheelset with the rails during the flange contact of the one wheel. The movement of the wheelset is modeled in the skewed position in the rail track with of the angle attack ψ . On fig. 1 shows the vectors of speeds in the contacts of the wheelset with the rails. vectors are represented as projections of speeds and forces on the horizontal plane Oxy . Two cases of contact are shown: with a three-point contact of the wheelset with the rails (contacts K11, K21, K22) (fig 1a) and with two-point contact of the wheelset with the rails, when the second wheel comes off the main contact K21 (fig 1b).

The case is considered when the approaching wheel is in the state of derailment. As a starting condition, the equality of zero load in the main contact of the running wheel is accepted.

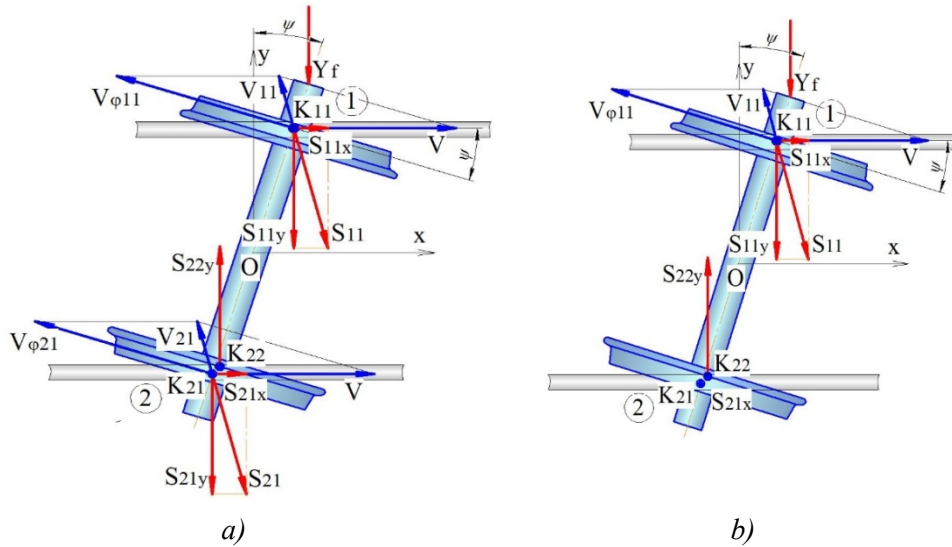


Fig 1. Vector scheme of velocities and forces in the wheelset-rails contacts: a) with three-point contact of the wheelset with the rails; b) at the moment of separation of the main contact of the second wheel from the rail

When modeling the kinematic characteristics of the wheelset-rails contact, the following parameters and their designations are considered:

V – is the velocity movement of the wheelset center along the track axis;

$V_{\phi 11}, V_{\phi 21}$ – is the circumferential velocity of the wheel at the contacts K_{11}, K_{21} , associated with the rotation of the wheelset relative to its own axis;

V_{11}, V_{21} – wheel sliding velocity on the rail at the contact points K_{11}, K_{21} ;

Y_f – axial reaction in the axle assembly acting on the wheelset – frame force;

S_{11y}, S_{22y} – projections of friction forces S_{22} in contacts K_{11}, K_{22} on the Oy axis;

$S_{11}, S_{21}, S_{11x}, S_{11y}, S_{21x}, S_{21y}, S_{22y}$ – friction force and projections of friction force in contacts K_{11}, K_{21}, K_{22} respectively, on the Ox, Oy axis;

On fig. 2 shows a diagram of the contact forces in the flange contact in projections onto the later vertical plane Oxz and the transverse vertical plane Oyz .

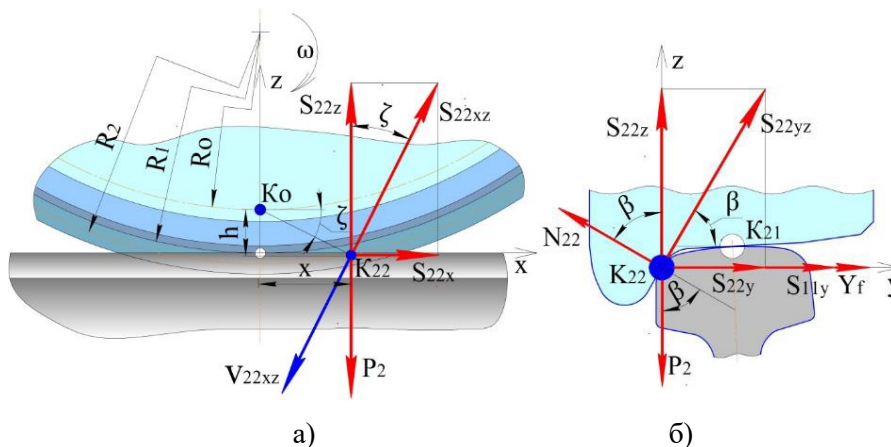


Fig.2. Projections scheme of forces in the flange contact: a) projections onto the longitudinal vertical plane Oxz ; b) projections onto the transverse vertical plane Oyz [17]

On fig. 2 advancing signs are accepted:

ζ – angle, which determines the position of the vector S_{22xz} along the vertical axis;

β – flange angle;

ω – angular speed of rotation of the wheel around its axis;

N_{22} – normal load in the flange contact K_{22} ;

K_0 – instantaneous center of the wheel rotation;

R_0 – the distance from the wheel center to the instantaneous center of the wheel rotation K_0 ;

R_1, R_2 – the radius of the wheels in the main and flange contacts;

P_2 – vertical load in the flange contact K_{22} .

In general, the total horizontal side load in the flange contact K_{22} is equal to the sum of the frame force Y_f and the contact forces S_{11y}, S_{21y} in the contacts K_{11}, K_{21} :

In general, the total guiding force Y acting on the wheelset is equal to the sum of the frame force Y_f and the contact forces $S_{11y}, S_{21y}, S_{22y}$ in the contacts K_{11}, K_{21}, K_{22} :

$$Y = S_{22y} - Y_f - S_{11y} - S_{21y}, \quad (1)$$

At the moment of separation of the second wheel from the main contact, the total guiding force increases:

$$Y = S_{22y} - S_{11y} - Y_f. \quad (2)$$

Contact forces $S_{11y}, S_{21y}, S_{22y}$ in contacts K_{11}, K_{21}, K_{22} in the control theory of wheeled machines are called guiding forces. Guiding forces are frictional forces and are directed opposite to the corresponding sliding velocity vectors V_{11y}, V_{22y} .

Thus, the guiding forces in the main contacts when the wheelset is misaligned are the forces of the negative guiding, which impede the process of reliable guidance the wheelsets by rail track. In fact, reducing the vertical load in the main contact (up to the separation of the main contact from the rail) on the oncoming wheel improves the conditions for guiding the wheelset by rail track.

The moment of guiding forces in the horizontal plane M is an additional factor that affects the process of guiding wheelsets by rails. Accounting for the moment of guiding forces is especially important at large misalignment angles of the wheelset. The moment of guiding forces in the horizontal plane can be determined by the following formula:

$$M = [(-S_{11y} + S_{21y} - S_{22y} - Y_f) \cdot \psi - S_{11x} - S_{21x}] \cdot s. \quad (3)$$

The forces S_{11y}, S_{21y} can be approximately determined by the formulas of Coulomb's law. At the same time, the most dangerous case in terms of derailment is considered, when the angle $\zeta=0$.

$$S_{11y} = P_0 \cdot \mu; \quad S_{22y} = N_{22} \cdot \mu \cdot \cos\beta, \quad (4)$$

where P_0 – is the vertical load in the contact K_{11} at the moment of separation of the second wheel from the main contact ($P_{11}=P_0$);

μ – the coefficient of sliding friction in the wheels-rails contacts.

Then

$$Y = \mu \cdot (N_{22} \cdot \cos\beta - P_0) - Y_f \quad (5)$$

he force contact interaction of a wheel and a rail is difficult to describe, but a very important issue for studying the direction of vehicles on a rail track. In the general case, the contact of the wheel with the rail occurs along two contact planes: on the rolling surface and on the flange. Simplified, the contact is considered as a two-point contact. At the same time, the main vector of contact forces interaction of the i -th wheel ($i=1$ – for the left wheel, $i=2$ – for the right wheel), the j -th wheelset, the k -th bogie with the rail has the following structure.

$$\vec{F}_{ijkI} = \vec{N}_{jkI} + \vec{N}_{jkII} + \vec{S}_{jkI} + \vec{S}_{jkII}, \quad (6)$$

where \vec{N}_{jkI} , \vec{N}_{jkII} , \vec{S}_{jkI} , \vec{S}_{jkII} – main vectors of normal reactions and adhesion force of the first (main) and second (comb) contacts

$$\vec{N}_{ijkI} = \vec{P}_{ijkI} + \vec{H}_{ijkI}; \quad \vec{N}_{ijkII} = \vec{P}_{ijkII} + \vec{H}_{ijkII}, \quad (7)$$

where \vec{P}_{ijkI} , \vec{H}_{ijkI} , \vec{P}_{ijkII} , \vec{H}_{ijkII} – vertical and horizontal transverse components of normal contact reactions, and

$$H_{ijkI} = P_{ijkI} \cdot g_{ijkI}; \quad H_{ijkII} = P_{ijkII} \cdot g_{ijkII}, \quad (8)$$

where $g_{ijkI} = \text{tg}(\gamma_{ijkI})$, $g_{ijkII} = \text{tg}(\gamma_{ijkII})$ – conditional tapers of wheel profiles at the corresponding contact points;

γ_{ijkI} , γ_{ijkII} – obliquity to the horizon of tangents at the corresponding points of wheels-rails contact.

Static vertical wheel load:

$$P_0 = P_{ijkI} + P_{ijkII}. \quad (9)$$

The total gravitational component \vec{H}_{ijk} from two contacts of one wheel is defined as the sum of two reactions \vec{H}_{ijkI} , \vec{H}_{ijkII} and

$$H_{ijk} = P_0 \cdot \left[k_{ijk} \cdot g_{ijk} + (1 - k_{ijk}) \cdot g_{ijk} \right], \quad (10)$$

where k_{ijk} – a coefficient that takes into account the redistribution of the vertical load between contacts I and II with values from 0 to 1.

With a linear law, the change of loads from P_{ijkI} to P_{ijkII} with two-point contact will be:

$$P_{ijkI} = P_0 \cdot k_{ijk}; \quad P_{ijkII} = P_0 \cdot (1 - k_{ijk}), \quad (11)$$

where; $k_{ijk} = \frac{d_{yjk} - d_{yI}}{d_{yII} - d_{yI}}$

d_{yjk} – the transverse current displacement of the wheel relative to the rail;

d_{yI} , d_{yII} – the transverse displacements of the wheel profile relative to the rail at the entry and exit points of the two-point contact.

The values of d_{yI} and d_{yII} depend on the profile shape of the rolling surface of the wheel and rail. Contact adhesion forces have a spatial structure:

$$\begin{aligned}\vec{S}_{ijkI} &= \vec{S}_{xijkI} + \vec{S}_{yijkI} + \vec{S}_{zijkI}; \\ \vec{S}_{ijkII} &= \vec{S}_{xijkII} + \vec{S}_{yijkII} + \vec{S}_{zijkII},\end{aligned}\quad (12)$$

where \vec{S}_{xijk} , \vec{S}_{yijk} , \vec{S}_{zijk} – longitudinal, transverse and vertical components at the respective contact points.

The reaction \vec{S}_{zijkI} can be neglected because its magnitude is negligible.

The values of other components are determined from the following equations:

$$\begin{aligned}S_{xijkI} &= N_{ijkI} \cdot \psi_0 \cdot K_x \cdot (\varepsilon_{xijkI}, \varepsilon_{yijkI}); \\ S_{xijkII} &= N_{ijkII} \cdot \psi_0 \cdot K_x \cdot (\varepsilon_{xijkII}, \varepsilon_{yijkII}); \\ S_{yijkI} &= N_{ijkI} \cdot \psi_0 \cdot K_y \cdot (\varepsilon_{xijkI}, \varepsilon_{yijkI}); \\ S_{yijkII} &= N_{ijkII} \cdot \psi_0 \cdot K_y \cdot (\varepsilon_{xijkII}, \varepsilon_{yijkII}); \\ S_{zijkII} &= N_{ijkII} \cdot \psi_0 \cdot K_z \cdot (\varepsilon_{zijkII}),\end{aligned}\quad (13)$$

where: ε_{xijkI} , ε_{yijkI} , ε_{xijkII} , ε_{yijkII} , ε_{zijkII} – longitudinal, transverse and vertical components of relative slips in the corresponding contacts;

N_{ijkI} , N_{ijkII} – normal reactions in the 1st and 2nd contacts;

ψ_0 – boundary (physical) adhesion coefficient;

$K_x(\varepsilon_{xijk}, \varepsilon_{yijk})$, $K_y(\varepsilon_{xijk}, \varepsilon_{yijk})$, $K_z(\varepsilon_{zijk})$ – experimental adhesion characteristics.

The adhesion characteristics are entered as external functions. The methodology and results of experimental studies of adhesion characteristics are described in [17].

Conclusions. Based on the study, the following conclusions can be drawn:

- the force contact interaction of the wheel and the rail is difficult to describe and at the same time very important for studying the dynamics of the frictional interaction of the vehicles and the rails and guiding of the vehicles by the rail track;
- the authors propose to use a three-point contact scheme of the wheelset-rails contact in the study of the wheelsets guiding by the rail track: two-point contact – for the oncoming wheel and one-point contact – for the second wheel;
- guiding forces in the main contacts with a positive misalignment of the wheelset are the forces of the negative guiding, which prevent the process of guiding the wheelsets by the rail track;
- reducing the vertical load in the main contact of the oncoming wheel (up to the separation of the main contact from the rail, which precedes the derailment of the wheelset) improves the direction of the wheelset by the rail track;
- flange reactions play a decisive role in the process of guiding the wheelsets of the vehicle by the rail track;
- the gravitational component of the vertical load in the flange contact increases by 95% with an increase in the flange angle cone β from 60° to 70° .

REFERENCES

1. Dusza, M. (2015). The wheel-rail contact friction influence on high speed vehicle model stability. *Transport Problems*. 10.3, 74-86. <https://www.infona.pl/resource/bwmeta1.element.baztech-1a388d2c-a63f-43ff-9b5d-fdc780296c47>.
2. Pieringer, A., Baeza, L., & Kropp, W. (2015). Modelling of railway curve squeal including effects of wheel rotation. *Noise and Vibration Mitigation for Rail Transportation Systems*. Springer, Berlin, Heidelberg, 417-424. http://dx.doi.org/10.1007/978-3-662-44832-8_50
3. Tkachenko, V., Saprionova, S., Zub, E., & Morneva, M.. (2020). Closed Power Loops in the Guidance of Vehicles by Railway Track System. *24th International Scientific Conference. Transport Means 2020: Sustainability: Research and Solutions (Kaunas, Lithuania). Part II*, 554-559. <https://transportmeans.ktu.edu/wp->

content/uploads/sites/307/2018/02/Transport-means-A4-II-dalis.pdf

4. Tkachenko, V., Sapronova, S., Kulbovskiy I., & Fomin A. (2017). Research into resistance to the motion of railroad undercarriages related to directing the wheelsets by a rail track. *Eastern-European journal of enterprise technologies*. 5(7(89)), 65-72. <https://doi.org/10.15587/1729-4061.2017.109791>.
5. Sapronova S., Tkachenko V., Fomin O., Gatchenko V., & Maliuk S. (2017). Research on the safety factor against derailment of railway vehicles. *Eastern-European journal of enterprise technologies*. 6(1(93)). 25-32. <https://doi.org/10.15587/1729-4061.2017.116194>
6. Dukkipati, R. (2000). Vehicle Dynamics. *Narosa Publishing House*, 227-228.
7. Zeng, J., Wei, L., & Wu P. (2016). Safety evaluation for railway vehicles using an improved indirect measurement method of wheel-rail forces. *Journal of Modern Transportation*, 24(2), 114-123. <https://link.springer.com/article/10.1007/s40534-016-0107-5>
8. Myamlin, S., Lingaitis, L., Dailydka, S., Vaičiūnas, G., Bogdevičius, M., & Bureika, G. (2015). Determination of the dynamic characteristics of freight wagons with various bogie. *Journal Transport*, 30(1), 88-92. <http://www.tandfonline.com/toc/tran20/30/1>.
9. Shabana, A. A. (2012). Nadal's formula and high speed rail derailments. *Journal of Computational and Nonlinear Dynamics*, 7(4), 41-93. https://www.researchgate.net/publication/275377482_Nadal%27s_Formula_and_High_Speed_Rail_Derailments
10. Weinstock, H. (1984). Wheel climb derailment criteria for evaluation of rail vehicle safety. *ASME Winter Annual*. https://rosap.nrl.bts.gov/view/dot/12061/dot_12061_DS1.pdf.
11. Ohno, K. (2003). Research and development for eliminating wheelclimb derailment accidents. *JR East Technical Review*, 2, 46-50. https://www.jreast.co.jp/e/development/tech/pdf_2/46-50.pdf.
12. Shahzamanian Sichani, M. (2013). Wheel-rail contact modelling in vehicle dynamics simulation. *Doctoral dissertation, KTH Royal Institute of Technology*. <https://www.diva-portal.org/smash/get/diva2:646708/FULLTEXT01.pdf>
13. Baek, K.S., Kyogoku, K., Nakahara, T., Baek, K.S., Kyogoku, K., & Nakahara, T. (2007). An experimental investigation of transient traction characteristics in rolling-sliding wheel/rail contacts under dry-wet conditions. *Wear*, 263(1-6), 169-179. https://jglobal.jst.go.jp/en/detail?JGLOBAL_ID=200902280680512218.
14. Uchida, M., Takai, H., Muramatsu, H. & Ishida, H.. (2002). Derailment Safety Evaluation by Analytic Equations. *Quarterly Report of Railway Technical Research Institute*, 43(3), 119-124. <https://doi.org/10.2219/rtrigr.43.119>.
15. Kardas-Cinal, E. (2009). Comparative study of running safety and ride comfort of railway vehicle. *Prace naukowe politechniki warszawskiej*, 71, 75-84. <https://www.infona.pl/resource/bwmeta1.element.baztech-article-PWA7-0037-0022>.
16. Iijima, H., Yoshida, H., Suzuki, K., & Yasuda, Y. (2014). A Study on the Prevention of Wheel-Climb Derailment at Low Speed Ranges. *Quarterly Report of Railway Technical Research Institute*, 30, 21-24. https://www.jreast.co.jp/e/development/tech/pdf_30/tec-30-21-24eng.pdf.
17. Sapronova S., Tkachenko V., Fomin O., Kulbovskiy I., & Zub E. (2017). Rail vehicles: resistance to movement and handleability. *Monograf: Ukrmetallurginform STA*, 160. <https://www.metaljournal.com.ua/assets/MonographKyivverstka.pdf>

Світлана Сапронова¹, Віктор Ткаченко², Надія Брайковська³, Іван Кульбовський⁴

¹Професор, професор кафедри вагонів та вагонного господарства, Державний університет інфраструктури та технологій, 04071, Україна, м. Київ, вул. Кирилівська, 9

²Професор, завідувач кафедри електромеханіки та рухомого складу залізниць, Державний університет інфраструктури та технологій, вул. Кирилівська, 9, м. Київ, 04071, Україна

³Професор, професор кафедри вагонів та вагонного господарства, Державний університет інфраструктури та технологій, вул. Кирилівська, 9, м. Київ, 04071, Україна

⁴доцент, доцент кафедри автоматизації та комп'ютерно-інтегрованих технологій транспорту, Державний університет інфраструктури та технологій, вул. Кирилівська, 9, м. Київ, 04071, Україна

Дослідження спрямування екіпажів рейковою колією

Проведено аналіз наукових публікацій, присвячених питанням спрямування колісних пар залізничного рухомого складу рейковою колією. Встановлено, що для правильного моделювання процесів спрямування колісних пар рейковою колією необхідний точний опис контактних сил зчеплення. Встановлено, що контакт гребня колеса з рейкою існує лише в поєднанні з кутом атаки та за наявності бічної сили зчеплення. Розроблено схему силової взаємодії колісної пари з рейками з гребневим контактом одного з коліс. Силовий контактна взаємодія колеса і рейки є складним для опису процесом, який водночас дуже важливий для вивчення динаміки фрикційної взаємодії транспортних засобів і колії та спрямування транспортних засобів рейковою колією.

У загальному випадку контакт колеса з рейкою відбувається в двох зонах контакту: на поверхні кочення і на реборді. Спрощено, контакт розглядається як двох-точковий контакт. Розглянуті силові фактори не можна однозначно віднести до напрямних чи факторів опору руху. Від положення колісної пари відносно рейкової колії залежать конкретні значення і орієнтування сил і моментів. Стверджується, що поздовжнє і поперечне ковзання колісних пар викликає опір руху і долається спрямовуючими силами.

Ключові слова: колісна пара, рухомий склад, гребеневі реакції, контактні сили зчеплення, спрямування екіпажу залізничною колією.

CONTENT

<i>Goolak S., Kostenko I., Keršys R., Riabov Ie., Demydov O.</i> Analysis of operation modes of shunting diesel locomotives when performing shunting work.	8
<i>Ozulu A., Lyubarsky B.</i> Calculation of the parameters of the electromechanical shock absorber of the high-speed electric train.	24
<i>Makarenko V., Voitovych O., Mieshkov Yu., Kliuiev O., Makarenko Yu.</i> Experimental studies of truck transport brake pads materials friction properties.	35
<i>Aharkov O., Tverdome V.</i> Comparative analysis of damages and defects in rails of different railway transport systems.	46
<i>Martynov I., Kalabukhin Yu., Trufanova A., Martynov S., Ostapenko Ya.</i> Determination of the efficiency of the modernization of passenger car bodies.	54
<i>Petrychenko O., Petrichenko Ie., Burmaka I., Vynohradova A.</i> Changes in modern university: challenges of today and development trends.	74
<i>Gritsuk I., Nosov P., Dyagileva O., Masonkova M.</i> Improving safety of navigation by constructing a dynamic model of the navigator's actions in the conditions of navigation risks	84
<i>Petrychenko O., Levinskyi M., Prytula D., Vynohradova A.</i> Fuel options for the future: a comparative overview of properties and prospects.	96
<i>Oliynyk O., Kushmar L.</i> Grapho-analytic method of determining the minimum groove at the pivot root of symmetrical switches.	107
<i>Soroka O.</i> Research of frogs point wear resistance in various conditions for transportation systems: main-line railway and subway.	117
<i>Samsonkin V., Biziuk I.</i> Development of the concept of simulation modeling of the ecological situation based on the theory of self-organization	131
<i>Gertsy O.</i> Models of criterion evaluation of the image processing systems effectiveness.	143
<i>Mykhailova Iu., Steba A., Silvanskaya G., Vil'shaniuk M.</i> Commercial and legal conditions for the organization of sea passenger transportation.	155
<i>Tkachenko K., Tkachenko O., Tkachenko O.</i> Modeling of transport infrastructure: ontological approach.	170

Sulym A., Khozia P., Strynzha A., Pavlenko Yu., Stolietov S. Improvements to the procedure for determination of the residual lifetime of railway vehicles. **180**

Shulika O., Orda O., Potaman N., Yashchuk Yu. Developing an efficient road-based batch freight delivery technology for intercity connections with a focus on resource conservation. **195**

Sapronova S., Tkachenko V., Braykovska N., Kulbovskiyi. Study of guiding vehicle by railway track. **213**

Наукове видання
Scientific edition

ЗБІРНИК НАУКОВИХ ПРАЦЬ
ДЕРЖАВНОГО УНІВЕРСИТЕТУ ІНФРАСТРУКТУРИ ТА ТЕХНОЛОГІЙ
COLLECTION OF SCIENTIFIC PAPERS
OF THE STATE UNIVERSITY OF INFRASTRUCTURE AND TECHNOLOGIES

Серія «Транспортні системи і технології»
Series "Transport Systems and Technologies"

Випуск 41

Issue 41

Відповідальний за випуск С. О. Гулак
Редактор Н. В. Щербак
Макет і верстка В. О. Зорьки

Підписано до видання 31.05.2023.
Ум. друк. арк. 13,3. Обл.-вид. арк. 12,00.
Наклад 50 прим. Зам. № 240-09/23.

Надруковано в друкарні редакційно-видавничого відділу
Державного університету інфраструктури та технологій.
Свідоцтво про реєстрацію Серія ДК № 6148 від 18.04.2018.
03049, м. Київ-49, вул. І. Огієнка, 19.
<https://tst.duit.in.ua/>