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ДЕРЖАВНИЙ УНІВЕРСИТЕТ ІНФРАСТРУКТУРИ ТА ТЕХНОЛОГІЙ

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ДЕРЖАВНОГО УНІВЕРСИТЕТУ ІНФРАСТРУКТУРИ ТА ТЕХНОЛОГІЙ

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Problems of ensuring the safety of pedestrian traffic across railway tracks and ways to solve them

From the analysis of the state of safety on the railways, it was established that a large number of collisions with pedestrians and their injuries occur outside railway crossings, which requires the development of technical means and the development of a safety culture for pedestrians when crossing railway tracks. The work deals with the urgent issues of ensuring the safety of pedestrian traffic when crossing railway tracks. It should be noted that the relevance of this issue today is also important from an economic point of view, since the loss of human life or injury to people has high economic losses for the country. For Ukraine, given the negative trends in population dynamics, preserving people's health and lives is of particular importance. Therefore, the improvement of safety measures for the movement of pedestrians across railway tracks in the conditions of urbanized cities should be considered in the interaction of all authorities and transport enterprises. It has been established that there is zero tolerance for road traffic fatalities in developed nations, so any measures that can improve road safety and prevent injury or death are urgent and require appropriate research and solutions. The proposed system for improving the safety of pedestrians at railway track crossings is primarily intended to create conditions for minimizing the number of traffic incidents involving pedestrians in populated areas.

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***Keywords**: safety of pedestrian traffic, urbanized spaces, pedestrian crossing, factors affecting pedestrians, information system.*

Introduction. Railway safety is everyone's responsibility. It is dangerous to take risks at level crossings and crossings, as any incident can lead to work disruptions, vehicle delays, property damage, injuries, and in the worst cases, the death of road users.

Existing studies [1] of the problem of traffic events at pedestrian crossings show that there is a high proportion of pedestrians who deliberately violate the rules of crossing the track. This may be due to various factors, but most studies [2] indicate the need to take into account not so much the geometrical and planning parameters of the pedestrian crossing, but the characteristics of train movement and patterns of pedestrian behavior.

It should be noted that there are practically no studies of pedestrian movement across railways in Ukraine. The issues of improving traffic safety at crossings are mainly considered. At the same time, the problems of crossing railway tracks by pedestrians, especially in the urbanized spaces of large settlements, remain neglected [3]. However, even in the majority of foreign works [4-11], it is noted that there are not enough studies of the functioning of pedestrian crossings over the railway, and the main problem of such studies is the lack of primary information. In particular, a train hitting a pedestrian is often the result of a deliberate violation or erroneous behavior or assessment of the situation [2-4, 6]. This, in turn, limits the development of adequate and effective measures to increase the safety of pedestrian traffic. Moreover, the impact of educational campaigns on curbing dangerous pedestrian behavior remains unclear [2]. At the same time, the researchers, in works [7-8], come to the conclusion that the study of the transport behavior of pedestrians is important for further research in the field of improving traffic safety.

Research analysis. A number of studies [4-6], mostly foreign ones, have been devoted to the problem of pedestrians crossing railway tracks, since in Ukraine the issues of functioning of railway crossings, not pedestrian crossings, are studied mainly [7-8].

Analyzing the problems of railway crossing by pedestrians, researchers [9-10] study various aspects of their functioning. Part of the research [11-13] focuses mainly on the diagnosis and classification of disorders. In particular, in [4], a detailed analysis of more than 7,000 transport events involving pedestrians on the railway was carried out. As a result, the basic regularities of pedestrian behavior at crossings of various types, taking into account geographical differences, have been established.

In work [5] based on the results of a study of accidents with pedestrians, it is shown that the main problem of such studies is the lack of reliable information, in particular, a train hitting a pedestrian is the result of a deliberate violation or erroneous behavior or assessment of the situation. And this, in turn, limits the development of adequate and effective measures to improve the safety of pedestrian traffic.

The paper [6] investigates the influence of pedestrian distraction during a railway crossing and shows that such factors as talking or looking at the phone screen while driving are extremely common causes of distraction. At the same time, it was also found that the vast majority of violations (disobeying traffic light signals) were observed precisely in attentive pedestrians, which indicates that such behavior was conscious and purposeful. The same thesis that violations at pedestrian crossings are a conscious behavior is confirmed by the results of research given in the work [9]. According to which, almost 25% of the respondents of the sociological research admitted that they deliberately violated the safety rules, while this was a violation not before, but after the passage of the train.

The work [10] is devoted to the study of the nature of decision-making by pedestrians crossing the railway and the analysis of risks related to the safety of pedestrian traffic.

There are a number of scientific works devoted to the study of mainly technical and operational characteristics of pedestrian crossings. In particular, in work [11], on the basis of real-time studies of the movement of pedestrians and cyclists across the railway, it was found that the train characteristics (speed of the train and duration of passage of the crossing train), technical characteristics of the crossing (duration of the warning signal and duration of traffic blocking) have the main influence on the probability of violation), as well as individual characteristics of pedestrians (gender, age). At the same time, the geometric parameters of the transition have a smaller influence, compared to the characteristics of the train and the individual characteristics of pedestrians.

A number of studies [12, 13] are aimed specifically at studying possible measures that should increase traffic safety during railway crossings. For example, the work [12] analyzed the patterns of behavior of schoolboys who regularly cross the railway, and the impact on behavior of additional training on traffic safety and penalties for violations.

In work [13], based on the analysis of transport accidents on the railway, various strategies that were proposed to prevent accidents with pedestrians on the railway are discussed, and it is also shown that the application of the modern theory of behavioral and cognitive of psychology may be useful for future research in the field of transport safety.

So, as can be seen from the analysis of scientific works [4-13], the problem of improving the safety of pedestrians crossing railway tracks has not been sufficiently studied, therefore the development of recommendations for improving the safety of pedestrians when crossing railway tracks is an urgent scientific task.

The purpose and tasks of the research. The purpose of the study is to improve traffic safety at pedestrian crossings over the railway by developing recommended measures to improve pedestrian traffic safety.

To achieve the specified goal, the following studies should be performed:

- to conduct an analysis of the state of safety on the railways of Ukraine and foreign countries;
- to conduct an analysis of the problems of ensuring the safety of pedestrian traffic when crossing railway tracks;
- to offer recommendations for improving the safety of pedestrian traffic when crossing railroad tracks;
- to develop a comprehensive information system for improving the safety of pedestrians crossing railway tracks.

Research materials and methods. As of 2023 (a 9-month report) in the regional branches of JSC "Ukrzaliznytsia" (at stations, tracks, territories of subdivisions) as a result of the collision of railway rolling stock, falling from it or other types of impact, 202 persons outside the railway transport industry received injuries of varying degrees of severity. including 128 with a fatal outcome, of which 16 people were electrocuted, including 6 fatally. During the same period in 2022 (Fig. 1), 177 people were injured, including 109 fatally injured, 15 of them were electrocuted, including 3 fatally [14].

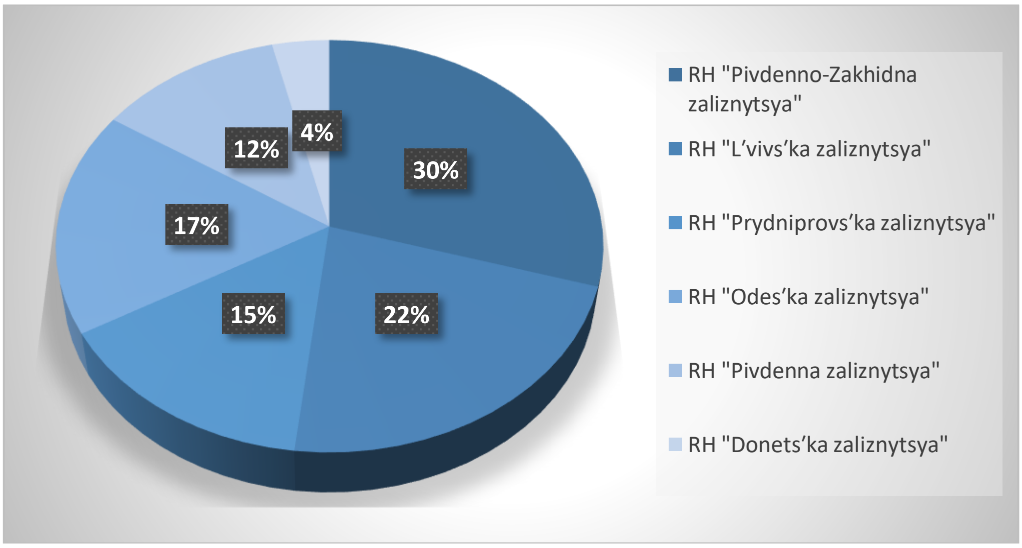

Fig. 1. **Chart of injured persons with fatal outcome in regional branches of JSC "Ukrzaliznytsia" in 2022**

In particular, 43 citizens were injured in the regional branch of "Lviv Railway" compared to 40 in 2022 (+3), of which 26 were fatal compared to 24 in 2022 (+2);

In addition, as of September 28, 2023, 13 children under the age of 16 were injured at railway infrastructure facilities, 7 of them fatally, including 10 children injured by electric shock, 4 of them fatally. During the same period in 2022, 6 children under the age of 16 were injured, 2 of them fatally, including 4 children injured due to electric shock, 1 of them fatal.

The analysis of cases of injury to third parties on railway transport shows that most of the cases occurred as a result of the victims' violation of the Rules for the safety of citizens on railway transport of Ukraine, approved by the order of the Ministry of Transport dated 19.02.1998 No. 54, registered in the Ministry of Justice on 24.03.1998 under No. 193/ 2633, namely: the crossing of railway tracks in unspecified places; walking on railway tracks; boarding and alighting while the train is moving; being in a state of alcohol intoxication on the territory of railway transport facilities.

According to UIC (International Union of Railways), there are more than half a million railway crossings in the world [15]. Monitoring the safety and interoperability of the EU rail system is one of the key tasks of ERA. The agency collects, processes and analyzes various data sets to support recommendations for action to be taken. Constantly monitoring and analyzing safety and interoperability indicators of the EU railway system. A report is then published every two years on a comprehensive overview of the development of railway safety and interoperability in the European Union (EU). The publication is the publication of a progress report on safety and interoperability in the Single European Railway Area (SERA). This report is based on data available in various EU databases and registers provided by national authorities such as national security agencies (NSAs) and national investigative bodies (NIBs), operators and other actors.

In 2020, the rate of major accidents, fatalities, and serious injuries (FWSI) per million train-kilometers has decreased significantly since 2010 [16]. Despite the decrease in passenger fatalities, taking into account the significant decrease in passenger kilometers (due to the COVID-19 pandemic), the passenger fatality rate increased compared to 2019, showing a slight upward trend since 2017.

The results of the most recent assessment [16] of the achievement of safety targets (annual ERA) show that safety performance remains acceptable at EU level, although possible deterioration of safety performance has been identified in eight cases. Every year, almost 300 road users or pedestrians die in accidents at railway crossings, causing economic damage of 1 billion euros [16]. Of these fatalities, 98% are caused by intentional or unintentional errors by road users, both vehicle drivers and pedestrians. Despite this, society still attributes most fatal accidents at level crossings to the railroad.

The railway community [17] considers this to be a particular problem mainly because it is impossible to predict the actions of individual vehicle drivers and pedestrians at level crossings, despite a number of risk control measures. Actions and misuse of rail infrastructure by members of the public across Europe are disproportionately responsible for more than 25% of all accidents and 29% of all rail fatalities affecting safe rail operations. Obviously, this is an area of significant risk for the railway sector.

However, only 1% of all road deaths in the EU (22,800 in 2019) occur at railway crossings [17]. Thus, the significant risk to the safe operation of the rail network is actually only a minor element of the overall road safety problem.

The level of accidents at level crossings varies significantly among EU member states. The countries with the lowest accident rates have generally developed comprehensive strategies to improve the safety of level crossings, and this has resulted in a small number of level crossings with poor or no protection.[17] Common features of the countries with the highest accident rate are low population density and low volumes of railway traffic. Perhaps these conditions create less incentive for integrated safety management of level crossings.

The accident indicators available at EU level [17] are a damaged track superstructure, faulty rolling stock, including wheelsets, faulty signaling and disregard of danger warning signs (SPADs). Their absolute numbers give an initial idea of their relevance and trends. Between 2016 and 2020, EU Member States reported more than 12,100 accident precursors as defined in the CSI each year. This is expressed as a ratio of approximately 7 warnings to 1 major accident. However, if we do not take into account accidents with l for people caused by rolling stock while driving, the ratio of warnings to accidents increases to 17:1. This highlights the potential of accident warning processing.

Problems of ensuring the safety of pedestrian traffic across railway tracks. Railroads are a significant barrier to pedestrian traffic and often cut or complicate established pedestrian connections in populated areas. The problems of ensuring the safety of pedestrian traffic across railway tracks are shown in fig. 2.

Pedestrians strive to simplify their path (which is especially relevant for low-mobility population groups), so they try to form their routes so that they are the shortest and fastest, and the lack of an organized crossing over the track is often not a reason to abandon the route.

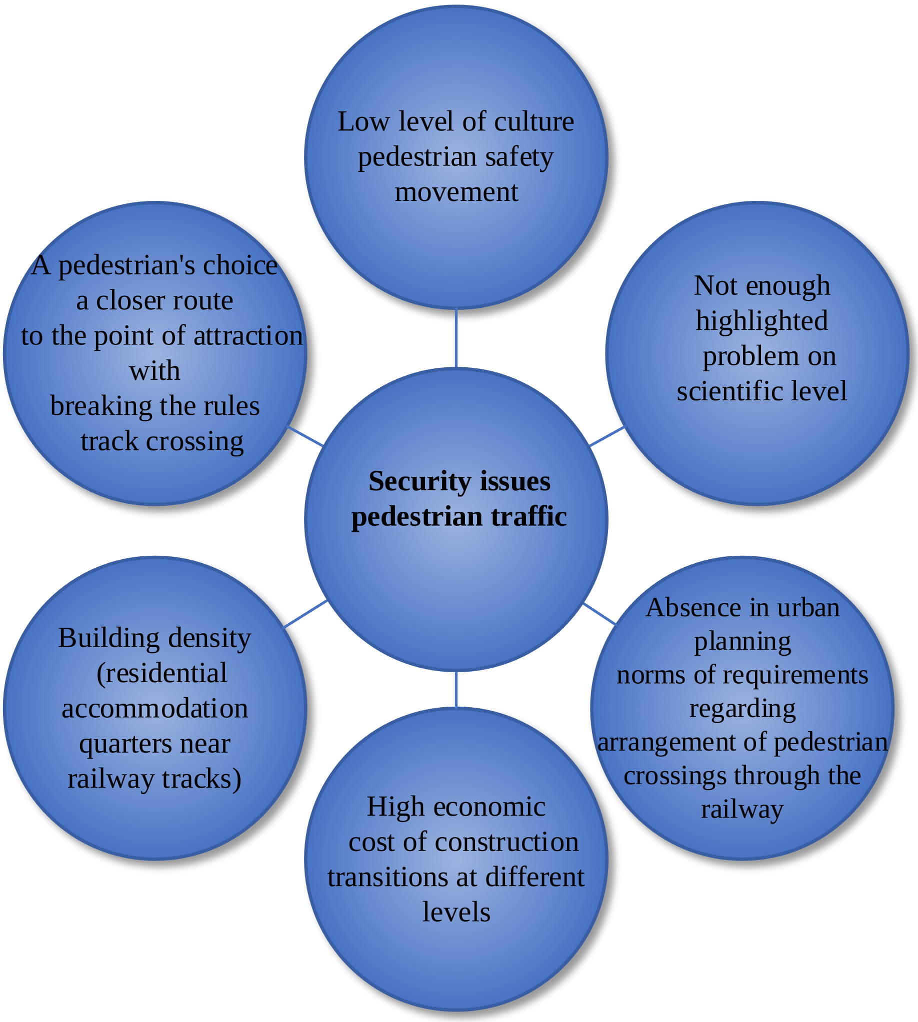

Fig. 2. **Problems of ensuring the safety of pedestrian traffic**

On the other hand, pedestrian connections in urbanized spaces are quite dense, and pedestrian traffic on them is intense. Modern approaches to city planning and street infrastructure prioritize pedestrian traffic over other types of transportation. At the same time, in case of crossing the railway track, the pedestrian loses his priority. But this is inconsistent with the principles of pedestrian behavior on the streets and spaces of populated areas, and pushes pedestrians to dangerous behavior.

In urbanized areas of cities, pedestrians may need to cross railways to reach a public transport stop. The design of these crossings is critical because a pedestrian collision with a train usually results in serious or fatal injuries. So, for example, in fig. 3 shows unauthorized crossings over railway tracks, which are caused by the installation of pedestrian crossings over roads near railway tracks.

As a result, pedestrians do not change their route and go to the center of gravity through railway tracks in unauthorized places. This once again proves that the interaction of all road services is extremely important to ensure the safety of pedestrian traffic.

The existing norms and instructions do not regulate the necessary frequency of the location of pedestrian crossings over the railway in populated areas, nor do they provide for taking into account the actual speed of the train (especially if passenger and freight trains can run at different speeds on the route), properly informing the pedestrian about the direction of approach train or the presence of a train on the opposite track, and also do not take into account the patterns of pedestrian behavior.

At the same time, almost all traffic accidents with pedestrians (at organized crossings or outside them) have serious or fatal consequences.

Fig. 3. **Unauthorized pedestrian crossing over railway tracks**

Even when crossing railways at equipped crossings, there are a number of challenges that provoke pedestrians to consciously or unconsciously violate safety rules. In particular, on long straight sections, pedestrians cannot correctly estimate the speed of the train (since the projection of the train practically does not change when approaching the crossing). However, in case of low speed of traffic, situations of excessively long waiting may arise, when pedestrians may decide to cross the track at the moment of dangerous approach of the train.

Similarly, a pedestrian may not recognize the approach of a high-speed train in time and step onto the track at a dangerous moment. In addition, on single-track sections with limited visibility or in the case of trains moving on the wrong track, existing pedestrian information systems do not indicate the direction of the approaching train in any way, and on double-track sections, when one train is passing, pedestrians cannot see or hear the approach of an oncoming train (at the same time, signaling that continues to work can be perceived as a certain feature of work, and not its activation to inform about the movement of an oncoming train). Therefore, although crossing at a prohibitory signal is not allowed, the pedestrian must make sure of the safety of his maneuver, but modern traffic safety management approaches provide that, in addition to the prohibition, there should also be proper informing of the pedestrian about the danger.

In Germany, ground warning lights are used to improve the safety of pedestrians at urban railway crossings [18] (Fig. 4).

The technology is lights installed in the carriageway, which are an additional technical safety factor when pedestrian’s cross railway tracks. They are controlled by the same signal image used for existing light signaling devices (red/dark). However, the conducted studies of the effectiveness of the use of warning ground lights are not high. Since the decrease in the number of people who cross the pedestrian crossing at the red-light circle is not high [19].

According to information on the state of accidents at railway crossings in the United States of America (according to the Federal Railroad Administration (FRA) from 2017 to 2023 [20], the total number of accidents at railway transport in the United States is 61 thousand cases, the number of deaths is 4.9 thousand persons, of which 3,300 are violators of the rules.

Fig. 4. **Ground warning lights**

In the USA, to improve the safety of pedestrians [21], when crossing railroad tracks, hinged sides are used.

In work [21] it is stated that the design of pedestrian crossings over railway tracks is important. Because collisions with pedestrians lead to injury and death of people.

In fig. Figure 5 shows the construction of a pedestrian crossing over the railway track [22], which is used to connect the local residential area with the center of Stonehouse. This crossing uses a red/green light system with constant warning time.

Fig. 5. **Pedestrian crossing over the railway track [17]**

In addition, work [21] states that when arranging pedestrian crossings, it is necessary to provide a minimum of 20 seconds of pedestrian warning time in the case of single-track railways. Crossings over more tracks require additional warning time built into the train detection system. Means that can be used to increase safety at railroad crossings include barrier gates, flashing lights, sound signals, active and passive warnings, fences, level crossings, and the use of penalties in the form of fines.

Also, in work [21] it is recommended to carefully study the location of the pedestrian crossing over the track. This includes an assessment of the number of tracks, the frequency of the location of footpaths across the road, which are located near railway tracks. The location of attractions near the tracks is very important, such as schools, hospitals, kindergartens, shopping centers, etc. At the same time, in cities where there are a large number of people, more effective means of improving the safety of pedestrian traffic should be developed.

In the UK, level crossing closures are believed to be the only way to tackle the risks, and since 2009 the country has closed 1,300 level crossings and invested £200 million in improving safety at thousands of crossings, including building level crossings, installing new barriers and warning systems, new signs, training people. The result of the activity is the approved strategy for improving safety at railway crossings 2019-2029 [23].

There are 3,000 crossings with active and passive safety devices in Spain. According to the National Agency for Railway Safety (AESF), in the last five years (from 2017 to 2021), 29 people died in 37 major accidents recorded at level crossings, with up to 98% of accidents being the result of human error rather than technical error means or infrastructure [24].

From the given data, it can be concluded that the real situation in the field of traffic safety at railway crossings and transitions constantly requires new approaches and solutions.

Proposed methods of improving the safety of pedestrians crossing railway tracks. In order to increase the safety of pedestrian traffic at railway crossings, it is necessary to use not only standardized automatic traffic signals, which are a cumbersome and expensive complex, but also other technical solutions that can be implemented at pedestrian crossings over railways in urbanized spaces (that is, where the intensity pedestrian traffic and the specific number of crossings per unit of track length are high). The proposed methods of improving the safety of pedestrian traffic at railway track crossings are shown in Fig. 6.

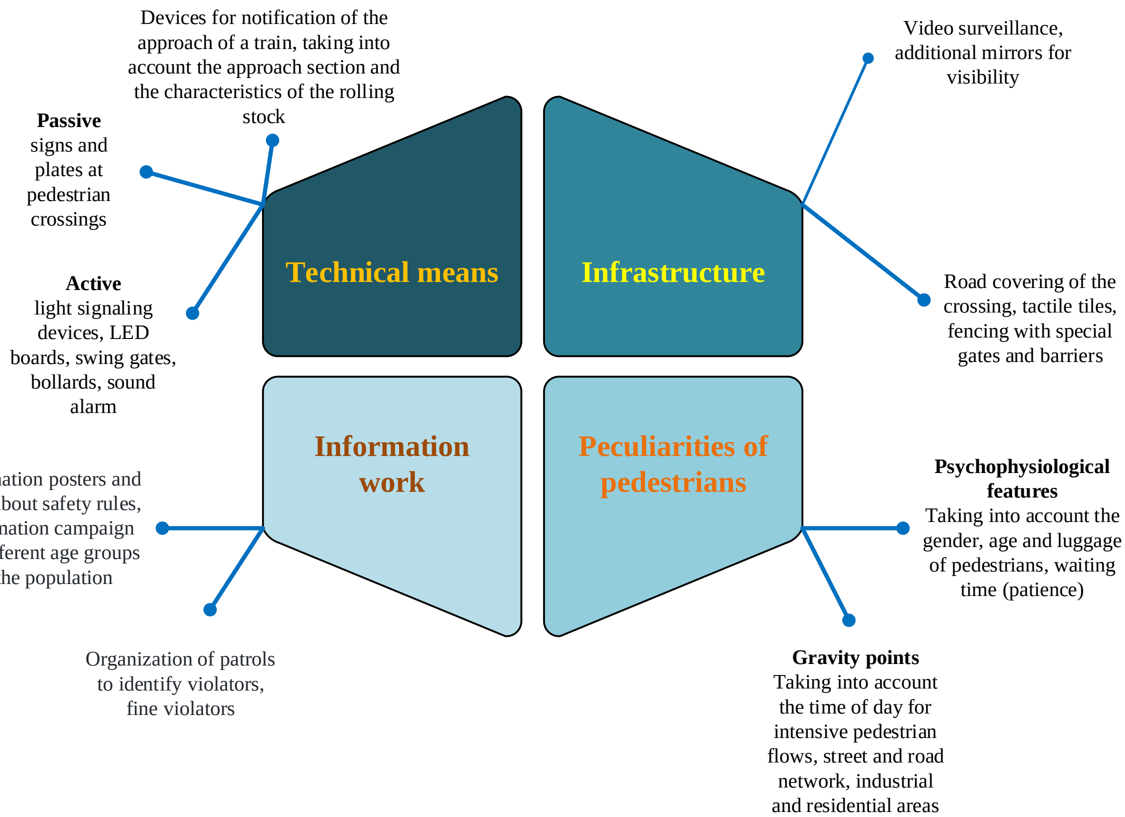

Fig. 6. **Proposed methods of improving the safety of pedestrian traffic when crossing railroad tracks**

Measures to increase the safety of pedestrian traffic include the development of infrastructure through the installation of pedestrian crossings over railway tracks, the use of technical means of warning about train movement, conducting information work for different age groups of the population and fining violators of the rules for crossing the tracks. Psychophysiological characteristics of pedestrians are also a special component of pedestrian safety.

At the same time, an important emphasis is placed not only on the technical provision of crossings, but primarily on the patterns of pedestrian traffic behavior. In particular, pedestrians are less inclined to unconditionally comply with the requirements of the prohibition of railway crossings, both with regard to the place of crossing and with respect to the acceptable interval to the approaching train.

In addition, measures to improve the safety of pedestrian crossings over railways in populated areas provide an improvement in the quality of life in populated areas, which additionally strengthens the relevance of such research.

At the same time, Ukrainian norms, standards and instructions do not contain requirements for the location and number of pedestrian crossings over the railway, requirements for ensuring the safety of traffic on them, etc. However, the absence of regulations does not mean that there is no need to cross the track (especially if it is due to the planning structure of settlements.

At the same time, the construction of transitions at different levels (bridges, tunnels), which take into account all the requirements for inclusiveness, is expensive. In turn, the installation of an overpass with an information and analytical system to inform pedestrians about the approach of a train will be a much cheaper solution in populated areas for existing or potential pedestrian crossings than the construction of overground or underground crossings.

In the case of taking into account the patterns of pedestrian behavior when crossing railway tracks, it will make it possible to avoid their excessive delays during the railway crossing in the case of trains moving on single-track sections or multi-track sections (when turning off the red lights and turning on the green lights occur after the train leaves the approach section, which is located by moving in relation to the movement of the train), as well as in the case of the actual movement of the train at a speed different from the calculated one.

Information system for improving the safety of pedestrian traffic at railway track crossings. The improvement of systems (Fig. 7) responsible for increasing the safety of pedestrian traffic when crossing railway tracks assumes that the system will take into account the characteristics of train movement, as well as the patterns of pedestrian behavior (speed of movement, length of patient waiting, delay before entering the track, the difference in behavior at regulated and unregulated crossings, etc.), and will clearly inform pedestrians about the direction of train movement and the moments when exiting the track is prohibited. Because the existing technologies used in Ukrzaliznytsia do not have reliable ways of recording the speed of the train's approach, as well as informing about the direction of its movement. Accordingly, the development of an information and analytical system is an urgent task.

The task is solved by the fact that when a train hits an inertial sensor, a rolling stock is detected in the area approaching the pedestrian crossing. Next, a signal is transmitted to the information board installed at the railway crossing about the approach of the train and the blocking alarm is activated. This allows you to warn the pedestrian about the movement of the train to the crossing, to close the pedestrian crossing by means of barrier signaling, which will ultimately lead to an increase in the safety of pedestrian movement across the railway track within the crossing.

It should be noted that pedestrian safety measures depend on the cooperation of infrastructure, technologies, systems and users, so changing one of these factors must take into account its impact on others, so as not to jeopardize safety.

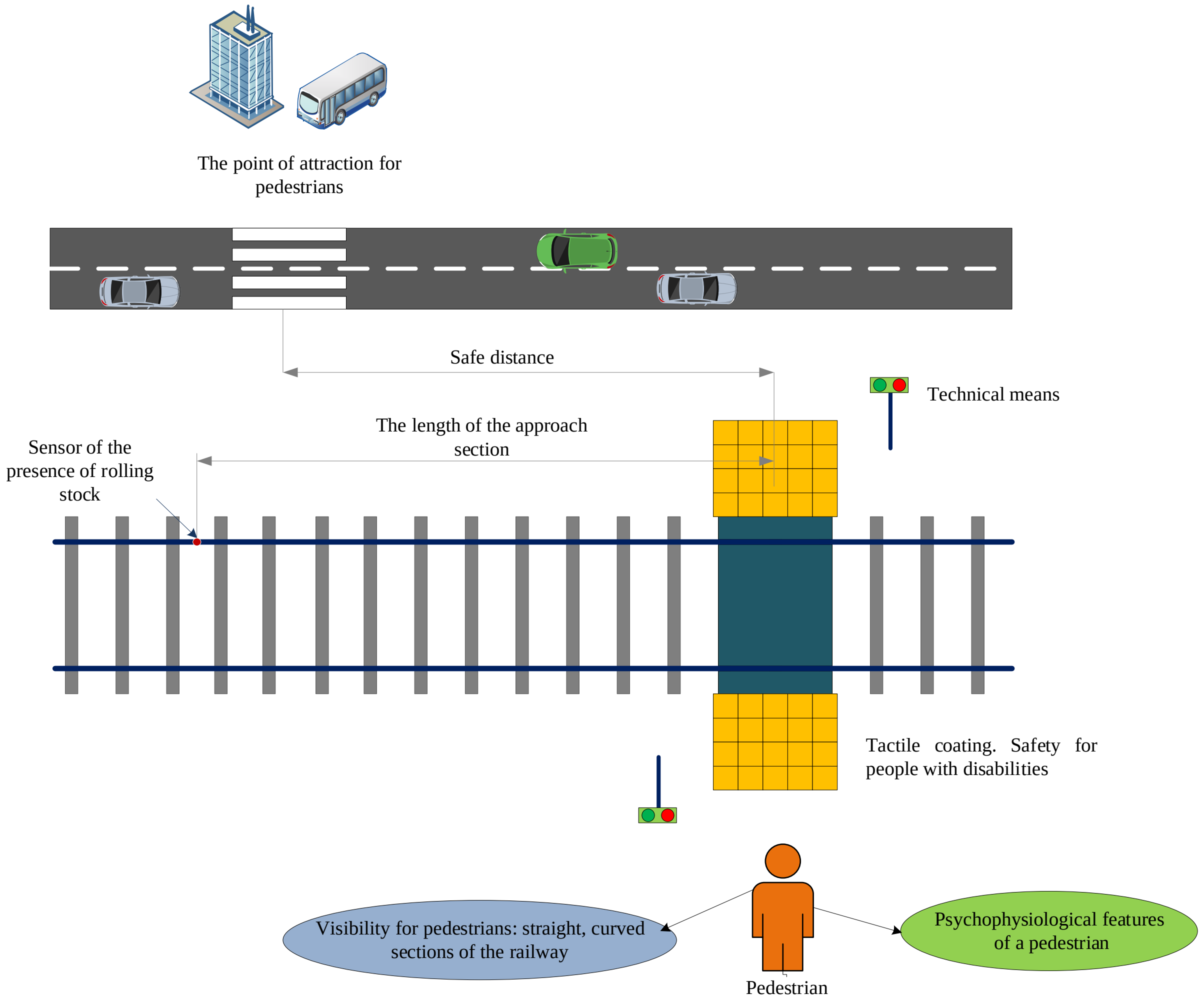

Fig. 7. **Recommended method of safe pedestrian crossing of railway tracks to the gravity point**

In today's world, the process of risk assessment at pedestrian crossings over railway tracks does not keep up with changes in the infrastructure and the increase in traffic flows, the number of pedestrians, and especially in urban areas where changes occur very intensively. Therefore, in our opinion, pedestrian safety measures and recommendations should be reviewed and improved every 10 years.

Conclusions. The following conclusions and recommendations can be made from the conducted research:

1. Based on the analysis of the state of safety on the railways of Ukraine and foreign countries, it was established that in 9 months of 2023, 202 persons not involved in railway transport received injuries of varying degrees of severity in the regional branches of JSC "Ukrzaliznytsia". At the same time, 128 were fatal. Therefore, improving the safety of pedestrian traffic on railways is a very important task.

Addressing safety issues at railway crossings is a complex task that requires the cooperation of various parties, including authorities, railway companies, public organizations and society, by implementing measures that combine technical, organizational and educational approaches. Ensuring the safety of pedestrians is an important aspect of sustainable development and ensuring convenient and safe transport connections.

2. The problems of ensuring the safety of pedestrian traffic when crossing railroad tracks include: the absence of requirements in urban planning regulations regarding the arrangement of pedestrian crossings over railroad tracks, although the density of buildings (location of residential blocks near railroad tracks) only increases every year in large cities. At the same time, the construction of pedestrian crossings at different levels across the track is economically expensive. In addition to infrastructural and

technical means, the problems of increasing safety include the low level of pedestrian culture regarding traffic safety, the pedestrian chooses a route closer to the point of attraction, while violating the rules of safe crossing of tracks.

It should also be noted that in DBN B.2.3-19:2018 "Railways with a gauge of 1520 mm", pedestrian paths should be designed at railway crossings located in populated areas, as well as in case of pedestrian traffic intensity of more than 100 people/hour. At the same time, there are no requirements and/or recommendations in these regulations regarding the arrangement of separate pedestrian crossings that are not part of railway crossings. Therefore, the determination of the criteria for the expediency of the arrangement of ground crossings over the railway additionally emphasizes the relevance of this issue and the large amount of scientific research that needs to be performed.

3. Taking into account all the factors that affect the safety of pedestrian traffic, a number of recommendations are proposed for the safe crossing of railway tracks by pedestrians:

- installation of safe pedestrian crossings near railway stations and centers of gravity, equipped with modern signaling and lighting systems to increase visibility and notify about the approach of a train;
- placement of appropriate road signs and signaling devices that will inform pedestrians about the danger of railway traffic and recommended places for crossing;
- increase or decrease the transition time in accordance with the set signaling by calculating the time and speed of the train approach and its features;
- regular inspection and maintenance of pedestrian crossings to identify and eliminate defects;
- conducting educational campaigns to raise pedestrian awareness of the dangers associated with crossing railroad tracks;
- use of modern technologies, such as motion sensors and monitoring systems, for automatic detection of pedestrians and timely notification of drivers about their presence at crossings.

4. Safety problems of pedestrian movement across railway tracks require various solutions for their solution. An information system has been proposed to increase the safety of pedestrians crossing railway tracks. This system takes into account the characteristics of train movement, as well as patterns of pedestrian behavior (speed of movement, duration of patient waiting, delay before entering the track, difference in behavior at regulated and unregulated crossings, etc.). It also provides for clear information to pedestrians about the direction of train movement and the moments when exiting the track is prohibited.

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Проблеми забезпечення безпеки руху пішоходів через залізничні колії та шляхи їх вирішення

Із аналізу стану безпеки на залізницях встановлено, що велика кількість наїздів на пішоходів та їх травмування відбувається за межами залізничних переїздів, що вимагає розробки технічних засобів та розвитку культури безпеки пішоходів при перетині залізничних колій. У *праці розглядаються актуальні питання забезпечення безпеки руху пішоходів при перетині залізничних колій. Слід зазначити, що актуальність цього питання сьогодні важлива також і з економічної точки зору, оскільки втрата людського життя або травмування людей для країни має високі економічні збитки. Для України, з огляду на негативні тенденції щодо динаміки чисельності населення, збереження здоров'я та життя людей набуває особливого значення. Тому покращення заходів безпеки руху пішоходів через залізничні колії в умовах урбанізованих міст повинні розглядатись в взаємодії усіх органів влади та транспортних підприємств. Встановлено, що у розвинених державах існує нульова толерантність до смертності у транспортних пригодах, тому будь-які заходи, які можуть підвищити безпеку руху та запобігти травмуванню чи смертності, є актуальними та потребують відповідних досліджень та рішень. Запропоновано систему підвищення безпеки руху пішоходів при перетині залізничних колій має на меті в першу чергу створити умови для мінімізації кількості транспортних подій з пішоходами в населених пунктах.*

***Ключові слова**: безпека руху пішоходів, урбанізовані простори, пішохідний перехід, фактори впливу на пішохода, інформаційна система.*

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Trends and preconditions for widespread adoption of liquefied natural gas in maritime transport

The need for sustainable and environmentally friendly maritime transport and the introduction of International Maritime Organization (IMO) regulations on ship emissions have led to the search for a new type of marine fuel. Today, liquefied natural gas (LNG) as a marine fuel is an attractive, potential and technically feasible option for new ships that are being built to comply with air pollution regulations. The aim of the work was to analyze the prospects for the use of LNG as a marine fuel. The set task was achieved by studying the current state of LNG shipping, analyzing the advantages and disadvantages of different types of fuels, and studying the dominant segments of LNG ships. The implementation of LNG on board ships is carried out along with the development of LNG-powered engines, their control and protection systems, fuel tanks, gas supply systems and infrastructure. The object of the study is the prospects for using LNG as an alternative type of fuel in shipping. The most important result is the conclusion that LNG has significant potential as an alternative to traditional types of fuel in shipping, but requires the development of appropriate infrastructure.

Key words: *LNG, marine fuel, emissions, environmental friendliness, sustainable development, engines.*

Introduction. In light of the global drive for economic decarbonization, the water transport sector is preparing for a transition to new technologies and energy sources, which will have a significant impact on costs, asset values and profitability. Shipowners are already feeling increased pressure to reduce greenhouse gas emissions from their activities. Over the next decade, decarbonization in shipping will be driven by three key factors: regulations and policies, access to investors and capital, and expectations from shippers and consumers [1-3].

The International Maritime Organization is developing greenhouse gas emission reduction policies for international shipping. The first regulations, in particular the Existing Vessel Energy Efficiency Index and the Carbon Intensity Indicator, will come into force on January 1, 2023. One of the goals of this activity is to achieve a reduction in the carbon intensity of all ships by 40% by 2030 compared to 2008 levels [4, 5].

The use of alternative fuels and renewable energy has the greatest potential for reducing greenhouse gas emissions. All alternative fuels for water transport face difficulties and barriers to their use, although the complexity of overcoming these barriers will differ for different types of fuels. Typical key barriers include the high cost of required machinery and equipment, on-board fuel storage systems, the need for additional storage space, low technical maturity, high fuel prices, limited fuel availability, lack of global bunkering infrastructure, and safety issues including flammability and explosiveness of fuels. As of June 2021, only 0.5% of ships worldwide used alternative fuels, but 11.8% of orders in 2021 were for ships running on alternative fuels. Of these, 6.1% of orders were for LNG-powered ships, 3.8% for electric battery-powered, 1.5% for LPG, 0.3% for methanol, 0.06% for hydrogen and 0.02% for ammonia [6, 7].

Analysis of recent research and problem statement. In recent years, among the alternative fuels for water transport, liquefied natural gas (LNG) has gained the most distribution. The key environmental benefit of LNG is reduced SOx, particulate matter, NOx and CO2 emissions compared to traditional petroleum products.

Methanol is a good substitute for gasoline, used in blended fuels, and can also provide good performance in diesel engines. To use methanol in diesel engines, a small amount of diesel fuel must be injected along with the methanol or an ignition enhancer must be used. Since methanol contains no sulfur, NOx emissions are formed in small quantities during combustion, and particulate emissions are absent, this fuel is considered promising for water transport. However, the toxicity of methyl alcohol should be emphasized.

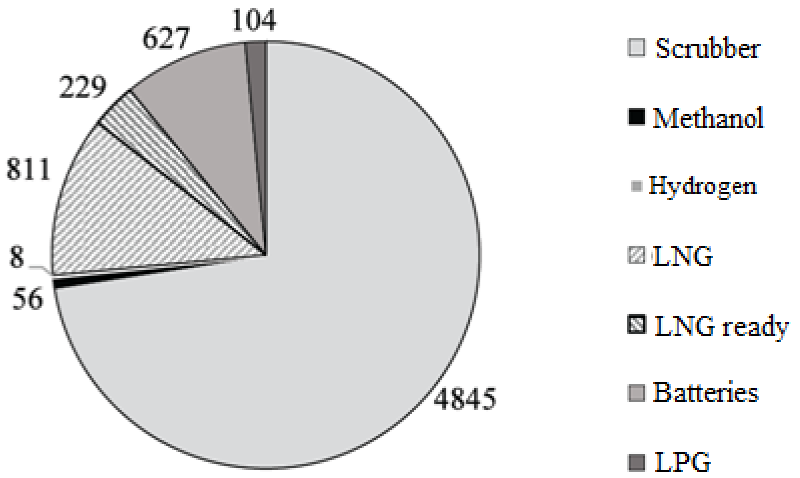

Fig. 1. **Number of ships in operation and on order by alternative fuel types and scrubber usage**

The purpose and tasks of the study. Ammonia is of considerable interest as a potential zero-carbon fuel for transportation. Compared to the marine fuel MGO, the energy content by mass of liquid ammonia is less than half and by volume is about 30%. Ammonia can be used as a marine fuel in both internal combustion engines and fuel cells. Due to its high autoignition temperature, ammonia requires a higher compression ratio (35:1 and higher) than typical diesel engines (16-23:1). Such an engine is difficult to design, and therefore additional fuel with a lower autoignition temperature needs to be used to ensure more stable combustion. Hydrogen is a colorless, odorless, non-toxic gas. For shipboard use it can be stored cryogenically liquefied, compressed, or chemically bonded. Hydrogen can be liquefied at temperatures down to minus 240°C by increasing the pressure to the "critical" point of 13 bar. The energy density per mass of hydrogen, taking into account the lower heating value of 120 MJ/kg, is approximately three times higher than the energy density of fuel oil. At the same time, the volumetric density of liquefied hydrogen (71 kg/m3) is only 7% of the figure for fuel oil. This results in an approximately fivefold increase in volume compared to the same amount of energy stored in fuel oil. When storing hydrogen as compressed gas, its volume is approximately 10-15 times (depending on the pressure) higher than the volume of the same amount of energy in fuel oil. The distribution and bunkering infrastructure for hydrogen in water transport is still absent.

From vegetable oil raw materials, three main types of biofuels are produced: straight (i.e. untreated) vegetable oil (SVO), biodiesel (FAME) and renewable diesel fuel (HVO), which are used as substitutes for diesel fuel or as component of blended fuels. SVO, FAME and HVO production technologies are proven and commercially available. Theoretically, it is possible to use marine diesel engines on 100%

biodiesel fuel, but this requires certain engine settings and certification, so more often FAME is used in blended fuels.

Based on the results of a comparative analysis and assessment, the following alternative fuels are considered the most promising for Ukraine's water transport: biomethane, which can be used in compressed or liquefied form; biodiesel (FAME) and hydrotreated vegetable oil (HVO); liquefied natural gas, as well as the use of electric power units with battery packs.

This work differs in that an analysis of alternative fuels was carried out, the main LNG ship segments were studied, on the basis of which some important conclusions can be drawn. LNG-fueled ships represent a growing market, driven by strict air pollution regulations; widespread development of LNG engines, fuel tanks and gas supply systems; and future LNG infrastructure projects. Indeed, significant LNG market growth is expected over the next decade, although external factors like LNG price and availability could impact it. Today, the main segments dominating the LNG fleet are car/passenger ferries, PSVs, harbor tugs, LNG carriers and container ships. The paper identifies several general points for LNG-powered ships, these findings can be used as a basis for further development for other ship types.

Table 1. **Characteristics of traditional and alternative fuels for water transport**

Characteristics	Diesel fuel	LNG	Methane	Methanol	LPG)	Hydrogen
Molecular formula	CnH1,8n; C_8-C_{20}	CnHm; 90-99% CH_4	CH_4	CH_3OH	C_3H_8 та C_4H_{10}	H2
Carbon content, wt.%	86,88	near 75	74,84	37,49		
Density at 160C, kg/m^3	833… 881	431… 4641)	422,51)	794,6	505	0,08
Boiling point at 101,3 кPa, ^{0}C$^{2)}$	163…399	-160 (-161)	-161,5	64,5	-42	-253
Lower heating value, MJ/kg	42,5	49	50	20	47	120
Lower heating value, GJ/m^3	35	22		16		
Autoignition temperature, ^{0}C	257	580	537	464	457	585
Flash point, ^{0}C$^{3)}$	52…96	-136		11	-60	
Cetane number	>40	0		5		
Flammability limits, vol.% in air	1,0…5,0	4,2…16,0	1,4…7,6	6,72…36,5	2,1…9,6	4…59
Solubility in water	No		No	Complete		
Sulfur content, %	varies, <0,5 oro <0,1	< 0,06	0	0		

Liquefied petroleum gas (LPG) is a mixture of saturated hydrocarbons: propane C3H8 and butane C4H10, whose molecules consist of hydrogen and carbon atoms [8]. LPG has two sources: approximately 60% is extracted during the production of natural gas and oil from the ground, while the other 40% is formed during the refining of crude oil.

Natural gas contains 90% methane CH4. The remaining 10% consist of 5% propane and 5% other gases, including butane. During the processing of crude oil, liquefied hydrocarbon gas is separated in the upper part of distillation columns during technological operations. LPG makes up 2 to 3% of all resulting products, meaning one ton of processed crude oil yields 20 to 30 kg of LPG.

LPG is gaseous at normal temperature (15°C) and atmospheric pressure (1013 mbar), and liquefies at low pressure: 1.7 bar for butane, 7 bar for propane. Their boiling temperatures are: 0°C for butane, -44°C for propane, – 25°C for liquefied petroleum gas. One liter of liquid butane releases 239 liters of gas (at 15°C - 1 bar); one liter of liquid propane releases 311 liters of gas (at 15°C - 1 bar).

The LPG components have high and constant calorific value. Butane provides a lower gross calorific value (PCI) of 12.66 kWh per kg, propane PCI is 12.78 kWh per kg. Given their high superior calorific power (SCP), butane and propane have 13.7 kWh and 13.8 kWh per kg respectively.

Advantages:

Energy density: LPG contains a high energy density, which means that less gas volume is needed to obtain more energy. This facilitates transportation and storage.

Versatility: LPG can be used for various purposes, including heating, cooking, powering vehicles and generating electricity. Ease of storage and transportation: LPG can be easily compressed to reduce volume, making it convenient to store and transport in liquid form.

Disadvantages:

High freezing temperatures: LPG can freeze at low temperatures, which can cause problems in cold climates. Oil dependence: LPG is produced from oil, so its prices may be subject to fluctuations in global oil markets.

The advantage of LPG is non-toxicity, no corrosiveness, high octane number (102-108). LPG burns much cleaner than gasoline or diesel.

Liquefied natural gas (LNG) is a form of natural gas that has been cooled to very low temperatures - minus 162 degrees Celsius at which it becomes liquid. The liquefaction process takes place in several stages and is quite costly. In vapor phase, natural gas has about three times less calorific value than propane.

LPG is transported under pressure of 10-15 atmospheres. LNG is used in vehicles at a pressure of 200-250 atmospheres. Due to the pressure difference, different cylinders are needed for storage. For LPG, a metal cylinder with a wall thickness of 4-5 mm is sufficient, while for LNG much thicker cylinders with low thermal conductivity are needed.

Advantages:

Environmental friendliness: Liquefied natural gas is considered more environmentally friendly as its combustion produces less carbon dioxide and other pollutants compared to other fuels.

Disadvantages:

Specialist infrastructure needed: Storing and transporting LNG requires specialist infrastructure such as gas liquefaction terminals and tankers.

High infrastructure costs: Constructing and maintaining infrastructure for LNG production, storage and transportation can require significant expenditure.

The above factors make LPG a more promising fuel type for internal combustion engines.

Materials and methods of research. More than 90% of the world's goods by mass and volume are transported by sea [2]. The water transport sector is expected to continue developing in the coming years thanks to investments in the shipbuilding industry and inland waterways in many countries. Diesel engines are the most popular in this sector. According to 2015 WLPGA data, they were installed on 70% of marine vehicles. However, as environmental fuel requirements tighten, maritime transport owners and operators will be forced to seek a more environmentally friendly alternative to fuel oil and other traditional fuels.

To date, LPG is the most common alternative motor fuel in the world [3, 9]. Despite this, propane-butane still cannot gain a foothold in the marine fuel market. Currently, LPG as a bunker fuel is used by recreational and fishing vessels mainly in the US, Chile, Germany, Italy, Spain, UK, Turkey, Northern European countries, as well as in Indonesia. At the same time, there are no large ships worldwide using liquefied gas as motor fuel. The vast majority of tankers are equipped with diesel engines, with natural gas being promoted as an alternative - LNG or CNG.

At the same time, this situation seems a bit illogical. If LPG has become the most popular alternative fuel in the automotive sector, then why can't it occupy the same niche in the water transport sector?

Especially since the International Maritime Organization (IMO) is tightening requirements for ship fuel quality from 2020. The maximum allowable sulfur content will be reduced from the current 3.5% to 0.5%. In addition, stricter environmental standards are already in effect off the coast of North America and in northern Europe – in the North Sea and the Baltic Sea – allowing no more than 0.1% sulfur in fuel oil. It is possible that in a few years, environmental standards for marine fuels will be further tightened, as it happened with gasoline and diesel fuel worldwide.

There is a growing realization in the maritime transport sector that the era of cheap and dirty fuel oil must end and be replaced by a more environmentally friendly fuel. The only question is how quickly this will happen. Against this background, ships using LNG as fuel began to emerge globally. Currently, natural gas is considered the main fuel oil alternative. There are already over a hundred ships running on this type of fuel worldwide, with about a hundred more under construction.

However, the World LPG Association (WLPGA) believes that propane-butane is more attractive for maritime transport than LNG. As the organization's report emphasizes, the transition of ships to LPG requires lower investment costs and, accordingly, has shorter payback periods. Moreover, propane-butane prices are less volatile. Propane-butane, which has proven itself well among motorists, certainly has a number of advantages over its competitors.

Firstly, LPG is an affordable fuel. Its global consumption is still below production volumes. According to WLPGA estimates, the surplus ranges from 15 million to 27 million tons per year. Falling liquefied gas prices in North America caused by the shale revolution are also an important factor that could influence the spread of LPG as a marine fuel.

Indeed, there are no problems with supplies of liquefied gas globally. According to WLPGA, world production of this fuel type in 2015 amounted to 284 million tons, which is equivalent in energy content to approximately 310 million tons of oil. At the same time, global LPG production is growing by about 2% annually. For comparison: fuel consumption in the maritime sector in 2010-2012 was estimated by the International Maritime Organization at 307 million tons. Liquefied gas production is growing fastest in North America and the Middle East. It is important to note that the US, as a result of increased hydrocarbon production from shale, became a net exporter of LPG back in 2012. As noted in the annual report of the large LPG carrier BW Group, LPG production in the US in 2016 amounted to 76.5 million tons (+1.8% over the previous year), while consumption was 54.3 million tons (-1 .5% compared to the previous year). Thus, the propane-butane surplus in the country is about 22 million tons per year.

Secondly, the LPG market has existed for a long time and there is no lack of infrastructure for transporting and storing this type of fuel worldwide, which cannot be said about LNG. In fact, around the world there are storage facilities, export terminals and refineries equipped with loading/unloading equipment for LPG tankers.

Liquefied gas exports from the US continue to grow as the country produces more product than it consumes. Over the next 10 years, according to forecasts by leading world analysts, the United States will become the world leader in oil production. This means that supplies of LPG to the world market will also grow. As a result of production growth, prices for the product in North America have fallen significantly, and this trend may continue, which is beneficial for consumers. The increase in hydrocarbon production in the US in the medium term will restrain world LPG prices, since American liquefied gas is already supplied to major consumers in Asia. After the Panama Canal was reconstructed in 2016, doubling its capacity, it has become even easier and more convenient to supply resources from the Gulf of Mexico to Asia.

According to BW Group, there are currently 244 large-capacity vessels for transporting LPG in refrigerated form (usually at -50°C) with a capacity of about 80 thousand m3 of gas (about 42 thousand tons) in the world. Tankers carrying semi-refrigerated LPG (at -10°C) usually have a capacity of 6 to 12 thousand m3, while propane-butane transported under pressure (about 17 atm) is usually transported in small batches - from 1 to 3 thousand m3. The way of storage is one of the advantages of LPG compared to LNG: it can be stored on board as a non-cryogenic liquid. Moreover, transportation and storage of propane and butane is cheaper since they do not require such low temperatures as LNG, which must be kept at -162° in cryogenic tanks.

Some marine operators and shipbuilders are already considering the possibility of creating and using LPG-powered tankers as the primary fuel. Moreover, there are no technical obstacles to using LPG for ships of various sizes - from ocean liners to small boats.

Most likely, large vessels using LPG as the primary fuel will soon appear on the water, as the relevant technologies are evolving. For example, last year in Tokyo, the design of the new LPG carrier LPGreen was presented, developed by a consortium of companies including Hyundai Heavy Industries (HHI), Wärtsilä Oil & Gas and DNV GL. Its creators sought to design an energy efficient, environmentally friendly vessel for transporting liquefied gas. And reportedly, they succeeded. Fuel cost savings for the LPGreen tanker, which will run on propane-butane, could reach up to 30%.

In addition, in May last year, GE Marine Solutions announced the development of the world's first ferry that will use LPG as its primary fuel. The vessel is intended for the Korean market. A consortium of companies has been working on its creation, in particular Youngung Global, DINTEC, Korea Industry Association, GE Marine Solutions and Far East Ship Design & Engineering Co. It was reported that the LPG ferry is being created both for economic benefits and for improving the environment through low fuel prices and low sulfur oxide emissions.

Recently, vehicle models with electric motors powered by a battery have also begun to emerge, however they use LPG as a source for generating electricity. Riding the wave of fighting air pollution that is gradually engulfing Europe, manufacturers have seen prospects in such hybrids, since "clean" electric vehicles still either have insufficient range per charge, or cost too much. For example, electric trucks have been created in the Netherlands that use LPG to generate electricity and increase range. This involves using an ordinary and perhaps somewhat simplified internal combustion engine that burns gas and charges batteries with electricity.

The same technology can also be used on ships. Its main advantages are low noise levels, as well as fuel cost savings. Quiet electric motors could first be used by military ships, survey ships, cruise ships, etc. As noted in the WLPGA report, ships that mainly move at low speed, with a hybrid engine system, could use 30-35% less fuel than those equipped with traditional internal combustion engines.

In addition, LPG can become the optimal fuel for use in nature reserves as an alternative to traditional types that emit much more exhaust gases. Besides, gasoline and diesel fuel pollute water bodies through fuel spills during refueling, which is excluded when using gas.

Maritime transport is an international industry, as over 80 percent of world trade according to IMO data is carried by ships [10, 11]. Although shipping is the most efficient and reliable means of international transport, it emits several gases and particles into the atmosphere, the most important of which are CO2, NOX and SOX. According to the third greenhouse gas study (IMO, 2014), in 2012 international shipping emitted 796 million tons of CO2, 18.6 million tons of NOX, and 10.6 million tons of SOX. This accounts for approximately 2.2%, 13% and 12% of global emissions of these gases, respectively.

Today LNG as a marine fuel is an available and potential solution for compliance with future air pollution requirements. In addition, the use of LNG to power ship engines is an attractive commercial solution for both new LNG-powered ships and existing ships. There are three main factors that make LNG a real alternative. Firstly, LNG as a marine fuel completely eliminates SOX emissions, reduces NOX emissions by up to 90%, and also minimizes CO2 emissions by about 20%. Secondly, there are a significant number of ships in the shipping industry that use LNG as fuel, as LNG carriers have been using it for several years. LNG carriers use the natural boil-off of LNG stored in their cargo tanks to power their engines. Finally, LNG as a marine fuel is commercially attractive due to its worldwide availability, as LNG stocks will be able to meet marine industry LNG demand in the coming years, as well as its low price compared to the main marine fuel used on board ships. Although it is the low price of natural gas and LNG compared to high sulfur marine fuels, including HFO or IFO, and low sulfur distillates (MDO and MGO) in some markets that makes LNG attractive as a marine fuel. Today in the United States (USA) and Europe (EU) the price of natural gas is much lower than high sulfur fuel oil and low sulfur distillates, while in Asia the price of LNG is higher than high sulfur fuel oil but lower than low distillates sulfur. However, it should be taken into account that natural gas requires infrastructure, as it needs to be liquefied, stored and supplied to ships. For this reason, the low price of natural gas may not translate into a low price for LNG.

However, LNG as a marine fuel faces several challenges: the development of LNG-fueled engines, LNG handling and storage equipment on board, and LNG bunkering infrastructure. Liquefied natural gas engines have already been used on LNG ships but not on other ship types such as ferries, containerships and naval vessels. As a result, engine manufacturers have started developing dual-fuel (DF) engines capable of burning both diesel fuel and LNG. Secondly, LNG needs to be stored at a very low temperature during voyages, for this reason, fuel tanks, pipes and conveying systems must be fitted with insulating alloys capable of keeping LNG at the proper temperature (-162°C). Finally, port facilities for the production, storage and fueling of bunkering stations or vessels are required to reliably and efficiently supply LNG-fueled ships.

LNG-fueled ships are mainly equipped with two types of engines: lean-burn gas engines and dual-fuel engines [12]. Lean-burn gas engines comply with IMO Tier III regulations while dual-fuel engines comply with IMO Tier II regulations when operating in liquid fuel mode and IMO Tier III regulations when operating in gas mode. Currently, the main manufacturers of LNG engines are Wärtsilä, Rolls Royce and MAN, which offer a wide selection of engine designs across all power ranges.

Lean-Burn Gas Engines

Lean-burn gas engines are designed to run on LNG only and operate on the Otto lean burn principle [13]. Lean-burn gas engines are fueled with natural gas through a Gas Valve Unit (GVU) which filters and controls the pressure of the natural gas. The cylinders of a gas engine are fed by separate pipes connected to a main double pipe running along the engine. Gas engines run on a pre-mixed lean air-gas mixture which is ignited in the pre-chamber by a spark plug. The air-gas mixture contains more air than required, resulting in a lower combustion temperature, hence NOx emissions are reduced and efficiency is increased due to higher compression ratios and optimized injection timing.

The air-gas mixture is injected at low pressure (4-5 bar) and is generated outside the cylinder behind the turbocharger. Gas can be supplied directly from LNG fuel tanks under pressure as lean-burn gas engines are low-pressure engines.

In addition, propulsion systems using lean-burn gas engines have two applications: mechanical and electric. In a mechanical scheme, the lean-burn gas engine provides propulsive power to the propellers through gearboxes and shaft lines, while in an electric scheme, generator sets driven by the lean-burn gas engine supply electric motors with electric power to propel the propellers.

Rolls Royce є основним виробником Rolls Royce is the main manufacturer of lean-burn gas engines and has developed a wide range of LNG-fueled propulsion systems with a power range from 1400 to 9400 kW. Rolls Royce lean-burn gas engines operate at medium speeds and are characterized by high efficiency, low operating costs and improved environmental performance resulting in very low emission levels. In addition, Rolls Royce gas engines have high tolerance for gas quality and reduce noise, lube oil consumption and maintenance costs. Rolls Royce has developed two series of lean-burn gas engines, Bergen B and C. The Bergen B series are engines designed for large ferries and Roll On-Roll Off (Ro-Ro) vessels and provide output power from 3500 to 7700 kW. In addition, the Bergen C series is intended for tugs, small ferries and cargo ships and provides output power from 1460 to 2430 kW. Both engine series are available in mechanical and electric versions.

Dual Fuel (DF) Engines

DF engines are designed to operate on both LNG and liquid fuel such as MDO or HFO [14]. DF engines operate on the lean burn Otto principle in gas mode and according to the normal diesel cycle in diesel mode. DF engines operating in gas mode are fueled with natural gas through a GVU which filters and regulates the pressure of the natural gas. The cylinders of the engine are fed by separate pipes connected to a main double pipe running along the engine. When operating in gas mode, DF engines are charged with a pre-mixed lean air-gas mixture which reduces peak combustion temperatures and NOx emissions as the air-gas mixture contains more air than required. The air-gas mixture is fed into the cylinder during the intake stroke and is ignited by a small amount of diesel injected into the combustion chamber at the end of the compression stroke, as the self-ignition temperature of the air-gas mixture is too high to be achieved by cylinder compression. In four-stroke engines, the air-gas mixture is injected at low pressure (4-5 bar) and is generated outside the cylinder behind the turbocharger. As four-stroke engines are low-pressure engines, natural gas can be supplied directly from LNG fuel tanks under pressure. To ensure minimum NOx emissions, the amount of diesel fuel injected at the end of the compression stroke is very small, usually less than 1% of the total fuel consumption. DF engines utilize micro-pilot injection and an engine speed and load monitoring and control system to optimize combustion.

When DF engines operate in diesel mode, diesel fuel is injected into the combustion chamber at high pressure directly before top dead center. Meanwhile, gas supply is switched off although the micro pilot is activated to ensure reliable pilot ignition when the engine shifts from diesel to gas mode.

DF engines easily switch between modes during operation. Switching from gas to diesel mode takes less than one second and does not affect engine load and speed. In case of LNG supply loss or engine component failure, the transition from gas to diesel mode occurs instantly and automatically. The transition from diesel to gas mode is a gradual process, the supply of diesel fuel is slowly reduced while the amount of natural gas is increased. However, shifting from diesel to gas mode minimally impacts engine load and speed. Although switching between LNG and MDO or vice versa does not require engine modification, switching between LNG and HFO requires minor engine modifications.

MAN is a major DF engine manufacturer although it has developed two-stroke DF engines that slightly differ from four-stroke DF engines. MAN DF engines operate at high pressure, hence they compress air, initiate combustion stroke by injecting fuel oil and inject natural gas into the air-fuel mixture. For this reason, natural gas pressure needs to be high (300 bar) and MAN two-stroke DF engines utilize pumps to boost LNG pressure. MAN DF engines can operate in three different fuel modes: fuel oil only mode, minimum fuel mode and set gas mode. Fuel oil only mode DF engines run on fuel oil only. When operating in minimum fuel mode, DF engines require pilot fuel and natural gas injection into the combustion chamber. The minimum amount of pilot fuel ranges from 5-8% of the total fuel consumption when the engine operates with load from 30% to 100%, and it can use either HFO or MDO as pilot fuel. At engine loads below 30%, stable combustion of natural gas and pilot fuel is not guaranteed. As a result, the engine switches from minimum fuel mode to fuel oil only mode. Finally, set gas mode DF engines allow operators to inject a set amount of natural gas.

In addition, DF engines are mainly represented by two propulsion system schemes: mechanical DF engines and electric DF engines. On the one hand, DF-mechanical engines provide propulsive power to propellers through a gearbox and shaft. On the other hand, electric DF engines supply electric motors with electric power to propel the propellers.

Wärtsilä is a major DF engine manufacturer and has developed a wide range of LNG-fueled propulsion systems with a power range from 0.9 to 18.3 MW. Wärtsilä DF engines operate at speeds ranging from 500 to 1200 rpm and feature fuel flexibility, low exhaust emissions and application flexibility as DF engines can operate either at constant speed as generator sets or at variable speed as mechanical drives. In addition, Wärtsilä DF engines utilize proven and reliable DF technology, an integrated mode switching automation system and provide fuel savings at any engine load. Wärtsilä has developed four DF engine series: Wärtsilä 20DF, Wärtsilä 34DF, Wärtsilä 46DF and Wärtsilä 50DF. The Wärtsilä 20DF is intended for tugs and small cargo vessels and ferries operating as a tug but it is also suitable for a wide range of vessels when operating as a generating set. It provides an output power from 0.9 to 1.6 MW. Secondly, the Wärtsilä 34DF is suitable for a wide range of vessels both as a main engine or generating set. It provides an output power from 2.8 to 8.0 MW. Thirdly, the Wärtsilä 46DF is designed to operate as either a DF-mechanical or DF-electric engine and provides an output power from 6.2 to 18.3 MW. Finally, the Wärtsilä 50DF is intended for large LNG carriers and ferries when operating as the prime mover. It provides an output power from 5.7 to 17.5 MW.

LNG Fuel Tanks and Gas Supply Systems

Due to increasingly stringent air pollution regulations, shipowners started ordering newbuilds and retrofitting their current fleet with LNG-fueled engines as LNG as a marine fuel is considered an available and feasible solution complying with international ship emission restrictions [15]. LNG-fueled engines require a gas fuel supply system and LNG fuel tanks storing the LNG needed to feed them throughout the entire voyage. However, LNG fuel tanks pose some challenges. First of all, LNG fuel tanks require more space compared to HFO storage tanks, in particular they are approximately 2.5 times bigger than HFO tanks. In addition, LNG fuel tanks need to maintain the very low temperature of LNG (-162°C) and minimize boil-off to avoid pressure build-up and as a consequence, they are fitted with insulation measures that also increase tank size.

LNG engine manufacturers have also started developing LNG storage and conveyance systems onboard ships that can supply their engines. Several LNG fuel tank and gas fuel supply system options are available depending on ship size and engine type. According to ship size, large vessels can be fitted with three different tank types although different tank options onboard large vessels require further optimization. On the other hand, small vessels are fitted with Type C vacuum insulated tanks. In addition, gas fuel supply systems differ depending on the working pressure of engines, low pressure engines and high pressure engines. LNG fuel tanks are designed according to the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC code). Moreover, IMO guidelines define the tank types allowed for storing LNG, namely type A, B and C tanks.

On the other hand, small LNG-fueled vessels are fitted with shop fabricated Type C vacuum insulated cryogenic tanks.

The main purpose of gas fuel supply systems is the safe handling of LNG and natural gas onboard ships. This is why the entire LNG supply chain, from shore bunkering stations to engine gas valves, needs to be properly integrated. The design of gas fuel supply systems varies depending on the working pressure of engines. LNG-fueled engine manufacturers have developed two gas fuel supply schemes: one for low pressure engines and another one for high pressure engines. Nevertheless, both gas supply schemes are quite similar in their mode of operation.

On the one hand, gas fuel supply systems for low pressure engines consist of a Pressure Build Up unit (PBU), a product vaporizer, GVU and a control system. Low pressure engines need to be fueled with natural gas at a pressure of 4-5 bar, hence LNG has to be stored at the proper pressure and vaporized. First of all, LNG from shore terminal or LNG bunker vessel is fed through a ship bunker station containing one bunker line, one return line and one nitrogen purging line, all fitted with adequate pressure relief valves. LNG circulates through vacuum insulated lines from the bunker station to the LNG cryogenic fuel tank where it is stored at around 5 bar pressure. Then LNG flows to the PBU whose purpose is to boost storage tank pressure after bunkering and maintain required storage tank pressure. Low pressure engines can achieve maximum power when tank pressure is kept at the required level (5 bar). Furthermore, gas inlet pressure requirements to the engine are met by keeping proper LNG fuel tank pressure since gas fuel supply system is not equipped with cryogenic pumps or compressors. Additionally, LNG flows out of the bottom of the tank into the PBU owing to pressure difference between top and bottom of the tank, then returns to the tank through its top. The natural circulation of LNG between storage tank and PBU ceases once required pressure in tank is achieved. Afterwards LNG is fed to the product vaporizer where it gets converted to natural gas and heated up to at least 0°C depending on engine requirements. Both PBU and product vaporizer utilize engine cooling water system hot water as heat source to boost tank pressure and vaporize LNG accordingly. Finally, natural gas enters the GVU which regulates natural gas pressure according to engine load and ensures safe disconnection of gas fuel supply system. The GVU is located between LNG handling system and LNG-fueled engine and placed inside hull to allow installation in same engine room reducing complexity and installation costs.

On the other hand, gas fuel supply systems for high pressure engines consist of a high pressure LNG pump, pump control system, heat exchanger and buffer tank system. High pressure engines need to be fueled with natural gas at 250-300 bar pressure, hence LNG has to be pressurized and vaporized. The high pressure pump is fed LNG stored in LNG cryogenic fuel tank by means of a pump located in the tank, and is utilized to boost LNG pressure to 200-300 bar and circulate pressurized LNG through a heat exchanger (LNG vaporizer). The heat exchanger utilizes engine cooling water system hot water as heat source to vaporize LNG. Then pressurized natural gas is conveyed to the buffer tank system (natural gas accumulator) where it is stored to feed the engine at a constant natural gas flow rate and pressure.

In essence, the gas fuel supply system stores LNG, converts LNG to natural gas and supplies engines with natural gas under ideal and stable conditions, and it is characterized by enhanced safety and reliability. The main advantages of a compact gas fuel supply system are efficient space utilization, fewer interfaces, reduced capital and operating costs and maximum increase in LNG storage space. Additionally, gas fuel supply system designs offer different configurations allowing installation of several tanks and GVUs depending on ship requirements.

LNG Infrastructure

LNG marine trade constitutes an important segment in global shipping as LNG has been transported as cargo for many years and currently large LNG volumes are transported by LNG carriers [16]. LNG exports from liquefaction and production plants to import terminals supplying local pipeline gas distribution LNG system by LNG carriers is a well-established sector with pricing mechanisms, fixed contract models and proven technology and operations. Additionally, it is regarded as one of the safest segments in the shipping industry. On the other hand, small scale re-export of LNG intended for supplying LNG-fueled vessels from large export or import terminals is not currently a well-oiled sector, although it appears to be an emerging sector owing to recent air pollution regulations reinforcing ship emission limits [17].

Nowadays LNG infrastructure faces two main challenges hindering it from becoming a consolidated market. Firstly, LNG infrastructures require massive investments owing to their high complexity level and necessity to comply with safety standards. The return on investment (ROI) for such infrastructures ranges from years to decades while charter agreements between ship owners and charterers span over a time period of months or in some cases years. As a result, this amortization uncertainty impacts infrastructure development. Secondly, prices for HFO used for conventional bunkering are most updated online while only LNG prices at export and import terminals rather than LNG as marine fuel prices are available online. Due to these reasons a well-established small scale LNG sector will develop once these challenges are overcome.

LNG bunkering facilities refer to all installations required for supplying ships with fuel, in this case LNG, at port and include all elements across LNG value chain. Additionally, key drivers for developing LNG bunkering infrastructure are the following:

- Availability of LNG
- Reliable and safe logistic concepts
- Established legislation and regulatory framework
- Favorable investment climate and tax regime
- Required competencies, know-how and skills
- Public acceptance.

Additionally, LNG bunkering facilities need to ensure safety at all times through: planning, design and operation; safety management; and risk assessments.

Speaking of global LNG infrastructure, five areas can be highlighted: Canada, US, EU, Middle East and Far East. Canada and US are major LNG exporters although they also have a growing demand for LNG as marine fuel. The Middle East is an LNG producer and supplier of LNG as marine fuel. The Far East is a major LNG consumer and could also become an LNG as marine fuel supplier. Finally, the EU is divided into three geographical zones: Northern Europe, Central Europe and Southern Europe. Northern Europe corresponds to European ECA where SOX emissions are limited to 0.1% and hence it is the main driver for LNG as marine fuel usage. In Central Europe, the main driver for LNG as marine fuel usage is reducing NOX emissions from inland navigation vessels. In Southern Europe, LNG bunker capacities could potentially supply vessels sailing the Mediterranean since LNG is available at many import terminals [18, 19].

Examples of using liquefied gas engines demonstrate various applications and advantages within different contexts.

Car/Passenger Ferries

Ferries are designed for transporting passengers and their vehicles, typically on fixed routes across coastal waters such as the Baltic Sea, North Sea, North America and Caribbean Sea United States. Supplying this type of vessels with LNG as marine fuel appears as a feasible option for operational, regulatory and economic reasons (IMO, 2016a). LNG-fueled ferries represent the largest LNG-fueled fleet segment as by March 2016 there were 26 LNG-fueled ferries and 12 LPG-fueled ferries in operation. One of the most popular LNG-fueled ferries is Viking Grace as it is the largest LNG-fueled passenger vessel (Wärtsilä). The Viking Grace is a combined ro-ro and passenger ferry powered by LNG. The ferry was built at STX Turku shipyard (Finland) and was delivered in January 2013. It is operated by Viking Line on a trans-Baltic route between Turku in southwest Finland and Stockholm in Sweden.

Viking Grace is manned by a 200 crew members and has a passenger capacity of 2800 with a total number of 880 cabins. It has a car deck capacity of 1275 lanemeter plus 500 lanemeter on deck 4 and 500 lanemeter on deck 5 for cars. Additionally, the hull was strengthened and hydro-dynamically optimized based on 1A Super ice class to be able to operate in ice waters during Baltic winter.

The vessel is supplied with LNG on a daily basis owing to limited LNG supply at Stockholm port. LNG bunkering operations take place while the vessel is loading or unloading passengers and cargo, and are conducted at sea via an LNG bunker barge, not hindering operational activity. An LNG bunkering takes 45 minutes while loading and unloading takes one hour. Thus, LNG bunkering does not delay vessel schedules. The RoPax ferry operates 21.5 hours a day over 300 days a year (6450 hours a year) [20].

LNG is stored in two vacuum insulated stainless steel fuel tanks of 200 m3 capacity each. The LNGPac system developed by Wärtsilä consists of both the LNG fuel tanks and gas supply system. The LNG storage tanks are located at the stern part of the vessel in an open space above the stern ramp. No cargo space was lost owing to space occupied by tanks.

Platform Supply Vessels (PSV)

PSVs are designed for supplying offshore oil rigs with provisions, household goods and spare parts [21]. Depending on their area of operation, this type of vessels may navigate within an ECA. A significant number of PSVs currently operate in the North Sea and since it is an ECA, they are supplied with LNG as marine fuel (IMO, 2016a). LNG-fueled PSVs represent an important LNG-fueled fleet segment as by March 2016 there were 18 LNG-fueled PSVs and 8 LPG-fueled PSVs. One of the most relevant LNG-fueled PSV currently in operation is Viking Energy as it was the first LNG-fueled PSV.

The Viking Energy is an LNG-fueled platform supply vessel whose hull and superstructure were built at Maritim Shipyard (Poland) then fitted out at Kleven Verft AS Ulsteinvik (Norway). The vessel was delivered in April 2003 and chartered by Statoil for carrying deck cargo to oil and gas platforms in the North Sea. The PSV is homeported in Haugesund (Norway).

Viking Energy's propulsion system is designed based on DF-electric concept. The PSV is fitted with four 6-cylinder Wärtsilä 6L32DF engines with an output power of 2010 kW each (total output power 8040 kW). The four Wärtsilä engines drive four main generator sets feeding two contra-rotating aft thrusters of 3000 kW each (total propulsive power 6000 kW) and other services with electric power.

Additionally, Viking Energy is fitted with two 1000 kW bow thrusters, one 880 kW retractable azimuth thruster and one 116 kW emergency generator. The marine engines develop a service speed of 16 knots at full load condition and this type of power drives minimize noise and vibrations.

LNG is stored in a horizontal cylindrical tank with domed ends made of stainless steel consisting of an inner and outer chamber insulating the LNG at -162°C. The storage tank is located amidships and has an effective fuel capacity of 220 m3. Additionally, the tank is placed in a compartment protected with fire insulation and gas lines and valves enclosed in ventilated enclosures (Wärtsilä, n.d.-c).

LNG Carriers.

LNG carriers are designed for transporting liquefied gases such as natural gas, petroleum gas and ethylene among others [22]. LNG carriers utilize the natural boil-off of LNG stored in their cargo tanks to power their steam turbines. However, new LNG carriers are fitted with DF engines allowing them to operate on both LNG and other marine fuel. LNG-fueled LNG carriers represent a significant LNG-fueled fleet segment as by March 2016 there were 7 LNG-fueled LNG carriers and 12 LPG-fueled LNG carriers in operation. The two most relevant LNG-fueled LNG carriers currently in operation are Coral Energy, which was the first LNG-fueled LNG carrier fitted with DF engines; and Coral Star, which was the first liquefied ethylene gas (LEG) carrier powered by LNG and fitted with DF engines.

The Coral Star is a LEG carrier fitted with DF-mechanical propulsion. The LNG carrier was built by AVIC Dingheng Shipbuilding Co., Ltd. (China) and was delivered in July 2014. The vessel carries LEG from SABIC Wilton plant at Teesside (UK) to manufacturing plants in Northwest Europe and Scandinavia.

Coral Star's propulsion system is designed based on DF-mechanical concept. The LNG carrier is fitted with one 6-cylinder Wärtsilä 6L34DF engine with an output power of 2700 kW at 750 rpm. The main propulsion engine drives a CPP through a gearbox. Additionally, Coral Energy is fitted with a 450 kW bow thruster and two 6-cylinder Wärtsilä 6L20DF generating set engines with an output power of 1056 kW each driving generators. The vessel engine develops an average speed of 13.5 knots. LNG is stored in two deck-mounted fuel tanks with an LNG capacity of 100 m3 each.

Containership.

Containerships are designed for transporting cargo packed into containers and are usually operated in liner trade [6, 23]. This type of vessels has a wide choice of sizes ranging from small feeders to ultra large container carriers and LNG-fueled containership designs have started to grow in LNG-fueled vessel market. Nevertheless, LNG fuel tank size seems to be a major issue for large container carriers due to loss of cargo space resulting from their larger size.

LNG-fueled containerships constitute a potential segment in LNG-fueled fleet as by March 2016 there were 2 LNG-fueled containerships and 13 LPG-fueled containerships in operation. One of the most relevant LNG-fueled containerships is Isla Bella as it was the first LNG-fueled containership.

The Isla Bella is a DF-propelled LNG-fueled containership. The containership was built at General Dynamics NASSCO (USA) along with sister-ship Perla del Caribe and was delivered in October 2015. It is operated by Sea Star Line covering a route from Jacksonville (Florida) to San Juan (Puerto Rico). Both vessels were built to cover this Puerto Rican trade lane and replace company vessels serving this route. Isla Bella has a cargo capacity of 3100 twenty-foot equivalent units (TEUs) and its optimized design allows increased cargo capacity compared to predecessor vessels. Additionally, the containership is able to transport a large volume of refrigerated containers.

Isla Bella's propulsion system is designed based on DF-mechanical concept. The containership is fitted with one 8-cylinder MAN 8L70ME-C8.2-GI engine with an output power of 25,191 kW at 104 rpm driving a propeller through a gearbox. Additionally, Isla Bella is fitted with three 1,740 kW HFJ7 638-10P auxiliary engines each. The vessel engine develops an average speed of 22.0 knots.

LNG is stored in two stainless steel cryogenic tanks with a total capacity of 900 m3 located at the stern part of the vessel. Bunkering is conducted while the vessel carries out cargo operations and takes place from shore through several LNG bunker barges.

After analyzing the main LNG-fueled vessel segments, some important conclusions can be drawn. LNG-fueled ships represent a growing market, driven by strict air pollution regulations; widespread development of LNG-fueled engines, fuel tanks and gas supply systems; and future LNG infrastructure projects. Indeed, significant LNG market growth is expected over the next decade, although external factors like LNG price and availability could impact it. Today, the main segments dominating the LNG-fueled fleet are car/passenger ferries, PSVs, harbor tugs, LNG carriers and containerships. Comparing the dominant LNG-fueled vessel segments highlights the following:

- Regardless of vessel type, LNG-fueled vessels operate in liner trade covering pre-agreed routes and spend most of their time inside ECAs or shuttle between ports located in ECAs.
- Most LNG-fueled vessels (car/passenger ferries, PSVs, LNG carriers and containerships) are fitted with DF engines allowing them to continue operation in case of LNG unavailability.
- Harbor tugs constitute a unique analyzed segment fitted with lean-burn gas engines as they only operate in ports where LNG is available.

- LNG-fueled vessels that shuttle short routes, have variable engine load and frequently port in and out are designed according to DF-electric concept such as car/passenger ferries and PSVs.
- LNG-fueled vessels operating longer routes and constant engine load are designed according to DF-mechanical concept such as LNG carriers and containerships.
- All analyzed LNG-fueled vessel segments are equipped with Type C vacuum insulated tanks, with the exception of LNG carriers as they utilize LNG stored in their cargo tanks.
- Bunkering operations are usually conducted by trucks indicating that currently small LNG volumes are transported to feed LNG-fueled engines.
- LNG bunkering operations take place concurrently with loading/unloading in order not to delay vessel schedule and minimize port stay.

All vessel types are capable of using LNG but certain vessel segments have higher potential depending on several features [23]. After analyzing them, several conclusions regarding LNG-fueled vessel potential can be drawn. Firstly, LNG as a marine fuel is available for both new LNG-fueled vessels and existing vessels although most LNG-fueled vessels are newbuilds since retrofitting existing vessels requires massive investments and implies major modifications in engine room. Secondly, domestic vessels and vessels serving SSS routes spend most of their time inside ECAs so ferries, tugs, PSVs and containerships are more likely to fuel their engines with LNG. Thirdly, vessels operating in areas where LNG infrastructure availability and LNG pricing lower than conventional marine fuel are guaranteed constitute potential LNG consumers to feed their engines. Then vessels sailing a fixed route with LNG bunkering facilities at homeport, ports of call or destination port are totally eligible for LNG supply. Additionally, vessel segments like cruise liners, passenger vessels and PSVs which are constrained to preserve green values or exploit sustainability bonuses require an environmentally friendly solution to minimize emissions such as LNG as marine fuel. Finally, when assessing financial viability of LNG-fueled vessels, equipment costs, operation time inside ECA and LNG pricing are taken into consideration.

Opportunities Ahead:

Engines will continue getting cleaner and more efficient following the progress of automotive and land-based industrial models.

The use of steam turbines, formerly preferred, is no longer popular for new builds owing to system complexity and low efficiency. Even the LNG sector is looking for new engine schemes to eliminate the need for outdated power stations. This leaves the competitive landscape wide open for diesel and gas turbines. No one can accurately determine which method is superior, however gas turbines have more advantages, yet the diesel engine is more reliable, with good maintainability characteristics.

Marine turbines use marine diesel fuel as fuel, and to take a step closer to the future, new fuel resources need to be opted for ensuring a clean and efficient shipping industry. Liquefied gas, CNG and hydrogen resources are candidates for this operation [24]. The shift towards using liquefied gas as a marine fuel will start to gain momentum with the introduction of new environmental regulations and expansion of bunkering capabilities.

Gaseous fuel will become the dominant fuel source for all trading vessels within 40 years The reason for such growth is the stringent emission standards requiring reductions of sulphur oxides (SOX) and nitrogen oxides (NOX). LPG/LNG, in addition, is becoming cheaper.

Conclusions and prospects for further work in this area. The final conclusions made in the paper regarding the use of LNG/LPG as marine fuel are explained as follows:

Maritime transport faces an alarming situation regarding air pollution owing to high ship emission levels provoking global atmospheric warming, environmental degradation, dense air pollution in cities located near major harbors and serious health issues, among others.

Due to the projected increase in global maritime trade driven by world population growth, ship emissions are expected to rise even further highlighting the need to develop a comprehensive regulatory framework significantly curbing ship emissions.

IMO along with other European bodies adopted regulations aimed at cutting ship emissions. These requirements reduced CO2 emissions by around 20-30%, NOX emissions by 80% and SOX and PM emissions by 95-98%.

LNG as marine fuel complies with current air pollution regulations, has been used onboard vessels for decades and is lower priced compared to other marine fuels. However, insufficient availability of LNG bunkering facilities distributed around high shipping activity areas and LNG price uncertainty in the future are major drawbacks for the use of LNG as marine fuel.

Nowadays the use of LNG as marine fuel is a technically feasible solution since manufacturers have designed and developed a wide range of liquefied natural gas fueled engines (lean-burn gas engines and DF engines), Type C vacuum insulated tanks and gas supply systems.

Lack of LNG bunkering installations due to massive investments and LNG not being established in the market yet hinders the use of LNG as shipping fuel in the maritime sector. Nevertheless, adoption of new air pollution regulations has stimulated LNG infrastructure project proposals and planning.

Regulations for gas-fueled ships have been developed to provide clear guidance regarding design and equipment of gas-fueled ships able to mitigate risks to ship, crew and environment.

Car/passenger ferries constitute the dominant LNG-fueled vessel segment followed by PSVs, LNG carriers and harbor tugs. Additionally, containerships represent a potential LNG-fueled vessel segment.

Regardless of LNG-fueled vessel segment, LNG-fueled vessels operate on fixed routes and spend most of their time inside ECAs or navigate between ports located within ECAs.

Most LNG-fueled vessels are fitted with DF engines. Indeed, propulsion systems of vessels with variable engine load engaged in short routes (car/passenger ferries and PSVs) are designed based on DF-electric concept while propulsion systems of vessels with steady engine load deployed on longer routes (LNG carriers and containerships) are designed based on DF-mechanical concept.

LNG-fueled vessel potential relies mainly on features like: newbuilds, operation time inside ECA, operational areas with LNG availability, LNG pricing, liner vessels and green profile. As a result, according to key LNG-fueled vessel segments, car/passenger ferries navigating the North and Baltic Seas have high potential for LNG utilization as marine fuel since their features match those mentioned above.

Current air pollution regulations greatly minimize NOX, SOX and PM emissions from vessels even though CO2 emissions are not sufficiently reduced and still constitute an environmental issue needing to be addressed. Policy makers need to tackle this problem rigorously and introduce stringent mitigation measures.

IMO along with MEPC will introduce measures aimed at enhancing ship energy efficiency and reducing greenhouse gas emissions although these are not stringent mitigation measures. The overall objective of these requirements is gathering and sharing reliable information on how to address ship energy efficiency and GHG emissions issue.

State-of-the-art emission reduction technologies for improving ship energy efficiency and decreasing greenhouse gas emissions do not totally diminish CO2 emissions, they just provide minor enhancements for different ship areas and components resulting in slight advantages regarding ship environmental performance. Only when a combination of technical improvements is implemented across various ship parts can some CO2 emissions reduction be attained.

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Тенденції та передумови для широкого поширення використання рідкого природного газу у морському транспорті

Потреба в стійкому та екологічно чистому морському транспорті та введення регулятив Міжнародної морської організації (ММО) з викидів суден привели до пошуку нового типу морського палива. Сьогодні рідкий природний газ (РПГ) як морське паливо є привабливою, потенційно важливою та технічно можливою опцією для нових суден, які будуються для відповідності нормам забруднення повітря. Метою роботи було проаналізувати перспективи використання РПГ як морського палива. Задачу вдалося виконати за допомогою вивчення поточного стану перевезення РПГ, аналізу переваг та недоліків різних видів палива та вивчення домінуючих сегментів суден на РПГ. Впровадження РПГ на борту суден відбувається разом із розвитком РПГ-двигунів, їх систем управління та захисту, паливних баків, систем постачання газу та інфраструктури. Прогнозується, що протягом наступного десятиліття кількість суден, які працюють на РПГ, буде швидко зростати. Об'єктом дослідження є перспективи використання РПГ як альтернативного типу палива у судноплавстві. Найважливішим результатом є висновок, що РПГ має значний потенціал як альтернатива традиційним видам палива у судноплавстві, але для цього потрібен розвиток відповідної інфраструктури.

***Ключові слова**: LNG, морське паливо, викиди, екологічна безпека, альтернативне паливо, двигуни.*

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Testing of the device for transporting semi-trailers without tractor on 13-9004M model platforms

For the implementation of a mixed type of transportation on the territory of Ukraine, a stable saddle for transporting cargo semi-trailers without a tractor on railway platforms of the 13-9004M model was developed and manufactured. This device for the transportation of cargo semi-trailers is a four-sided structure of the "Eiffel Tower" type, the lower plane of which is fixed on the platform car through the plate with the help of bolted connections. This work describes the running tests of the 13-9004M model platform car with a saddle rack installed on it for the transportation of cargo semi-trailers without a tractor. According to the results of the tests of the saddle rack for the transportation of semi-trailers on the platform wagon model 13-9004M, the maximum values of the stresses that occur in the structure of the saddle rack during running strength tests, as well as compliance with such indicators as the coefficient of vertical dynamics of the sprung mass of the cart, the coefficient of vertical dynamics of the unsprung mass, were determined trolley frame, coefficient of horizontal dynamics, coefficient of reserve of stability of the wheel from derailment.

Keywords: *railway transport, wagon, tests, transportation of semi-trailers.*

Introduction. In order to evaluate quality indicators, the safety of the movement of wagons and other types of rails rolling stock, a variety of approaches to the assessment of safety conditions and the solution of the specified problem are noted.

In the study guide [1], the basics of theoretical and experimental methods of determining the dynamics of cars are laid out, information is given on the safety conditions of train movement based on dynamic indicators.

Standards DSTU 7598 (2014) [2] will describe requirements for calculations, design of new and modernized wagons of gauge 1520 mm, and requirements for their strength and dynamic qualities. Standards DSTU GOST 33211 (2017) [3] describes requirements for the strength and dynamic qualities of freight cars.

The coverage of the results of work on determining ways to increase the degree of ideality of freight cars and forecasting the evolution of the chassis of new-generation cars is described in the work [4]. Work [5] describes the principle of cataloguing the construction of the wagon according to its design and construction. In article [6] features of the mathematical modelling of the dynamic load of containers placed on the platform during a shunting collision are given. Numerical values of accelerations acting on the container are determined. The results are confirmed by computer simulation. The article [7] gives promising directions for constructing half-car frames and their features, which can be applied to other types of freight cars. The methods [8] for determining the locomotive wheel-rail angle of attack are considered. To reduce the power impact of the wheel flange with the rail head when the locomotive moves on curved sections of the track, it is advisable to change the locomotive wheel-rail angle of attack by turning the wheel pairs. Controlling the locomotive wheel pair position is possible by means of an operational measurement of the actual wheel-rail angle of attack. Measurement of the wheel-rail angle of attack is not performed because it is impossible to determine the value directly. In the [9] describes the method of determining the technological stresses that arise in the structure being repaired during the hardening of the composite patch. A special wagon for intermodal transportation is presented in the article [10], which can transport cars with a weight of up to 36 tons and a height of up to 4 m. These developments can be used in the design of new wagons for intermodal transportation. Identification of the causes of cracks in the frames of wagons for transporting containers and evaluation of the fatigue strength of welded joints is described [11]. In work [12] described the design of the car for various loading conditions, taking into account the actual condition of the track. The article [13] discusses the study of the elastic system dynamics for spindle assembly of drilling-milling-boring machining center type. A three-dimensional model of the spindle assembly on rolling bearings is built. A constructive and design diagram of the spindle assembly and a system of forces acting in the process of milling workpieces are formed. Work [14] is devoted to the development of electrohydraulic drives of technological equipment. The engineering method of calculating the automatic electro-hydraulic drive of rotary motion with volume regulation is presented. This method allows you to estimate the main parameters and select drive elements and devices based on the maximum load moment and rotation speed of the hydraulic motor, predict its static and dynamic characteristics. Analysis of wagon body strength calculations and real tests of the series wagon Sdggmrss-twin given in work [15].

Purpose and objectives of the study. The purpose of the research is to carry out tests of the saddle rack for the transportation of semi-trailers without a tractor on platform wagons of the 13-9004M model for further safe operation.

Materials and methods of research. For the introduction of a mixed type of transportation on the territory of Ukraine, a device for transporting semi-trailers on railway platforms of the 13-9004M model was developed and manufactured, and a set of tests aimed at evaluating the dynamics of the car and the strength of the device for transporting cargo semi-trailers was conducted. The device for the transportation of cargo semi-trailers is a four-sided construction of the "Eiffel Tower" type, the lower plane of which is fixed on the platform car through the plate with the help of bolted connections. A saddle with a lock is installed on the upper plane of the device to fix the semi-trailer against longitudinal and transverse movements. This design makes it possible to obtain optimal strength properties and uniform distribution of weight transmitted from the semi-trailer seat. If necessary, such a structure can be flexibly folded for the transportation of containers on platform wagons of the 13-9004M model. The wheels of the cargo semi-trailer have 2 fixing options:

1) supports that are installed in the corresponding grooves;

2) special platforms installed under the wheels and stretched by cables attached to the external brackets of the 13-9004M platform car.

From the lateral displacement of the rear part of the semi-trailer, the design of the platform car model 13-9004m provides for the lowering of the floor with the formation of the corresponding side walls due to the external longitudinal beams of the car.

The test facility, consisting of a 13-9004M platform car with a device for transporting semi-trailers and a loaded semi-trailer installed on it, is shown on Fig. 1.

In accordance with the test program according to the layout of tensor resistors shown in Fig. 2 and 3, strain gauges were installed on the elements of the device for transporting semi-trailers on the platform wagon and on the carriage of the platform wagon model 13-9004M and their connection into a Wheatstone half-bridge circuit with one active and compensating strain gauge. Such a scheme provides a measuring channel, which is supplemented by a strain gauge module NI 9237, which performs scaling of instantaneous values of the input voltage and analog-digital conversion into a digital signal. After connecting and checking the performance of the measuring equipment, stress measurements were made in the elements of the device for transporting semi-trailers on the 13-9004M platform car during experimental trips in a loaded state at speeds up to 90 km/h to evaluate the strength indicators and natural frequencies of oscillations.

Fig.1. **Platform car model 13-9004M with a device installed on it for transporting semi-trailers and loaded semi-trailers**

Processing of the test results was performed on a computer using specialized mathematical software for statistical processing of the primary results obtained during the experimental trip. The measuring complex for diagnostics and testing of rolling stock consists of a software-hardware automatic recorder, a set of communication cables, a computer and software. The automatic hardware and software recorder based on the NI 9012 controller consists of the NI 9237 ADC strain gauge modules, the NI 9205 ADC modules and the GPS module.

In order to evaluate the running qualities based on the values of the measured dynamic indicators of the car, the probable maximum values of the coefficients of vertical dynamics of the sprung K_{do} and non-sprung K_{dn} masses of the car, lateral (frame) forces, and the value of the coefficients of the reserve of stability from falling off the K_{yc} rails are determined using ratios taking into account the calibration data.

The maximum values of the coefficients of vertical dynamics and frame forces are determined with a confidence probability of 0.97 (according to the amplitude value) and 0.97 (according to the instantaneous values), and the minimum values of the coefficients of the stability margin against derailment, with a confidence probability of no more than 0.0001. The sum of the frame forces acting at the same instant of time on the frame from each axle of one wheel pair is taken as the value of the lateral (frame) force of the H_p.

The calculation of the coefficient of stability of the wagon against derailment when the wheel ridge creeps onto the rail under the action of dynamic forces arising during movement, the coefficients of vertical dynamics of the sprung and unsprung masses of the wagon are given below. The coefficient of vertical dynamics K_d is generally determined from the following expression:

$$К_{d} = \frac{\sigma_{d}}{\sigma_{ct}}, \quad (1)$$

where σ_d - is the dynamic stress from the vertical load in the section of this element; σд;
σ_{ct} - static load from vertical load in the same section.

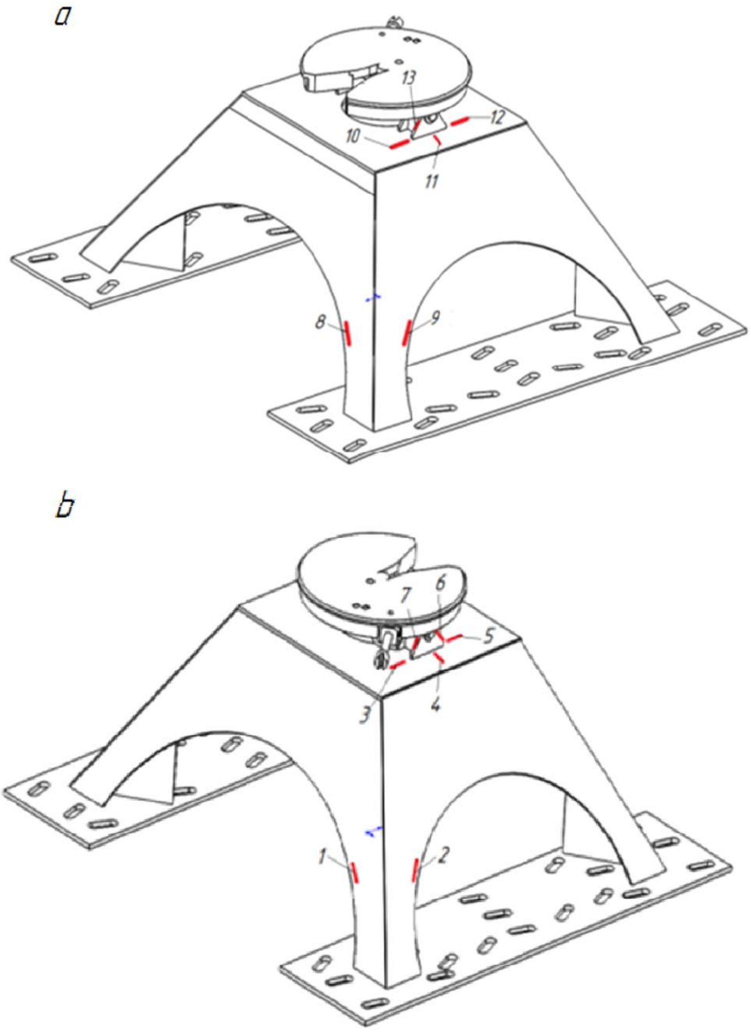

Fig. 2. **Locations of strain gauges on the device for transporting semi-trailers on a platform wagon(a) front view; (b) back view**.

The coefficient of horizontal dynamics (frame force in portions of the axial load) – $К_{dg}$ is determined by the formula:

$$К_{dg} = \frac{H_r}{P_o}, \quad (2)$$

where Hr – horizontal lateral frame force;
P_o - vertical static load from the axle to the rails.

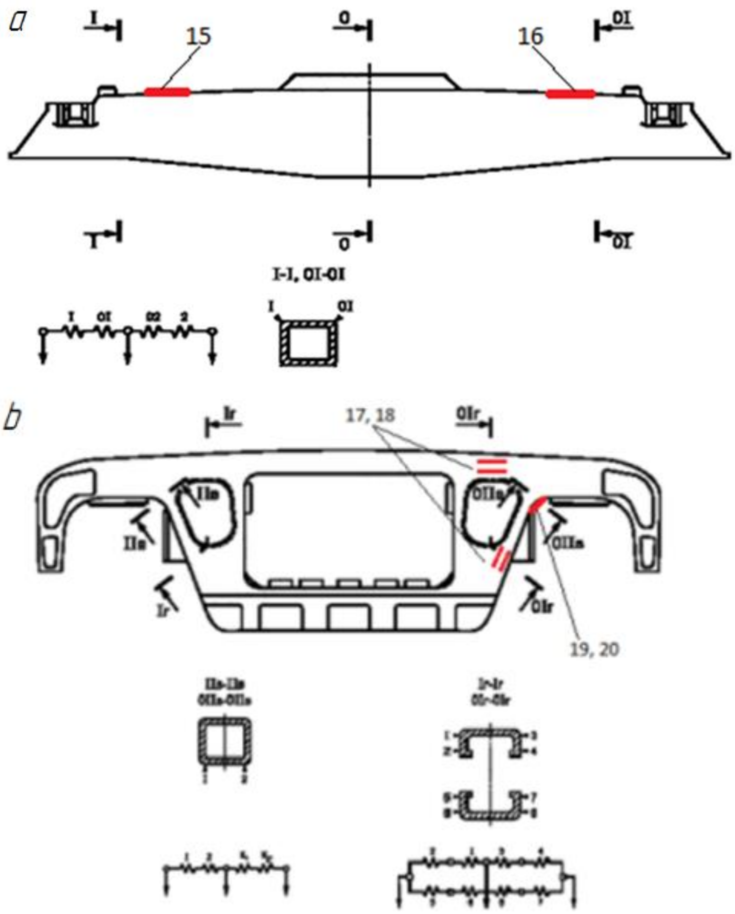

Fig. 3. **Location of strain gauges (a) on cart beam; (b) on cart frame**

The coefficient of stability of the wheel from derailment is determined by calculation based on the integral coefficient calculated for the range of operating speeds with a probability of 0.001. The stability of the wheel against derailment was evaluated using the following formulas:

$$К_{yc} = \mathcal{E}\frac{P_v}{P_b} \geq [К_{yc}] \,, \tag{3}$$

$$\mathcal{E} = \frac{tg\beta - \mu}{1 + \mu tg\beta}, \tag{4}$$

where β - angle of inclination of the generating ridge of the wheel to the horizontal axis;
$\beta = 60°$;
μ - coefficient of friction, = 0.25;
R_v - the vertical component of the reaction force of the running wheel on the head of the rail;
R_b - the horizontal component of the reaction force of the running wheel on the head of the rail, which acts simultaneously with P_v;
$[К_{yc}]$ - is the permissible value of the stability margin coefficient.

When using type 2 wheelbarrows, the formula looks like this:

$$К_{yc} = \frac{tg\beta - \mu}{1 + \mu tg\beta} * \frac{Q_{sh}\left(1{,}03 - 1{,}17К_d^h + К_d^{hh}\right) + 0{,}15q_{kp} + 0{,}305Н_p}{Q_{sh}\left(0{,}242 + 0{,}042К_d^{hh} - 0{,}285К_d^{hh}\right) + 0{,}121q_{kp} + 0{,}92Н_p}, \quad (5)$$

where $К_d^h$ - coefficient of vertical dynamics on the running wheel;
$К_d^{hh}$ - coefficient of vertical dynamics on a non-running wheel;
$Н_p$ - horizontal lateral frame force;
Q_{sh} - the force of gravity of the over-spring parts of the car, acting on the neck of the axle of the wheel pair, kN, is determined by the formula:

$$Q_{sh} = \frac{Q - nq_{kp}}{2n_o}, \quad (6)$$

where Q - weight of the wagon, kN,
q_{kp} - the force of gravity of unreinforced parts, which falls on the wheel pair, kN;
n_o - the number of wagon axles;

The value of $Н_r$ is accepted as positive in the case of directing it in the direction of the wheel run-up, and - in the case of unloading the wheels.

The results of running strength testssaddle racks for transporting semi-trailers on platform wagons 13-9004M with an installed semi-trailergiven in Table1 and 2.Figs 4 and 5 show the histograms of the speed ranges during the experimental trip on the section of Art. Darnytsia - art. Nizhin - st. GiftAccording to the registered data of dynamic processes, the indicators of the running dynamic qualities of the car with a stable saddle with an installed semi-trailer in the loaded state were calculated. The results are given in Table 3 and 4.

Table 1. **Maximum stresseson the Darnytsia - Nizhyn section**

Strain gauge	Speed ranges km/h															
	10-20		20-30		30-40		40-50		50-60		60-70		70-80		80-90	
	MAKC MPa	SKO	MAX MPa	SKO	MAX MPa	SKO	MAX MPa	SKO	MAX MPa	SKO	MAX MPa	SKO	MAX MPa	SKO	MAX MPa	SKO
1	7.22	1.06	4.43	0.97	3.51	0.98	5.28	1.40	6.94	2.13	8.02	2.14	8.91	2.20	7.34	2.12
2	19.92	3.26	12.51	3.23	10,15	2.70	14.71	4.08	15.61	4.80	18.81	5.51	21.34	5.50	17.85	5.54
3	4.31	0.66	3.44	0.88	2.47	0.71	4.19	1.15	4.26	1.28	5.58	1.48	7.38	1.41	4.80	1.31
4	8.37	1.66	4.72	1.42	6:00 a.m	1.89	7.21	2.16	9.37	3.21	11,24	3.50	15.25	3.96	12.91	3.85
5	2.15	0.40	1.59	0.49	1.23	0.39	2.09	0.53	2.31	0.66	3.12	0.86	4.76	0.99	3.70	0.98
6	2.03	0.47	1.64	0.46	1.48	0.38	1.88	0.53	2.61	0.72	3.56	0.92	7.45	1.20	4.60	1.21
7	3.10	0.80	3.51	1.21	2.99	0.94	4.80	1.64	5.73	1.90	6.51	2.10	8.73	2.13	6.80	2.25
8	8.75	1.66	5.87	1.68	5.06	1.61	7.85	2.23	8.87	2.78	10,15	2.96	10.97	2.93	9.17	2.89
9	6.34	1.93	5.88	1.86	5.45	1.74	8,11	2.66	9.97	3.27	11.75	3.80	14,28	4.17	13.31	4.22
10	2.37	0.65	2.14	0.78	1.93	0.57	2.61	0.76	3.19	0.96	4.29	1.29	7.32	1.71	5.56	1.67
11	12.70 p.m	3.22	13.38	5.04	10.60	3.43	17.93	5.47	19.42	5.80	24,14	7.40	28,42	9,14	26.79	8.86
12	3.95	1.11	4.97	1.67	4.39	1.42	6.95	2.43	8.42	2.86	8.93	2.98	10.91	2.78	8.57	2.64
13	11.33	1.68	8.32	1.78	6.21	1.31	7.52	1.79	8,13	2.07	11.08	2.83	26.61	3.93	11,10	3.41

Table 2. **Maximum stresses on theNizhyn - Darnytsia section**

Strain gauge	Speed ranges km/h													
	10-20		20-30		30-40		40-50		50-60		60-70		70-80	
	MAKC MPa	SKO	MAX MPa	SKO	MAX MPa	SKO	MAX MPa	SKO	MAX MPa	SKO	MAX MPa	SKO	MAX MPa	SKO
1	2.68	0.67	3.72	1.09	3.10	0.99	3.74	1.22	4.99	1.57	5.99	1.70	6.08	1.85
2	6.90	2.15	11,12	3.42	9,13	2.88	10.92	3.74	12.67	4.21	12.79	4.12	17.96	5.74
3	1.40	0.45	2.91	0.94	2.46	0.76	3.21	0.96	3.73	1.18	5.00	1.15	3.55	1.12
4	5.50	1.35	6.28	1.46	6.71	1.73	7.61	2.17	8.57	2.72	10.52	3.40	11.41	3.75
5	1.01	0.31	1.45	0.43	1.31	0.40	1.65	0.50	2.63	0.77	2.99	0.87	3.61	0.99
6	1.30	0.42	2.16	0.57	1.97	0.50	3.10	0.65	3.05	0.82	3.70	0.99	5.31	1.42
7	2.40	0.69	4.26	1.40	3.31	1.08	4.29	1.37	5.40	1.74	5.45	1.67	6.66	2.19
8	4.49	1.21	6.02	1.71	5.09	1.48	6.59	2.17	7.22	2.27	7.23	2.30	8.02	2.41
9	5.30	1.68	7.51	2.22	6.37	1.89	8,17	2.69	10,13	3.23	10.98	3.47	14,22	5.01
10	1.68	0.56	2.10	0.63	1.79	0.53	2.64	0.80	3.73	1.14	4.20	1.31	5.22	1.72
11	9.38	2.54	12.90	4.00	9.94	3.05	15.39	4.61	20.89	6.44	21.61	7.09	25.49	8.28
12	3.07	0.95	5.66	1.86	4.72	1.52	6.23	2.11	6.98	2.40	6.66	2.23	7.78	2.41
13	5.49	1.32	12.49	2.68	13.54	1.86	18.48	2.73	9.53	2.44	13,24	2.79	11.05	3.60

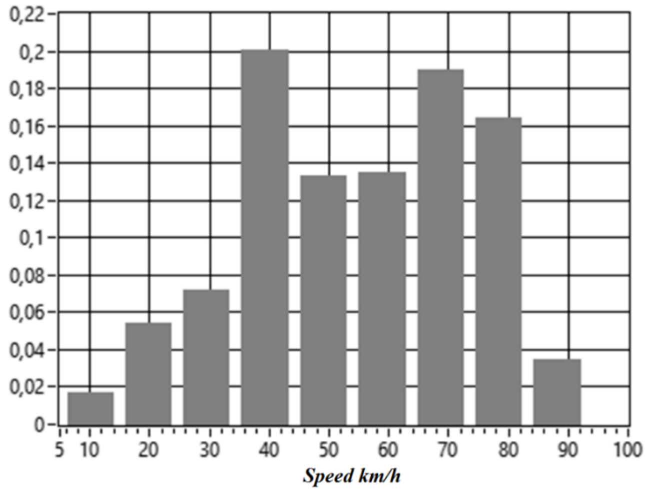

Fig. 4. **Histogram of speedon the Darnytsia - Nizhyn section**

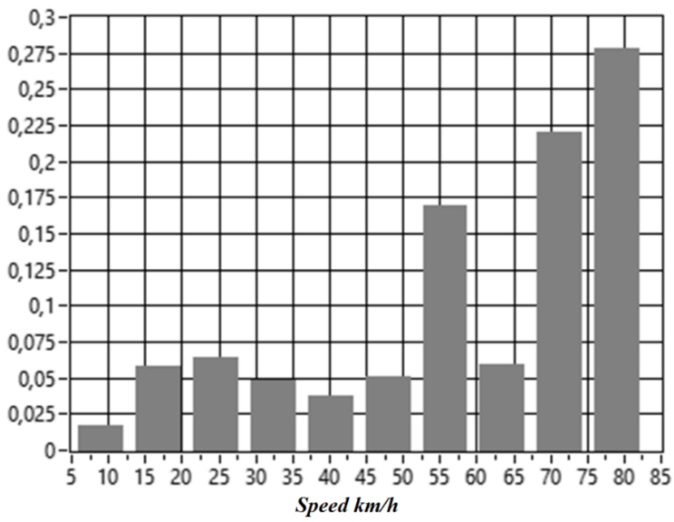

Fig. 5. **Histogram of speedon the Nizhyn - Darnytsia section**

Table 3. **Results of running dynamic testsplatform car 13-9004Mfromdevicefor transportation of semi-trailers on a platform wagonand an installed semi-trailer in a loaded state on the Darnytsia - Nizhyn section**

Monitored characteristics	Normative value	The value of the indicator at a speed of km/h							Unrecognized honesty, %
		20	30	40	50	60	70	80	
The coefficient of stability margin of the wheel from derailment on straight and curved sections of the track	At least 1.3	1.9	1.85	1.75	1.67	1.62	1.48	1.46	2.1
Frame forces Nr, t	-	0.38	0.47	0.5	0.69	0.9	1.1	1.3	2.1
Coefficient of horizontal dynamics (frame force in parts P0 (Hp/P0), from the wheel pair to the trolley frame)	Not more than 0.4	0.07	0.09	0.1	0.13	0.18	0.22	0.26	2.1
Coefficient of vertical dynamics of the suspended mass of the cart, Kd,	Not more than 0.75	0.16	0.19	0.2	0.22	0.25	0.28	0.3	2.1
Coefficient of vertical dynamics of the unreinforced trolley frame, Kdn	Not more than 0.90	0.24	0.26	0.29	0.32	0.37	0.43	0.46	2.1

Table 4. **Results of running dynamic testsplatform car 13-9004Mfromdevicefor transportation of semi-trailers on a platform wagonand an installed semi-trailer in a loaded state at the Nizhyn - Darnytsia section**

Monitored characteristics	Normative value	The value of the indicator at a speed of km/h							Unrecognized honesty, %
		20	30	40	50	60	70	80	
The coefficient of stability margin of the wheel from derailment on straight and curved sections of the track	At least 1.3	1.92	1.83	1.78	1.65	1.6	1.49	1.47	2.1
Frame forces Nr, t	-	0.39	0.45	0.52	0.72	0.95	1.2	1.32	2.1
Coefficient of horizontal dynamics (frame force in parts P0 (Hp/P0), from the wheel pair to the trolley frame)	Not more than 0.4	0.07	0.09	0.1	0.14	0.19	0.24	0.26	2.1
Coefficient of vertical dynamics of the suspended mass of the cart, Kd,	Not more than 0.75	0.18	0.20	0.23	0.24	0.27	0.31	0.32	2.1
Coefficient of vertical dynamics of the unreinforced trolley frame, Kdn	Not more than 0.90	0.26	0.27	0.31	0.34	0.38	0.46	0.48	2.1

Conclusions. According to the results of the tests of the saddle rack for the transportation of semi-trailers on the platform wagon model 13-9004M, it was established:

1. During running strength tests, the maximum stress values:
   - on the siteArt. Darnytsia - art. Nizhin – 28.42 MPa, channel 11 speed range 70-80 km/h;
   - on the siteArt. Nizhin - st. Darnytsia – 25.49 MPa, channel 11 speed range 70-80 km/h.
2. Platform wagon model 13-9004M withsemi-trailer rack for cargo semi-trailers without a tractor with an installed semi-trailer in a loaded state meets the requirements [2] according to the following parameters: the coefficient of vertical dynamics of the sprung mass of the trolley, the coefficient of vertical dynamics of the unsprung trolley frame, the coefficient of horizontal dynamics, the coefficient of the reserve of stability of the wheel from derailment in the range of speeds up to and including 80 km/h.

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Випробування пристрою для перевезення напівпричепів без тягача на платформах моделі 13-9004М

Для впровадження змішаного виду перевезень на території України розроблено та виготовлено стійку сыдельну для транспортування вантажних напівпричепів без тягача на залізничних платформах моделі 13-9004М. Даний пристрій для перевезення вантажних напівпричепів являє собою чотиригранну конструкцію типу «Ейфелева вежа», нижня площина якої закріплена на вагоні-платформі через плиту за допомогою болтових з'єднань. В даній роботі описано проведення ходових випробувань вагона-платформи моделі 13-9004М з встановленій на ній стійко сідельної для перевезення вантажних напівпричепів без тягача. За результатми випробувань стійки сідельної для перевезення напівпричепів на вагоні-платформі моделі 13-9004М встановлено максимальні значення напружень, що виникають в конструкції стійки сідельної під час ходових міцнісних випробувань, а також відповідність таким *показникам як коефіцієнт вертикальної динаміки обресореної маси візка, коефіцієнт вертикальної динаміки необресореної рами візка, коефіцієнт горизонтальної динаміки, коефіцієнт запасу стійкості колеса від сходу з рейок.*

Ключові слова: *залізничний транспорт, вагон, випробування, перевезення напівпричепів.*

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Ways of improving of freight car design

The article presents the dynamics of freight cars production by domestic enterprises by years. The necessity of renewal of the domestic operating fleet of freight cars.The following main vectors of design improvement have been identified based on the results of putting new and modified freight car models into production: use of high-strength steels in load-bearing structural elements and innovative components; improving existing and creating fundamentally new bearing structures; the most efficient use of space; development of freight cars with an axle load of 25 tonnes; creation of multifunctional structures; increasing the structural strength of long-base flat cars; application of the latest assembly and welding technologies. The following main vectors for improving the design of cars have been identified based on the results of a analysis of scientific and applied research, in addition to the above: the use of new materials; development of six-axle articulated wagons with an axle load of 23.5 tonnes and 25 tonnes; development of railcars using new generation bogies and components; achieving a uniform load on the supporting structure; design of flat cars for transporting containers in two tiers; development of new cars for intermodal, interoperable and combined transport.

Keywords: *freight car, design, fleet, rolling stock, improvement.*

Introduction and problem statement. In recent years, the dynamics of freight car production has been on a downward trend [1]. The dynamics of freight car production in recent years is shown in Fig. 1.

Over the past few years, the number of freight rolling stock manufacturers has declined significantly. The armed aggression of the russian federation was the main reason for the destruction of enterprises, insufficient supply of metal and castings, the need to import certain components of freight cars, and the destruction of logistics routes that had been developed over the years. The main reasons for the decline in freight car production in recent years are the following: the purchase of expired freight cars from the Customs Union; lack of a comprehensive programme to renew the domestic freight car fleet, decrease in demand for rail freight transportation due to various reasons (competition from other modes of transport, economic downturn, COVID-19, armed aggression of the russian federation, etc.), lack of incentives to purchase innovative freight rolling stock [1-3].

All of this demonstrates the need and urgency to support the freight car building industry at the state level to prevent its complete destruction. Therefore, in the context of significant depreciation of the freight rolling stock fleet, a catastrophic drop in freight car production, and martial law in the country, it is of paramount importance that the government supports the freight car industry by adopting appropriate legislative initiatives. One of such effective measures and support mechanisms from the central executive body that ensures and implements state policy in the field of transport may be to stimulate the purchase of modern innovative freight cars with improved technical characteristics.

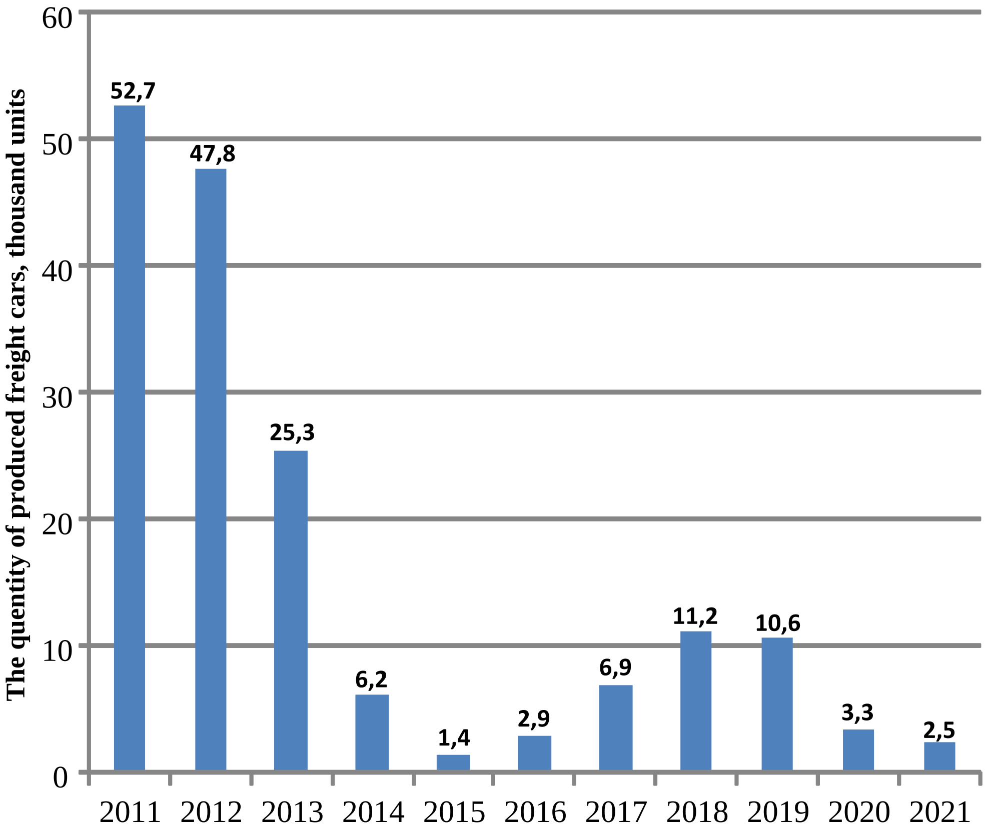

Fig. 1. **Freight car production dynamics by years [1]**

Analysis of recent research. The first steps in this direction were taken in 2015-2021. Thus, in 2015, the Technical Council of Ukrzaliznytsia adopted technical requirements for innovative freight rolling stock [4]. In July 2020, the Resolution of the Cabinet of Ministers of Ukraine No. 1147 dated 30.12.2015 "On the Prohibition of Importation of Goods Originating from the Russian Federation into the Customs Territory of Ukraine" [5] was amended to prohibit the importation into the customs territory of Ukraine of railway cars that are or have been in use among the railway administrations of the Russian Federation since 20.02.2014. In December 2021, the Ministry of Infrastructure approved the concept of renewing the freight car fleet by registering this order with the Ministry of Justice of Ukraine [6]. However, the proposed concept from the Ministry of Infrastructure has a number of problematic issues in its implementation, which are discussed in detail in the publication [1]. The main problematic issues are the uncertainty of the sources of funding for this renewal concept and the lack of incentives for the purchase of innovative freight cars from the state.

At the same time, taken into account the challenges of today, the issue of further development of the freight car fleet in the country remains open and relevant. One of the components of the effective implementation of innovative freight rolling stock is the compliance of its technical characteristics with modern requirements. Therefore, updating the technical requirements for the development of innovative freight rolling stock is an important and urgent task. A prerequisite for updating and formulating technical requirements should be a review and analysis of ways to improve the design of freight cars during 2015-2022. This paper proposes to focus on this issue in detail.

The goal is to identify the main areas for improving the design of freight cars by reviewing and analysing technical documentation for freight cars, research and development works, research and development studies, and recent titles of protection.

Research material and results. It is proposed to determine the main directions for improving the design of freight cars by reviewing and analysing the technical documentation for freight cars, research papers, numerous existing studies of a scientific and applied nature, and titles of protection published and approved recently [7-75].

The technical documentation and research works on new models of freight cars produced by domestic enterprises [7-12], which were put into production during the recent period, were reviewed and analysed firstly. The exterior of some cars with the improved innovative design that have recently been put into production is shown in Figs. 2-5.

Fig. 2. **Freight cars of models 15-776Э, 19-7126, 19-7053-04, 13-7132, 13-7138, 11-7139, 15-7140, 33-7141, 19-7154 produced by PJSC "KRCBW"**

Based on the results of the analysis of technical documentation for new and modified models of freight cars that have been put into production by domestic enterprises recently, as well as research and development work, the following main vectors of design improvement have been identified:

– the use of high-strength steels in structural load-bearing elements and innovative component parts, which allows for a longer life cycle and increased overhaul interval of railcars;

– strengthening, improving of existing cars and creating fundamentally new types of freight car load-bearing structures;

– maximum efficient use of dimensions, including inter-car space;

– development of a freight cars range with an axle load of 25 tonnes;

– development of multifunctional freight car designs capable of transporting a wide range of goods;

– increasing the structural strength of long-base flat cars;

– application of the latest assembly and welding technologies.

Fig. 3. **Freight cars of models 31-4154, 19-4146-01, 19-4152, 12-4106-01, 13-4147, 33-4099 produced by LLC "Dniprovagonmash"**

Fig. 4. **Freight cars of models 19-6869, 19-9951, 13-9589, 11-9983, 32-8525, 19-8530, 12-8520, 19-1883, 17-1890 produced by LLC "RMF "Karpaty"**

Fig. 5. **Freight cars of models 13-6961, 19-6938 produced by "Panyutyn Carriage Repair Plant" branch of JSC "Ukrzaliznytsia" and model 12-6708-02 produced by LLC "Zhmerynka Railway Repair Plant "Express"**

It should also be noted that domestic railcar manufacturers are currently actively developing the production of freight cars for use on a 1435 mm gauge. Thus, PJSC "KRCBW" received certificates for specialised articulated flat cars of the Sggrss 80 and Sggmrss 90' types for compliance with European standards. The general view of the articulated flat cars manufactured by PJSC "KRCBW" is shown in Fig. 6.

a) b)

Fig. 6. **General view of articulated flat cars type Sggrss 80 (a) and Sggmrss 90' (b) produced by PJSC "KRCBW"**

Numerous scientific and applied studies have been reviewed and analysed [13-28]. In their publications, based on the studies of freight car structures loaded, the authors propose to improve both their single components and the metal structures of freight cars as a whole, in order to increase their strength, service life and maintenance intervals. In these studies, it was proposed to improve the technical characteristics of freight cars by using higher steel classes and new materials with improved mechanical properties, a different design of components and parts, and achieving uniform load on the bearing structure. To increase the strength of the load-bearing structure of freight cars, the use of fillers in their load-bearing structures, in particular in the girders, was proposed in the publications [29-31]. Some of the promising load-bearing metal structures of freight cars proposed in these studies are shown in Fig. 7.

Studies [32-37] are devoted to the modernization and other design of coupling devices and mechanisms of undercar braking equipment of freight cars. Also, a sufficient number of works [38-47] are devoted to the improvement of freight car bogies and their components. In the vast majority of these studies, the possibility of using welded bogies as part of freight cars is considered. A lot of work has also been done to study the functioning of improved or new components of the freight car bogie, such as side frames, wheel sets, spring suspension elements, etc. Some of the improved designs of freight car side frames and bogies are shown in Fig. 8.

Particular attention should be paid to the works of domestic and foreign researchers [48-55], which propose to create multifunctional freight cars, platform cars for the transportation of containers in two tiers, as well as to develop new types of cars for intermodal, interoperable, combined transportation.

Multifunctional freight cars are capable of transporting a wide range of goods, their design is versatile and allows them to be used as a boxcar, gondola car, platform car, etc. The introduction of multifunctional railcars will significantly reduce the empty mileage rate during operation and increase the technical and economic effect of their use. The introduction of platform wagons for transporting containers in two tiers, as well as new types of wagons for intermodal, interoperable and combined transport, will generally increase the efficiency of freight transport by improving logistics and the speed of cargo delivery.

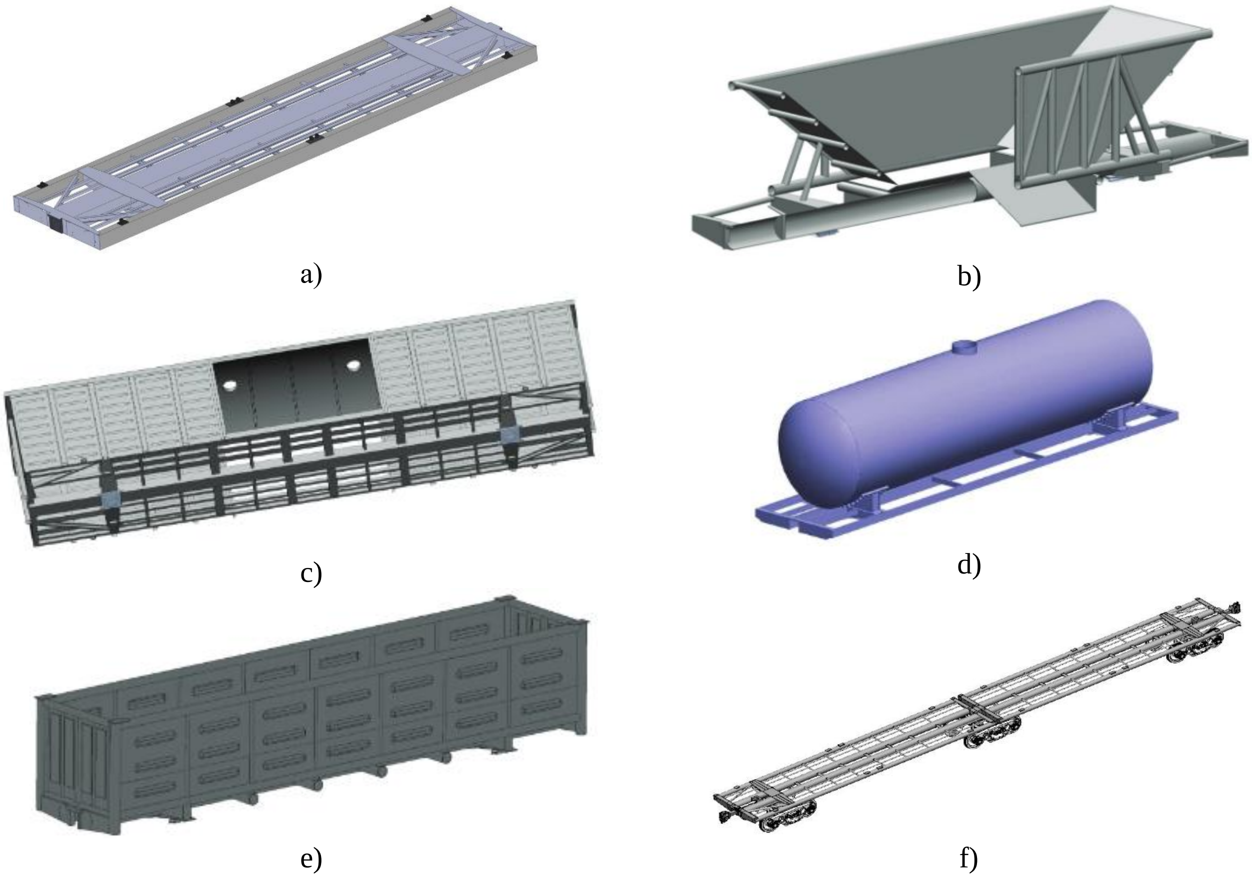

Fig. 7. **Spatial models of load-bearing structures: a) fitting flat car[29]; b) hopper car [14]; c) boxcar [31]; d) tank car [30]; e) open-top car [18]; f) articulated flat car[13, 30]**

Papers [56-60] are devoted to research in the direction of increasing the axle load on the railway track, which will increase the carrying capacity of freight cars, increase the volume of cargo transportation, and reduce the number of operating freight cars. Fig. 9 shows the models of universal gondola cars of Ukrainian manufacturers with a load capacity of 25 tf/axle, which have passed the production procedure and can be mass-produced. The manufacturer of gondola car model 12-9791 on bogies model 18-9817 is “Diesel Plan” OJSC (now Aurum Group); model 12-7039 on bogies model 18-7033 is PJSC “KRCBW”; model 12-1905 on bogies model 18-1711 is PJSC “Azovmash”.

Publications [61-63] are aimed at conducting and highlighting the results of scientific and experimental studies of newly developed models of freight cars with the purpose to putting them into production. Some of the existing studies [64, 65] focus on the development of modern requirements for the technical characteristics of freight cars in order to improve their design. Publications [66-75] are aimed at refining the calculations, mathematical and computer models in the design of freight cars.

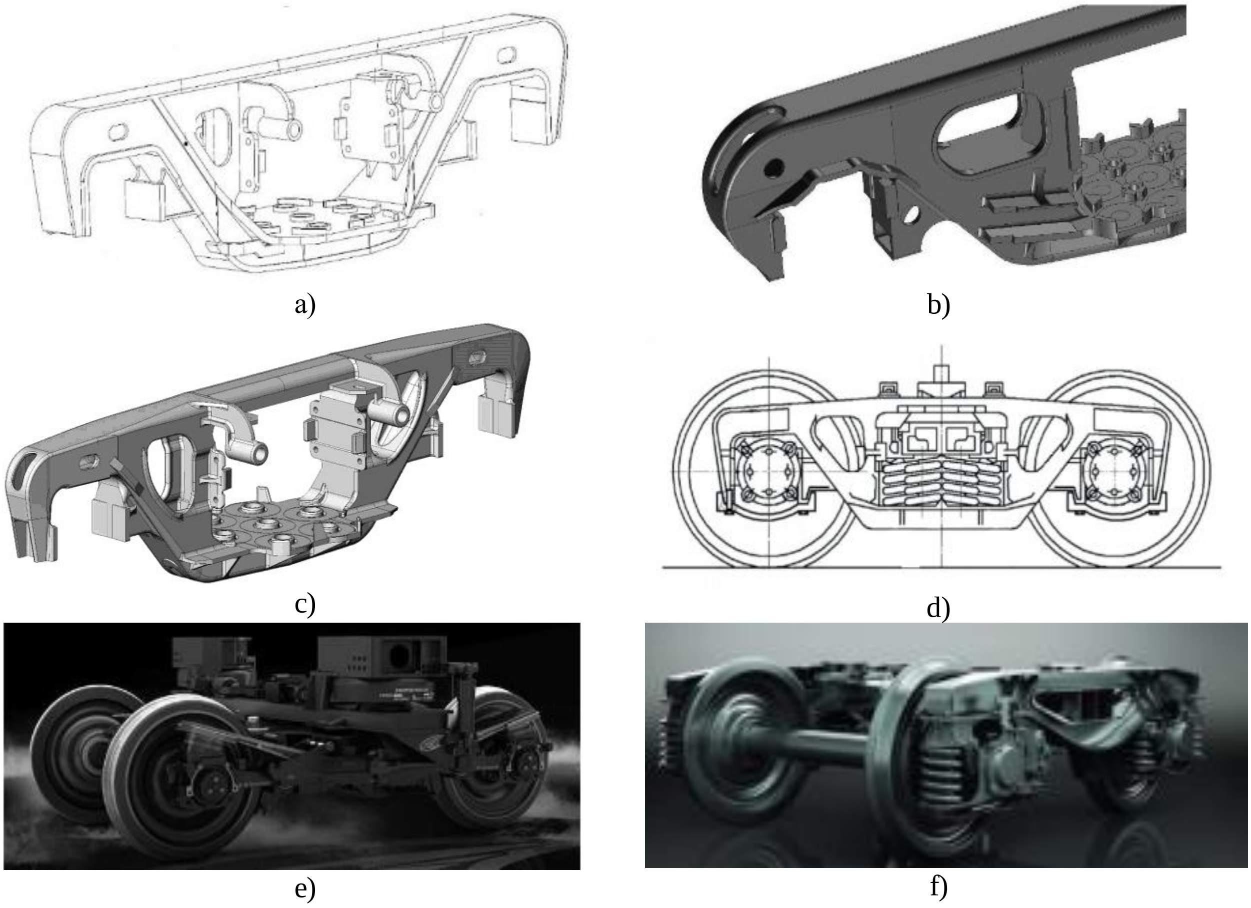

Fig. 8. **Running parts models of freight cars: a) side frame of welded structure [38]; b) comprehensively modernized cast side frame [44]; c) cast side frame of an improved design [41]; d) cast bogie of an improved design with a box string [40]; e) new bogie of welded structure [46]; f) welded bogie of improved design [47]**

a) b) c)

Fig. 9. **Freight cars of models with axle load 25 tonnnes:**
a) model 12-9791 on bogies model 18-9817; b) model 12-7039 on bogies model 18-7033; c) model 12-1905 on bogies model 18-1711

Thus, based on the results of the review and analysis of scientific and applied research by domestic and foreign scientists, in addition to the above-mentioned results of the technical documentation analysis for newly developed freight car models and research works, the following main vectors of design improvement were identified:

– development of a wide range of six-axle articulated cars with axle loads of 23.5 tonnes and 25 tonnes;

– development of cars using welded bogies and new generation components for them;

– achieving a equal load on the load-bearing structure;
– design of flat cars for transporting containers in two tiers;
– development of new types of wagons for intermodal, interoperable, combined transport.

An analysis of domestic titles of protection relating to freight cars published recently allowed us to identify the following main vectors of improvement:

– strengthening, improving existing and creating fundamentally new types of freight car bodies and load-bearing structures;
– modernisation of existing freight car bogies and their components;
– creation of six-axle articulated cars;
– development of a wide range of freight cars with improved technical characteristics, including new types of cars for intermodal, interoperable and combined transport;
– application of the latest assembly and welding technologies.

Based on the results of the review and analysis of technical documentation for freight cars, research and development works, scientific and applied research, and titles of protection, it was found that the teams of scientific and educational institutions have recently made a significant contribution to the development of domestic freight car building: State enterprise «Ukrainian Scientific Railway Car Building Research Institute», State University of Infrastructure and Technologies, Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan (now Ukrainian State University of Science and Technology), Institute of Electric Welding named after E.O. Paton, Eastern Ukrainian National University named after V. Dahl, LLC "Head Specialized Designing Car Building Bureau named after V. M. Bubnov", Ukrainian University Railway Transport, "Scientific Research Design And Technological Institute of Railway Transport" branch of JSC "Ukrzaliznytsia", enterprises and companies: JSC "Ukrzaliznytsia", LLC "RMF "Karpaty", PJSC "INTERPIPE NTRP", PJSC "KRCBW", JSC "KSP", LLC "Dniprovagonmash", CLG "Popasnian Car Repair Plant", LLC "AZOVVAGON", LLC "BTsP "Tribo", LLC "ZCRP "Express", LLC "POLTAVVAGON", LLC "Poltava Locomotive Repair Plant", LLC "UKRNAFTOZAPCHASTYNA", "Panyutyn Carriage Repair Plant" branch of JSC "Ukrzaliznytsia" and others.

At the same time, it should be noted the significant personal contribution to the development of new and improvement of existing designs of freight cars and their components of the following Ukrainian scientists, engineers and researchers: Babaev A.M., Bagrov O.M., Bubnov V.M., Vatuli G.L., Vodiannikova Yu.Ya., Golubenko O.L., Gorbunova M.I., Hrygoroshenka M.V., Dolinskoho S. V., Donchenko A.V., Dyomina Y.V., Ilchyshyn V.V., Kalashnyka V.O., Kara S.V., Kebal Y.V., Kelrich M.B., Kostrytsya S.A., Kravchenko K.O., Lobanov L.M., Lovska A.O., Mankevich M.B., Martynov I.E., Mozheyko E.R., Muradyan L.A., Myamlin S.V., Myamlin S.S., Neduzha L.O., Nozhenko O.S., Panchenko S.V., Petrenka V.O., Prokopenka P.M., Ravlyuka V.G., Rybina A. V., Reidemeister O.G., Sapronova S.Yu., Trufanova A.V., Fedosov-Nikonov D.V., Fomin V.V., Fomin O.V., Chernyak G.Yu., Shaposhnyk V. Yu., Shvets A.O., Shikunov O.A.

Among foreign scientists in the field of creating multifunctional railcars and new types of railcars for intermodal, interoperable and combined transport, the following works should be highlighted Płaczek M., Wróbel A., Buchacz A., Gerlici J., Lack T., Dižo J., Harušinec J., Blatnický M., Šťastniak P., Moravčík M., Smetanka L., Chuan-jin, O., Bing-tao., Wiesław K., Tadeusz N., Michał S., Kurčík P., Pavlík A., Lewandowski K., Krason W., Niezgoda T., Stoilov V., Simić G., Purgić S., Milković D., Fabian P., Masek J., Marton P., Lee H.-A., Jung S.-B., Jang H.-H., Shin D.-H., Lee J. U., Kim K. W., Park G.-J., Nandan S., Trivedi R., Kant S., Ahmad J., Maniraj M.

Conclusions. The following main ways of improving the design of freight cars have been identified based on the results of review and analysis of technical documentation for freight cars, research works, research and development works, and titles of protection published recently:

– use of new materials with enhanced mechanical properties and high-strength steel classes in the manufacture of freight cars and its individual components, which will help to improve the strength and reliability of the structure, increase the overhaul intervals and service life of cars;

– improvement of existing and creation of fundamentally new types of load-bearing structures, in the construction of which innovative rational technical solutions are used, which will allow modifying outdated structures and improving the technical and economic performance of freight cars;

– the most efficient use of dimensions, including the inter-car space, which will increase the carrying capacity and volume of the car body;

– development of a range of freight cars with an axle load of 25 tonnes, which will increase the carrying capacity and body volume of the freight car and reduce the tare ratio;

– creation of six-axle articulated freight cars of a wide range with an axle load of 23.5 and 25 tonnes, which will increase the carrying capacity and body volume;

– development of freight cars with new-generation bogies and components, as well as other removable components and mechanisms of improved design, which will increase safety, improve the dynamics and smoothness of freight car movement, and extend the time between overhauls;

– strengthening the bearing structures of freight cars and individual component parts to improve their reliability, achieve uniform loading of the bearing structure elements and increase service life by reducing damage from loads during operation;

– creation of multifunctional freight car designs capable of transporting a wide range of goods, which will significantly reduce the empty mileage ratio and increase the efficiency of rail freight transportation;

– increasing the structural strength of long-base platform cars, which will improve the reliability and service life of such cars and reduce their damage from loads during operation;

– development of a platform car design for the transport of large containers in two tiers, which will increase the speed and efficiency of container transport by rail;

– development of new types of freight cars for intermodal, interoperable, combined transport, which will increase the speed of cargo delivery in general and the efficiency of rail transport in particular;

– application of the latest assembly and welding technologies, which will reduce labour intensity, the cost of manufacturing railcars and the environmental impact of railcar manufacturing companies.

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Шляхи удосконалення конструкції вантажних вагонів

В статті наведено динаміку виробництва вітчизняними підприємствами вантажних вагонів за роками. Обґрунтовано необхідність оновлення вітчизняного експлуатаційного парку вантажних вагонів. Встановлено такі основні вектори удосконалення конструкції за результатами постановки на виробництво нових та модифікованих моделей вантажних вагонів: використання сталей підвищеної міцності у несучих елементах конструкції та інноваційних комплектуючих; удосконалення існуючих та створення принципово нових несучих конструкцій; максимально ефективне використання габариту; розроблення вантажних вагонів з осьовим навантаженням 25 тс; створення багатофункціональних конструкцій; підвищення міцності конструкцій довгобазних вагонів-платформ; застосування новітніх технологій збірки та зварювання. Визначено такі основні вектори удосконалення конструкції вагонів за результатами аналізу науково-прикладних досліджень, окрім вищезазначених: застосування нових матеріалів; створення шестивісних вагонів зчленованого типу з осьовим навантаженням 23,5 тс та 25 тс; розроблення вагонів з використанням візків та комплектуючих деталей до них нового покоління; досягнення рівномірного навантаження несучої конструкції; створення конструкції вагонів-платформ для перевезення контейнерів в два яруси; розроблення нових вагонів для інтермодальних, інтероперабельних, комбінованих перевезень.

Ключові слова: *вантажний вагон, конструкція, парк, рухомий склад, удосконалення.*

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Theoretical foundations of calculation cylindrical parts tank car boilers using the MathCAD environment

The article is devoted to the numerical calculation of the cylindrical part a tank car boiler, which is represented as a single-layer shell, and the study of its stress-strain state using the provisions of the semi-momentum theory shells. In some cases, under actual operating conditions of a tank car boiler, when the base metal wears out under the influence of corrosive phenomena arising from the interaction an aggressive environment and a storage and transportation tank, it becomes necessary to assess the stress-strain state and search for the most dangerous areas. The authors of this article propose a calculation algorithm that allows determining the stress state cylindrical shell of a structure, taking into account the decrease in metal thickness when corrosion occurs, using the method of calculated sections in the MathCAD software environment. The constructed mathematical model makes it possible to determine: the values of longitudinal and transverse displacements a flexible homogeneous shell of constant stiffness under the acting combined load; the values of normal forces, bending moments, and equivalent stresses in accordance with the adopted design scheme of the cylindrical part the boiler. The simplicity of implementing the proposed numerical algorithm makes it possible to use it in engineering practice, for example, during technical inspections and making decisions on the further safe operation tank car boilers according to the adjusted methodology at the early stages of research

Keywords: *boiler, cylindrical part, shell, method of design sections, equivalent stresses, algorithm.*

Introduction. When performing engineering calculations of the stress-strain state a cylindrical tank car shells, momentless shells are used as design models. In such calculations, the load in the form of internal pressure acting on the shell is considered constant in magnitude, and the stresses are determined without taking into account bending, torques, and transverse forces. At the same time, calculation errors are partially taken into account using various coefficients.

In fact, the design model of the cylindrical shell of a tank car boiler must take into account the uneven loading along the meridional coordinate, since the boiler perceives different inertial forces during the braking period at the initial and final moments of the change in the mode of movement of the car. In addition, the shell is loaded with variable pressure from the mass of the liquid cargo with a significant density along the circumferential coordinate. There is also a need to take into account the fastening of the tank shell to the frame: in most designs, a semi-rigid fastening of the circumference part with free support on the leg supports that take vertical and horizontal loads is used in the pivotal section, and in the places where the shaped feet are located, a rigid fastening is used to prevent the boiler from moving in the longitudinal direction under the action of traction and braking forces.

The determination of the stress-strain state requires the use of approximate calculation methods, of which the most promising is the numerical method using the semi-momentum theory of shells.

Analysis of recent research and problem statement. The use and development of the semi-momentumless theory of shells as a mathematical basis for analyzing the stress-strain state of tank railcars remains one of the most important problems in solid mechanics today. A rather difficult task is to develop an algorithm and create an optimal mathematical model for determining the stress-strain state of a cylindrical boiler shell resting on the supporting parts of the car's load-bearing structures, taking into account its geometric features and contact perception and transmission of loads. The development of modern approaches to applying the provisions of the semi-instantaneous theory of shells is based on the general theory created by O. Cauchy, S. Poisson, A. Saint-Venant, G. Kirchhoff, A. Lyav, V. Vlasov, V. Darevsky, and other scientists. In particular, O. Cauchy proposed the method of step series when considering static and dynamic loads of flat and curved plates behind a cylindrical surface, and G. Kirchhoff became the founder of the hypothesis of a straight and undeformed normal, which was later used in the theory of shells by A. Lyav and V. Vlasov.

The problem of finding a sufficiently simple and accurate solution for determining the stress-strain state of a thin-layer shell under its loading by distributed and local forces in problems of an applied nature consists in various individual approaches to formulating the dependencies between stresses and strains on the basis of compliance with the Kirchhoff hypothesis or its rejection, as well as elasticity relations, which attracts the attention of specialists and scientists when assessing calculation errors.

In recent years, the study of the stress-strain state of cylindrical shells using the classical theory and its further development has been covered by scientists from different countries of the world. In particular, Schellhammer and Fries [1] proposed a revised theory of shells with the formulation of differential operators on a distributed surface in the global coordinate system, taking into account the tangential differential calculation. This eliminated the need to parameterize the geometry of the shell using the surface coordinates that were used previously. The authors of [2] presented the developed theory of deformable shells of the first order for the analysis of free and transient vibrations of layered open cylindrical shells with general boundary conditions. To analyze orthotropic cylindrical shells, researchers [3] derived a hierarchy of shell equations in the form of power series along the shell thickness. Depending on the linear-elastic state of the shell under the action of dynamic loads, the authors of [4] obtained systems of equations in integral-differential form instead of partial differential equations. In [5], a variant of the Kirchhoff-Lyav theory of shells extension was proposed for material anisotropy, not only in tension and out-of-plane bending, but also in in-plane bending by introducing an effective stress tensor, as well as in-plane and out-of-plane moment tensors, which are identified by the balance of mechanical forces.

The purpose and tasks of the study. Determining the effect of changes in the geometric dimensions of the metal shell of a tank car boiler on its structural strength remains an urgent scientific and technical problem that needs to be solved using refined methods and research programs both during operation and in determining the possibility of further extending the service life of railcars [6]. It is known that in accordance with the current regulatory documentation [7, 8], according to the established design load modes, the strength of individual parts of railcars is determined by the permissible stress values. The assessment of strength indicators can be carried out using the calculation method or during various types of field tests using measuring equipment. The need to assess the service life of a railroad car boiler structure requires finding the most rational methodology for studying its stress-strain state using adaptive mathematical calculation models.

The aim of the present study is to create a calculation algorithm that can determine the stressed state of the cylindrical shell of a tank car boiler, taking into account changes in the thickness of the metal of the structure due to corrosion phenomena [9] using the method of calculated sections in the MathCAD software environment.

Materials and methods of research. In the present work, the use of the classical semi-momentum theory of shells based on the Kirchhoff-Love hypotheses is proposed to determine the stress-strain state of the cylindrical part of a tank car boiler under the condition of reducing the shell thickness to obtain its maximum permissible values. It should be noted that in the presented calculation, the effect of static and dynamic loads on the boiler shell is taken into account. According to the design scheme (Fig. 1), the cylindrical shell is freely supported by absolutely rigid supports. This support implies that individual segments on the shell surface (Fig. 2) can move along the diaphragm in the direction of the cylindrical part, while in the final cross-sections of the shell, free rotation is allowed, but no movement is possible.

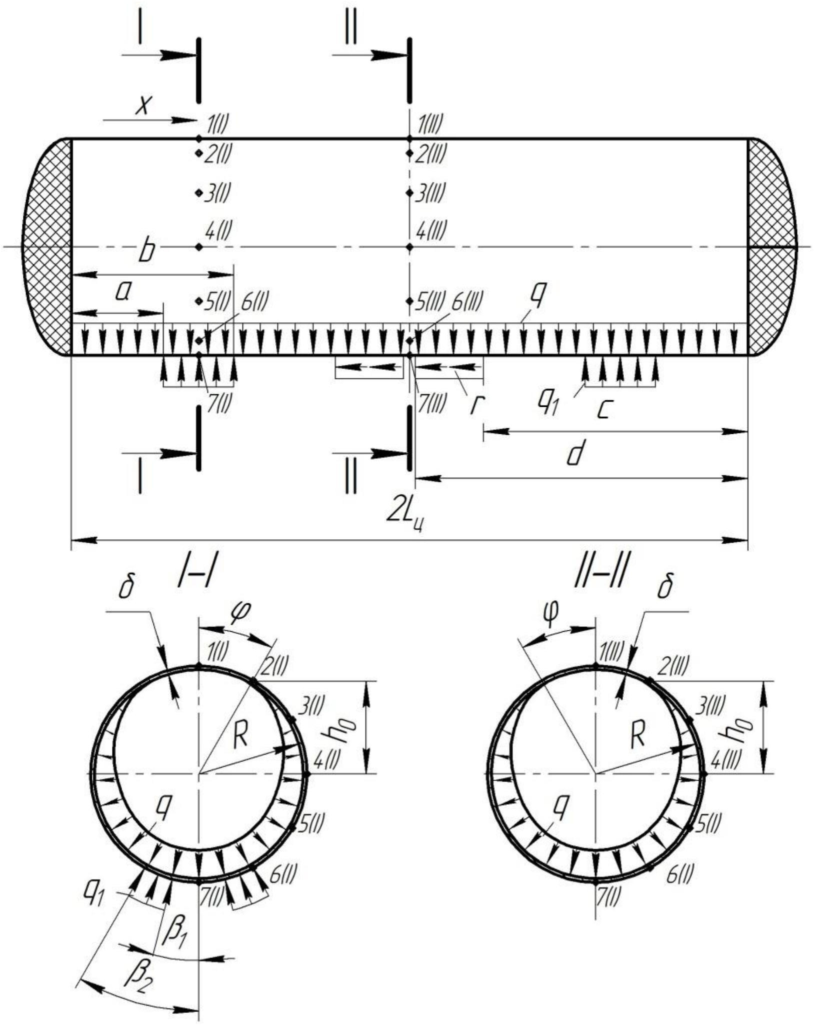

Fig. 1. **Design scheme of a cylindrical boiler shell**

In accordance with the adopted design scheme, the boiler of a tank car is subjected to the action of a distributed load from the mass of cargo q with a height of h_0, which is perceived by the bed supports q_1, and the transfer of longitudinal forces r to the shaped legs, which prevent the boiler from shifting during transient modes of movement, is taken into account. The geometric dimensions $b-a$ and $d-c$ determine the length of the supporting parts of the leg supports and shaped feet, respectively. The girth angles of the support parts for the kingpin part are determined by the difference $\beta_2 - \beta_1$.

In general, five internal forces act on the shell segment: normal forces T, shear forces S, transverse forces N, bending moments M, and torques M_κ. In accordance with the semi-momentumless theory of shells, it is taken into account that bending moments and forces acting in the transverse direction, as well as torsional moments in the transverse and longitudinal directions, are equal to zero.

The algorithm for calculating the stressed state of the cylindrical part of the tank car boiler shell involves the following sequence of actions:

1) determination of the local reference coordinate system in accordance with the adopted design scheme;

2) setting the input parameters taking into account the geometry of the structure, acting loads, and elastic properties of the shell material;

3) determination of the bearing load in the considered design sections;

4) determination of the longitudinal load distributed over the contact surface of the boiler shell at the location of the shaped feet;

5) determination of vertical and longitudinal load coefficients using Fourier series [10];

6) forming a system of algebraic equations in matrix form to find the components of tangential displacement, shear forces, and normal forces;

7) determination of the coefficients of the series of tangential displacement, shear forces, and normal forces at the point of the shell by the angular coordinate in the studied section;

8) construction of bending moment diagrams and determination of their values in the section under consideration;

9) determination of equivalent stresses under the influence of force factors and comparison with permissible values;

10) variation of the input parameter of shell thickness change and repeated calculation cycle.

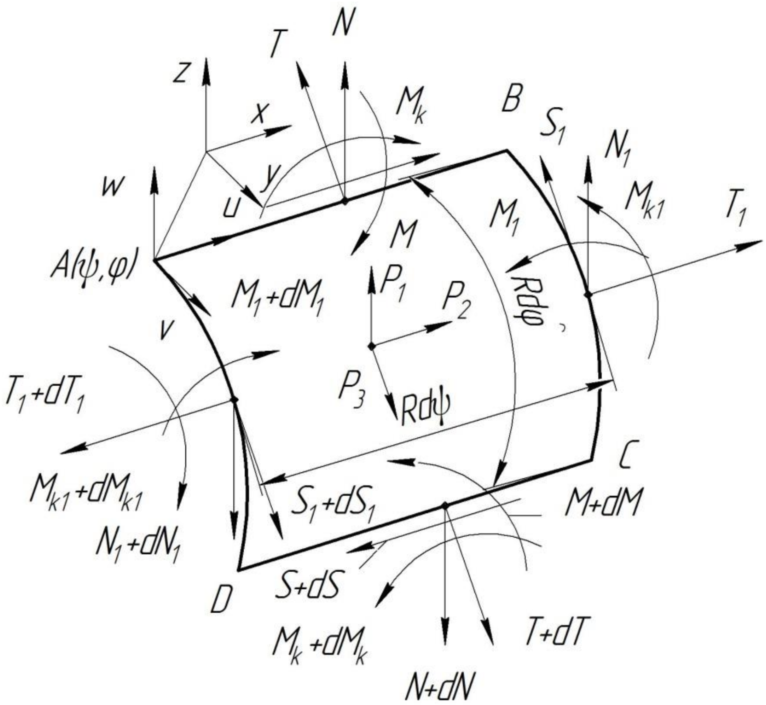

Fig. 2. **Effect of force factors on the boiler shell segment**

The method of calculated sections (sections I-I and II-II) Fig. 1 involves dividing the cylindrical part of the shell into a certain number of sections and determining the desired values (displacements, stresses) in the studied locations using the polar coordinate system. This makes it possible to determine the output parameters at each separately considered point, which is located on the surface of the cylindrical shell by the angular coordinate in accordance with the specified boundary interval of its length.

The system of differential equations for the equilibrium of the shell segment is as follows:

$$\left.\begin{aligned}&\frac{\partial T_1}{\partial\psi}+\frac{\partial S}{\partial\varphi}=0\\&\frac{\partial S}{\partial\psi}+\frac{\partial T}{\partial\varphi}-N=0\\&\frac{\partial^2 M_1}{\partial\psi^2}+\frac{\partial^2 M}{\partial\varphi^2}-2\frac{\partial^2 M_\kappa}{\partial\psi\partial\varphi}+RT=0\end{aligned}\right\}\quad(1)$$

where T, T_1 – normal forces;
N, N_1 – transverse forces;
S, S_1 – shear forces;
M, M_1 – bending moments;
M_κ – torque;
ψ, φ – coordinates of the cylindrical system;
R – radius of the cylindrical shell of the boiler.

In general, linear deformations ε_x and ε_y, angular γ_{xy}, the deformation of the curvature change χ_x and χ_y, twisting γ_{xy} expressed through displacement w, v, u. Let's write those that will be needed when deriving the main ones, which represent the complete system of equations of the semi-momentless theory:

$$\left.\begin{aligned}&\varepsilon_x=\frac{\partial u}{\partial x}\\&\varepsilon_y=\frac{\partial v}{R\partial\varphi}+\frac{w}{R}\\&\gamma_{xy}=\frac{\partial v}{\partial x}+\frac{\partial u}{R\partial\varphi}\\&\chi_y=\frac{1}{R}\left(\frac{\partial v}{\partial\varphi}+\frac{\partial^2 w}{\partial\varphi^2}\right)\end{aligned}\right\}\quad(2)$$

According to the theory, it is assumed that Poisson's ratio $\mu=0$, a linear and angular strain $\varepsilon_y=\gamma_{xy}=0$, that is, the elasticity ratio for forces T_y and S_y cannot be expressed through deformations. According to the considered option, such relations can be represented for force T_x and the moment M_y :

$$\left.\begin{aligned}&T_x=E\delta\varepsilon_x\\&M_y=\frac{E\delta^3}{12}\chi_y\end{aligned}\right\}\quad(3)$$

where E – modulus of elasticity of the shell material;
δ – shell thickness.

Taking into account the effect of loads P_1, P_2 and P_3, distributed over the surface of the plane of the shell segment, we get the sum of the projections of the net forces on the normal, axis x and tangential y to the circumference of the cross-section, as well as the moment relative to the axis x. After the transformation, the differential equations of equilibrium of the shell segment will have the form (4).

The solution to the problem of determining additional internal forces in the cylindrical part of the boiler, caused by deformations of the contour of its cross sections, can be obtained on the basis of geometric equations (2), ratios (3) and equations (4). Let's convert these equations to a convenient solution, abandoning the traditional approach according to which the load P_1, P_2 and P_3 differentiable by any variable. Let's exclude the forces from the balance equations N_y, given that it is a moment ratio ∂M_y, which is applied at a distance $R\partial\varphi$ of the considered segment.

$$\left.\begin{aligned} &\frac{\partial N_y}{\partial\varphi}+T_y-P_1R=0 \\ &\frac{\partial T_x}{\partial x}R+\frac{\partial S_y}{\partial\varphi}+P_2R=0 \\ &\frac{\partial T_y}{\partial\varphi}+\frac{\partial S_y}{\partial x}R-N_y+P_3R=0 \\ &\frac{\partial M_y}{\partial\varphi}-N_yR=0 \end{aligned}\right\} \tag{4}$$

After the transformations, we will have an equation of the form:

$$\left.\begin{aligned} &\frac{\partial^2 M_y}{R\partial\varphi}+T_y-P_1R=0 \\ &\frac{\partial T_x}{\partial x}R+\frac{\partial S_y}{\partial\varphi}+P_2R=0 \\ &\frac{\partial T_y}{\partial\varphi}+\frac{\partial S_y}{\partial x}R-\frac{\partial M_y}{R\partial\varphi}+P_3R=0 \end{aligned}\right\} \tag{5}$$

Since for forces T_y and S_y there are no elasticity ratios, they can be found from equation (5). By turning off the power T_x and moment M_y let's transform these equations using relation (3) under the condition that the linear and angular deformations are equal to zero. Based on this, we will have:

$$\left.\begin{aligned} &w=-\frac{\partial v}{\partial\varphi} \\ &\frac{\partial u}{\partial\varphi}=-\frac{R\partial v}{\partial x} \end{aligned}\right\} \tag{6}$$

In accordance with the first and fourth relations (2), expressions (3) and (6) yield:

$$\left.\begin{aligned} T_x &= -E\delta\int_{\varphi}\frac{\partial^2 v}{\partial x^2}R\,d\varphi \\ M_y &= -\frac{E\delta^3}{12}\left(\frac{\partial^3 v}{\partial\varphi^3}+\frac{\partial v}{\partial\varphi}\right) \end{aligned}\right\} \tag{7}$$

By substituting expression (7) into the system of equations (5), we will have a system of integral differential equations of the form:

$$\left.\begin{aligned} &-\frac{E\delta^3}{12R^3}\left(\frac{\partial^5 v}{\partial\varphi^5}+\frac{\partial^3 v}{\partial\varphi^3}\right)+T_y-P_1R=0 \\ &E\delta\int_{\varphi}\frac{\partial^3 v}{\partial x^3}R^2 d\varphi-\frac{\partial S_y}{\partial\varphi}-P_2R=0 \\ &\frac{\partial T_y}{\partial\varphi}+\frac{\partial S_y}{\partial x}R+\frac{E\delta^3}{12R^3}\left(\frac{\partial^4 v}{\partial\varphi^4}+\frac{\partial^2 v}{\partial\varphi^2}\right)+P_3R=0 \end{aligned}\right\} \tag{8}$$

Such a system reflects the equilibrium conditions of an extremely small segment of the shell of the cylindrical part of the boiler, obtained taking into account geometric and physical relationships, i.e. it is equivalent to three groups of equations of the shell theory taking into account the hypotheses of the semi-momentless theory. The system of equations is complete and contains three equations with three unknowns.

The laws of load distribution acting on the boiler shell are represented by double trigonometric series with coefficients P_{1mn}, P_{2mn} and P_{3mn}, determined by the Fourier formulas (9). The combination of trigonometric functions reflects the nature of the distribution of movements according to the corresponding load.

For the adopted settlement scheme at x, located within the length of the cylindrical part of the shell, there should be no movement w and v, due to the fact that the contour of the cylindrical part of the boiler is not deformed at the end diaphragms. Sliding along the diaphragm can occur along the cylindrical part of the shell, namely $u \neq 0$.

$$\left.\begin{aligned} P_1 &= \sum_{m=1}^{\infty}\sum_{n=2}^{\infty}P_{1mn}\cos n\varphi\sin\lambda x \\ P_2 &= \sum_{m=1}^{\infty}\sum_{n=2}^{\infty}P_{2mn}\cos n\varphi\cos\lambda x \\ P_3 &= \sum_{m=1}^{\infty}\sum_{n=2}^{\infty}P_{3mn}\sin n\varphi\sin\lambda x \end{aligned}\right\} \tag{9}$$

where m i n – – numbers of row members;

λ – ratio of the first number of the term of the series to the length of the cylindrical part of the shell.

The nature of the distribution of additional forces is reflected in contour deformations. When the load is symmetrical with respect to the longitudinal vertical plane of symmetry of the cylindrical part of the movement w and u symmetrical, and displacements v directed obliquely. Therefore, they can be presented in the following records:

$$v=\sum\sum v_{mn}\sin n\varphi\sin\lambda x \tag{10}$$

$$\left.\begin{aligned} S_y &= \sum\sum S_{ymn}\sin n\varphi\cos\lambda x \\ T_y &= \sum\sum T_{ymn}\cos n\varphi\sin\lambda x \end{aligned}\right\} \tag{11}$$

In formulas (10) and (11) coefficients v_{mn}, S_{ymn}, T_{ymn} unknown In the case of finding the values of the load coefficients P_{1mn}, P_{2mn} and P_{3mn} possible movements will look like:

$$\left.\begin{aligned} w &= 1\cdot\cos n\varphi\sin\lambda x \\ v &= 1\cdot\sin n\varphi\sin\lambda x \\ u &= 1\cdot\cos n\varphi\cos\lambda x \end{aligned}\right\} \tag{12}$$

The equations of system (12) are continuous within the surface of the shell and correspond to the boundary conditions at the end sections of the cylindrical part of the shell and periodicity along the arc of the cross section.

Substituting the series from formulas (10), (11) and (12) into equation (8), the first of which is equivalent to the projection of internal and external forces on the direction of movement w, the second is equal to the projection on displacement u, and the third defines the projection on displacement v.

The work of force projections on the corresponding possible displacements is calculated by integration over the surface of the cylindrical part within the limits of $x=0$ to $x=2L_ц$, at the angular coordinate from $\varphi=0$ to $\varphi=2\pi$, that is:

$$\left.\begin{aligned} &\int_0^{2L_ц}\int_0^{2\pi}\left(\cos n\varphi\sin\frac{m\pi x}{2L_ц}\right)\left(\cos k\varphi\sin\frac{i\pi x}{2L_ц}\right)dx d\varphi \\ &\int_0^{2L_ц}\int_0^{2\pi}\left(\sin n\varphi\sin\frac{m\pi x}{2L_ц}\right)\left(\sin k\varphi\sin\frac{i\pi x}{2L_ц}\right)dx d\varphi \\ &\int_0^{2L_ц}\int_0^{2\pi}\left(\cos n\varphi\cos\frac{m\pi x}{2L_ц}\right)\left(\cos k\varphi\cos\frac{i\pi x}{2L_ц}\right)dx d\varphi \end{aligned}\right\} \tag{13}$$

Given the orthogonality of trigonometric functions, if $n=k$ and $m=i$ these integrals will be equal $L_ц\pi$, and in case $n\neq k$ and $m\neq i$ they will be zero.

The system of integral differential equations (8) in the process of determining the work will be reduced to the systems of algebraic equations (14) with respect to the coefficients of the series v_{mn}, S_{ymn}, T_{ymn}. According to these equations, the coefficients of the series are found, and according to formulas (11), there are intrinsically balanced forces, which are associated with deformations of the contour of the sections of the cylindrical shell. The forces at the studied points are the addition of series at the given coordinates x and φ.

Coefficients of normal force and moment with known coefficients v_{mn} can be determined by expression (7), then the system of equations will have the form (15).

$$\begin{vmatrix} -\dfrac{E\delta^3}{12R^3}n^3(n^2+1) & 0 & 1 \\ \dfrac{E\delta R^2\lambda^3}{n} & -n & 0 \\ \dfrac{E\delta^3}{12R^3}n^2(n^2-1) & \lambda R & n \end{vmatrix} \times \begin{vmatrix} v_{mn} \\ S_{ymn} \\ T_{ymn} \end{vmatrix} = \begin{vmatrix} P_{1mn}R \\ P_{2mn}R \\ P_{3mn}R \end{vmatrix} \tag{14}$$

$$\left. \begin{aligned} T_{xmn} &= -\frac{E\delta R\lambda^2}{n}v_{mn} \\ M_{ymn} &= -\frac{E\delta^3}{12R^3}n(n^2-1)v_{mn} \end{aligned} \right\} \tag{15}$$

For the coefficients of equations (15), we have:

$$\left. \begin{aligned} T_x &= \sum\sum T_{xmn}\cos n\varphi \sin\lambda x \\ M_y &= \sum\sum M_{ymn}\cos n\varphi \sin\lambda x \end{aligned} \right\} \tag{16}$$

Equivalent stresses are calculated according to the deformation energy criterion according to the formula:

$$\sigma_e = \sqrt{\sigma_x^2 - \sigma_x\sigma_y + \sigma_y^2 + 3\tau_{xy}^2} \tag{17}$$

To ensure the required strength of the boiler shell, the condition must be met $\sigma_e \le [\sigma]$, according to [7], and individual components of the equivalent stress (17) are determined by the system of equations of the form:

$$\left. \begin{aligned} \sigma_x &= \sigma + \frac{T_x}{\delta} \\ \sigma_y &= \frac{T_y}{\delta} \pm \frac{6M_y}{\delta^2} \\ \tau_{xy} &= \frac{S_y}{\delta} \end{aligned} \right\} \tag{18}$$

Hydrostatic pressure q (Fig. 1) distributed according to the law:

$$q_1 = \gamma R(\cos\varphi - \cos\beta_0) \tag{19}$$

where γ – specific weight of cargo;
β_0 – angle that determines the position of the free surface of the cargo.

When bearing loads are applied, the angular width of the planes is taken into account $\beta_2 - \beta_1$ in cities, leaning on horizontal supports, and the load is distributed q oriented along the radius.

Load factors P_{1mn}, P_{2mn} and P_{3mn} for the supporting parts of the boiler without taking into account tangential loads will be determined by the formula:

$$\left. \begin{aligned} P_{1mn} &= \frac{4}{mn} q\left(\cos\lambda a - \cos\lambda b\right)\left(\sin n\beta_2 - \sin n\beta_1\right) \\ P_{2mn} &= \frac{4}{mn} r\left(\sin\lambda d - \sin\lambda c\right)\left(\sin n\beta_4 - \sin n\beta_3\right) \\ P_{3mn} &= 0 \end{aligned} \right\} \tag{20}$$

where r – intensity of the distributed longitudinal load on the contact surface of the cylindrical shell and legs.

The longitudinal load distributed over the contact surface of the cylindrical shell and legs is determined by the formula:

$$r = \frac{T_1\left(m_{к} + m_{в}\right)}{4m_{бр} R\left(d-c\right)\left(\beta_4 - \beta_3\right)} \tag{21}$$

where $m_{к}$ – tank car boiler mass;

$m_{в}$ – mass of cargo transported in a tank car;

$m_{бр}$ – gross weight of the tank car;

$d-c$ – paw length;

$\beta_4 - \beta_3$ – angle of the boiler shell envelope with a shaped leg.

According to the presented methodology, the stress-strain state of the tank car boiler for improved sulfuric acid model 15-1548-02 was calculated. The calculation scheme of the cylindrical part of the boiler takes into account its geometric dimensions and operating loads (Table 1).

Table 1. **Input data for calculation**

Parameter, dimension	Size
1	2
Tank car carrying capacity, kg	67000
Gross weight of the wagon, kg	90300
Wagon base, cm	780
Length of the cylindrical part of the boiler, cm	927
Radius of the cylindrical part of the boiler, cm	110
Inner angle of the girth of the supine support, degrees	34
Outer angle of the girth of the supine support, degrees	36
Inner angle of the girth of the shaped support, degrees	5
Outer angle of the girth of the shaped support, degrees	9
Distance from the extreme point of the cylindrical part of the boiler to the outer part of the lying support, cm	50
Distance from the extreme point of the cylindrical part of the boiler to the inner part of the lying support, cm	150
Distance from the extreme point of the cylindrical part of the boiler to the outer part of the shaped support, cm	378,5
Distance from the extreme point of the cylindrical part of the boiler to the inner part of the shaped support, cm	448,5

Table 1. **Continued**

Thickness of the boiler shell, cm	0,7-1,1
Longitudinal force, kg	350000
Modulus of elasticity of the material, kg/cm^2	$2{,}1\cdot10^6$

Calculation of the strength of the tank car boiler is carried out according to the I regime, in which, according to the requirements [7] a longitudinal force of 3.5 MN acts on the car. The thickness of the boiler shell is a variable parameter that takes into account the amount of its change due to damage to the surface by corrosion [11]. At the same time, in the calculation, the thickness of the shell is assumed to be the same in all sections, that is, it is assumed that corrosion is evenly distributed over the entire surface of the metal at the same depth.

When determining the bending moments, the boiler is considered as a beam on two supports with a rigid contour of the cross section [12, 13]. The values of these moments depend on the longitudinal coordinate x, which determines the length of the cylindrical part of the boiler on the cross-section section in question, and the stresses in the cross-sections change in proportion to the bending moments.

Using MathCAD software [14-17] a plot of bending moments (Fig. 3) was constructed for individual sections of the cylindrical part of the boiler based on the equation written according to the syntax of the calculation program:

$$M(x) := \begin{vmatrix} q\dfrac{x^2}{2} \text{ if } 0 \le x \le x_L \\ q\dfrac{x^2}{2} - \dfrac{G}{2}(x - x_L) \text{ otherwise} \end{vmatrix} \tag{22}$$

where q – distributed load acting on the cylindrical shell of the boiler;
x – coordinate of the half-length interval of the cylindrical part of the boiler;
x_L – length of the cantilever part of the cylindrical part of the boiler, which is outside the base;
G – vertical load from the weight of the cargo.

According to the established input data, the calculated maximum values of the bending moments of the shell at the supporting points of support at $x_1 = 73{,}5$ cm and in the middle part of the boiler at $x_2 = 463{,}5$ cm constitute $M(x_1) = 1{,}952\cdot10^5$ kg·cm and $M(x_2) = 5{,}301\cdot10^6$ kg·cm in accordance.

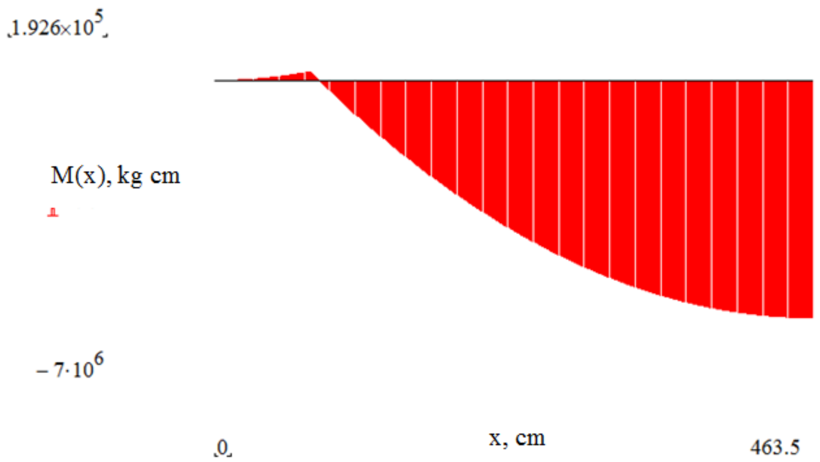

Fig. 3. **Bending moment diagram of the half-length of the cylindrical part of the boiler**

In accordance with the method of calculated intersections, to determine the forces and stresses acting on the boiler shell, the intersection point is first selected and the angular reference in the polar coordinate system is determined. Taking into account the fact that the support of the boiler on the lying supports and shaped legs is symmetrical in the profile plane, only half of the section is considered in the calculation (according to the following example, the left part is discarded, and the right part remains). Such an intersection has seven main positions, which correspond to a certain angle of inclination, in relation to the center, in steps of 30°. Positions are numbered clockwise. The angle that determines the coordinate, oriented along the cross-section of the cylindrical part of the boiler is $\varphi = 0...180°$. The number of intersections is chosen by the researcher depending on the task, and is determined by the direction coordinate x.

In this work, based on the described calculation algorithm based on the presented method, the pivot points of the boiler on the frame of the car and its middle part are considered as the main calculation sections. Taking into account the fact that the places of the greatest deformations and stresses occur in the contact zone of the boiler and supporting parts, the greatest attention is focused on the areas of positions 5, 6, 7 within the corner $\varphi = 120...180°$.

For cases of changes in the thickness of the boiler shell in the range from 1.1 to 0.7 cm in different design sections, according to the results of the calculations, it was established that the equivalent stresses (Fig. 4) exceed the permissible values of the yield strength of the material 09Г2С $[\sigma_m] = 325$ MPa at the minimum value of the shell thickness $\delta = 0.7$ cm in the pivot cross-section at the place where the boiler rests on the bearing supports and are 330.1 MPa (Fig. 5).

As can be seen (Fig. 4, a), for the kingpin section, the largest equivalent stresses in the boiler shell are in the range from 290° to 310° of the polar coordinate system, while their values at the accepted lower and upper limits of the shell thickness differ by a factor of 2.2. For the middle part of the boiler, the maximum values of equivalent stresses are in the range from 270° to 260° of the polar coordinate system and have a similar level of growth.

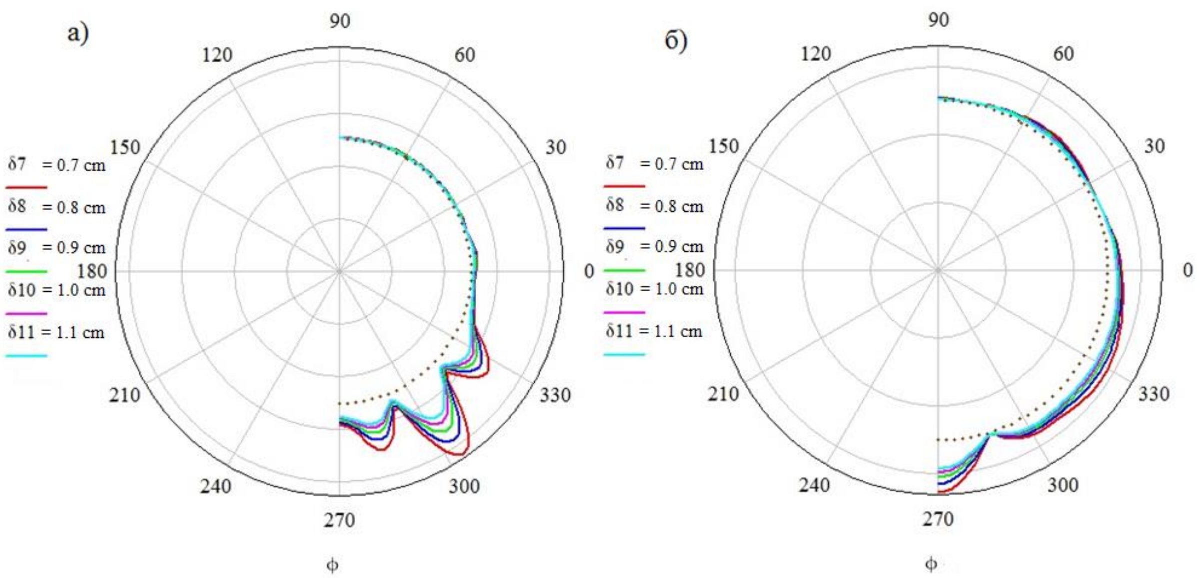

Fig. 4. **Diagram of the distribution of equivalent stresses in the tank car boiler shell in the design sections using MathCAD software:**
a) pillar part; b) middle part of the boiler

Determining the most stressed areas taking into account the reduction of the thickness of the metal shell is a priority task when calculating the strength of the tank car boiler, therefore changing the parameter δ is carried out from the permissible value to the minimum possible.

So for the case of the thickness of the boiler shell $\delta = 0.7$ cm it was established that the maximum values of tangential and radial displacements in the place of the supine support of the boiler on the frame are 1.95 mm and 10.54 mm, respectively. At the same time, the action of normal forces in the specified places corresponds to the values of 1.2 kN for the longitudinal direction and 1.76 kN for the transverse direction. For the cross-section in the middle part of the boiler, the maximum values of tangential displacements are 1.91 mm, and radial displacements are 6.13 mm. The maximum values of normal forces in this section for the longitudinal direction are equal to 0 kN, and for the transverse direction are 0.025 kN.

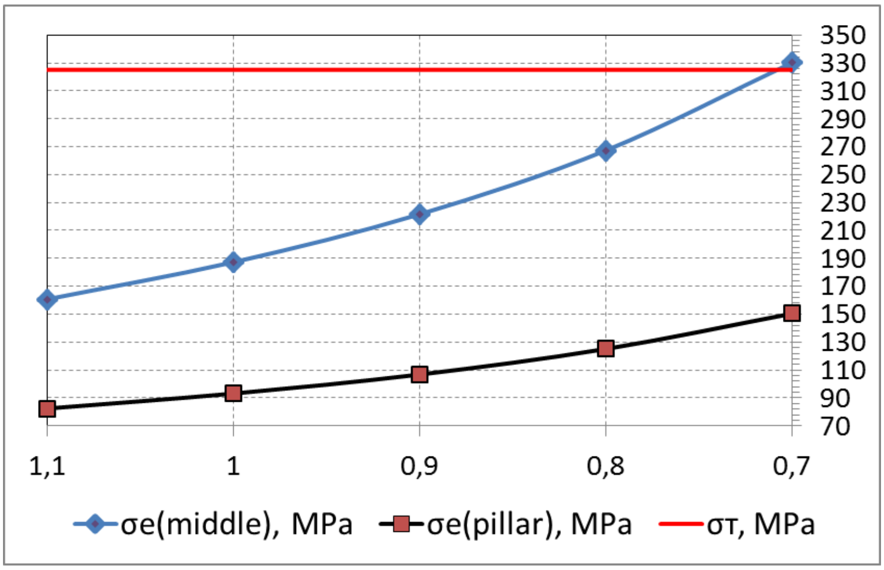

Fig. 5. **Diagram of maximum values of equivalent stresses (MPa) in the range of changes in the thickness of the boiler shell (cm)**

The obtained calculated values of stresses in the directions of action for the accepted minimum value of the boiler shell thickness are presented in Table 2.

Table 2. **Calculated values of the studied quantities for the case of the boiler shell thickness $\delta = 0.7$ cm**

Parameter, dimension	Position number where the measurement is performed						
	1	2	3	4	5	6	7
1	2	3	4	5	6	7	8
Angular position of the measurement point in the polar coordinate system, degrees	90	60	30	0	330	300	270
Normal stresses in the transverse direction in the cross section of the middle part of the boiler, MPa	3,45	13,36	11,31	44,54	57,47	30,33	84,05
Normal stresses in the longitudinal direction in the cross-section of the middle part of the boiler, MPa	3,99	7,15	4,71	34,56	29,04	35,15	89,55
Tangential shear stresses in the cross-section of the middle part of the boiler, MPa	0	0	0	0	0	0	0

Table 2. **Continued**

1	2	3	4	5	6	7	8
Equivalent stresses in the cross-section of the middle part of the boiler, MPa	6,45	18,04	14,26	40,48	76,25	56,76	150,4
Normal stresses in the transverse direction in the pivot (support) section of the boiler, MPa	5,46	2,96	1,92	2,81	51,56	106,1	92,91
Normal stresses in the longitudinal direction in the pivot (support) section of the boiler, MPa	2,71	2,41	0,82	18,68	115,1	202,8	32,35
Tangential shear stresses in the pivot (support) section of the boiler, MPa	0	2,88	3,71	3,51	11,61	15,96	0
Equivalent stresses in the pivot (support) section of the boiler, MPa	7,21	6,83	6,64	18,47	149,2	273,2	81,68

The distribution of equivalent stresses for each calculated value of the boiler shell thickness is presented in the form of a function that allows determining extremes localized within the angular position.

Conclusions. In the vast majority of works related to the calculation of cylindrical shells under local loads, equilibrium equations in real form are used as initial equations, which are reduced to the main 8th-order partial differential equation. The high order of this equation is a significant drawback when obtaining specific numerical values of the results. To eliminate the fundamental complications that arise when calculating the system of equilibrium equations, the determination of the vertical and longitudinal load coefficients is performed with the introduction of Fourier series.

Using the semi-momentum theory of shells, local problems were formulated and solved to determine the stress-strain state of a tank car boiler, taking into account the decrease in the thickness of the base metal of its cylindrical part when corrosion occurs. On the basis of these problems, analytical expressions for calculating the components of forces and stresses as functions of transverse and longitudinal coordinates were derived without using additional hypotheses about the nature of the stress distribution or displacements along the shell thickness.

As an example, the calculation of stresses in a cylindrical single-layer boiler shell under static load is presented. Explicit analytical expressions for all components of the stress tensor are obtained. MathCAD software was used to perform theoretical stress calculations. This made it possible to fully implement the calculation algorithm and automate the process of obtaining research results.

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Теоретичні основи розрахунку циліндричних частин котлів вагонів-цистерн з використанням середовища MathCAD

Стаття присвячена питанням чисельного розрахунку циліндричної частини котла вагон-цистерни, яка представлена у вигляді одношарової оболонки, дослідженню її напружено-деформованого стану з використанням положень напівбезмоментної теорії оболонок. У ряді випадків в дійсних умовах експлуатації котла вагон-цистерни при виникненні зношень основного металу під дією впливу корозійних явищ, що виникають під час взаємодії агресивного середовища та резервуара при зберіганні і транспортуванні, виникає необхідність оцінки напружено-деформованого стану та пошук найбільш небезпечних ділянок. Авторами даної статті запропоновано алгоритм розрахунку, за яким можна визначати напружений стан циліндричної оболонки конструкції з урахуванням зменшення товщини металу при появі корозії за методом розрахункових перетинів в програмному середовищі MathCAD. Побудована математична модель дозволяє визначати: величини поздовжніх і поперечних переміщень гнучкої однорідної оболонки постійної жорсткості при діючому комбінованому навантаженні; величини нормальних сил, згинальних моментів та еквівалентних напружень у відповідності до прийнятої розрахункової схеми циліндричної частини котла. Простота реалізації запропонованого чисельного алгоритму надає змогу використовувати його в інженерній практиці, наприклад, під час проведення технічних оглядів та прийнятті рішення щодо подальшої безпечної експлуатації котлів вагонів-цистерн за скоригованою методикою на ранніх етапах дослідження.

Ключові слова: *котел, циліндрична частина, оболонка, метод розрахункових перетинів, еквівалентні напруження, алгоритм.*

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Justification of choice of methods for diagnostics of insulation condition of electrical machines of electric railway stock

The object of the study is the process of monitoring the technical condition of electrical insulation of traction electric machines in order to determine the need for their maintenance or repair. Diagnostics of electric machines is an important aspect of supporting the operation of electric drives. Failure of the windings is one of the main reasons for failure of electric motors. Therefore, the task of developing operational methods for diagnosing the insulation of windings of traction electric motors is urgent. A study of the negative impact of operating conditions on the technical condition of electrical insulation of motors was carried out. The analysis of the existing methods of diagnosis of insulation systems of electric machines was carried out. Special attention was paid to the selection of predictive parameters of the insulation state. A mathematical model was developed to study the frequency characteristics of the stator insulation system of the traction electric motor model AD914. Refined dependences of the effect of changes in the insulation parameters of the motor stator winding on its frequency characteristics were obtained. It was concluded that the method of monitoring the insulation state of electric motor windings based on the assessment of electrical resistance relative to the stator core and amplitude-frequency characteristics is the most effective. The field of practical application of the obtained results is the system for monitoring the condition of electrical insulation of traction electric machines to determine the schedule of their maintenance and repair. The conducted research is a scientific justification for the choice of methods and devices for diagnosing the insulation state of electric motors of railway traction rolling stock.

Keywords: *diagnostics, mathematical model, electrical insulation, damage, amplitude-frequency characteristic*

Introduction. The stability of the insulation characteristics of electric machines is one of the main factors that guarantee the reliability of the traction electric drive of locomotives and electric trains. The problem of the stability of the technical condition of the electric motors of locomotives and electric trains is becoming more and more acute, which is explained by the following objective reasons: a long period of operation, which leads to aging of the insulation material; deterioration of the voltage quality in the power supply network due to the emission of high-frequency harmonics; increase in traffic speeds, etc.

Analysis of cases of failure of traction rolling stock and linear equipment during the warranty period of operation for the period of January 2021. – December 2022 indicates a steady trend of growth in the number of refusals. Thus, during 2022, the number of failures of traction rolling stock and its equipment as a whole in the locomotive industry of JSC "Ukrzaliznytsia" increased from 34 to 85 cases. Moreover, 25% of the total number of failures of traction motors is due to damage (breakdown) of electrical insulation. The failure mechanism of asynchronous motors depends on various parts, the most important of which is the stator winding. At the same time, the main cause of failures of auxiliary alternating current machines (AE-92-4 asynchronous electric motors, RF-1 splitters) is insulation breakdown of the stator windings, which accounts for up to 85% of the total number of failures of the specified type of machines. Failures of DC traction motors (NB-418, RT-51) in 60% of cases are associated with insulation breakdown of the armature windings, main and additional poles.

In the operation process of electric machines of locomotives and electric trains, the insulation is under the influence of electrical, mechanical, climatic and physic-chemical factors. The results of the operation show that the deterioration of the insulation is primarily due to the nature of the load. Frequent starts of machines under load, which are accompanied by significant starting currents and electrodynamic forces. Under the influence of these efforts, cracks appear in the insulation, which contribute to the further development of defects.

Vibration, cyclic temperature changes of the windings – heating during operation and cooling after operation – create thermomechanical stresses in the insulation system, contribute to the formation of condensate and moistening of the insulation. The combined effect of the listed factors leads to irreversible physicochemical processes in the structure of the insulation, which deteriorates over time, that is, to its aging, which is expressed in drying, evaporation of volatile components, loss of elasticity, the appearance of pores and cracks and their filling with moisture due to condensate. In addition, in the process of manufacture or repair, damage to the inter-turn insulation, gas inclusions after the process of impregnation of the windings, which reduces the breakdown inter-turn voltage, may be allowed. Contamination and deposition of dust with metal impurities can create a conductive layer on the insulation of the windings. Around this layer, the electric field increases, which can lead to insulation damage due to partial discharge.

Analysis of the causes of failure of electric machines shows that the main cause of damage to the stator winding is a short circuit between the turns, which is accompanied by overheating of the short-circuited sections of the turns. If an inter-turn short circuit is not detected and eliminated in time, an inter-phase short circuit or a breakdown of the machine body may occur.

2. Literature review and problem statement. Currently, considerable attention is paid to the development of methods for detecting and diagnosing electrical faults in three-phase asynchronous motors, especially failures occurring in the stator winding.

The work [1] indicated a high probability of insulation breakdown in the stator winding due to overload, aging and mechanical vibrations. Therefore, it is necessary to use a reliable toolkit to detect the degradation of electrical insulation of electric motors in order to avoid any potential consequences.

The article [2] gives an overview of the existing methods of diagnosing the technical condition of insulation of electrical machines. These methods are organized according to the type of tests performed. The issue of operational supervision, maintenance and diagnostics of insulation systems of electric machines is discussed. The negative influence of operating conditions and various factors on the technical condition of the insulation system is described. Special attention is paid to the review of available methods of diagnosis of insulation systems of electric machines and their systematization according to the type of tests.

In work [3], an analysis of the methods of diagnosing electric machines, types of defects, as well as means for their detection during production and operation was carried out. The work provides an opportunity to evaluate the effectiveness of the analyzed methods and predict the future development of diagnostic methods.

More and more attention is paid to the design of new insulation materials and insulation systems. The article [4] discusses the latest achievements in the field of insulation systems of electric machines.

Two categories of electrical insulation tests are considered: online tests; testing in off-line mode. Test standards and methods for detecting insulation damage are given. A study of developing technologies was conducted. The effect of partial discharges on insulation systems was discussed.

The article [5] discusses practical approaches to detecting single-turn short circuits. It is emphasized that this type of short circuit belongs to the most serious type of insulation damage, when the inductance of the winding decreases and the circulating current increases. In the work, it is proposed to use the method of high-frequency signal supply to the windings of the electric machine and its analysis for reliable online diagnostics of malfunctions. The obtained results of the experiments confirm the effectiveness of the proposed method.

According to the study [6], existing and potential methods for diagnosing the insulation of electric machines should include the following partial discharge tests; insulation resistance tests between the coil and the core and dielectric spectroscopy. Dielectric spectroscopy is possible in the time and frequency domain. A partial discharge test can reveal insulation defects between turns, between phases and earth. For example, voids, cracks and delamination in the insulation, as well as degradation of the insulation of its chemical composition.

In [7], a new approach to monitoring partial discharge test data based on the condition index is proposed. The types of partial discharge, equipment for substantiating the maintenance schedule and the need for repair are considered. The issue of detecting partial discharges and reducing their negative consequences is discussed in works [8–10].

The work [11] presents a developed methodology for determining the type of malfunction and the location of damage by analyzing the amplitude-frequency characteristic. It is noted that it is necessary to conduct a number of measurements to form a database of frequency characteristics. The expediency of using the method of amplitude-frequency characteristics as a diagnostic tool for detecting internal malfunctions in asynchronous motors is also evidenced by the results of experiments given in works [12, 13].

Using the method of amplitude-frequency characteristics, it is possible to evaluate the mechanical integrity of the winding inside the machine, detect broken tires, broken rods in short-circuited rotors of asynchronous motors, and obtain a comprehensive assessment of the state of the bearings of the rotor shaft [14–16]

The results of the studies presented in [17, 18] show the high accuracy of the method of amplitude-frequency characteristics for detecting short circuits in the windings of asynchronous motors. In particular, in [18] the application of the method of amplitude-frequency characteristics in the online mode is proposed.

In [19], the insulation test with voltage pulses, which is applied between the winding and the machine body during the production and overhaul of asynchronous motors, is considered for diagnostic purposes and is used as a comparative method. The method of impulse tests is also considered in [20]. The method consists in disconnecting the charged capacitor from the winding and recording the transient process in the winding circuit. On the basis of the created mathematical model of switching processes in the windings of electric machines, a diagnostic system for assessing the quality of insulation of the windings is proposed based on multi-physical processes that occur when the current breaks in the windings of electric machines.

The method of high-frequency capacitance impedance is also used to monitor the deterioration of the insulation condition of electric motor coils. Periodic measurements of partial discharges, dielectric losses and capacitance, as shown in [21], are the most effective for assessing the phenomenon of insulation aging.

The article [22] presents the results of experimental research on the dependence of thermal, mechanical and electrical changes in capacitance and the dielectric loss angle on aging time and applied voltage.

The above analysis of well-known information sources on this topic allows to assert the feasibility and prospects of improving the methods of diagnosing electric machines by modifying tests, improving the effectiveness of predictive parameters, optimizing diagnostic periods, and expanding online testing based on the use of modern sensors and modern digital signal processing algorithms.

The aim and objectives of the study. The aim of the study is the development of methods for diagnosing the state of electrical insulation of traction electric motors of electric locomotives and electric trains. The main tasks of the study are as follows: the study of the possibility of using the impedance of the insulation capacity as a test for monitoring the insulation state; improvement of the method of detecting insulation defects based on the use of impulse diagnostic methods; comparison of the accuracy and efficiency of the amplitude-frequency and impulse methods of monitoring the insulation state.

Materials and methods of the study. It is accepted that the condition of the electrical insulation of electric motors is determined using diagnostic tests that allow to assess the degradation degree of the insulation caused by aging. Two categories of electrical insulation tests are considered: on-line tests and off-line tests. Testing by the method of partial discharge in real time is performed at a frequency of 50 Hz in the stator windings with a nominal voltage of 2 kV and above according to the "phase-earth" scheme on one phase simultaneously with the grounding of the other two phases. Partial discharge is one of the main factors that can lead to insulation damage. It usually appears in voids, pores between the insulating material, inside or on the surface of the insulating system and is characterized by spark impulses that lead to heating of the insulation. Due to their repetition, partial discharges create conditions for insulation breakdown. The list of parameters by which the insulation state can be evaluated, the reasons for their deterioration, which lead to a decrease in the reliability of electric machines, is considered. Tests that make it possible to detect malfunctions in the windings and timely prevent failures of electric machines in operation are considered.

Research results.

Study of parameters characterizing the insulation state. The most important parameter that must be monitored and which helps to check the condition of the electrical insulation is the electrical resistance of the insulation. The resistance is estimated by the current flowing in the insulation circuit when the voltage is applied. The flowing current includes polarization current, through current and surface conduction current. However, measuring resistance does not give a complete picture of the insulation state. The absolute value of the resistance is an integral characteristic that is insensitive to local changes in its value, which most often lead to a breakdown. The polarization index test consists of testing the insulation between phase and earth with a high DC potential. The method allows to detect and localize pollution, the main defects in the insulation and is a sensitive indicator of the presence of moisture in the winding.

The equivalent model of replacing the insulation of individual coils of an electric machine, as a type of solid dielectric, can be simplified in the form of a parallel replacement scheme (Fig. 1).
The parallel substitution circuit can be considered as a dielectric model, in which the elastic polarization current is modeled by the capacitance C, and the electrical conductivity by the resistive resistance R.
The current caused by the polarization processes of displacement of bound charges in the dielectric takes place in the presence of an alternating electric field. Polarization of the dielectric under the influence of an alternating electric field causes losses of active electric power – dielectric losses that are released as heat in the dielectric and cause heating of the insulation. Dielectric losses are characterized by the dielectric loss angle tangent $tg\delta$, that is, the ratio of the intensity of the real component I_R to the imaginary component I_C of the electric current flowing through the dielectric in an alternating electric field.

The vector of the total current I is obtained by adding the vectors of the active I_R and reactive I_C currents, the ratio of which in the right-angled triangle of currents gives the dielectric loss angle tangent $tg\delta = I_R/I_C = 1/(\omega \cdot R \cdot C)$, where the angular frequency is $\omega = 2 \cdot \pi \cdot f$, s^{-1}.The value of the capacitance C between the stator conductors and the grounded core can be a parameter that characterizes thermal wear, moisture absorption and contamination of the winding. Tracing the trend over time of the dielectric loss angle tangent $tg\delta$ can provide a general idea of the dielectric loss and the general condition of the stator insulation.

Fig. 1. **Model of replacing the insulation of an electric machine**

The ability of the dielectric to polarize characterizes the relative dielectric constant, however, *tg*δ is a more sensitive characteristic for diagnosing the technical condition of the electrical insulation of electrical equipment than the relative dielectric constant, because it changes within wider limits when external factors change. A change in the *tg*δ value during operation allows to judge the drying, wetting and damage of the electrical insulation, the appearance of cracks and the loss of plasticizer.

The results of experiments [22] show that, regardless of the type and strength of the voltage, the insulation characteristics deteriorate with aging. At the same time, the capacity *C* and *tg*δ increases. Long-term thermal stresses lead to an increase in *tg*δ, and the breakdown voltage is significantly reduced in the case of combined electrical and mechanical stresses due to the presence of defects.

Dielectric losses represent the sum of conduction losses and polarization losses, that is, losses due to the occurrence of a partial discharge. If there are voids or cracks in the insulation, and the magnitude of the electric field is lower than the dielectric strength of air, the ionization process will not occur. As long as the voids of the insulation are not ionized, the value tgδ will depend only on the loss coefficient of solid particles $tg\delta = tg\delta_S$ [21]. In this case, the measured value *tg*δ is only slightly affected by the applied voltage. When the electric field strength of the air increases, the void begins to ionize (partial discharges occur), the parameter will increase sharply with the applied voltage. Measuring the dielectric loss of the insulation of a three-phase electric machine involves testing each winding in turn. When measuring, a 50 Hz alternating sinusoidal voltage is applied between the phase winding and ground, and the other two phases are grounded to the stator core.

Diagnostic methods. Existing and promising diagnostic methods include on-line and off-line testing. In the on-line mode, the technical condition of the insulation system can be determined using continuous monitoring of the electric machine. For this, measurements of various physical quantities are used: magnetic flux; temperature; stator winding current. The most common types of on-line insulation testing include: thermal monitoring; partial discharge test; current spectral analysis and overvoltage monitoring. On-line tests are carried out during operation of the electric machine. However, only with the help of online monitoring, it is impossible to detect all malfunctions of an electric machine. Therefore, off-line tests are necessary, during which the electric machine is disconnected from the network and testing methods are applied. The disadvantage of the on-line monitoring method is the need to install additional equipment at each machine monitoring object. Compared to off-line testing, some insulation defects are more difficult to detect. Further development of diagnostic methods, hardware and monitoring algorithms will undoubtedly make it possible to expand the scope of application of the online monitoring method.

The method of high-voltage impulse tests is one of the effective methods of assessing the insulation state of machine windings. This method is comparative. It consists in connecting the test voltage of the charged capacitor between the winding and the magnetic circuit and recording the current discharge or voltage drop on the winding. Deterioration of the insulation affects the high-frequency behavior of the machine. This is the basis of the condition monitoring method, which allows detecting changes in the insulation by estimating the transient current when the pulse is applied.

Depending on the parameters of the circuit, the process of changing the voltage on the winding has an oscillatory or aperiodic damping character. The resulting oscillogram of the transient process is compared with the previously recorded oscillogram (for a working or new winding) and on this basis the deterioration of the winding insulation is assessed. Any anomaly in the insulation system of the windings is manifested by a change in the frequency and decrement of the attenuation of the evanescent wave. Analysis of time oscillograms allows to quickly and easily determine the state of inter-turn insulation. This makes it possible to detect both short circuits and deterioration of the insulation between individual turns, as well as between winding coils.

Another method that is similar to the high voltage pulse method is the DC off method. The research methodology consists in supplying the tested circuit with a direct current, the value of which is much lower than the rated current of the tested machine. Measurements can be made on the windings connected together, or on the windings of each phase separately. The technical condition of the insulation of the windings is assessed based on the analysis of the voltage parameters generated at the winding terminals. Based on the analysis, the following values are compared: the frequency of the induced voltage; the shape of the induced voltage and the logarithmic damping factor.

One of the most common methods for diagnosing electrical machines and transformers is the dielectric spectroscopy (DS) method, which can be considered in both the time and frequency domains. In the time domain, the method includes measurement of current, capacitance, and dielectric loss angle tangent. DS in the frequency domain mainly involves the analysis of the amplitude-frequency response (FRA). Frequency Response Analysis (FRA) consists in calculating the impedance of the winding over a wide frequency range and comparing it with a reference set.

The FRA method is based on the fact that the electrical circuit of the stator and rotor is equivalent to an electrical network consisting of active resistance, capacitance and inductance, which has its own unique frequency response. The FRA test is used to diagnose inter-turn faults in coils during the repair of an electric machine and during its operation. In order to determine the sensitivity and effectiveness of the frequency testing method for assessing the insulation state and localization of defects, the transfer function of the winding insulation system is considered in the work.

Results of traction motor insulation research. When performing capacitance tests, tgδ or polarization index, it is desirable to measure each phase separately under the same conditions to monitor changes over time in the parameters of each phase and to compare values between phases. A mathematical model was created in the Matlab-Simulink software environment to conduct research on insulation parameters of electrical machine windings. In the model, each winding of an asynchronous machine is considered taking into account its inductance L, phase capacitance C_f, distributed transverse capacitance relative to the stator C_n and insulation resistance R relative to the stator (Fig. 2).

Capacitance C_n and dielectric loss of insulation between the phase winding and the case will be obtained from experiment XX (Fig. 1) when the winding terminals are closed (C_f=0; L=0) and the alternating voltage U with a frequency of 50 Hz is applied to the phase.

Complex of the total winding leakage current

$$I = U \cdot Y,, \tag{1}$$

where $Y = \sqrt{G^2 + B_C^2} = G + e^{j\cdot\frac{\pi}{2}} \cdot B_C \cdot Y$ – complex conductivity;

G=1/R – active conduction;

$e^{j\cdot\frac{\pi}{2}} \cdot B_C = e^{j\cdot\frac{\pi}{2}} \cdot \omega \cdot C_n$ – capacitive conductivity complex.

With known values of applied voltage U, leakage current I_R and total current I_Σ, let's obtain:

$$Y = \frac{I_\Sigma}{U}; \quad G = \frac{1}{R}; \quad B_C = \sqrt{Y^2 - G^2} = \omega \cdot C_n.$$

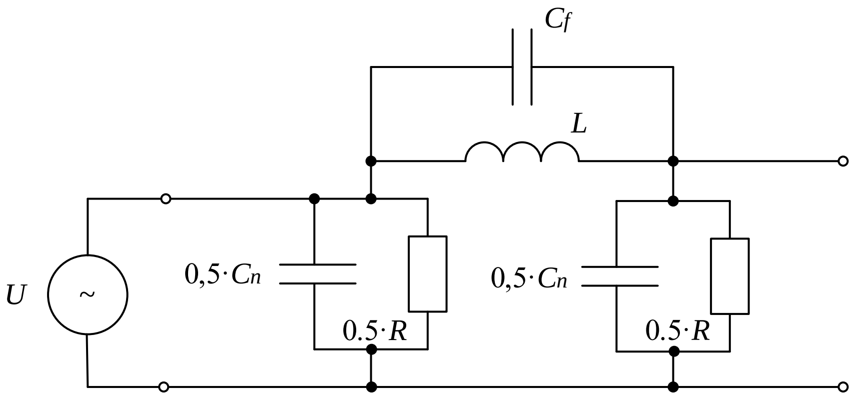

Fig. 2. **Simplified model of insulation of one winding of an electric machine**

From the last expression, the winding capacity is distributed: $C_n=1/(X_C\cdot\omega)$.

Reactive current $I_C=B_C\cdot U$.

Dielectric losses of active power are obtained from the ratio of active current and reactive current, or the resistor conductivity $1/R$ to the reactive conductivity:

$$\frac{\omega\cdot C_n}{tg\delta}=\frac{1}{R\cdot\omega\cdot C_n}. \quad (2)$$

With the help of the model, research was carried out on the insulation of the winding of the AD914 asynchronous traction motor (Table 1).

Table 1. **Input data of the AD914 asynchronous traction motor**

Power at terminals Pн, kW	**1200**
Active resistance of the stator phase R_f, Ω	0.0344
Total active resistance of the motor R_Σ, Ω	0.0619
Inductive resistance of the stator phase X_L at a frequency of 50 Hz, Ω	0.213
Short-circuit resistance Z_k at a frequency of 50 Hz, Ω	0.379

When applying to the stator phase an alternating voltage with a frequency of 50 Hz, the obtained calculated parameters are given in the Table 2.

Table 2. **Results of calculating the parameters of traction type AD914 insulation**

Reactive current I_C, A	$1.192\cdot10^{-3}$
Active current I_R, A	$1.0\cdot10^{-3}$
Complete current I_Σ , A	$3.923\cdot10^{-3}$
Active resistance R_2, Ω	$1.0\cdot10^{6}$
Capacitive resistance X_C , Ω	$-2.6362\cdot10^{5}$
Distributed winding capacity C_n, mF	$1.192\cdot10^{3}$
Dielectric loss angle tangent $tg\delta$	$0.2671\cdot10^{-5}$

The model of the insulation system of a three-phase alternating current electric machine when checking the insulation of the windings must take into account the capacity of each phase C_f relative to the stator core, the capacity between the phases C_M and the resistance of the insulation between the winding phases R_M and the core R_f (Fig. 3).

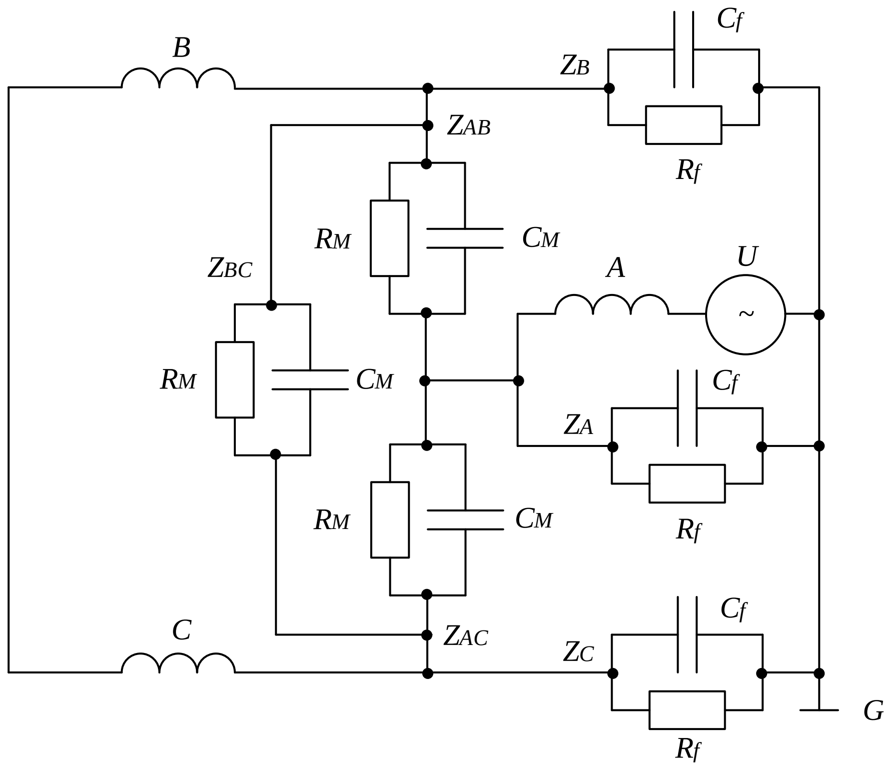

Fig. 3. **A model of the insulation system of a three-phase electric machine**

Impedances of windings relative to the body are marked as Z_A, Z_B, Z_C and between phases – Z_{AB}, Z_{AC}, Z_{BC}. Assuming that the insulation system of all three phases is balanced, and their impedances are equal to each other:

$$Z_A = Z_B = Z_C = Z_F; \quad (3)$$

$$Z_{AB} = Z_{AC} = Z_{BC} = Z_{MF}. \quad (4)$$

Here, the impedances of each parallel *R-C* model between phase insulation are Z_{MF}, and the insulation of each phase relative to the case is Z_{MF}.

Complex conductivity of insulation of one phase $\underline{Y}=G+jB_C$,
where $G=1/R_\Sigma$ – active conductivity;
$B_C=\omega\cdot C_\Sigma$ – reactive conductivity.

The total active resistance of the phase insulation in accordance with the scheme of Fig. 3:

$$Z_\Sigma = \frac{R_f\cdot\left(R_M+R_f\right)}{R_M+3\cdot R_f}. \quad (5)$$

The total capacity of one winding, taking into account the capacity relative to the case and between the windings:

$$C_\Sigma = \frac{2\cdot C_M\cdot C_f}{C_M+C_f}+C_f. \quad (6)$$

The analytical expression for the leakage current consists of resistive and capacitive components:

$$\underline{I} = \underline{U} \cdot \underline{Y} = G \cdot \underline{U} + j \cdot B_C \cdot \underline{U}. \quad (7)$$

The phase shift between voltage and current $\varphi = arctg(B_C \cdot R_\Sigma)$, the dielectric loss angle tangent

$$tg\varphi = 90^\circ - arctg\left(B_C \cdot R_\Sigma\right). \quad (8)$$

The results of the study of frequency characteristics. A simplified winding scheme of one phase of an electric machine (Fig. 4) includes: active resistance R_M relative to other phases and the core; the total capacity C_{Mf} of the winding phase, taking into account the capacity between winding turns and between phases; inductance L; resistance R_f relative to the stator core.

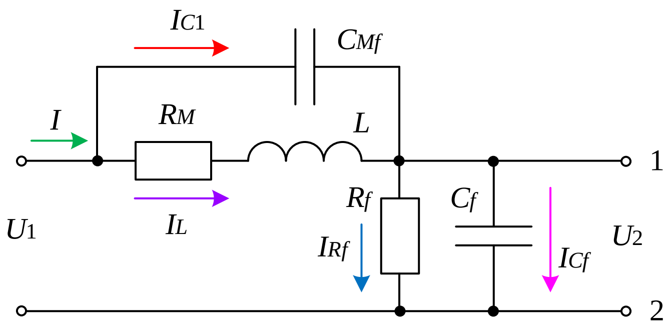

Fig. 4. **A simplified winding diagram of one phase of an electric machine**

The transfer function of the winding is defined as the frequency dependence of the voltage ratio at the output terminals of the winding applied to the power source. The electric circuit of the winding of the electric machine (Fig. 4) corresponds to the system of equations for the instantaneous values of the voltage drops on the elements:

$$U_1 = U_{C_{Mf}} + U_2; \quad (9)$$

$$U_{C_{MF}} = \frac{1}{C_{MF}} \int I_{C_{MF}} dt = I_L \cdot R_M + L \cdot \frac{dI_L}{dt}; \quad (10)$$

$$U_2 = \frac{1}{C_f} \int I_{C_f} dt = I_{R_f} \cdot R_f .. \quad (11)$$

The resulting system of equations provides a mathematical description of the physical processes in the winding insulation system and is the starting point for obtaining the transfer function and studying frequency characteristics. Using the direct Laplace transform, it is possible to obtain a system of algebraic equations in the images:

$$U_1(p) = \frac{1}{C_{Mf} \cdot p} \cdot I_{C_1}(p) + \frac{1}{C_f \cdot p} \cdot I_{C_f}(p); \quad (12)$$

$$U_{C_{Mf}}(p)=\frac{I_{C_{Mf}}(p)}{C_{Mf}\cdot p}=I_L(p)\cdot R_M(p)+I_L(p)\cdot L_{_L}(p)\cdot p; \quad (13)$$

$$U_2(p)=\frac{1}{C_f\cdot p}\cdot I_{C_f}(p)=I_{R_f}(p)\cdot R_f, \quad (14)$$

where p - the Laplace operator.

Given that the total current in the circuit is $I(p)=I_L(p)+I_{C1}(p)=I_{Cf}(p)+I_{Rf}(p)$.

As a result of solving the system of equations (2) and a number of algebraic transformations, it is possible to obtain the dependence of the output voltage $U_2(p)$ on the input action:

$$U_1(p)\cdot(C_{Mf}\cdot p\cdot(L\cdot p+R_M)+1)=U_2(p)\cdot\left(C_{Mf}\cdot p\cdot(L\cdot p+R_M)+\left(C_f\cdot p+\frac{1}{R_f}\right)\cdot(L\cdot p+R_M)\right). \quad (15)$$

The transfer function of the winding insulation system is the ratio of the Laplace images of the output voltage and the input action under zero initial conditions:

$$W(p)=\frac{U_2(p)}{U_1(p)}=\frac{L\cdot C_{Mf}\cdot p^2+C_{Mf}\cdot R_M\cdot p+1}{(L\cdot C_{Mf}+L\cdot C_f)\cdot p^2+(C_{Mf}\cdot R_M+C_f\cdot R_M+\frac{L}{R_f})\cdot p+\frac{R_M}{R_f}+1}. \quad (16)$$

The resulting transfer function includes a capacitance C_{Mf}., which is still unknown. Features of the windings of electric machines are their distributed parameters C_{Mf}., L. The winding capacity C_{Mf}. can be determined from a short-circuit test when points 1, 2 of the circuit are connected. The unknown parameter values are found through the equivalent conductivities:

$$B_C=\frac{1}{X_{C_{Mf}}}; \qquad B_L=\frac{X_L}{Z_1^2}; \qquad G=\frac{R_M}{Z_1^2}, \quad (17)$$

where the total resistance of the parallel branch R_M, L:

$$Z_1=\sqrt{R_M^2+X_L^2}. \quad (18)$$

During resonance of currents, the phase shift between the voltage and the full current of the circuit is φ=0, and the condition of resonance of currents is:

$$\frac{X_L}{Z_1^2}=\frac{1}{X_{C_{Mf}}} \quad \text{or} \quad \frac{X_L}{R_M^2+X_L^2}=\frac{1}{X_{C_{Mf}}},$$

whence the resonant frequency of the circuit:

$$\omega=\sqrt{\frac{1}{L\cdot C_{Mf}}-\frac{R_M^2}{L^2\cdot C_{Mf}}}. \quad (19)$$

The resulting dependence makes it possible to calculate the winding capacity of one of the phases.

The following example uses the parameters of the AD914 asynchronous traction electric motor, the active resistance of the winding R_M and the inductance L, the values of which are given in Table 1. The resonance of the current took place at a frequency of f=5.185·10^4 Hz. The distributed capacity of the winding is determined from the expression (19):

$$C_{Mf} = \frac{L}{\omega^2 \cdot L^2 + R_M^2} = 1.388817 \cdot 10^{-8}, F. \quad (20)$$

Transfer function of the third-order link (16) makes it possible to analyze the frequency characteristics of the insulation system of the windings of electric machines. When investigated, it is possible to consider the system's response to a sinusoidal test signal. The output signal in this case will also be sinusoidal of the same frequency as the input signal, but differs from it in amplitude and phase. The study of frequency characteristics is significantly simplified when using logarithmic ones

The LFRA study was conducted for the stator winding insulation system of the AD914 asynchronous traction electric motor using a model.

Research was carried out for four variants of transfer functions:

W_1 – no insulation defects; W_2 – insulation resistance relative to the stator 1 kΩ; $W3$ – inter-turn short circuit; W_4 – phase-to-phase short circuit.

Different types of stator winding insulation faults were specified by changing the parameters L, R_M, C_{Mf}, C_f, R_f for the corresponding transfer functions. LFRA configurations for the specified options are shown in Fig. 5.

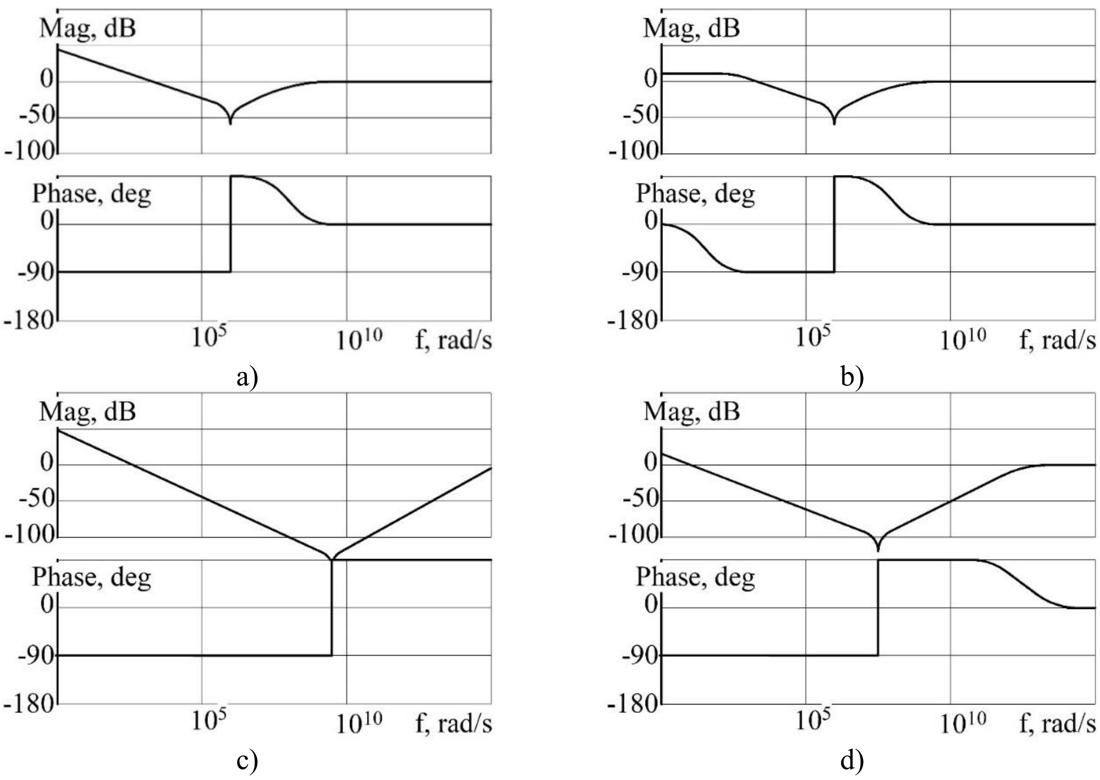

Fig. 5. Logarithmic frequency characteristics of the insulation system of the stator winding of the AD914 asynchronous traction electric motor: a) reference LFRA – no insulation defects; b) reduction of insulation resistance relative to the stator core to 1 kΩ; c) inter-turn short circuits of phase sections; d) short circuit between winding phases.

The results of the LFRA simulation in comparison with the reference LFRA signature (Fig. 5, b) show that when the insulation resistance relative to the stator core is reduced to 1 $k\Omega$, a decrease in the amplitude of the frequency response in the low-frequency range from 50 to 20 Db is observed. The phase response has no initial shift at low frequencies. When the frequency increases, the shift goes towards the value –90°. The resonant frequency remains unchanged.

Fig. 5, c shows that the winding circuit between the phase sections sharply shifts the resonance frequency to the right from the mid-frequency to the high-frequency range.

The phase characteristic in the high-frequency range has a constant phase shift by +90°. Short circuit between phases of the winding (Fig. 5d) affects the LFRA signature in the same way as the effect of turn-to-turn short circuits, but slightly reduces the frequency of the resonance point. It can be seen that when the winding is shorted between phases, the phase characteristic has a phase shift 0° in a higher frequency range.

The phase lock shows the largest change in the LFRA signal due to the change in the inductance of the winding circuit. When short circuit between the phases of the winding, the assumption was made that there were no interturn short circuits in the phase windings.

The obtained results indicate that the deterioration of the insulation leads to a change in the frequency characteristics of the electric motor. The LFRA signature depends on the value of all the capacitances, inductances and resistances of the windings relative to the stator core. The presence of a set of typical LFRA or FRA signatures, which are unique for different types of damage, will make it possible to use the frequency diagnostic method to detect and locate faults in the windings of rotating electrical machines.

Conclusions. Conducted research and modeling of malfunctions in the stator winding of the traction motor show that the most promising methods for diagnosing the insulation of electric machines of electric locomotives and electric trains are the method of amplitude-frequency characteristics and the method of insulation resistance. Diagnosing insulation during manufacturing and monitoring its condition during operation using these methods will make it possible to ensure the required level of reliability The method of amplitude-frequency characteristics is the simplest and most reliable and makes it possible to control the dynamics of insulation parameters, localize the location and type of damage. The oscillograms of Figures 5 (a-d) show that each type of insulation damage corresponds to a certain frequency response signature with a shift in resonant frequency and amplitude. If the insulation is damaged, there is a sudden shift in the resonant frequency caused by thermal effects and aging of the insulation. The method of amplitude-frequency characteristics is the cheapest and safest alternative to the standard overvoltage test. The method of amplitude-frequency characteristics, due to the ability to detect various types of malfunctions and the lack of influence on the normal operation of the machine, can be used as a method of continuous on-line monitoring of the insulation condition of electrical machines. The method contributes to the timely assessment of the state of the insulation and makes it possible to protect the windings from further aging and avoid unexpected downtime thanks to scheduled maintenance. In further research, it is planned to conduct experimental studies of the insulation of electrical machines of electric rolling stock, select the most informative diagnostic parameters of the insulation state of specific machines, and study the dynamics of these parameters during operation.

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Обґрунтування вибору методів діагностики стану ізоляції електричних машин електрорухомого складу залізниць

Об'єктом дослідження є процеси моніторингу технічного стану електричної ізоляції тягових електричних машин з метою визначення необхідності їх технічного обслуговування або ремонту. Діагностика електричних машин є важливим аспектом підтримки роботи електроприводів. Відмова обмоток є однією з основних причин виходу з ладу електродвигунів. Тому задача розробки оперативних методів діагностики ізоляції обмоток тягових електродвигунів є актуальною. Виконано дослідження негативного впливу умов експлуатації на технічний стан електричної ізоляції двигунів. Проведено аналіз існуючих методів діагностики ізоляційних систем електричних машин. Особливу увагу приділено вибору прогнозуючих параметрів стану ізоляції. Розроблена математична модель для дослідження частотних характеристик ізоляційної системи статора тягового електродвигуна моделі AD914. Отримано уточнені залежності впливу змін параметрів ізоляції обмотки статора двигуна на його частотні характеристики. Зроблено висновок, що метод моніторингу стану ізоляції обмоток електродвигунів на основі оцінки електричного опору відносно осердя статорів та амплітудно-частотних характеристик є найбільш ефективним. Сферою практичного застосування отриманих результатів є система моніторингу стану електричної ізоляції тягових електричних машин для визначення графіку їх технічного обслуговування і ремонту. Проведені дослідження є науковим обґрунтуванням вибору методів та приладів діагностики стану ізоляції електричних двигунів тягового рухомого складу залізниці.

Ключові слова: *діагностування, математична модель, електрична ізоляція, ушкодження, амплітудно-частотна характеристика*

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The security of IoT systems in railway transport

The widespread adoption of Internet of Things (IoT) devices in the railway industry is creating new cybersecurity challenges. These devices, which collect and transmit data on train movements, infrastructure and passengers, can be vulnerable to cyberattacks, which can lead to disruption of operations, security threats or compromise of sensitive data. A wide range of potential threats have been described, such as unauthorised access, data misuse and denial of service (DoS) attacks. These threats can have serious consequences, such as train accidents, data theft, or disruption of supply chains. The article is devoted to the study of the cybersecurity aspects of IoT systems in railway transport and the identification of the necessary measures to ensure the safety and reliability of these systems. Potential threats to IoT on the railway, including vulnerabilities of network devices and insufficient protection of network traffic, are considered. Simple and effective cybersecurity measures are proposed, including authentication and authorisation of IoT devices, network connection protection, and monitoring of potential threats. Threat modeling using the Microsoft Threat Modeling Tool allowed us to identify the main security issues and propose solutions. The conclusions of the article emphasise the importance of investing additional resources in ensuring the cybersecurity of IoT systems in railway transport and recommend active cooperation with experts in this field for the successful implementation of digital transformation in the railway industry.

Keywords: *The Internet of Things (IoT), cybersecurity, cyberattacks, data protection, security of IoT systems, threats, vulnerabilities, unauthorised access, railway transport.*

Introduction. The development of the Internet of Things (IoT) has created new opportunities in the railway transport industry, but it has also brought with it cybersecurity threats. With almost every connected IoT device, we can access infrastructure and personal data. However, there are also new risks associated with IoT due to its interoperability, applications and autonomous decision-making [1-3]. This creates an opportunity for abuse and potential system vulnerabilities, which has led to the issues of data security and privacy becoming increasingly relevant (Fig. 1).

The Internet of Things is a combination of mobile networks, social networks, the Internet, and smart devices that provide users with various services and applications.

Security at various levels has a direct impact on the success of IoT systems, as it ensures secure interaction of objects, reliability, and interoperability. IoT has reached a point where it can connect different spaces, such as digital and physical space, where different sensors interact with physical objects. These sensors are used in a wide range of applications, from toys to healthcare systems and the industrial sector. This illustrates how the vulnerabilities of the digital world affect the real world. A system will only be considered successful if it is guaranteed to provide security against vulnerabilities. The success of IoT applications and infrastructure depends heavily on security guarantees and the absence of vulnerabilities.

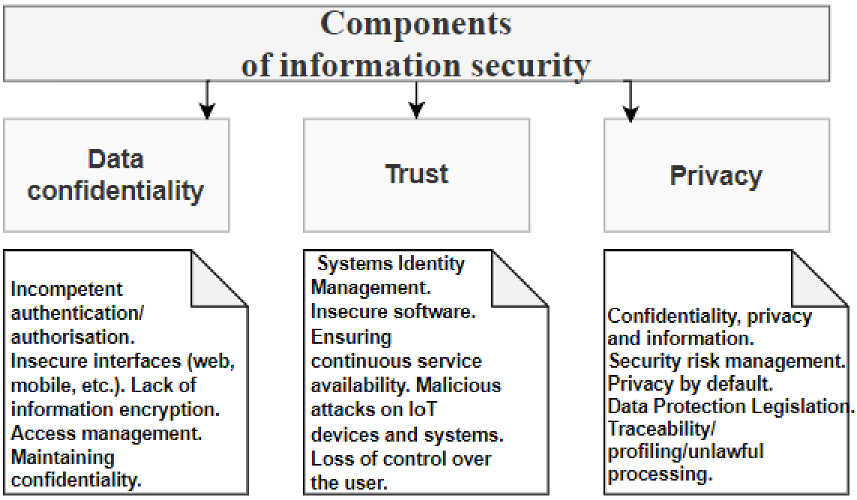

Fig. 1. **Components of information security**

A review of recent research and a statement of the problem. In recent years, there has been a great deal of research into the cybersecurity issues surrounding the IoT in the railway industry. These issues include the lack of adequate security for network devices and the lack of sufficient protection for network traffic. Researchers have identified a wide range of potential threats, including unauthorised access, data misuse and denial of service (DoS) attacks [1-3, 5]. These threats can have serious consequences, such as train accidents, data theft, or disruption of supply chains.

The purpose and objectives of the study. The objective of this study is to identify the necessary measures to ensure the safety and reliability of IoT systems in railway transport and to develop recommendations for their solution. The specific objectives of this study are as follows:

- To study the main problems of IoT cybersecurity in the railway industry;
- To analyse existing cybersecurity methods and technologies;
- To develop recommendations for ensuring the security of IoT systems in the railway industry.

In order to achieve this goal, the analysis of the latest research in this area is employed, as well as threat modeling using the Microsoft Threat Modeling Tool software.

Materials and methods of the study. The requirements for the Internet of Things security system consist of 6 main criteria [4-6]:

1. Confidentiality criterion - all data is protected;
2. Integrity criterion - data is reliable;
3. Availability criterion - data is available when and where it is needed;
4. Fail-safe criterion - reliable audit trail;
5. The criterion of authenticity - components can confirm their identity;
6. Secrecy criterion - the service does not automatically see customer data.

Data protection risks arise when IoT objects collect and aggregate data-related fragments [4, 5]. As time and frequency provide context for viewing events, personal data is transformed by matching a certain number of points. This is one aspect of the big data challenge, and security professionals must consider the potential privacy risks associated with the entire data set. Key security concerns in IoT scenarios include data privacy, secrecy, and trust.

Data privacy protection has several aspects to consider. First of all, insufficient authentication and authenticity can create problems. This implies that the system may be unable to verify the authenticity of the individual attempting to access the data. Insecure interfaces, such as the Internet or mobile phones, can also pose a risk to data privacy. Lack of transport encryption can result in data being made available for unauthorised access. Confidentiality and access control are other important aspects of data protection. Secrecy also has its aspects that need to be considered. These include data protection, risk management, and confidentiality. The concept of secrecy by default implies that data protection should be incorporated into the system from its inception. A privacy policy represents a crucial instrument for guaranteeing privacy. The tracking, profiling and illicit processing of data can also contravene privacy.

Another crucial aspect of IoT systems is trust. This encompasses identity management systems that ensure trust between users and the system. Insecure software or firmware can undermine trust in the system. Trust is also required to ensure service continuity and availability. Malicious attacks on IoT devices and systems can erode trust. Furthermore, the loss of user verification and the difficulty in decision-making can also affect system trust.

To illustrate the security requirements of the Internet of Things, its architecture is modelled in four layers: sensor, network, service, and interface. Each layer can have corresponding security controls, including access control, authentication, data integrity and confidentiality, availability, and the ability to protect IoT tools from viruses and attacks. Table 1 provides a summary of the most important security threats in IoT [5].

Table 1. **The most prevalent Internet of Things (IoT) vulnerabilities across all levels of the architectural framework.**

Security issues	**Interface layer**	**Service layer**	**Network layer**	**Sensor layer**
Insecure web interface	+	+	+	
Insufficient authentication	+	+	+	+
Insecure network services		+	+	
Lack of transport encryption		+	+	
Privacy issues		+	+	+
Insecure cloud interface	+			
Insecure mobile interface	+		+	+
Insecure configuration	+	+	+	
Insecure software/firmware	+		+	
Poor physical security			+	+

In order for modern manufacturing facilities and smart cities to be connected to a single platform, a security architecture must be created that is optimised primarily for devices connected to the Internet of Things. The security system that is created should monitor each device connected to the network individually, warn of possible malicious access, and protect or disable devices that pose a threat when necessary [3-6]. Consequently, the development and implementation of standards represent a pivotal aspect of the Internet of Things (IoT) ecosystem.

At the vanguard of this endeavor is the standardisation of IoT protocols, which is currently spearheaded by several prominent organisations, including the IEEE (Institute of Electrical and Electronics Engineers) and ISO/IEC (International Electrotechnical Commission).

Sensors represent a crucial element of Internet of Things devices, as they facilitate the collection of a diverse range of data from the physical environment [5-8]. Such sensors are capable of measuring a multitude of parameters, including temperature, humidity, light intensity, and pressure. The data is then transmitted to the central IoT nodes for further analysis and utilisation. Given that sensors are situated within and interact with the physical world, it is of the utmost importance to guarantee their security to prevent potential attacks and infringements upon privacy.

The Internet of Things presents a multitude of security challenges for sensors, including the following [5]:

a) Sensors can be physically damaged or compromised [7, 8]. For instance, attackers may attempt to short-circuit the sensor's contacts, impose electromagnetic interference, or affect the ambient temperature.

b) Sensors often collect personal data, such as location, physiological indicators, or audio recordings. It is of paramount importance to protect this data from unauthorised access and misuse.

c) Attackers may attempt to falsify data, correlate it, or introduce errors to distort analysis and decision-making [8].

To guarantee the security of IoT devices at the sensor level, the methods illustrated in Fig. 2 must be employed.

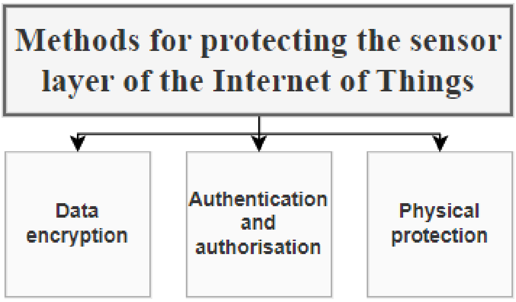

Fig. 2. **Protection methods at the sensor level of the Internet of Things**

Data encryption: the use of data encryption allows for the protection of data from unauthorised access [5, 8]. The utilisation of robust encryption algorithms will diminish the probability of sensitive data being divulged.

It is of paramount importance to implement authentication and authorisation mechanisms to verify access rights to sensors and data transmission [5]. This will prevent unauthorised access and manipulation of data.

Physical protection can be achieved through the use of protective enclosures, access control to devices, or the implementation of tampering detection mechanisms [5, 8].

It is of paramount importance to ensure the security of IoT devices at the sensor level during the development of this technology. The main challenges faced by IoT sensors include physical attacks, privacy violations, and data fraud.

In order to ensure the security of IoT devices at the network level, it is necessary to conduct a comprehensive analysis of the potential threats and vulnerabilities. One of the most prevalent threats is the interception of communications with intruders via attacks on the network stack of devices [5, 9]. Such attacks may exploit vulnerabilities in communication protocols and security services installed on IoT devices.

In order to guarantee the security of the network level of IoT devices, a number of security measures are employed. One such measure is the encryption of communication between devices. The utilisation of contemporary encryption algorithms, such as the Advanced Encryption Standard (AES), enables the safeguarding of data transmitted between IoT devices from interception and decryption by unauthorised third parties [10]. Furthermore, in order to guarantee the security of the network, it is essential to implement network security measures such as firewalls and intrusion detection systems. Firewalls permit the regulation of traffic leaving and entering the IoT network, with the capacity to block any connections that may be deemed suspicious [11]. Intrusion detection systems are designed to monitor and identify any unusual activity within the network, thereby alerting the user to potential attacks.

It has been demonstrated in practice that a significant proportion of IoT devices possess software vulnerabilities that can be exploited by attackers. It is not uncommon for device manufacturers to fail to provide regular updates, which can result in the continued presence of vulnerabilities in devices. Nevertheless, the implementation of regular software updates for IoT devices represents a pivotal aspect of network-level security. Updates permit the rectification of identified vulnerabilities and the incorporation of novel security measures. Furthermore, it is of significant importance that device manufacturers implement automatic update mechanisms, which would facilitate the process of maintaining security for users [11].

It is of paramount importance to ensure the security of IoT devices at the network level to protect the privacy of users and to prevent any unwanted attacks. A comprehensive approach to the security of IoT devices at the network level necessitates the integration of several key elements, including threat analysis, encryption, the utilisation of network security measures, and the implementation of regular software updates.

One of the most crucial aspects *of ensuring the security of IoT devices at the service level* is to achieve technical security alignment. This entails the development and implementation of common security standards and protocols that can be applied to a range of IoT devices. For instance, standards such as MQTT (Message Queuing Telemetry Transport), CoAP (Constrained Application Protocol), and TLS (Transport Layer Security) facilitate secure connections, authentication, authorisation, and data confidentiality [5, 10]. Additionally, there is a prevalent security protocol known as Zigbee, which is employed to establish secure networks with embedded devices [5, 10].

Nevertheless, ensuring security at the service level of IoT devices is not solely a technical matter. It is also important to consider the physical security of devices, as this plays an important role in preventing unauthorised access and misuse. Physical security measures may include the implementation of access control mechanisms, the use of protective enclosures, and the restriction of physical access to critical components [11].

In order to guarantee the security of IoT devices at the service level, it is essential to implement a rigorous and comprehensive security lifecycle management strategy. This implies that security must be contemplated at each stage, including the conceptualisation, construction, manufacturing, implementation, and operation of devices. For instance, the application of the tenets of the Secure Software Development Lifecycle (SSDLC) enables the identification and rectification of potential vulnerabilities at the nascent stages of development [10]. Furthermore, it is essential to implement regular software updates and patches to address known security vulnerabilities and protect devices from emerging threats [5, 9].

To ensure the security of IoT devices at the service level, it is necessary to adopt a comprehensive approach that encompasses technical, physical, and managerial aspects. Technical security alignment, physical security, and security lifecycle management are essential elements in ensuring the security of IoT devices at the service level.

At the interface level of Internet of Things devices, there are a significant number of issues that require reliable security measures. Each layer of the IoT network presents its distinctive challenges, necessitating the implementation of bespoke security measures. One of the most crucial aspects is the assurance of security at the level of the IoT device. Even devices with limited resources must be protected to ensure the confidentiality, integrity, and trustworthiness of data exchanged on the network [12].

Furthermore, it is necessary to reconcile consumer privacy and business privacy in the context of the IoT. The vast quantity of data generated by IoT devices is considerable, and it is of the utmost importance to ensure that it is adequately protected and processed in order to prevent privacy breaches and potential cyberattacks [12].

Ensuring security at the interface level of IoT devices is a complex task that requires an integrated approach and the use of specialised methods and protocols. Adherence to these principles will help ensure the security, confidentiality and reliability of the IoT network.

IoT systems in the railway transport industry can be subject to cyberattacks due several vulnerabilities. One such vulnerability is the insufficient security of network devices. A significant proportion of the IoT devices deployed on railways lack inherent security features, as they were designed with a primary focus on functionality and efficiency. Insufficient security of network devices can serve as an entry point for attackers who can exploit these vulnerabilities to gain unauthorised access to the system and carry out cyberattacks. For instance, attackers may alter device settings, execute malicious code, or even deactivate the devices entirely [7, 13].

Another potential vulnerability is the insufficient protection of network traffic. A significant proportion of IoT devices on railways communicate over open networks without adequate encryption.

This implies that attackers can to intercept transmitted data and gain access to confidential information or modify data remotely [14-16].

It is evident that cyberattacks on rail transport can have serious consequences. One potential consequence is a breach of passenger safety. Attackers can utilise cyberattacks to disable train speed control systems or security systems, which could result in accidents, injuries to passengers, or even fatalities [16]. Furthermore, cyberattacks can also result in difficulties in the transportation of goods. Attackers can utilise cyberattacks in order to disrupt cargo monitoring systems or those responsible for managing cargo flows. Such incidents can result in the loss or damage of cargo, financial losses for companies, and delays in the global supply chain [14-16].

The preceding discussion highlights the necessity of robust cybersecurity measures in IoT systems employed in rail transport. Security gaps can have significant consequences for passenger safety, train efficiency, and freight reliability.

The Internet of Things in railways encompasses a multitude of interconnected devices, including sensors, controllers, and monitors, which facilitate the efficient operation of railway infrastructure [14-16]. However, it also creates new cybersecurity threats that can have serious consequences for passenger safety and the operation of railway systems. In light of the above, it is necessary to examine the structural scheme of security measures designed to safeguard IoT systems in railway transport (Fig. 3).

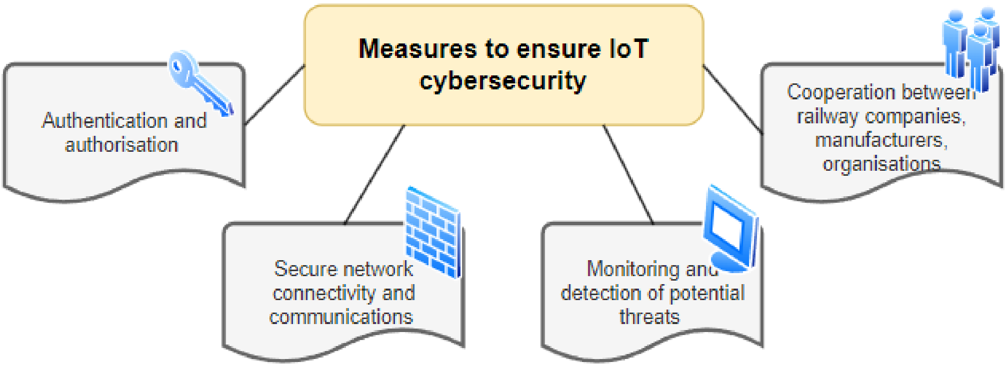

Fig. 3. **The measures that are in place to ensure the cybersecurity of the Internet of Things**

The initial step in ensuring cybersecurity in rail transport is the authentication and authorisation of IoT devices (Fig. 3). This process ensures that the connected devices in the IoT network are identified and accessed legitimately. A variety of authentication methods may be employed to achieve these objectives, including encryption, digital signatures, and authentication protocols such as OAuth or OpenID. Authorisation, in turn, defines access levels and allows for the control of user rights to interact with the IoT system in railway transport [17].

One of the most crucial elements of IoT security in railway transport is the safeguarding of network connections and communications between connected devices (Fig. 3). This is achieved through the utilisation of secure data transfer protocols, such as SSL/TLS, which provide encryption and identification of the parties exchanging information. Furthermore, it is essential to consider the implementation of protective measures against cyberattacks such as DDoS (distributed denial of service), which can result in the denial of service and the disruption of the operation of IoT systems on the railways [17].

Monitoring and detection of potential cybersecurity threats (Fig. 3) represent a pivotal aspect of security measures for IoT systems in railway transport. In order to achieve this, it is possible to utilise internet threat detection systems (intrusion detection system, IDS) and internet protection systems (intrusion prevention system, IPS) in order to detect and prevent attacks on IoT network traffic. A block diagram of the IDS and IPS systems is presented in Fig. 4.

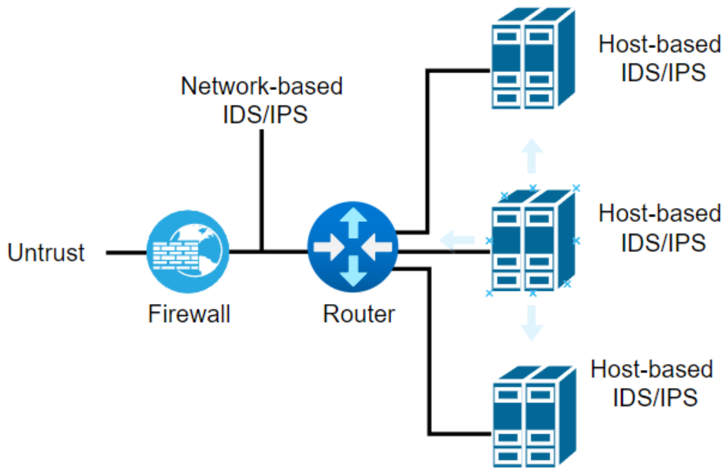

Fig. 4. **A block diagram of the IDS/IPS systems is provided below**

Furthermore, it is recommended that a centralised monitoring system be installed, which would allow for a rapid response to potential threats and the analysis of security events [52].

In order to achieve a high level of cybersecurity in the field of IoT in the railway transport sector, it is important to cooperate between railway companies, device manufacturers, and cybersecurity organisations (Fig. 3). This interaction between the parties allows them to share best practices, identify and develop solutions to potential threats, and respond to new vulnerabilities and attacks. Furthermore, joint initiatives to create security standards and certification can assist in enhancing the security of IoT systems on railways [17].

Utilising the Microsoft Threat Modeling Tool software [18], we will develop a simplified scheme of IoT use on the railway (Fig. 5). Modeling this system will assist in identifying potential threats and implementing measures to address them, even before the system is fully implemented on the railway section.

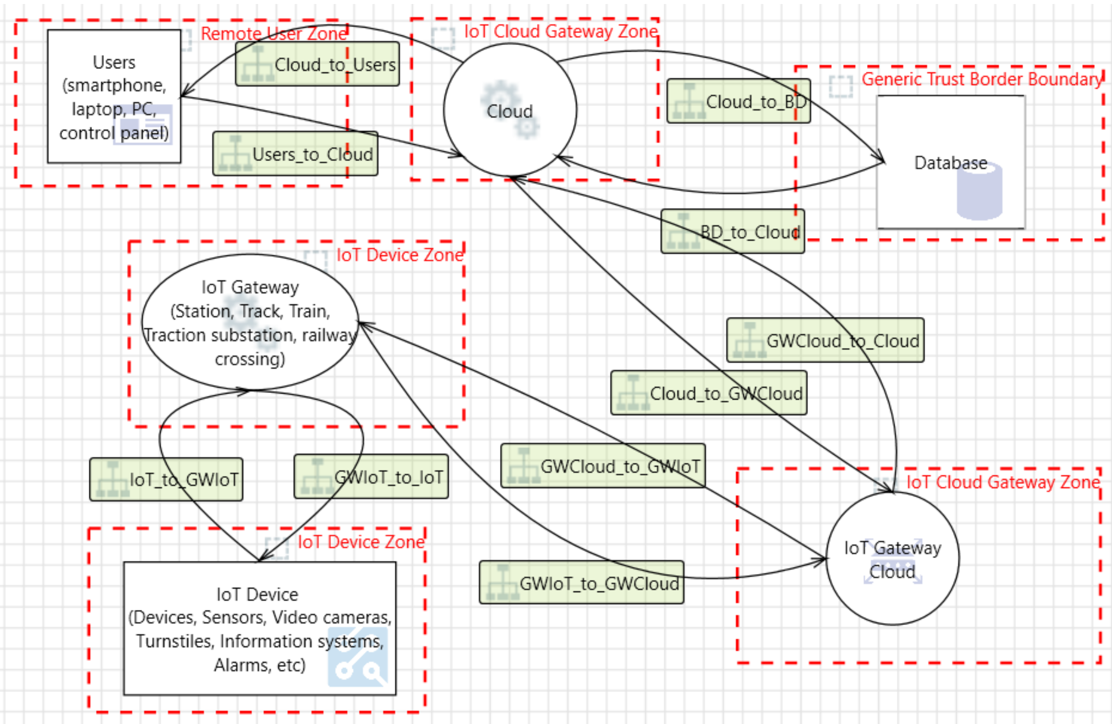

Fig. 5. **Threat Modeling Scheme**

The Microsoft Threat Modeling Tool represents a pivotal component of the Microsoft Security Development Lifecycle (SDL), which enables software developers to identify and mitigate potential security issues at an early stage of development, when they are still relatively straightforward and cost-effective to resolve. Consequently, this markedly reduces the overall cost of development.

Following the development of the model within the application environment and the execution of the simulation, a report is generated, which lists the potential threats and provides guidance on how to resolve them.

After analysing the threat modeling report, we can identify specific system vulnerabilities that need to be addressed during the implementation of IoT technologies in the railway sector (Table 2). This will help to increase the efficiency of spending money on the development and implementation of IoT in the Ukrainian railway transport system.

Table 2. **List of major system vulnerabilities**

№	Vulnerability and solutions
1	If there are no restrictions on access to the database at network or host firewall level, anyone can attempt to connect to the database from an unauthorised location. The solution to this problem is quite simple, simply configure the firewall to only allow access from authorised locations.
2	The possibility of malicious code being executed in the gateway by people outside the system. The solution is to prohibit the execution of unknown code on corporate devices.
3	Possible use of weak authorisation checks on devices and remote execution of unauthorised and confidential commands. This can be overcome by using authorisation checks on the device if it supports different actions requiring different levels of authorisation.
4	Hackers can exploit known vulnerabilities in a device if the firmware is not updated promptly. Solution: Timely software updates for IoT devices.
5	Possibility of unauthorised access to the system and access to confidential information in the gateway. Workaround: Use Bitlocker encryption.
6	An attacker can access the admin interface or privileged services such as WiFi, SSH, shared folders, FTP, etc. on the devices, so it is necessary to secure all admin interfaces with strong accounts.

The table below shows the top 6 security challenges associated with IoT adoption. The rest of the less significant issues are listed in the modeling report provided by the threat modelling software. The table shows the top 6 security challenges associated with the deployment of the Internet of Things. The rest of the less significant issues are listed in the modeling report provided by Threat Modeling.

Conclusions. The paper examines the security aspects of IoT at different levels and identifies the need to implement reliable security systems for IoT technologies in railway transport. It was found that security is one of the main factors affecting the successful implementation of digital transformation in the railway industry.

The modeling of IoT security threats carried out using the Microsoft Threat Modeling Tool software allowed the identification of the main security problems of the IoT system on the railway. The proposed easy-to-implement measures were considered as ways to solve these problems and ensure the reliability and security of the IoT system.

It was found that the introduction of the Internet of Things in rail transport will require additional efforts to ensure cybersecurity. This means that it is necessary to invest additional resources in the development and implementation of modern security systems that ensure the reliable and safe operation of IoT in rail transport.

Therefore, it is recommended to pay due attention to cybersecurity when implementing digital transformation projects. Project participants should actively cooperate with cybersecurity experts and implement reliable security systems that guarantee protection against possible threats and misuse in the area of IoT on the railway. It should be borne in mind that the cost of developing and implementing these systems will be justified in the context of ensuring the safety and efficiency of rail transport in the context of digital transformation.

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Безпека систем інтернету речей на залізничному транспорті

Широке впровадження пристроїв Інтернету речей (IoT) в залізничній галузі створює нові виклики кібербезпеки. Ці пристрої, які збирають та передають дані про рух поїздів, інфраструктуру та пасажирів, можуть бути вразливими до кібератак, що може призвести до порушення роботи, створення загроз безпеці або компрометації конфіденційних даних. Описано широкий спектр потенційних загроз, таких як несанкціонований доступ, зловмисне використання даних та атаки типу "відмова в обслуговуванні" (DoS). Дані загрози можуть мати серйозні наслідки, такі як аварії поїздів, крадіжка даних або порушення логістичних ланцюгів. Стаття присвячена дослідженню аспектів кібербезпеки систем IoT на залізничному транспорті та визначенню необхідних заходів для забезпечення безпеки та надійності цих систем. Розглянуто потенційні загрози для IoT на залізниці, включаючи вразливості мережевих пристроїв та недостатній захист мережевого трафіку. Запропоновано прості та ефективні заходи забезпечення кібербезпеки, такі як автентифікація та авторизація пристроїв IoT, захист мережевого з'єднання та моніторинг потенційних загроз. Моделювання загроз за допомогою Microsoft Threat Modeling Tool дозволило ідентифікувати основні безпекові проблеми та запропонувати шляхи їх вирішення. Висновки статті підкреслюють важливість вкладення додаткових ресурсів у забезпечення кібербезпеки систем IoT на залізничному транспорті та рекомендують активну співпрацю з експертами з цієї галузі для успішної реалізації цифрової трансформації у залізничній індустрії.

***Ключові слова**: Інтернет речей (IoT), кібербезпека, кібератаки, захист даних, безпека IoT-систем, загрози, вразливості, несанкціонований доступ, залізничний транспорт.*

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Development of the traction system structure of a shunting diesel locomotive with a hybrid power supply scheme

In this work, the structure of the traction system of a shunting diesel locomotive with hybrid power, which performs both shunting work at the station and hauling work, is proposed. In order to develop the structure of the traction system, which will work effectively in both modes of operation of the shunting diesel locomotive, an analysis of the structures of the traction systems of diesel locomotives with hybrid power, produced by the world's leading companies, is carried out. In order to choose the optimal type of storage device, an analysis of the advantages and disadvantages of supercapacitor batteries and lithium-ion batteries is carried out. On the basis of the analysis of the structures of traction systems of diesel locomotives with hybrid power of leading companies and the advantages and disadvantages of supercapacitor batteries and lithium-ion batteries, the structure of the traction system of a shunting diesel locomotive with hybrid power, which performs both shunting work at the station and hauling work, is developed. In the proposed traction system structure, each traction motor receives power from a separate traction converter. The power for powering the traction motors during shunting work is transmitted from supercapacitor batteries, when carrying out hauling work - from lithium-ion batteries. This study can be used in the design of the traction system of a new and in the modernization of an existing shunting diesel locomotive.

Keywords: *hybrid power supply, supercapacitor, lithium-ion battery, shunting diesel locomotive, traction system.*

Introduction. Railway transport is the main transport artery of Ukraine. About 46...60% of all cargo transportation was carried out by railway in 2009-2023 [1]. The wear and tear of rolling stock, in particular locomotives, has a negative impact on the process of rail transport. Most of the locomotives in the stock of JSC "Ukrzaliznytsia" are obsolete. Their technical characteristics are worse than those of modern locomotives, which leads to an increase in operating costs and maintenance and repair costs. Solving this problem can be implemented in two ways, namely: purchase of new locomotives, or modernization of existing ones.

Execution of shunting operations is an integral part of the organization of railway transportation. There are more than 1,200 diesel locomotives of the ChME3 series in the inventory of JSC "Ukrzaliznytsia". Their wear is 100%. This leads not only to an increase in maintenance and repair costs, but also to an increase in fuel and lubricant costs. In this regard, the priority task is the restoration of shunting diesel locomotives through major repairs and modernization of individual units. The advantages of this option are relatively small capital investments and the presence of a developed repair and technological base. It should be noted that during overhaul it is impossible to restore the passport characteristics of diesel locomotives. This factor leads to significant costs for ongoing maintenance of locomotives. At the same time, the low quality of repairs will lead to an increase in unscheduled repairs.

Complex modernization with remotorization is an alternative for updating the fleet of shunting diesel locomotives. This will improve the traction and energy characteristics of diesel locomotives, reduce the costs of maintenance, repairs and fuel and lubricants. This will ensure a decrease in the cost of rail transportation.

Analysis of recent research and problem statement. At JSC "Ukrzaliznytsia" diesel locomotives of the ChME3 series are used for both shunting and haulage work [2]. Despite the fact that the wear and tear of these diesel locomotives is 100%, for some diesel locomotives of this series, the service life of the load-bearing structures has been extended to 15 years. Deep modernization is used on such diesel locomotives, namely: replacing the diesel unit with a more modern one, replacing the existing direct current power transmission with alternating current power transmission, improving the drive of auxiliary machines, introducing a microprocessor control system, etc. [3]. Depending on the nature of operation, fuel savings on modernized electric locomotives is 30...45%.

The analysis of the results presented in the study [4] shows that the duration of operation of a shunting diesel locomotive in idle mode is at least 50% of the total operating time. The change in power of the traction generator is within 50...250 kW when maneuvering works at the station. In addition, work [4] states that the execution of maneuvering operations is characterized by large and rapid changes in power in the traction system.

When starting from a standstill, accelerating and moving uphill, the required diesel locomotive must work at rated power. However, the duration of such regimes is insignificant [5]. In connection with this fact, the use of a diesel engine of lower power on a modernized diesel locomotive is impractical, since in this case the dynamics of the movement of such a diesel locomotive will be unsatisfactory. The solution to this problem during modernization can be the use of a traction system of a diesel locomotive with parameters that most closely correspond to the modes of operation of the diesel locomotive. In the paper [6], the authors proposed to modernize the traction system of a diesel locomotive by using several diesel engines. Another way to modernize the traction system is to use the traction system of a diesel locomotive with hybrid power [7, 8]. In these works, the authors proposed and substantiated the feasibility of using a hybrid power system in the traction system of diesel locomotives performing shunting work at the station. This will lead to a decrease in fuel consumption and a decrease in harmful emissions into the atmosphere.

In works [9, 10], the authors proposed and substantiated the feasibility of using a hybrid power system in the traction system of diesel locomotives performing export work. In these studies, the authors note that, unlike the shunting operation at the station, in this mode of operation of the diesel locomotive, there are no large and rapid changes in power in the traction system. However, when organizing a hybrid power system, one should take into account the fact that for this mode of operation of the diesel locomotive, the on-board batteries must have a large capacity to ensure long-term energy storage.

In the study [11], the authors analyzed the operation of the ChME3 diesel locomotive when carrying out hauling work on a specific site. In this work, the authors analyze the traction characteristics of the diesel locomotive on the specified section. Based on the analysis of the traction characteristics for the production diesel locomotive of the ChME3 series, for the diesel locomotive with a modern diesel engine and for the diesel locomotive with a hybrid power system, as a result of simulation modeling, it was established:

- a locomotive with a modern diesel engine consumes 18...22% less fuel than a conventional locomotive;

- for a diesel locomotive with a hybrid power system, fuel consumption can be both lower and higher compared to a diesel locomotive with a modern diesel engine. But the use of a hybrid power system allows to accumulate energy during electrodynamic braking and use it in traction modes, which helps reduce fuel consumption.

Since shunting diesel locomotives are used both for shunting and hauling work, the task of developing the traction system structure of a shunting diesel locomotive that would work effectively in both modes is urgent.

The purpose and tasks of the study. The purpose of the study is to develop the structure of the traction system of the shunting diesel locomotive, which would work effectively both when performing shunting work at the station and when performing hauling work.

To achieve the purpose in the work, the following tasks were completed:

- an analysis of the structures of traction systems of diesel locomotives produced by leading global companies was carried out;
- the choice of the type of batteries for the implementation of the traction system of a shunting diesel locomotive, which works both when performing shunting work at the station and when performing hauling work, is substantiated;
- the structure of the traction system of the shunting diesel locomotive has been developed, which will work effectively both when performing shunting work at the station and when performing hauling work.

Analysis of the structures of locomotive traction systems produced by leading global companies. Vehicles with a hybrid power system include locomotives and diesel trains with energy batteries based on electric or hydropneumatic energy batteries, locomotives capable of using different types of fuel. The development of technologies in the field of storage devices has made it possible to significantly improve their mass-dimensional indicators. As a result, it became possible to use several storage devices of different types on one locomotive.

Since induction traction motors are used on diesel locomotives of world manufacturers, the structures of traction systems are made taking this fact into account. Diesel locomotives of the ChME3 series use manifold engines as traction. But the approach to building the implementation of energy exchange in traction systems of diesel locomotives with both induction and collector traction motors is the same. Therefore, the analysis of the structures of traction systems of diesel locomotives with hybrid power is expedient for developing on their basis the structure of the traction system with hybrid power of a shunting diesel locomotive, which works both when performing shunting work at the station and when performing hauling work.

Hybrid shunting locomotives HD 300, HDB800 and DB CARGO HELMS by Toshiba

HD 300 diesel locomotives [12] are in operation on Japanese railways, and DB CARGO HELMS are in the design stage at the request of DB Cargo [13]. The first is a hybrid diesel locomotive with an electric transmission, the second is a modernized diesel locomotive equipped with a mechanical transmission.

In accordance with the accepted classification, hybrid locomotive power schemes belong to the fourth type (electric locomotives with a different type of energy storage (compared to the main engine).

The basis of the DB CARGO HELMS locomotive drive is a series-parallel hybrid scheme, in which a planetary gearbox serves as a device that coordinates power transmission from the diesel unit to the generator, wheel pairs and SCiB battery. The considered locomotives are obtained as a result of conversion of typical German diesel locomotives BR 294 (V90). The design of the latter included ballast, which increases the towed weight, so it was possible to place the battery and the hybrid drive without increasing the weight and axial load. In the course of modernization, the hydraulic transmission is replaced by a mechanical cable with planetary gearboxes, a battery pack, traction motors and a generator. The battery unit is similar to the one installed on the HD 300 hybrid diesel locomotive of

Japanese railways, which was produced earlier, but has a higher energy capacity: up to 150 kWh.

The electrical scheme of the DB CARGO HELMS hybrid locomotive provides for the installation of a storage device in the direct current link. Thus, the hybrid drive can work both in series and in parallel (Fig. 1).

It should be noted that DB CARGO HELMS diesel locomotives have the ability to transmit torque directly from the diesel engine to the wheel pairs. Since this paper considers only the electrical circuits of diesel locomotives, in fig. 1 torque transmission directly from the diesel engine to the wheel pairs is not shown.

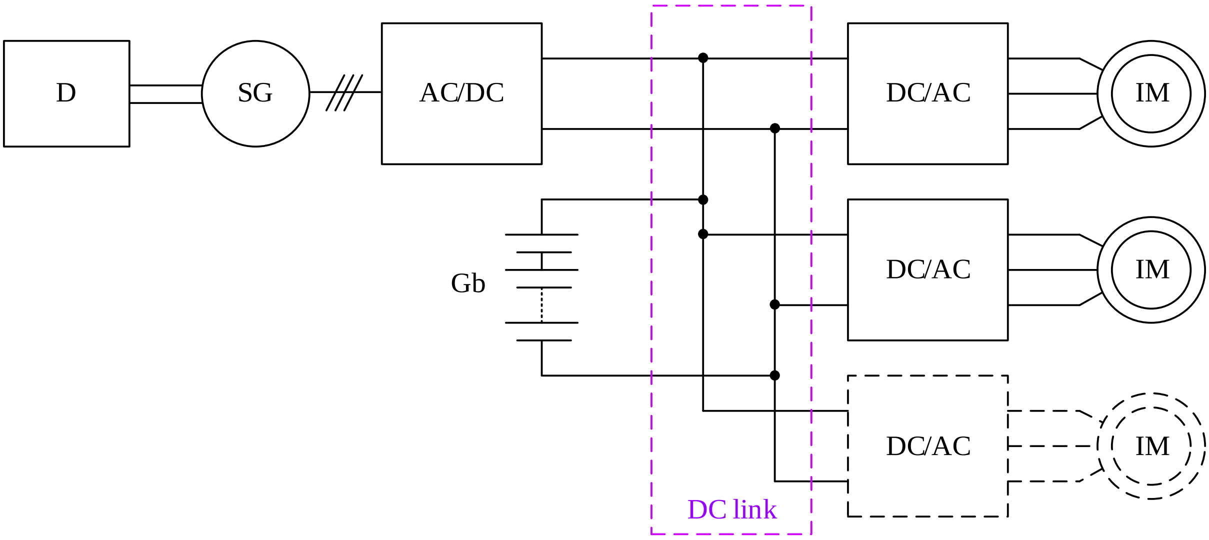

Рис. 1. **Scheme of the Toshiba CARGO HELMS hybrid electric drive: D – diesel; SG - generator; AC/DC - rectifier; DC/AC - autonomous voltage inverter; IM - induction traction electric motor**

Traction characteristics of the hybrid diesel locomotive CARGO HELMS of the Toshiba company are shown in fig. 2. When moving from a place, the traction force is 300 kN. The transition to the hyperbolic part (calculated mode) of the characteristic occurs at a speed of about 10 km/h, which is considered normal for a shunting machine.

The traction electric drive based on induction electric motors ensures a constant power of 750 kW in the entire range of speed values. Thus, the locomotive will be able to perform shunting work with warehouses weighing up to a thousand tons or train work with light-weight trains.

ALSTOM hybrid locomotives

In recent years, the Alstom company has established the production of a series of hybrid locomotives, primarily diesel locomotives with batteries based on battery batteries. The company produces a series of hybrid locomotives of the PRIMA H3 family [14] with different technical characteristics and schemes. Now more than 20 locomotives are in operation. The line includes a battery car (battery electric locomotive), a two-diesel version and the most powerful diesel-battery hybrid with a diesel engine up to 1000 kW. A nickel-cadmium battery is used on locomotives. Locomotives are produced in three-axle design (axle formula A_0-A_0-A_0).

The structural diagram of the PRIMA H3 hybrid diesel locomotive is shown in Fig. 3.

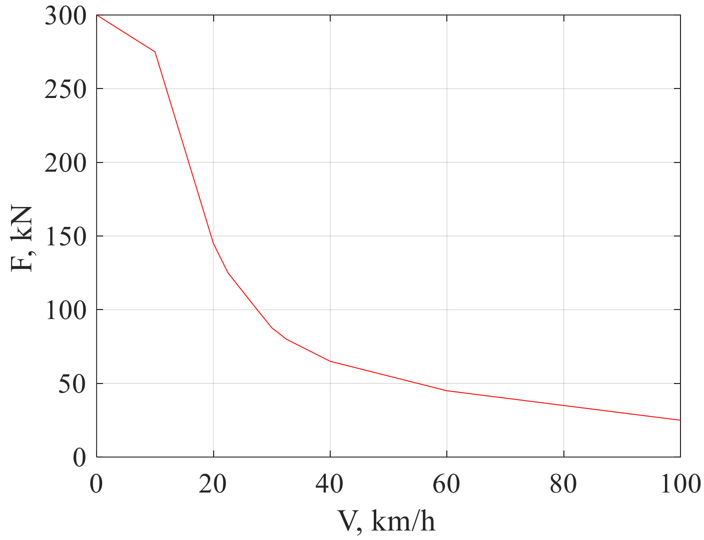

Fig. 2. **Traction characteristics of the Toshiba CARGO HELMS hybrid locomotive**

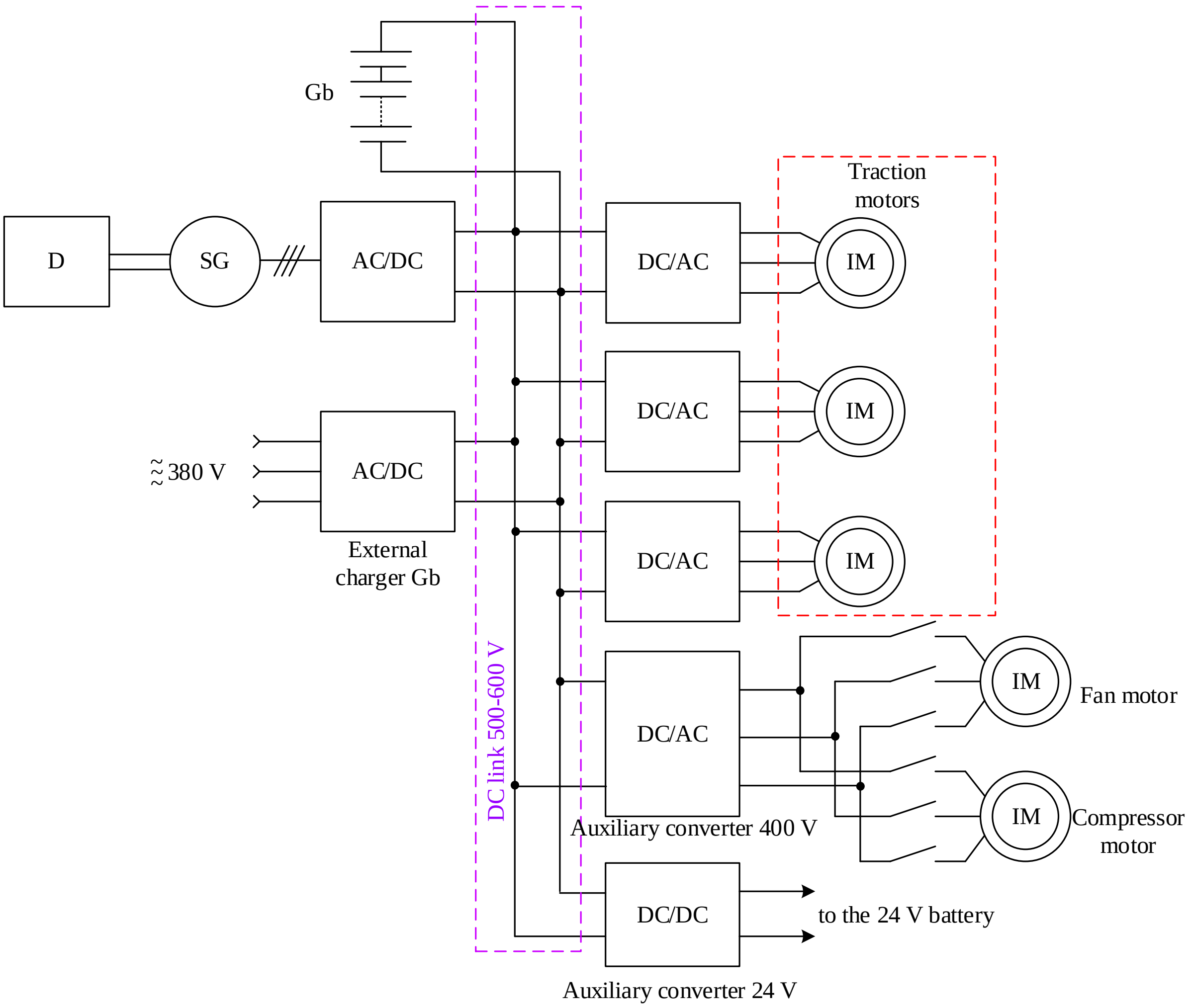

Рис. 3. **Схема гібридного тепловозу PRIMA H3**

As in the considered Toshiba hybrid scheme, induction traction motors are powered by individual inverters, the battery is connected in parallel to the direct current link. The scheme of the hybrid diesel locomotive includes a battery charger, which makes it possible to use the diesel without operation.

HSL 700 Hybrid diesel locomotive

The hybrid diesel locomotive was obtained as a result of a significant modernization of the DE 11000 shunting diesel locomotive (carriages and power elements of the body remained from the original design). The structure was developed in cooperation between TCCD (Turkey State Railways), TULOMSAS (locomotive construction company) and ASELSAN (manufacturer of electronic equipment in the field of armaments).

For the hybrid locomotive, ASELSAN developed a high-voltage battery unit based on lithium-titanate batteries. The structural diagram of the diesel locomotive is significantly different from the previously considered ones (Fig. 4).

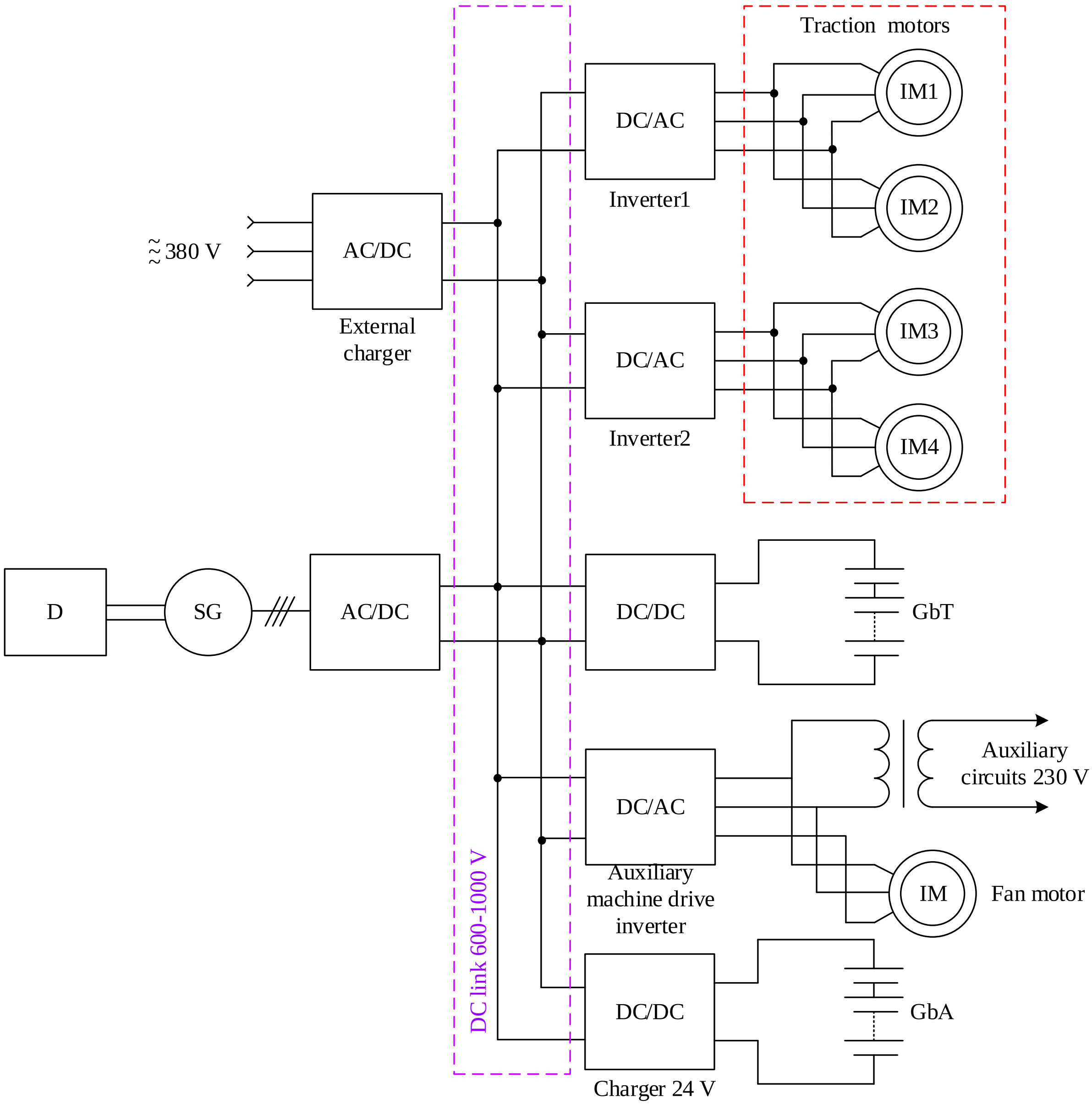

Fig. 4. **Scheme of the HSL-700 hybrid diesel locomotive**

The traction battery (GbT) is connected to the link via a step-up DC/DC converter that provides battery charge and reverse power. This makes it possible to improve battery operation and stabilize the voltage. Traction motors are powered by inverters based on silicon oxide IGBTs (DC/AC). The continuous power (total) is 400 kW with a short-term increase to 700 kW. The converter is designed for an input voltage of 600-1000 V and a current of up to 700 A. A rectifier (AC/DC) is used to charge the battery from an external source, which can provide pulse width modulation (PWM) operation. The auxiliary converter (DC/AC) is fed from the intermediate link and has output channels with three-phase and single-phase alternating voltage for power of 5, 125 and 10 kW. There is a charger for the auxiliary battery (GbA) with a voltage of 24 V.

The converter (DC/DC) has a modular design and a liquid cooling system. The traction battery consists of (GbT) cells, each of which contains four lithium-titanate batteries connected in parallel. Such a battery provides power to consumers with a large current with a significant number of charge-discharge cycles.

Development of the structure of the traction system of the ChME3 electric locomotive with a hybrid power system. The most common way to modernize diesel locomotives is to replace the power plant while retaining the traction electric drive based on collector electric motors. This significantly reduces capital costs. However, there is no significant increase in traction properties of the diesel locomotive, since outdated traction electric motors are used. For such a case, the traction system shown in Fig. 5.

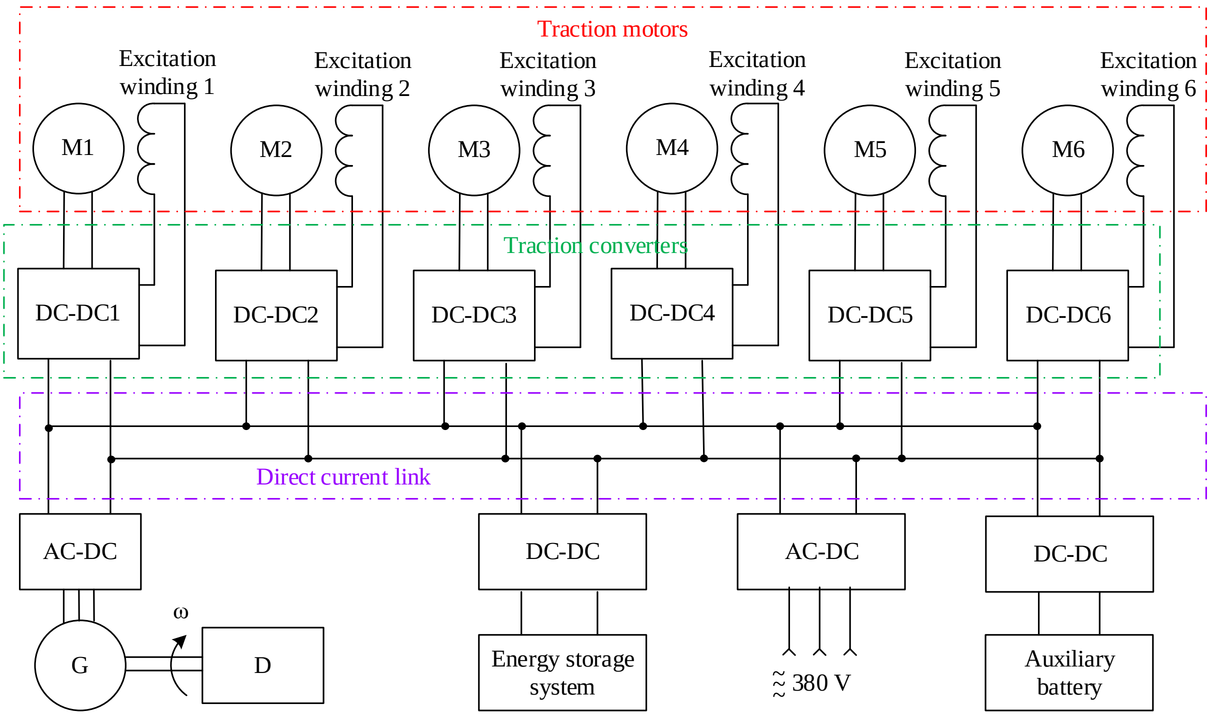

Fig. 5. **Modernized traction system of the ChME3 diesel locomotive with hydrogen power**

The hybrid power plant consists of a modern diesel engine and an alternating current generator, which is connected to the intermediate circuit through a semiconductor converter. The energy storage system through matching converters is also connected to the intermediate circuit. Since the ChME3 diesel locomotive has six traction motors - direct current electric machines with series excitation (M), in the modernized traction system, six controlled constant voltage (DC/DC) converters, which receive power from the intermediate circuit, are used as traction converters. Auxiliary converters are also connected to the intermediate circuit for powering consumers of the locomotive's own needs.

The ChME3 diesel locomotive is used both for shunting and haulage work. When carrying out hauling work, it is possible to move a diesel locomotive as part of a heavy train along a section of the road with long climbs. In this case, movement is carried out with all traction motors. When moving in reserve or with small trains on horizontal sections of the diesel locomotive, a large tractive force is not required. Therefore, movement can be carried out with several turned off electric traction motors. Potentially, this will help reduce energy consumption and, accordingly, fuel.

The following algorithm of power plant operation is proposed. When performing maneuvering operations, the traction electric drive is powered by the energy storage system. This is possible because maneuvers are performed with limited power. If necessary, power is supplied from a diesel generator

During export operation, the power supply of the traction system is provided by a diesel generator, and, if necessary, by an energy storage system that works together.

Charging of the energy storage system is carried out from the external power grid, a diesel generator and during electrodynamic braking.

Justification of the structure of the energy storage system. At present, inertial energy batteries [15], supercapacitors [16] and various types of lithium batteries [16] are used as energy storage schemes in the construction of on-board energy storage for railway rolling stock. There are well-known technical solutions for the construction of on-board energy storage systems that combine supercapacitors and lithium batteries [16]. In addition, lead batteries of various types are used on electric locomotives [17]. It follows from what has been said that when building an energy storage system, a different element base can be used. Determining the parameters of the energy storage system is a complex technical and economic problem [16], when solving which, in order to identify the priority parameters, a preliminary assessment of the options for building an on-board energy storage system should be performed.

Many studies are devoted to the analysis of the properties of various types of energy storage [16]. When choosing an element base for creating an on-board energy storage system for a specific locomotive, the following aspects are taken into account:

1. Inertial energy storage is a complex system that combines electrical, mechanical, aerodynamic subsystems and is created for a specific project taking into account operating conditions. The final appearance of such an inertial energy storage device is difficult to predict, as it requires a detailed study of the engineering and technological solutions necessary for its creation. Capital costs for the creation of an inertial energy store are included in the cost of the locomotive.

2. Compared to other energy storage devices, supercapacitors have the highest specific power values (5-10 kW/kg), but have a low specific energy capacity (5-10 W·h/kg) and the highest specific cost (5000-10000 USD/ kWh) [16]. Therefore, the cost of the energy storage system, which is built on supercapacitors, is high and is included in the cost of the locomotive.

3. In order to analyze the efficiency of application, table 1 shows the parameters of some types of modern lithium batteries [16]. It should be noted that lithium batteries can be optimized for both energy and power.

Table 1. **Parameters of lithium batteries**

Parameter	Battery type		
	NMC	LFP	LTO
Nominal voltage, V	3.6-3.7	3.2-3.3	2.2
C-rate	1	1…10	1…20
Number of charge/discharge cycles	1000…2000	1000…2000	10000…20000
Specific energy capacity, Wh/kg	150…220	90…120	70…205
Specific power, W/kg	-	-	500
Specific value, USD/kWh	100	100	500

From the analysis of the data given in the table 1, it follows that the specific energy cost of lithium batteries is at least an order of magnitude lower than the specific energy cost of supercapacitors. However, it will be necessary to replace the lithium batteries in the energy storage system several times during the entire life of the diesel locomotive. According to the data presented in the study [18], the total cost of lithium batteries, which will be used throughout the life of the diesel locomotive, is close to the cost of supercapacitors. However, the advantages of using lithium batteries when creating an on-board energy storage system are the following factors:

- lower initial cost of the diesel locomotive;
- constant improvement of lithium batteries, which leads both to the improvement of their parameters and to the reduction of their cost;
- other types of lithium batteries appear that can be used in the energy storage system;
- change of modes of operation of the diesel locomotive.

Thus, replacing the elements of the energy storage system after a certain period of time will allow to optimize its parameters taking into account the new operating conditions of the diesel locomotive. Taking into account the above, the most effective element base in the creation of on-board energy storage units of diesel locomotives is the use of lithium batteries.

The structure of the energy storage system requires a separate analysis. The traditional way of performing maneuvering operations is intensive acceleration followed by inertial movement. During acceleration, traction electric motors can work with currents that exceed the nominal by more than 40%. Accordingly, the same level of current overload must be ensured in the energy storage system. This can be done either through cell parameters or by creating a combined storage device from cells of different types.

Conclusions. The paper proposes the structure of the traction system of a shunting diesel locomotive with hybrid power on the example of a ChME3 diesel locomotive, which can perform shunting work at the station and hauling work. The following results were obtained in the work:

- an analysis of the structures of traction systems of diesel locomotives produced by leading global companies was carried out, as a result of which it was established that the most effective scheme is traction power from a separate traction converter;
- the structure of the traction system of a shunting diesel locomotive was developed, where each traction engine receives power from a separate traction converter. Traction engines will be powered from the energy storage system during shunting work, and from the diesel generator or jointly from the energy storage system and the diesel generator during hauling work. Such a traction system will work effectively both when performing shunting work at the station and when performing hauling work.

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Розробка структури тягової системи маневрового тепловозу з гібридною схемою живлення

В цій роботі запропоновано структуру тягової системи маневрового тепловозу з гібридним живленням, що виконує як маневрову роботу на станції, так і вивізну роботу. Для розробки структури тягової системи, що буде ефективно працювати в обох режимах роботи маневрового тепловозу проведено аналіз структур тягових систем тепловозів з гібридним живленням, що випускаються провідними світовими компаніями. З метою вибору оптимального типу накопичувача проведено аналіз переваг та недоліків суперконденсаторних батарей та літій-іонних акумуляторів. На основі проведеного аналізу структур тягових систем тепловозів *з гібридним живленням провідних компаній та переваг і недоліків суперконденсаторних батарей та літій-іонних акумуляторів, розроблено структуру тягової системи маневрового тепловозу з гібридним живленням, що виконує як маневрову роботу на станції, так і вивізну роботу. В запропонованій структурі тягової системи кожен тяговий двигун отримує живлення від окремого тягового перетворювача. Потужність для живлення тягових двигунів при виконанні маневрової роботи передається від суперконденсаторних батарей, при виконанні вивізної роботи – від літій-іонних акумуляторів. Дане дослідження може бути використане при проектування тягової системи нового та при модернізації існуючого маневрового тепловозу.*

Ключові слова: *гібридне живлення, суперконденсатор, літій-іонний акумулятор, маневровий тепловоз, тягова система.*

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Analysis of stress state of passenger car bodies

The overwhelming majority of compartment cars owned by Ukrzaliznytsia JSC were manufactured in Germany in the 70-80s of the last century. They have exhausted their resource. The metal structures of the frame and body are badly worn. Extending the service life of such cars requires a thorough study of the possibilities of their further use. The article discusses the results of an analysis of the stress-strain state of passenger car bodies. A three-dimensional model of the body was built. Body strength calculations were performed using the finite element method using the ANSYS software package. The racks and upper trim of the side walls, roof arches, etc. were considered as rods. The body frame, substructure, side wall cladding, end walls, roof cladding and floor deck were modeled using plate finite elements. Calculations were carried out in accordance with the requirements of current regulatory documents. The maximum speed was assumed to be 160 km/h. The developed model was verified. The results obtained were compared with the results of experimental studies (strength tests). The similarity of the results confirmed the correctness of the created model. A study was carried out of the stress-strain state of the body at nominal sizes with standard skin thicknesses. It has been established that the stresses arising in the most loaded areas do not exceed the permissible values for structural steels. The resulting model of the body will subsequently make it possible to determine the wear limits of the load-bearing structures of the frame and body. It also allows, using the calculation-probabilistic method, taking into account the probabilistic nature of all existing loads, to calculate the reliability indicators of the car and its final life.

Key words: *passenger car, body, resource, wear, stresses.*

Introduction. Ukraine's movement into the European Union poses various challenges for the country's society and economy. But for railway transport, the primary task is the integration of domestic 1520 mm gauge railways into the European transport system [1].

This issue is especially relevant for ensuring passenger transportation. Passenger cars of JSC "Ukrzaliznytsia" were mainly inherited from the former USSR. The level of wear in the vast majority of cars exceeds 90%. The rolling stock primarily used by Ukrzaliznytsia is not only physically outdated but also morally obsolete.

But, in addition to physical wear and tear, passenger rolling stock is morally outdated and does not meet even the minimum requirements for comfort systems. The compartment width, fire safety system, ventilation system, toilets, and smoothness of movement do not meet European standards.To successfully compete with road transport, the railway must provide passengers with more comfortable conditions along the route, and the duration of a train trip should not exceed the time spent on a bus.

Passenger cars of the Kryukov Carriage Works fully comply with European sanitary standards and have improved design and comfort. However, the factory's production capacity and limited funding do not allow for the replacement of the entire fleet of passenger cars.

Another problem facing railway workers is ensuring the required speeds. To do this, it is necessary that the load-bearing elements of the body and frame comply with the requirements of current regulatory documents. Therefore, for cars that have already been in use for many years and have exhausted their service life, it is necessary to study the stress-strain state of the body and frame, taking into account wear.

The aging of the cars continues at a rapid pace, and it is not compensated by the arrival of new cars. Extending the service life of passenger cars through modernization, reconstruction, and modification is not a temporary measure but a fundamental requirement of market economic relations. However, while these cars still meet normative requirements in terms of passenger comfort, their operation is unacceptable in terms of ensuring safe movement due to a decrease and even loss of the body's load-bearing capacity.

Analysis of recent research and problem statement. A large number of studies have been devoted to increasing the strength and durability of passenger cars. Problems and prospects of passenger carriage construction are discussed in article [2]. Standard [3] contains structural and crashworthiness requirements for railroad passenger equipment of all types

The authors of article [4, 5] consider the technical condition of frames and bodies of passenger cars with a service life that exceeds the standard. A statistical analysis of the dependence of wear on the duration of operation for various types of cars was carried out.

The study [6] states that in conditions of systematic underfunding of the industry, carrying out overhaul repairs of passenger cars is a possible alternative to purchasing newly manufactured cars. At the same time, it is necessary to ensure the necessary level of strength, reliability and modern level of comfort.

Articles [7, 8] discuss possible options for organizing the repair and maintenance of passenger cars after major overhauls.

Works [9, 10] discuss the issues of reducing the weight of the body of a passenger car built by the Kryukov Carriage Plant, model 61-779. The authors built a three-dimensional computational model. Then, using the finite element method, strength calculations of the car body were performed.

Research [11, 12] is devoted to the analysis of the residual life of passenger cars, taking into account the strength of the bodies of open and compartment type cars.

In [13, 14], using the finite element method, a collision of a passenger car with a rigid wall was simulated. Structural weaknesses in the original design were identified. The authors assessed the accident rate and developed proposals for modernizing the passenger car.

A method to analyze the impact of design features of the integral scheme of passenger cars bodies on their stiffness and strength characteristics is proposed in [15].

Article [16] is devoted to the results of modeling the load of urban rail rolling stock. The calculations simulate various loading modes. The authors come to the conclusion that the resulting stresses are 75% of the permissible ones.

In this framework, the paper [17] proposes a new dynamic optimization approach to support the design of railway vehicle car bodies subject to static loads. The proposed methodology aims to minimize the mass of the metallic structure.

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 (the stress-strain state of compartment cars bodies that have exhausted their resource). To do this, it is necessary to build a calculated 3D model of the body and frame of the 47D car without a spinal beam in the middle part and, using the finite element method, determine the stress-strain state of the load-bearing elements of the body and frame, taking into account possible wear and tear in operation.

Materials and methods of research. The finite element method (FEM) is currently a fundamental method for solving solid mechanics problems using numerical algorithms. The method is based on discretization of the object in order to solve the equations of continuum mechanics under the assumption that these relationships are satisfied within each of the elementary regions. These areas are called finite elements. They can correspond to a real part of space or be a mathematical abstraction, like the elements of rods, beams, plates and shells. Within the finite element, the properties of the area of the object limited by it are assigned (this could be, for example, characteristics of the rigidity and strength of the material, density, etc.) and the fields of quantities of interest are described (in relation to solid body mechanics, these are displacements, deformations, stresses, etc.). d.). Parameters from the second group are assigned at the nodes of the element, and then interpolating functions are introduced, through which the corresponding values can be calculated at any point inside the element or on its boundary. The task of a mathematical description comes down to connecting the factors acting at the nodes. In continuum mechanics, these are, as a rule, displacements and forces.

The problem of determining the displacement field in the design of an axle box unit can be reduced to the problem of minimizing the total potential energy based on nodal displacements,

Body strength calculations were performed using the finite element method using the ANSYS software package in accordance with the requirements of DSTU [18]. The body was considered as a system of rod and plate finite elements. The calculation scheme is shown in Fig. 1 and in Fig. 2.

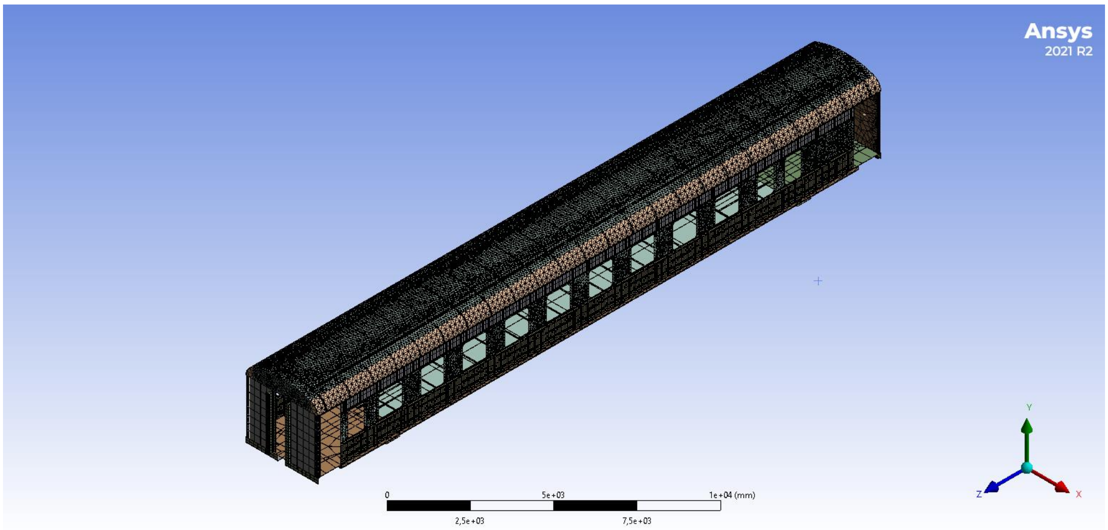

Fig. 1. **Passenger car 47Д body model**

As the rods, the racks and upper strapping of the side walls, roof arches, etc. were considered. The body frame, lower trim, side wall cladding, end walls, roof cladding and flooring were modeled using plate finite elements.

Rod finite elements work in tension (compression), bending, torsion and displacement. Flat finite elements work for bending (like plates) and for stretching (compression) under the action of forces whose lines of action lie in the middle plane.

In total, the design scheme contains 1,659,958 nodes and 722,470 finite elements.

Normative documents [18] provide for the need for calculations according to three calculation modes:

- I calculation mode corresponds to touching from a place, emergency braking at low speeds, collision during maneuvering, etc.;
- II calculation mode - train movement on the calculation climb (for passenger cars when they are included in freight trains);
- III calculation mode - movement with design speed and adjustable braking.

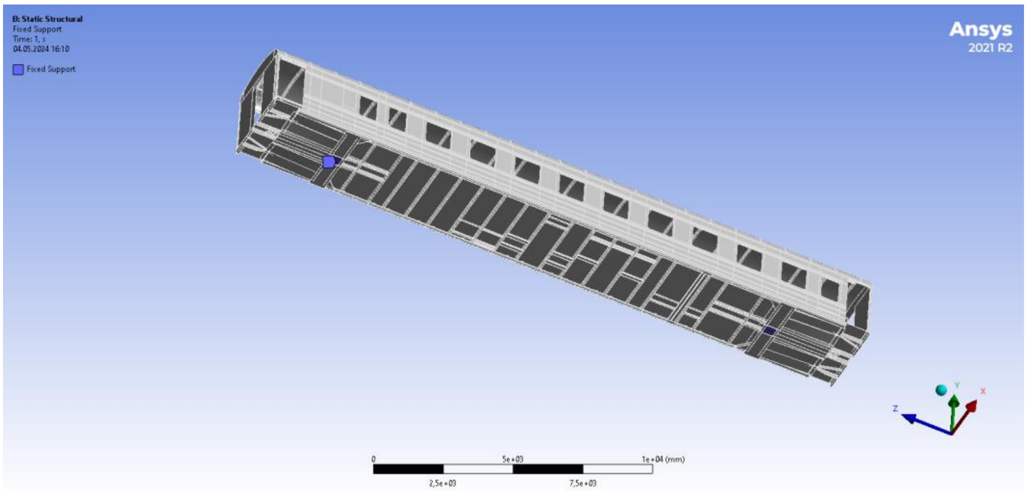

Fig. 2. **Passenger car 47D frame model**

Each of these calculation modes corresponds to a combination of loads that are added to the car body. Three groups can be distinguished: about longitudinal, vertical and lateral loads. Below is a description of each group.

Longitudinal loads are the longitudinal tensile or compressive force applied to the front or rear gussets, respectively. When calculating according to mode I, a compressive force of 2.5 MN is applied, mode II is not considered by the authors, when calculating according to mode III, the strength of the body is separately evaluated both under the action of a tensile force of 1 MN and under the action of a compressive force of the same magnitude (the case is considered action of a stretching force).

The group of vertical loads is formed by the gravity of the car body, the gravity of the internal equipment, equipment and passengers with luggage. This group, in addition to the static loads listed above, also includes additional dynamic components caused by the acceleration of the body in the vertical direction during the carriage movement.

The force of gravity Q acting on the car body is equal to the difference between the gross weight of the car and the weight of the trolleys. During the calculations, the car body was initially loaded by the force of gravity acting on the body's metal structure and by the gravity of large equipment units. A force equal to the difference between Q and the weight of the metalwork and equipment was applied to a uniformly distributed load acting on the floor of the car (Fig. 3).

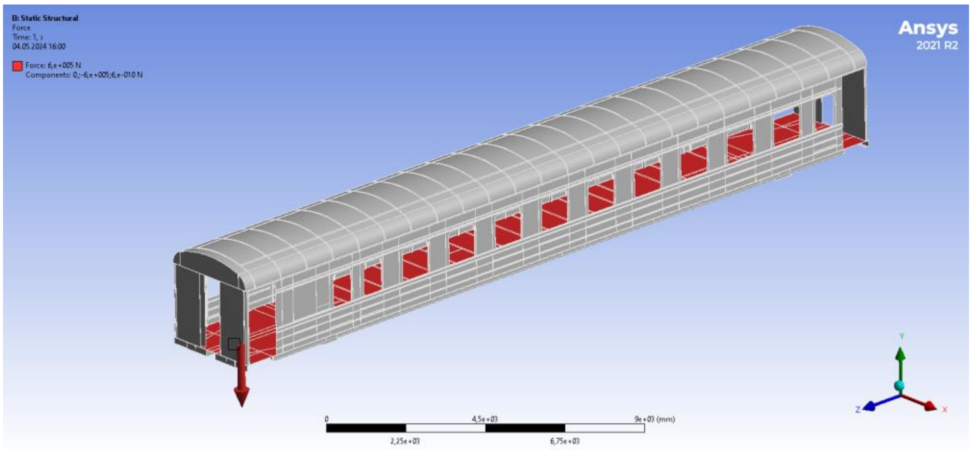

Fig. 3. **Scheme of application of a vertical load on the body of a passenger car**

When calculating according to the I mode, only the vertical static load is taken into account. When calculating according to mode III, the dynamic component is also taken into account by multiplying the static load by a factor $1 + k_{dv}$, where k_{dv} – calculated value of the coefficient of vertical dynamics for the car body.

The value k_{dv} is calculated according to known formulas [18].

$$k_{dv} = \overline{k}_{dv} \sqrt{\frac{4}{\pi} ln \frac{1}{1 - P(k_{dv})}}, \quad (1)$$

where $\overline{k}_{dv}$ is the average value of the vertical dynamics coefficient (mathematical expectation of the random process of changing the vertical dynamics coefficient $k_{dv}(t)$;
$P(k_{dv})$ – confidence probability. It is equal to $P(k_{dv})$=0.97.

The average value of the vertical dynamics coefficient $\overline{k}_{dv}$ визначається за наступною формулою

$$\overline{k}_{dv} = a + 3{,}6 \cdot 10^{-4} \cdot b \frac{V - 15}{f_{ст}}, \quad (2)$$

where a is an empirical coefficient, which for car bodies is equal to a=0.05;
b – coefficient depending on the number of axles in the cart (for biaxial carts b is equal to 1);
f_{st} – static deflection of spring suspension ($f_{st} = 0{,}15\ v$);
V – speed of movement in m/s.

During the calculations, it was assumed that the car moves at a maximum speed of 160 km/h and the third calculation mode is used.

Thus, for movement at a speed of 44.4 m/s, the average value of the coefficient of vertical dynamics $\overline{k}_{dv}$ was

$$\overline{k}_{dv} = 0{,}05 + 3{,}6 \cdot 10^{-4} \cdot 1 \frac{44{,}4 - 15}{0{,}15} = 0{,}121$$

$$k_{дв} = 0{,}121 \sqrt{\frac{4}{3{,}14} ln \frac{1}{1 - 0{,}97}} = 0{,}25.$$

The action of the lateral load should be taken into account only when calculating according to mode III. The force, which is equal to the difference of the centrifugal force and the horizontal component of the gravity force, which arises as a result of the elevation of the outer rail, for passenger cars is 10% of the gross force of gravity, i.e. 61 kN. Also taken into account is the force of wind pressure, which divides the area of the side projection of the body by the specific wind pressure (500 N/m^2), which for this car is equal to 38.6 kN. Thus, the total lateral load will be 99.6 kN. It is applied to the upper and lower lining of the side walls.

When carrying out calculations, two options for applying loads were considered. The first option corresponds to the I calculation mode, the second option – to the III calculation mode at a speed of 160 km/h.

The following options for changing the design and parameters of the body were considered:

– the thickness of the sheathing of the side walls and roof is 2.5 mm;

– the thickness of the sheathing of the side walls and roof is 2 mm;

– the thickness of the sheathing of the side walls and roof is 1.5 mm;

The developed model was verified. At the first stage, the calculation of the body with standard skin thicknesses was carried out. The obtained results were compared with the results of experimental studies (strength tests). The similarity of the results confirmed the correctness of the created model.

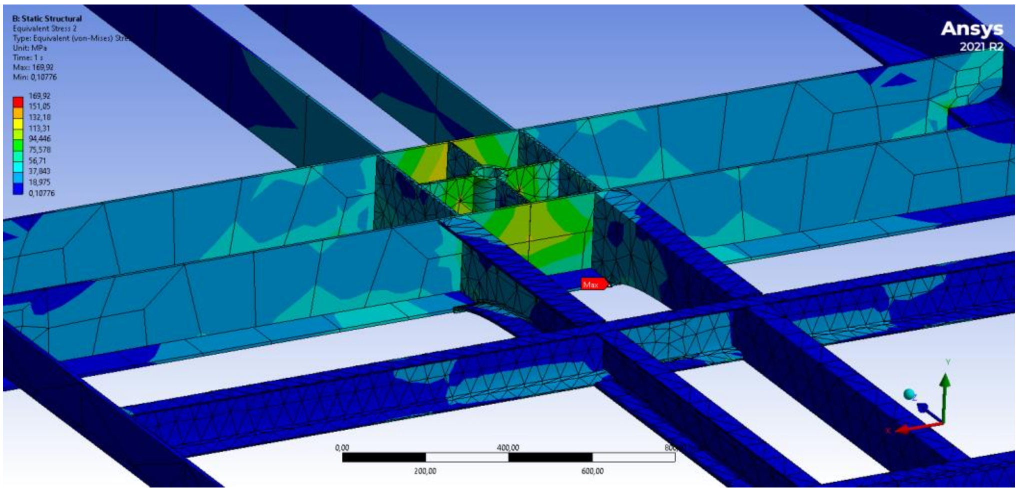

Fig. 4. **Diagram of stress distribution in the frame pivot assembly**

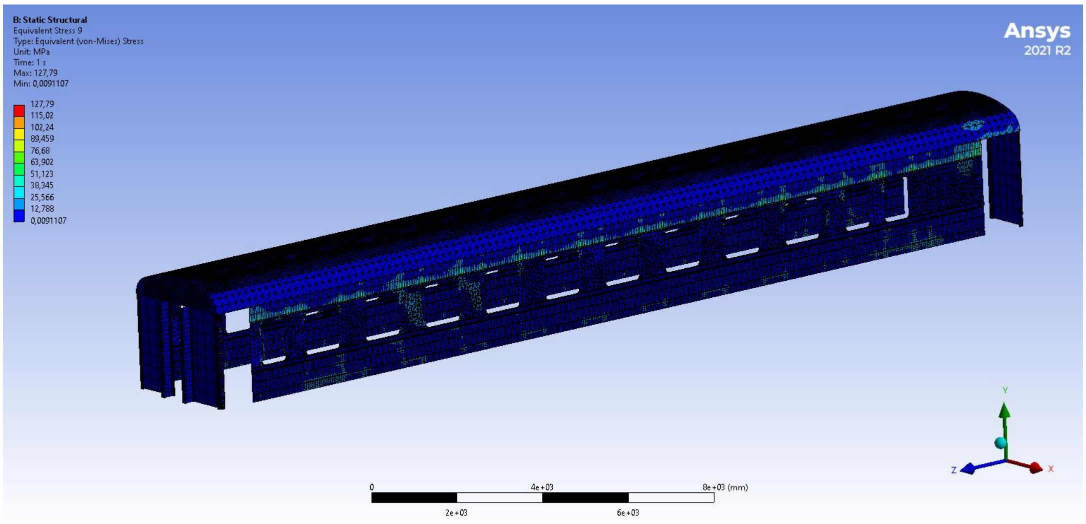

Fig. 5. **Diagram of stress distribution in the body of passenger car**

It has been established that the most loaded part of the structure is the thrust bearing unit. The maximum stress in the frame occurs at the junction of the pivot and center beams. When calculated according to 3 calculation mode, it reaches a value of 203 MPa.

The greatest stress in the body occurs in the upper corners of window openings, which are natural stress concentrators. With a sheathing thickness of 2.5 mm, it is 114 MPa. When the sheathing thickness is reduced to 1.5 mm, the stress increases to 178 MPa.

In the area above the window openings at the boiler end, when calculated according to 3 calculation mode , the maximum stress was 105 MPa with a sheathing thickness of 2.5 mm. When the sheathing thickness is reduced to 1.5 mm, the stress increases to 171 MPa, which is acceptable for the 09G2Kh steel grade used.

The dependences of stress on thickness are presented in Fig. 6 and 7.

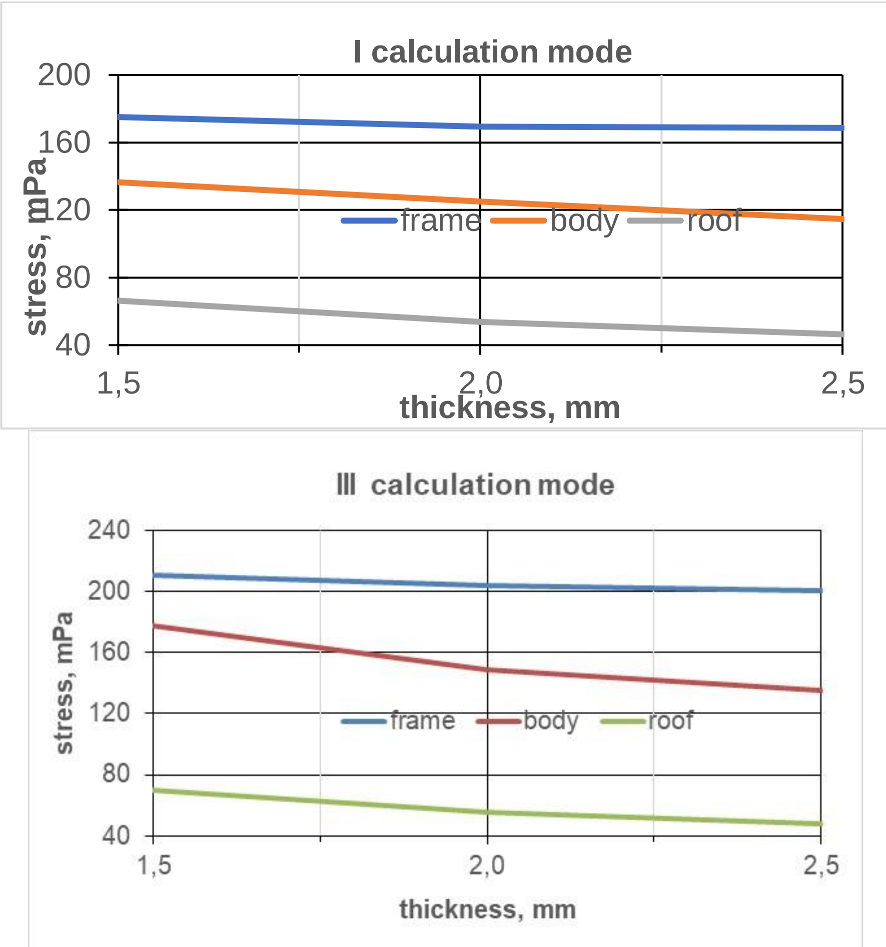

Fig. 6. **Diagram of stress distribution in the body of passenger car (speed 160 km/h)**

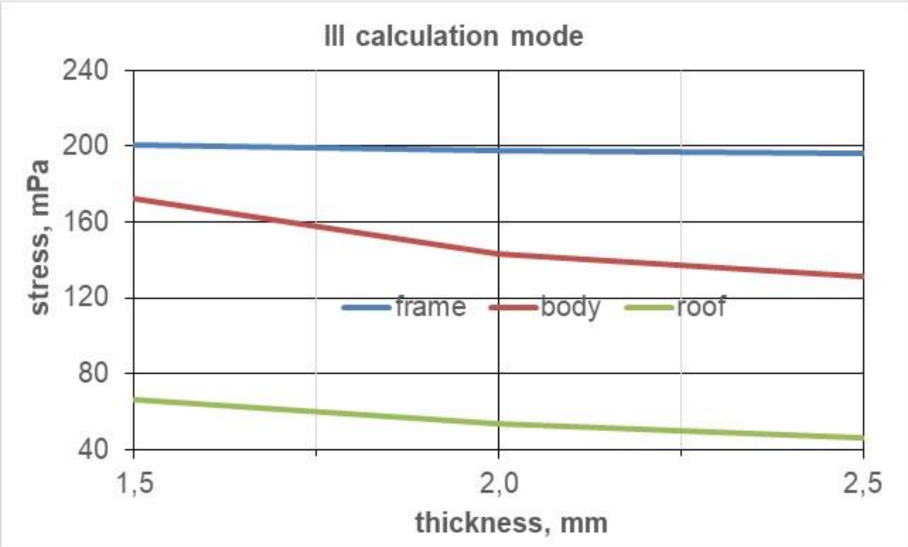

Fig. 7. **Diagram of stress distribution in the body of passenger car (speed 120 km/h)**

Analyzing the obtained dependencies, we can conclude that such body elements as the frame, roof and end walls, regardless of the design mode, have a sufficient margin of safety.

Thus, based on the results obtained, it can be concluded that the decrease body skin thickness up to 2 mm is significant does not affect the stress-strain joint standing.

The proposed option for reducing metal containers of the car body structure together with other activities will increase travel speed, reduce electrical consumption energy for traction and thereby increase the technical economic characteristics of passenger car.

Conclusion:

1. A finite element model of the body of a rigid compartment car 47D has been constructed. Beam and plate finite elements were used for modeling.
2. A study of the stress-strain state of the body at nominal dimensions with standard sheathing thicknesses was conducted. It was found that the stress occurring in the most loaded areas do not exceed the permissible values for structural steels.
3. The obtained body model will further allow determining the limit values of wear for the load-bearing structures of the frame and body and calculating, by probabilistic methods considering the probabilistic nature of all acting loads, the reliability indicators of the car and its ultimate service life.

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Аналіз напруженого стану кузовів пасажирських вагонів

Переважна частина купейних вагонів власності АТ Укрзалізниця була виготовлена у Німеччині у 70-80-х роках минулого століття. Вони вичерпали власний ресурс. Металоконструкції рами та кузова сильно зношені. Продовження терміну служби таких вагонів потребує ретельного вивчення можливостей їхнього подальшого використання. У статті розглянуто результати аналізу напружено-деформованого стану кузовів пасажирських вагонів. Побудовано тривимірну модель кузова. Розрахунки кузова на міцність виконувались методом скінчених елементів за допомогою програмного комплексу ANSYS. Як стрижні розглядалися стояки та верхня обв'язка бічних стін, дуги даху і т. д. Рама кузова, нижня обв'язка, обшивка бічних стін, торцеві стіни, обшивка даху та настил підлог моделювалися за допомогою пластинчастих скінчених елементів. Розрахунки проводилися відповідно до вимог чинних нормативних документів. Максимальна швидкість руху приймалася рівною 160 км/год. Було здійснено верифікацію *розробленої моделі. Отримані результати порівнювали з результатами експериментальних досліджень (випробувань міцності). Подібність результатів підтвердила правильність створеної моделі. Проведено дослідження напружено деформованого стану кузова при номінальних розмірах зі стандартними товщинами обшиви. Встановлено, що напруги, що виникають у найбільш навантажених місцях, не перевищують допустимі значення конструкційних сталей. Отримана модель кузова надалі дозволить визначати граничні величини зношування несучих конструкцій рами і кузова і розраховувати розрахунково-імовірнісним методом з урахуванням імовірнісного характеру всіх навантажень, що діють, показники надійності вагона і його остаточний ресурс.*

Ключові слова: *пасажирський вагон, кузов, ресурс, спрацювання, напруження*.

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Innovative approaches to developing national railway safety policy and training safety leaders

The article is aimed at considering innovative approaches in the formation of the national policy on safety in railway transport and on the training of safety leaders in this strategically important field. Focusing on today's challenges and opportunities, the article aims to identify key areas of development where innovation can improve safety and improve leadership training. It assesses the impact of technological and innovative changes on railway safety. The research also examines mechanisms and methods for introducing innovations into national railway safety policy, focusing on best practices from other countries and analysing the positive outcomes of such implementations. Additionally, it evaluates the competencies and skills required for leaders in the rail safety industry, highlighting key aspects of a leadership approach to solving security problems and developing national strategies. Furthermore, the study aims to develop training programs for security leaders by identifying essential elements and directions for training and creating innovative methods for skill development that address modern requirements and challenges in railway safety. This research provides a roadmap for enhancing railway safety through innovation and effective leadership, proposing actionable solutions and best practices to improve safety standards in the railway sector.

***Key words**: Railway safety, national policy, safety leadership, risk factors, training programs*

Introduction. Maintaining public trust in the safety of the railway transportation system is crucial for the sustainable development of the industry. Transparent communication about safety measures, incident investigations, and corrective actions is essential for building and maintaining trust among passengers and stakeholders.

Modern railway transportation systems are characterized by increased volumes of passenger and freight traffic. Such a change in operational conditions places additional stress on railway infrastructure and operations, increasing the likelihood of accidents and incidents. Technological progress, such as automation and digitalization, opens new opportunities for enhancing railway safety but simultaneously creates new risks, particularly in the area of cybersecurity. Meanwhile, many railway transportation systems, especially in Ukraine, suffer from aging infrastructure, which poses safety risks due to deteriorating track conditions and outdated signalling systems.

It is worth noting that addressing environmental issues, such as climate change and pollution, is becoming increasingly important for railway safety. The implementation of environmentally friendly technologies and practices can reduce the impact of railway operations on the environment while simultaneously enhancing safety.

Railway networks often operate across multiple countries, requiring coordination and harmonization of safety standards and regulations. Enhanced cooperation between EU member states and neighboring countries, such as Ukraine, is crucial for ensuring consistent safety practices across borders.

Changes in the legal framework for railway safety, both in the EU and Ukraine, aim to raise safety standards and ensure compliance with international norms. However, effectively implementing these changes at all levels of the industry remains a challenging task.

The ability to effectively manage and respond to incidents, such as derailments or collisions, is crucial for minimizing their impact on railway safety.

The human factor continues to be a significant contributor to railway accidents. Ensuring comprehensive training programs for railway personnel, including drivers, maintenance workers, and signaling staff, is essential for mitigating risks associated with human safety [1-3].

Analysis of recent research and problem statement.

The research [1] conducted by the Institut pour une culture de sécurité industrielle (Icsi) focuses on enhancing safety improvements in businesses that have already made significant strides in the domain. The key focus of this study is on the Human and Organizational Factors of Safety, specifically the development of managerial leadership in safety.

The research emphasizes that managerial behavior has the most substantial influence on staff conduct. This finding underscores the critical role that managers play in shaping the safety culture within an organization (Fig. 1).

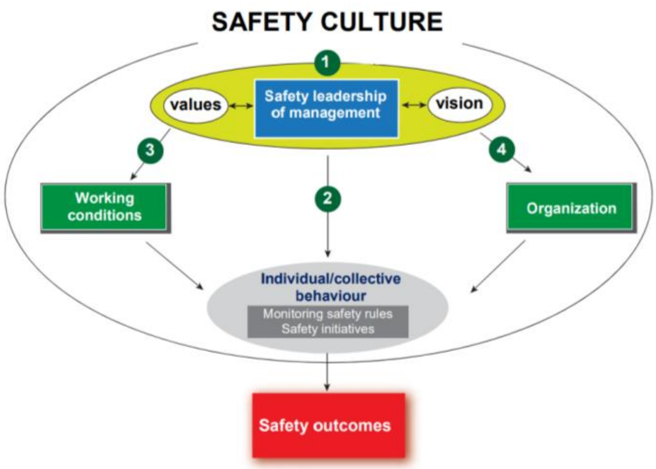

Fig. 1. **Safety leadership [1]**

Management is highlighted as pivotal in handling trade-offs between safety and other operational concerns. This role requires managers to prioritize safety without compromising other essential aspects of the business.

The study asserts that site safety cannot solely be the responsibility of Health, Safety, and Environment (HSE) specialists. Instead, it requires a broader involvement from all levels of management and staff.

The discussion group faced difficulties in making specific recommendations for establishing leadership in safety. This led to the formation of the "Leadership in Safety" Working Group to delve deeper into understanding the conditions that foster leadership.

The Working Group began by examining professions where leadership is critical, such as plant directors, construction managers, maintenance shutdown managers, and HSE actors. This approach provided initial insights but was deemed insufficiently comprehensive.

Recognizing the need for a broader perspective, the research expanded to include views from local supervisors, team leaders, and members of the Health and Safety committee. This inclusion aimed to develop a more grounded and practical concept of leadership.

The Working Group identified a set of broad leadership principles applicable across various professions and functions. These principles served as a foundation for further exploration.

This research underscores the indispensable role of managerial leadership in enhancing safety culture and practices within industrial settings. It highlights the necessity for inclusive and comprehensive approaches that involve various levels of the organization. The practical advice derived from the seminars and discussions aims to aid professionals in effectively implementing and improving safety leadership, thereby fostering a safer working environment.

The Leadership in Safety Working Group identified and described seven general leadership principles that are crucial for promoting safety in the workplace [1]. These principles were developed based on typologies used by the employers of the group members. Each principle was translated into concrete action axes, summarizing good practices and action principles aimed at safety leaders at all levels. Below is a detailed analysis of these principles (Table 1).

Table 1. **Analysis of safety leadership principles and action axes**

Principles	The name of the principle	Analysis
1	2	3
Principle 1	Create a safety vision coherent with management values and principles	A coherent safety vision aligns with management values, ensuring that safety is integrated into the core values of the organization. This principle emphasizes inclusivity and collective responsibility, involving all stakeholders in developing a shared safety vision. The action axes focus on establishing clear goals and fostering a culture of accountability.
Principle 2	Give safety its rightful place in the organization and management	This principle ensures that safety is embedded in the organizational structure and daily operations. It emphasizes clear role definitions, resource allocation, and proactive obstacle removal to facilitate a continuous focus on safety. Involving all stakeholders, including service providers, in safety monitoring fosters a comprehensive safety culture.
Principle 3	Share the safety vision	Effective communication is key to sharing the safety vision. Regular reminders, clear communication, and fostering a culture of trust and transparency are crucial. Encouraging risk observation and supporting initiatives help maintain high safety standards and collective responsibility.
Principle 4	Be credible and provide a coherent example	Credibility in leadership is vital for fostering a safety culture. Leaders must demonstrate expertise, fairness, and daily commitment to safety. Personal involvement in safety plans and the ability to challenge and question practices reinforce the leader's commitment and credibility.
Principle 5	Promote team spirit and horizontal cooperation	Promoting team spirit and cooperation is essential for effective safety management. Encouraging discussion, sharing tools, and fostering close relationships between safety officials and field workers ensure a collaborative approach to safety. Emphasizing collective responsibility and transparency enhances the overall safety culture.

Continuation of Table 1.

1	2	3
Principle 6	Be available on-site to observe, listen, and communicate	On-site presence and active listening are crucial for effective safety leadership. Regular field visits, meetings, and involving service providers enhance communication and understanding of safety issues. Highlighting successes and addressing challenges directly with stakeholders foster a proactive safety culture.
Principle 7	Acknowledge good practice and apply fair sanctions	Recognizing and rewarding good practices, while fairly sanctioning unacceptable conduct, reinforces the importance of safety. Transparent justification of sanctions and celebrating successes motivate employees to adhere to safety standards and foster a positive safety culture

The seven principles and their corresponding action axes provide a comprehensive framework for enhancing safety leadership in industrial settings. By emphasizing vision, integration, communication, credibility, cooperation, presence, and recognition, these principles aim to create a robust safety culture that permeates all levels of an organization.

The implementation of innovations in the formation of national railway safety policies in the European Union (EU) is based on various mechanisms and tools. Here are some of them along with examples:

1. *Creation of innovative programs and initiatives*. The EU actively promotes the creation of programs and initiatives aimed at supporting innovations in the railway sector. For example, the "Evaluation of Rail Innovation Programme" [4, 5] funds research and the development of new technologies and safety practices.
2. *Standardization and harmonization*. The EU encourages the standardization and harmonization of the regulatory environment to facilitate the implementation of innovations. For instance, Directive 2016/798/EC [6] on railway safety establishes common principles and safety requirements for EU railways.
3. *Establishment of innovative partnerships*. The EU actively supports the creation of partnerships between industry players, government bodies, and academic institutions for the joint implementation of innovative projects. An example is the Shift2Rail project [7, 8], a joint initiative between the EU and railway companies to develop new technologies and market solutions for railway transport.
4. *Funding of innovative projects*. The EU provides financial support for innovative projects in the railway sector through various programs and funds. For instance, the Horizon Europe program [9] finances research and innovation across all sectors, including transport.
5. *Stimulating the development of the innovation market*. The EU actively promotes the creation of a competitive market for innovations in the railway sector by ensuring equal access conditions for various suppliers and developing innovative market models.

An example of a successful EU innovative initiative is the Shift2Rail program, which aims to create new technologies and innovative solutions for railway transport to enhance the efficiency, safety, and sustainability of the system. This program unites the efforts of industry players and railway companies for the joint implementation of projects focused on the development of new technologies and innovative solutions [10].

The purpose and tasks of the study. The purpose of this research is to explore innovative approaches towards the establishment of a comprehensive national policy on railway safety and the cultivation of effective safety leaders within the railway industry.

Objectives of the study:

1. To study the mechanisms of introducing innovations into national policy. Consider various mechanisms and methods of introducing innovations in the formation of national railway safety policy, focusing on best practices from other countries. To analyse the positive results of the implementation of innovative approaches in national security strategies.

2.To evaluate leadership competencies in railway safety. Conduct an analysis of the competencies and skills needed by leaders in the rail safety industry. Identify the key aspects of a leadership approach to solving security problems and developing national strategies.

3. Develop training and training programs for security leaders. Identify the key elements and directions of the training and training program for leaders in the field of railway safety. To develop innovative methods of training and development of skills that will meet the modern requirements and challenges of railway safety.

Materials and methods of research. *Implementation of innovations in national policy for railway safety in Ukraine.*

The goal is enhance the safety and efficiency of Ukraine's railways through innovative approaches and align with international best practices and standards.

Mechanisms for introducing innovations is shown in the Fig. 2.

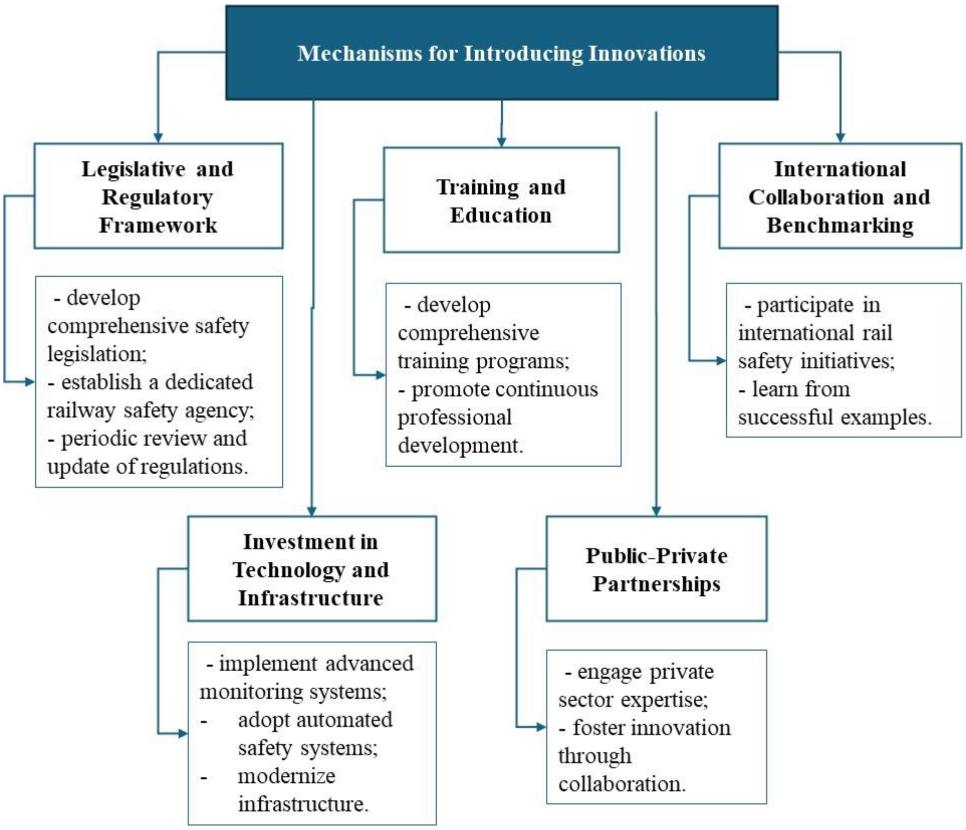

Fig. 2. **Mechanisms for introducing innovations**

Developing comprehensive safety legislation involves updating existing rail safety laws and ensuring compliance with European Union (EU) rail safety directives. An important condition is the creation of an independent body responsible for overseeing railway safety. Investments in technology and infrastructure should ensure the implementation of real-time monitoring systems for track condition, train operation and environmental factors. Predictive maintenance technologies must be used to identify and resolve potential problems before they cause incidents.

Development of specialized training programs for railway personnel incorporating the latest technology and safety practices is a necessity for the industry. Simulation-based learning to gain hands-on experience is also important. Promotion of continuous professional development should encourage the improvement of skills and include certification of railway safety professionals.

Creating innovation hubs and collaborative platforms where government, industry and academia can work together on security projects is also important. The development and testing of new security technologies should be encouraged through pilot programs. International cooperation will make it possible to compare railway safety indicators in Ukraine with international standards, which will make it possible to adapt best practices in accordance with the specific conditions and needs of Ukrainian railways.

Practical examples of successful implementation:

1. *Japan:*
   - Shinkansen High-Speed Rail:
     - Uses advanced earthquake detection and automatic train control systems [11].
     - Achieved an unparalleled safety record with no passenger fatalities due to train accidents since its inception in 1964.
   - Key innovations:
     - Continuous track monitoring and maintenance.
     - Automated train protection systems and rigorous safety protocols.
2. *Germany:*
   - Deutsche Bahn's Digital Rail Strategy:
     - Implementation of the European Train Control System (ETCS) for standardized train control [12].
     - Use of digital technologies to enhance signaling, communication, and train operations.
   - Key innovations:
     - Predictive maintenance through digital diagnostics.
     - Enhanced safety through real-time monitoring and automation.
3. *France:*
   - SNCF's Safety Management Systems:
     - Comprehensive safety management systems integrating risk assessment, incident reporting, and continuous improvement [13].
     - Strong emphasis on staff training and safety culture.
   - Key innovations:
     - Implementation of advanced signalling systems like ERTMS (European Rail Traffic Management System) [14].
     - Proactive safety culture with regular safety drills and training programs.

Steps for implementing innovations in the formation of the national safety policy on the railways of Ukraine:

1. *Assessment of the current state*. A thorough assessment of the current railway safety situation in Ukraine needs to be carried out and key areas for improvement and potential for innovation identified.

2. *Development of a strategic plan.* It is necessary to formulate a strategic plan for the implementation of innovative technologies and practices and establish clear, measurable goals and time frames for implementation.

3. *Launch of pilot projects.* Pilot projects should be launched to test new technologies and approaches in selected regions or routes. This will allow you to evaluate the results and refine the implementation strategy based on the results.

4. *Expansion of successful initiatives.* In the future, it is necessary to gradually bring successful pilot projects to the national level and ensure constant monitoring and evaluation for adaptation to new challenges and opportunities.

5. *Involvement of interested parties.* It is important to involve all relevant stakeholders in the planning and implementation process, including government agencies, railway operators, industry experts and

the public. This will create a collaborative environment to ensure broad support and successful innovation.

Assessment of leadership competencies in the field of railway safety.

Railway safety leadership is a specific form of leadership focused on creating and maintaining a safe working environment in the railway industry. It includes management approaches, strategies and practices aimed at preventing injuries and accidents on the railway, as well as improving the safety culture among staff. Leadership in railway safety involves the active role of managers in setting safety standards, spreading safety skills and knowledge among employees, and establishing mechanisms for monitoring and controlling the implementation of safe work practices. Key characteristics of rail safety leadership include a commitment to safety, effective communication, the ability to make decisions in the face of uncertainty, and encouraging initiative and responsibility for safety in all employees.

Based on the analysis of the Leadership in Safety Working Group's principles [1] and their application to rail safety, here are seven principles specifically tailored for rail safety leaders (Table 2).

Table 2. **Seven principles specifically tailored for rail safety leaders**

Principles	The name of the principle	Action axes
1	**2**	**3**
Principle 1	Establish a Coherent Safety Vision	1. Develop a comprehensive rail safety policy aligned with management values. 2. Prioritize safety within the context of operational challenges. 3. Conduct regular safety assessments to set future goals. 4. Set specific, measurable, and achievable safety objectives. 5. Involve all stakeholders in creating and understanding the safety vision. 6. Use the vision to define accountability and expected conduct for all employees.
Principle 2	**Integrate Safety into All Levels of the Organization**	1. Embed safety practices across all organizational levels and departments. 2. Clearly define roles and responsibilities for safety among all staff. 3. Develop and implement an improvement plan that aligns with the overall safety vision. 4. Identify and mitigate obstacles to achieving safety goals. 5. Allocate necessary resources to support safety initiatives. 6. Make safety a daily priority and protect it from competing interests. 7. Involve service providers and staff in safety monitoring and improvement efforts.

Continuation of Table 2.

1	2	3
Principle 3	**Communicate and Share the Safety Vision**	1. Regularly communicate safety goals and expectations to all staff. 2. Reinforce safety messages to maintain vigilance and engagement. 3. Use clear, appropriate language to ensure understanding across all levels. 4. Create systems to identify and report safety risks, including weak signals. 5. Foster a climate of trust and transparency in safety communications. 6. Encourage and recognize good safety practices and initiatives. 7. Emphasize that safety is a collective responsibility.
Principle 4	**Demonstrate Credibility and Lead by Example**	1. Ensure all leaders have sufficient expertise in rail safety. 2. Exercise fair and honest judgment in safety matters. 3. Exemplify compliance with safety standards, even under challenging conditions. 4. Show daily commitment to safety through decisions and actions. 5. Be personally involved in implementing the Safety Action Plan. 6. Challenge and question safety practices, including those of senior staff. 7. Provide clear reasoning for safety decisions and ensure they are understood.
Principle 5	**Foster Team Spirit and Horizontal Cooperation**	1. Encourage team discussions to address safety issues and share best practices. 2. Implement coordination methods for a comprehensive view of risks. 3. Promote the sharing of safety tools and methodologies. 4. Strengthen relationships between safety officials and operational staff. 5. Ensure all team members feel included and share responsibility for safety. 6. Make teams accountable for each other’s safety results. 7. Support transparency and collective progress in safety practices.

Continuation of Table 2.

1	2	3
Principle 6	**Be Present and Engage on the Ground**	1. Conduct regular site visits and establish clear safety requirements. 2. Hold frequent safety meetings with various departments. 3. Involve service providers in site visits and safety discussions. 4. Recognize and highlight positive safety practices. 5. Address and correct unsafe practices promptly. 6. Review field reports and follow up with relevant staff. 7. Meet with accident victims to understand issues and improve safety measures.
Principle 7	**Recognize Good Practices and Enforce Fair Sanctions**	1. Highlight and reward good safety practices and initiatives. 2. Offer incentives and raise safety awareness. 3. Celebrate collective safety achievements. 4. Select service providers committed to safety standards. 5. Define unacceptable safety behaviors and corresponding sanctions. 6. Analyze the context before applying sanctions to ensure fairness. 7. Transparently justify sanctions based on established safety rules.

These principles provide a comprehensive framework for rail safety leaders to cultivate a robust safety culture within their organizations. By focusing on vision, integration, communication, credibility, cooperation, presence, and recognition, rail safety leaders can effectively enhance safety standards and practices across all levels of their operations.

Competencies and skills needed by safety leaders in the rail industry.

Safety leaders in the rail industry require a diverse set of competencies and skills to effectively manage and enhance safety standards. These can be categorized into technical skills, interpersonal skills, strategic skills, and specific knowledge areas (Fig. 3-6).

Technical Skills

- *Risk Assessment and Management:*
  - Ability to identify, assess, and prioritize risks.
  - Proficiency in using risk assessment tools and methodologies.
- *Incident Investigation and Analysis:*
  - Competence in conducting thorough investigations to determine root causes of incidents.
  - Skills in applying analytical techniques to derive actionable insights.
- *Regulatory Compliance:*
  - Deep understanding of national and international railway safety regulations and standards.
  - Capability to ensure compliance with all relevant safety laws and guidelines.
- *Safety Management Systems:*
  - Expertise in developing, implementing, and maintaining effective safety management systems (SMS).
  - Knowledge of best practices in safety auditing and monitoring.

Fig. 3. **Technical Skills**

Interpersonal Skills

- *Communication:*
  - Strong verbal and written communication skills to convey safety policies and procedures clearly.
  - Ability to engage with all levels of the organization, from top management to frontline workers.
- *Leadership and Influence:*
  - Skills to inspire, motivate, and influence others to prioritize safety.
  - Ability to lead by example and foster a safety-first culture.
- *Conflict Resolution:*
  - Proficiency in addressing and resolving conflicts related to safety issues.
  - Capability to negotiate and mediate between different stakeholders.

Fig. 4. **Interpersonal Skills**

Strategic Skills

- *Visionary Thinking:*
  - Ability to develop a long-term vision for railway safety and align it with organizational goals.
  - Competence in setting strategic safety objectives and creating a roadmap to achieve them.
- *Change Management:*
  - Skills in managing and leading organizational change to improve safety culture and practices.
  - Ability to handle resistance to change and ensure smooth transitions.

Fig. 5. **Strategic Skills**

Specific Knowledge Areas

- *Human Factors:*
  - Understanding of how human behavior impacts safety and how to design systems that minimize human error.
  - Knowledge of ergonomic principles and their application in the railway environment.
- *Emergency Preparedness:*
  - Skills in planning and executing emergency response drills and procedures.
  - Capability to develop and maintain robust emergency preparedness plans.
- *Technological Innovations:*
  - Awareness of new technologies and innovations in railway safety.
  - Ability to evaluate and implement technological solutions to enhance safety.

Fig. 6. **Specific Knowledge Areas**

The importance of a leadership approach to solving railway safety problems and creating a national strategy is based on:

1. *Coordinated efforts and consistency.* A leadership approach ensures that safety initiatives are consistently implemented across the entire railway network. This coordination helps in avoiding fragmented efforts and ensures uniform safety standards.
2. *Strategic alignment.* Leadership is essential for aligning safety objectives with the broader goals of the railway industry. It ensures that safety is integrated into all strategic decisions and operational plans.
3. *Cultural transformation*. Effective leadership drives cultural change within organizations, promoting a safety-first mindset. Leaders can influence attitudes and behaviors, fostering a culture where safety is a shared responsibility.
4. *Enhanced communication and collaboration.* Safety leaders play a crucial role in facilitating communication and collaboration among various stakeholders, including regulatory bodies, railway companies, and the public. This collaboration is vital for addressing complex safety challenges.
5. *Proactive risk management.* Leadership enables proactive identification and management of risks. Leaders can anticipate potential safety issues and implement preventive measures before they escalate into serious incidents.
6. *Adaptability and innovation.* Leaders are pivotal in promoting and adopting innovative solutions to safety problems. They can drive the adoption of new technologies and practices [15, 16] that improve safety outcomes.
7. *Regulatory and public trust.* Strong safety leadership enhances compliance with regulatory requirements and builds public trust in the safety of the railway system. This trust is crucial for the continued growth and success of the railway industry.

Safety leaders in the rail industry need a comprehensive set of competencies and skills, spanning technical expertise, interpersonal abilities, strategic vision, and specific knowledge areas. A leadership approach to railway safety is critical for ensuring coordinated efforts, strategic alignment, cultural transformation, enhanced communication, proactive risk management, adaptability, and innovation. By fostering strong safety leadership, the railway industry can effectively address safety challenges and create a robust national safety strategy that protects both passengers and employees.

Key elements of an education and training program for rail safety leaders.

1. Program overview.

- Objectives:
  - Develop a comprehensive understanding of rail safety principles.
  - Equip leaders with skills to manage and improve rail safety.

    - Foster a safety-first culture within the organization.

2. Curriculum design.
- Core Modules:
    - Introduction to Rail Safety:
        - Overview of rail safety principles and regulations.
        - History and evolution of rail safety standards.
    - Risk Assessment and Management:
        - Techniques for identifying and assessing risks.
        - Strategies for mitigating and managing risks.
    - Incident Investigation and Analysis:
        - Methods for investigating rail incidents.
        - Root cause analysis and reporting.
    - Human Factors and Ergonomics:
        - Understanding human error and its impact on safety.
        - Designing systems to minimize human error.
    - Safety Management Systems (SMS):
        - Components and implementation of SMS.
        - Continuous improvement and auditing of safety systems.
    - Emergency Preparedness and Response:
        - Developing and executing emergency response plans.
        - Conducting drills and evaluating readiness.
    - Leadership and Communication:
        - Effective communication strategies for safety leaders.
        - Building and leading safety-focused teams.
    - Technological Innovations in Rail Safety:
        - Latest technologies and their application in rail safety.
        - Case studies of successful technology implementations.

3. Innovative learning methods.
- Interactive Workshops:
    - Hands-on sessions with real-life scenarios and case studies.
    - Group discussions and problem-solving activities.
- Simulations and Role-Playing:
    - Simulated incidents to practice response and decision-making.
    - Role-playing exercises to develop communication and leadership skills.
- E-Learning Modules:
    - Online courses for flexible learning schedules.
    - Multimedia content including videos, quizzes, and interactive materials.
- Field Visits and Practical Training:
    - Visits to operational rail facilities to observe best practices.
    - Practical training sessions on-site to apply learned concepts.
- Mentorship and Coaching:
    - Pairing trainees with experienced safety leaders for guidance and support.
    - Regular feedback and performance reviews.

4. Skill development.
- Technical Skills:
    - Proficiency in safety management tools and technologies.
    - Ability to conduct thorough risk assessments and safety audits.
- Analytical Skills:
    - Competence in analysing data to identify trends and areas for improvement.
    - Capability to develop and implement effective safety strategies.
- Leadership Skills:

  - Strong leadership qualities to inspire and influence others.
  - Skills to build a safety-first culture and manage safety teams.
- Communication Skills:
  - Clear and effective communication to convey safety policies and procedures.
  - Ability to engage with stakeholders at all levels.
- Decision-Making Skills:
  - Making informed decisions under pressure.
  - Balancing safety with operational efficiency.

5. Evaluation and continuous improvement

- Performance Assessments:
  - Regular assessments to evaluate trainees' knowledge and skills.
  - Feedback mechanisms to identify areas for improvement.
- Continuous Learning:
  - Opportunities for ongoing education and professional development.
  - Access to the latest research and developments in rail safety.
- Program Evaluation:
  - Regular review and update of the training program to ensure relevance and effectiveness.
  - Incorporation of trainee feedback to enhance the learning experience.

An education and training program for rail safety leaders should be comprehensive, covering all essential aspects of rail safety, and should employ innovative learning methods to ensure effective skill development. By focusing on both technical and leadership skills, and incorporating continuous improvement practices, the program can prepare safety leaders to effectively manage and enhance rail safety, fostering a culture of safety within the organization.

The main objective of the course is to raise the awareness of managers and professionals of the railway industry about the importance of safety leadership. The training emphasizes the need to put safety first in everyday actions, in every decision made. Upon completion of the course, each participant should have a clear understanding of what safety leadership is and how to improve it.

The Rail Safety Leadership training course has been designed to raise awareness among railway managers and professionals about the importance of safety leadership and to teach them how to improve safety through their daily actions and decision-making. The main objectives of the course include:

- awareness of the importance of safety;
- development of leadership skills;
- introduction of safety culture;
- learning through practicality;
- stimulation of changes.

Course participants will gain an understanding that safety is a critical component of successful rail operations and that leadership plays a key role in ensuring safety. The course enables participants to develop effective security leadership skills, including communication, decision-making and staff motivation skills. During training, participants should be encouraged to actively incorporate safety principles into their daily activities and management practices to create a safe and healthy work environment. It is important to provide hands-on experience and interactive exercises that allow participants to learn specific strategies and techniques for rail safety leadership. Participants should also be encouraged to be change agents in their organizations, which will contribute to the improvement of security practices and processes.

Rail safety leaders must have a variety of competencies and skills to effectively implement and maintain safety standards and practices. Here are some of them:

1. Expert knowledge in the field of railway transport safety. Leaders must have an in-depth knowledge of the safety requirements, standards and regulations that apply to the rail industry. This includes understanding operational processes, technical aspects of infrastructure and rolling stock, as well as security risks and threats.

2. Leadership skills. Leaders must have the skills to effectively manage and motivate staff. This includes the ability to create an open and supportive work environment, the ability to communicate effectively with employees at various levels, and the ability to lead and develop a team.

3. Analytical abilities. Leaders must be able to analyze complex situations and make informed decisions based on available data and security information.

4. The ability to make decisions in conditions of uncertainty. In the railway industry, situations may arise where you need to react quickly and make decisions in conditions of uncertainty. Leaders must have risk assessment skills and the ability to make informed decisions, even in difficult circumstances.

5. Ability to communicate and influence. Leaders must have excellent communication skills to effectively communicate with and influence various stakeholders to support rail safety.

6. Strategic thinking. Leaders must have the ability to plan long-term and develop strategies to improve rail safety.

7. Creativity and innovativeness. Leaders must be open to innovative approaches and innovations in security that can help achieve goals and improve results.

Conclusions. Safety leadership is essential to ensuring employee safety, reducing risk and incidents, increasing employee engagement, and enhancing organizational reputation. Safety leadership contributes to the formation and strengthening of the safety culture in the organization. Leaders who actively support and embody the principles of safety in their work create a positive example for subordinates and contribute to the establishment of norms and values related to safety. Leaders who prioritize safety help avoid and reduce the risk of incidents and accidents. Their management and decision-making is based on putting safety first, helping to ensure a safer work environment for all employees. Leaders who take an interest in safety and actively involve staff in decision-making and safety implementation processes create a more engaged and accountable work environment.

Organizations with strong security leadership typically have a better reputation with consumers, investors, and regulators. This can help increase brand trust and create positive relationships with stakeholders.

The research has explored innovative approaches to establishing a comprehensive national policy on railway safety and cultivating effective safety leaders within the railway industry. The study's objectives were successfully addressed through the following findings:

Firstly, the research examined various mechanisms and methods for introducing innovations into national railway safety policies. By focusing on best practices from other countries, the study highlighted how the integration of advanced technologies, standardized regulations, and collaborative initiatives can lead to significant improvements in railway safety. Positive outcomes from the implementation of these innovative approaches in national security strategies were analyzed, providing a framework for potential adaptation in other contexts.

Secondly, the evaluation of leadership competencies in railway safety revealed the critical skills and attributes required by safety leaders. The analysis underscored the importance of a leadership approach in addressing security challenges and developing robust national strategies. Effective safety leaders must possess a blend of technical expertise, strategic thinking, and the ability to foster a culture of safety across all organizational levels.

Lastly, the study developed a comprehensive framework for training programs aimed at security leaders in the railway sector. Key elements and directions for these programs were identified, emphasizing innovative training methods and skill development tailored to contemporary railway safety requirements. The proposed training initiatives aim to equip safety leaders with the necessary tools to effectively manage and mitigate safety risks in the ever-evolving railway environment.

In conclusion, the research provides valuable insights into the formation of a national railway safety policy and the development of competent safety leaders. By leveraging innovative approaches and focusing on best practices, the railway industry can enhance its safety standards and ensure a secure and efficient transportation system.

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Simulation of the operation of the on-board energy storage in the tractional system of a quarry locomotive

The ways of updating the rolling stock of open-pit railways have been considered and the main methods of using the energy storage on the locomotive for open-pit railways have been determined. A mathematical model has been developed, which includes a model of train movement along the railway section and during maneuvering and a model of energy processes in the traction system with onboard energy storage. Simulations were performed in a cycle that included movement from the crushing plant to the transshipment point with empty dump trucks, maneuvering during loading, movement from the crushing plant to the transshipment point with loaded dump trucks, and maneuvering during unloading. The simulation took into account the limitation of power consumption at the level of 4000 kW. The parameters of the energy storage device were determined, for which Toshiba SCiB 20Ah-HP cells were selected. The power of the energy storage is 3600 kW, and the energy capacity is 414 kWh. The use of modules for the formation of an energy storage device is proposed. It was determined that the energy consumption per work cycle with the selected energy exchange algorithm taking into account electrodynamic braking is about 200 kWh, and the charge reduction per drive cycle is 36%. The service life of the energy storage with the selected cells is estimated at 8 years.

Keywords*: locomotive, rolling stock, modeling, energy storage*

Introduction . According to explored iron ore reserves, 18% of the world's reserves are located in Ukraine, and in terms of iron content, Ukraine's share is 10.5-11% of the world's reserves [1]. The transition to "green" steel requires the use of technologies that minimize CO2 emissions at all stages of extraction and processing of iron ore raw materials. In this context, the use of electrified railway transport at mining and beneficiation plants for the transportation of raw materials corresponds to the general direction of the "green course". Taking into account the fact that the cost of transportation with electric traction is lower compared to diesel traction, electric transportation also reduces the cost of final products. In addition, the introduction of powering the electric traction system of open-pit railways from renewable energy sources will make it possible to approach transportation with zero CO_2 emissions.

For the effective use of electric traction, a fundamental renewal of the rolling stock of electrified quarry railways is necessary. At present, domestic quarries mainly operate traction units produced by JSC "Dnipro Electric Locomotive Plant" (Dnipro). The long period of operation of the traction rolling stock and its traction-energy indicators, which do not correspond to the conditions of operation, determine the urgency of the task of creating a modern locomotive for open-pit railways.

Analysis of recent research and problem statement. Rail transport in quarries is widely used in the CIS countries. Renewal of rolling stock is carried out both by purchasing new traction units and by modernizing old models.

At present, the renewal of electric vehicles in Ukrainian enterprises is carried out by modernizing existing traction units [2-4]. The most progressive can be considered the modernization of the traction unit OPE1A(M), which involves the replacement of the outdated traction-controlled rectifier and part of the contact apparatus, the compressor unit, and the use of a microprocessor control system. This contributes to increasing the reliability of the traction unit and improving the working conditions of the locomotive crew. However, the preservation of traction commutator motors does not allow improvement of traction-energy characteristics, and the use of zone-phase control of the input converter makes it impossible to improve energy consumption from the traction network. In addition, the uncontrolled electric drives of motor fans for cooling traction electrical equipment lead to inefficient energy consumption by auxiliary systems. Another drawback is the too low traction properties of the traction unit in an autonomous mode of operation in the case of powering by the diesel section (if it is available). In the absence of a diesel section, movement in non-electrified parts of the route is impossible. It is worth noting that such technical solutions are also used on new traction units. At the same time, a traction unit NPM2 equipped with a traction electric drive based on asynchronous electric motors was developed and manufactured. This corresponds to modern approaches to the creation of locomotives. This traction unit has increased traction and energy properties**.**

Domestic developers worked out a project of a traction unit with an asynchronous electric drive [5,6]. It is indicated that their use will allow for a change in the structure of the locomotive fleet. As a result, a significant decrease in energy consumption during the operation of new traction units is predicted. The life cycle cost of such traction units is significantly lower compared to the life cycle cost of advanced traction units equipped with a traction electric drive with commutator motors.

In [7], the authors proposed an electric locomotive with an asynchronous traction electric drive and an on-board energy storage device. Based on observations of the operation of traction units at domestic mining and beneficiation plants, the use of an on-board storage device is proposed not only for the accumulation of energy during electrodynamic braking but also for powering its traction system when the power of the traction network is limited [8]. In [9], the energy required to maneuver the traction unit during loading at the overload point and unloading at the crushing plant has been estimated. The use of energy storage devices to ensure maneuvering of mainline locomotives ("last mile" function) is becoming widespread on modern locomotives [10, 11]. Another way of using onboard energy storage devices is powering the traction system of electric rolling stock while moving through non-electrified areas [12-14]. In practice, this concept is applied to rolling stock [15-17]. This approach can also be applied to the rolling stock of quarry railway transport. This will allow, firstly, to move through areas where the deployment of a catenary network is impractical or impossible. Secondly, it will allow the movement with traction during passing through neutral inserts and car crossing roads, over which there is no contact wire. The last-mentioned are arranged for the movement of quarry dump trucks. The train follows such sections with the pantograph lowered, in virtue of inertia. As a result, the speed of movement decreases. At the end of the section without a contact wire, traction mode is established. And since the speed of the train has decreased, the train accelerates to the permissible speed. This leads to additional energy consumption. As we can see, the energy storage can be used for various purposes. It is necessary to carry out modeling, which allows evaluation of the traction systems and energy storage parameters for taking into account all before mentioned aspects.

The purpose and tasks of the research. The purpose of the work is to study the operation of the traction system and on-board energy storage of the locomotive for mining railways. The tasks of the article consist of modeling and researching the processes of energy exchange in the traction system of a mining locomotive equipped with onboard energy storage.

Research materials and methods. The locomotive data given in [7] has been used for the research. The research will be conducted by solving the traction task for the section of the road, as well as determining the movement indicators during maneuvering [9].

The mathematical model of train movement on the section of the track was developed based on the provisions of the theory of locomotive traction [18]. The motion is described by a system of equations in the following form

$$\begin{cases} \dfrac{dV}{dt} = \dfrac{\xi}{\rho}\left(f_L - (w_L + w_W) - b \right); \\ \dfrac{dS}{dt} = V, \end{cases} \qquad (1)$$

where ξ – the coefficient that takes into account the units of measurement;
V – train speed;
t – time;
S – distance;
ρ – the coefficient that takes into account the rotation of the parts of the crew part;
f_L – the specific tangential force of the locomotive in the mode of traction or electrodynamic braking;
w_L – the specific force of resistance to the movement of an electric locomotive;
w_W – the specific force of resistance of moving wagons;
b– specific braking force of pneumatic brakes.

The specific tangential force of the locomotive in the mode of traction or electrodynamic braking was determined by the expression

$$f_L = \frac{F_L}{\sum_{k=1}^{s} M_{Lk} + \sum_{j=1}^{n} M_{Wj}}, \qquad (2)$$

where F_L– the tangential force of the electric locomotive in traction mode or electrodynamic braking mode;
M_{Lk} – mass of the locomotive section;
s – number of locomotive sections;
M_{Wj} – dump truck mass;
n – the number of dump trucks.

Specific resistance to movement was calculated as

$$w = w_0 + w_a, w = w_0 + w_a, \qquad (3)$$

where w_0 – the main specific resistance of the train;
w_a – additional specific resistance of the train.

The main specific resistance of the train is determined by the expression

$$w_0 = \frac{w_L \sum_{k=1}^{s} M_{Lk} + w_w \sum_{j=1}^{n} M_{Wj}}{\sum_{k=1}^{s} M_{Lk} + \sum_{j=1}^{n} M_{Wj}}, \tag{4}$$

where w_L – the main specific resistance of the locomotive movement;
w_w – the main specific resistance to the movement of thoughts.

The main specific resistance during the movement of the locomotive for the link track is determined by the following expression [18]

$$w_L = \begin{cases} \left(2.6 + 0.07V + 0.0025V^2\right) g,\ F_L > 0 \\ \left(2.8 + 0.023V + 0.00075V^2\right) g,\ F_L \le 0 \end{cases}, \tag{5}$$

where V – speed of movement, expressed in km/h;
g – acceleration of free fall, which is 9.81 m/s^2.

The main specific resistance to the movement of loaded dump trucks of type 2VC105 is determined by the expression

$$w_w = \left(3.6 + 0.04 \cdot V\right) \cdot g,. \tag{6}$$

The main specific resistance to the movement of empty dump trucks type 2VC105 is determined by the expression

$$w_w = \left(4.8 + 0.05 \cdot V\right) \cdot g. \tag{7}$$

The additional specific resistance to the movement of the train was determined by the expression

$$w_a = w_i + w_r + w_s + w_e + w_t, \tag{8}$$

where w_i – additional specific resistance of the movement caused by the slope;
w_r – additional specific resistance of the movement in curved areas;
w_s – additional specific resistance while the start of the moving;
w_e – additional specific resistance of the forward movement of wagons;
w_t – additional specific resistance caused by conditions of the railway track.

Changes in the value of additional resistance caused by changes in climatic conditions were not taken into account in the calculations.

Additional resistance during moving on a slope was determined as

$$w_i = i \cdot g,, \tag{9}$$

where i – slope of the site, expressed in thousandth.

Specific additional resistance from movement along a curved section of the track was determined by the expression

$$w_r = \frac{700}{R} \cdot g, \tag{10}$$

where R – the radius of the curve.

Additional resistance during movement was determined by the expression

$$w_s = \frac{\left(\frac{20}{q_l}\right)\sum_{k=1}^{s} M_{Lk} + \left(\frac{20}{q_w}\right)\sum_{j=1}^{n} M_{Wj}}{\sum_{k=1}^{s} M_{Lk} + \sum_{j=1}^{n} M_{Wj}} g, \quad (11)$$

where q – axle load of a rolling stock unit, expressed in tons.

Additional resistance during moving was taken into account at a speed of less than 10 km/h.

The additional specific resistance from the forward movement of the wagons is determined by the expression

$$w_e = \left(0.15 + \frac{|i|}{1000}\right) \cdot w_0. \quad (12)$$

Additional resistivity due to track condition

$$w_t = \left(k_{tr} - 1\right) \cdot w_0, \quad (13)$$

where k_{tr} – coefficient that takes into account the technical condition of the track. In calculations, it is taken equal to 1.1.

Control of traction force or electrodynamic braking is carried out so, that the permissible speed is maintained. There are no limits on the intensity of changes in traction and braking. Expressions (1)-(13) make up a mathematical model of train movement along a section of the track.

The mathematical description of the processes in the traction system of a mining electric locomotive equipped with an onboard energy storage system has been developed taking into account [8, 9, 19].

In traction modes, the power consumed from the energy storage is determined by the expression

$$P_{ES} = \begin{cases} 0, & \left(P_{TD} + P_{AUX}\right) \le P_{IN}; \\ \left(P_{TD} + P_{AUX}\right) - P_{IN}, & \left(P_{TD} + P_{AUX}\right) > P_{IN}, \end{cases} \quad (14)$$

where P_{TD} – the power consumed by the traction electric drive from the intermediate circuit;
P_{AUX} – the power consumed by auxiliary systems of the electric locomotive;
P_{IN} – the maximum power that can be drawn from the input converter.

In expression (14), it is assumed that the storage capacity is sufficient to power the traction system of the locomotive ($P_{ESN} \geq P_{TD} + P_{AUX} - P_{IN}$)().

The power consumed by the traction electric drive can be simply determined by the expression

$$P_{TD} = \frac{P_L}{\eta_{TD}}, \quad (15)$$

where P_L – tangent power of the electric locomotive;
η_{TD} – the efficiency of the traction electric drive is 0.9.

For refined calculations, it is necessary to use the efficiency dependence calculated for the entire traction area.

Due to the significant power and capacity of the onboard energy storage system, it will have a modular composition. Assuming that the models have an identical design and operating modes, we will consider the operation of one module in the future.

The power that is consumed from the storage system module is defined as

$$P = \frac{P_{E\Sigma}}{m \cdot \eta_B}, \; P = \frac{P_{ES}}{m\eta_B}, \tag{16}$$

where m – the number of modules that are connected in parallel;
η_B – the efficiency of the matching converter, which for simplicity is taken as a constant value equal to 0.97.

The voltage of the energy storage is determined by the expression

$$U = E - R \cdot I, \tag{17}$$

where E – EMF of the module;
R – equivalent electrical resistance of the cells of one module;
I – current of one energy storage module.

The EMF of the module is determined by the expression

$$E = N_s \cdot E_{cell}, \tag{18}$$

where N_s – the number of cells connected in series;
E_{cell} – EMF of one cell.

Equivalent electrical resistance of elements of one module

$$R = R_{cell} \cdot \frac{N_s}{N_p}, \tag{19}$$

where R_{cell} – electrical resistance of one cell;
N_p – the number of parallel branches in the module.

The EMF of the cell E_{cell} and the resistance of the cell R_{cell} depend on the degree of discharge, temperature, number of spent cycles, etc. [20-22]. For estimated calculations, it is sufficient to take into account the dependence of EMF on the degree of discharge. The resistance of the cell can be assumed as constant. For modeling, the R-int cell model is adopted [23-25].

The dependence of EMF on the degree of discharge can be described analytically [26,27]. It is possible to use tabular data and interpolation procedures when performing numerical calculations. This approach will be used in the simulation.

The current of the storage module is determined by the expression [28, 29]

$$I = \frac{E - \sqrt{E^2 - 4P \cdot R}}{2 \cdot R}. \tag{20}$$

In the simplest case, the estimation of the degree of charge of the battery can be performed by determining the degree of charge of one cell [30]. The calculated ratio looks like this

$$SOC_t = SOC_0 - k \frac{1}{Q_{cell}} \int_0^{\tau} \eta_C \left(\frac{I}{N_p} \right) dt, \tag{21}$$

where SOC_0 – degree of charge before discharge;
τ – duration of the discharge stage;
Q_{cell} – nominal capacity of one cell;
η_C – Coulomb efficiency is assumed equal to 1 according to [30];
k – coefficient, which takes into account the units of measurement.

Let`s neglect Discharge losses. Charging of the energy storage device while driving is carried out in the mode of electrodynamic braking.

The power supplied to the on-board energy storage system is determined by the expression

$$P'_{ES} = \begin{cases} 0, & P'_{TD} \le P'_{AUX}; \\ P'_{TD} - P'_{AUX}, & 0 < \left(P'_{TD} - P'_{AUX}\right) \le P_{ESN}; \\ P_{ESN}, & \left(P'_{TD} - P'_{AUX}\right) > P_{ESN}, \end{cases} \tag{22}$$

where P'_{TD} – the power supplied to the intermediate circuit from the traction electric drive;
P'_{AUX} – the power consumed by the auxiliary systems of the electric locomotive in the mode of electrodynamic braking.

The power supplied to the intermediate circuit from the traction electric drive is determined by the expression

$$P'_{TD} = \eta'_{TD} P_L, \tag{23}$$

where η'_{TD} – the efficiency of the traction electric drive in the electrodynamic braking mode is 0.9.

The power that is transferred to one module of the energy storage system is determined by the expression

$$P' = \frac{\eta'_B \cdot P'_{ES}}{m}, \tag{24}$$

where η'_B – The efficiency of the matching converter, which for simplicity is taken as a constant value equal to 0.97.

The storage voltage is determined by the expression

$$U = E + R \cdot I', \tag{25}$$

where I' – current of the module during charging.

The current of the storage module is determined by the expression [28, 29]

$$I' = \frac{E - \sqrt{E^2 - 4P \cdot R}}{2 \cdot R}, \; . \tag{26}$$

The degree of charge is determined by the expression

$$SOC_t = SOC_0 + k \frac{1}{Q_{cell}} \int_0^{\tau} \eta_C \left(\frac{|I'|}{N_p} \right) dt. \tag{27}$$

Expressions (14)-(27) make up a mathematical model of energy exchange processes in a traction system with onboard energy storage.

Motion simulation during maneuvering is carried out according to the method given in [9]. During maneuvering, energy is only consumed from the accumulator, therefore energy processes are described by expressions (14)-(21).

The developed mathematical model will provide a study of the operation of the traction system and the energy storage during the movement cycle, which consists of movement from the crushing plant to the overloading point, maneuvering at the overloading point during ore loading, movement from the overloading point to the crushing plant, and maneuvering during unloading.

Research results. *Input data.* The study was carried out for traffic conditions at PrJSC "Poltava Ferrexpo Mining" [7]. The movement of a train with a locomotive equipped with an asynchronous traction electric drive and an on-board energy storage device is studied.

The energy storage parameters are determined according to [31]. Previous studies [8,9] show that energy storage must be optimized for high power and relatively small capacity. Therefore, it is accepted that the SCiB 20Ah-HP cell manufactured by Toshiba will be used in the energy storage system [32]. The technical parameters of the cell are listed in Table 1

Table 1. **Technical parameters of the cell SCiB 20Ah-HP cell [32]**

Parameter	Value
Capacity, Ah	20
Capacity, kWh	46
Nominal voltage, V	2.3
The highest charging voltage, V	2.9
The lowest discharge voltage, V	1.5
C-rate for long modes	5
C-rate for short-term modes	10
Power (SOC50%, 10 s, 25 ºC), W	1900
The electrical resistance of the cell, Om	$0.6 \cdot 10^{-3}$
WxLxH, m	0.116x0.022x0.106
Weight, kg	0.545

The dependence of the no-load voltage on the degree of discharge is shown in Fig. 1

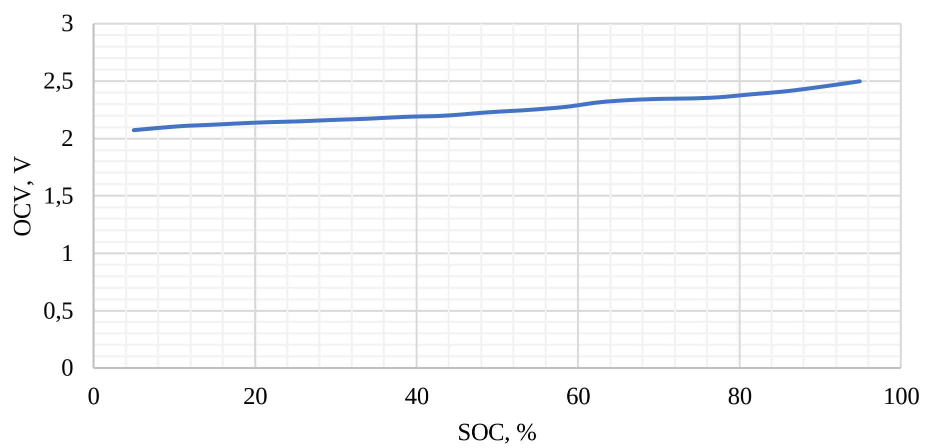


Fig.1. **Dependence of open-circuit voltage (OCV) on the degree of SOC discharge [32]**

Calculations of energy storage parameters [31] are given below. Preliminary calculations show that the energy change in the accumulator is 192 kW*h. We will assume that the voltage of the constant voltage circuit is 900 V. Authors will take into account that when the SOC changes in the range of 5...95%, the cell voltage changes from 2.1 V to 2.5 V in the calculations. We will take these values as the lowest and highest voltage.

The number of serially connected elements is determined by the expression

$$N_s = \frac{U_{dc}}{U_{ch}}, \tag{28}$$

where U_{dc} – intermediate circuit voltage;
U_{ch} – the voltage at which the charging of the element ends, equal to 2.5 V.

Then the number of serially connected elements will add up N_s=360.

In [9] it was determined that the power of the energy storage should be 3540 kW, but accepted equal to 3600 kW.

The number of parallel branches, determined from the condition "by power", is determined by the expression

$$N_2 = \frac{P_{OESS}}{N_S U_{dis} I_{cell}}, \tag{29}$$

where P_{OESS} – nominal power of the energy storage;
U_{diss} – cell discharge voltage;
I_{cell} – permissible charge/discharge current, accepted as 200 A.

After performing the calculation, the number of parallel branches is 24.

The capacity of the on-board SNE is determined by the formula

$$E_{OESS} = \frac{\Delta E}{(SOC_1 - SOC_2)k_1 k_2}, \tag{30}$$

where ΔE – storage capacity;
SOC_1 – the highest degree of charge in the operating mode, accepted as 90%;
SOC_2 – the smallest degree of discharge in working mode, accepted as 10%;
k_1 – the coefficient that takes into account the decrease in the capacity of the OESS during the period of operation, we will take 0.9;
k_2 – the coefficient that takes into account the decrease in the capacity of the OESS with a change in temperature, self-discharge, etc., we will take 0.95.

After performing the calculations, it was determined that the capacity of the onboard energy storage system is 285 kWh.

The number of parallel branches, determined from the "by energy" condition, is determined by the expression

$$N_1 = \frac{E_{OESS}}{N_S E_{cell} k_{ch}}, \tag{31}$$

where k_{ch} – a coefficient that takes into account the decrease in energy, which the energy storage element can store during charging with a current that exceeds the optimal value, accepted equal to 0.9.

After the calculation, it was found that the number of branches is 20.

Finally, it has been assumed that, taking into account the reserve, the number of parallel branches of the drive will be N_p=25 [31].

It is advisable to form the energy storage from separate modules because the power of the energy storage is 3600 kW. Let's assume that there will be 5 such modules (N_m=5). Each module will then have five parallel-connected branches, each of which will have 360 series-connected cells.

The total energy capacity of the accumulator is determined by the expression

$$E_{ES} = \frac{E_{cell} N_m N_s N_p U_{cell}}{1000}. \tag{32}$$

After calculations, we will get a result 414 kWh.

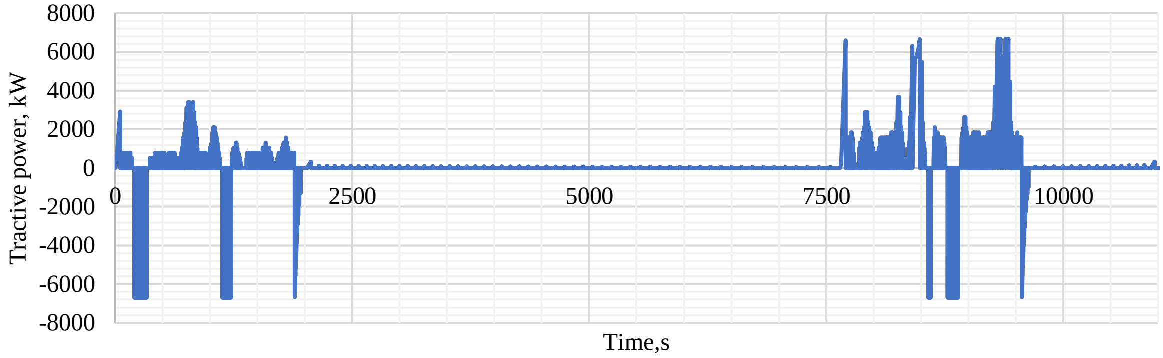
Table 2 shows the dependence of the idling voltage on the degree of discharge for one module.

The equivalent resistance of the module, calculated according to (19), is 0.0432 Ohm.

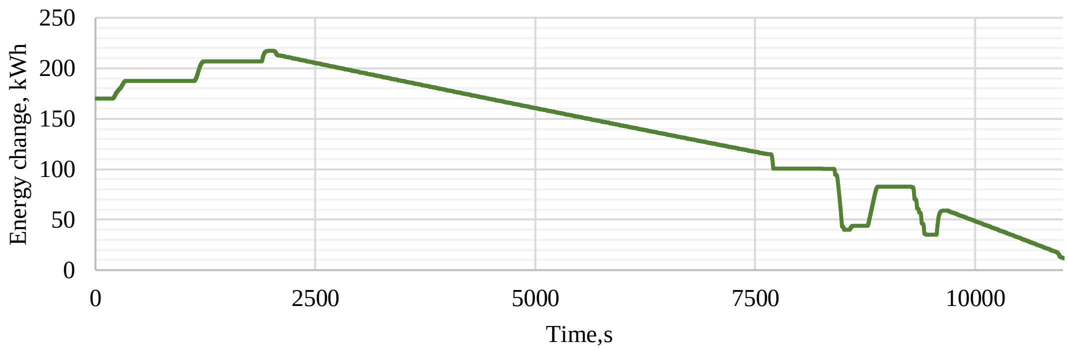
Table 2. **Dependence of OCV open-circuit voltage on SOC for one module**

Parameter	Value										
SOC, %	5	10	14	18	22	25	30	34	39	43	49
OCV, V	746	758	763	767	771	773	778	782	788	791	802
SOC, %	54	58	63	66	70	74	77	81	85	89	95
OCV, V	809	819	833	841	844	845	849	858	867	879	899

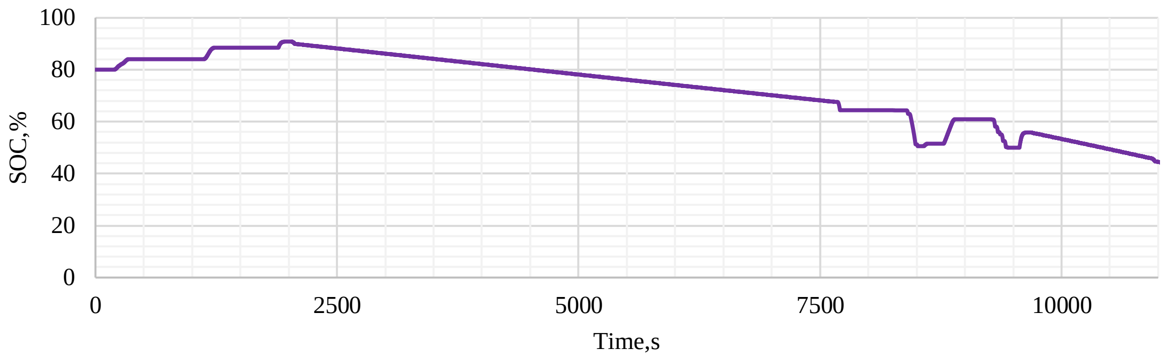
Simulation results. Fig. 2, a shows the time dependence of the tangential power, Fig. 2, b shows the time dependence of the energy change in the accumulator, Fig. 2, c – the time dependence of the change in the degree of charge at the initial charge value of 80%.



a)



b)



c)

Fig.2. **Time dependences of traction system parameters**

Depending on the tangential power (Fig. 2, a), four characteristic stages can be distinguished. From the beginning of movement to 2000 s, movement is carried out along the section of the path. The presence of negative values in the power curve is characteristic, which indicates electrodynamic braking. Accordingly, on the time dependence of the change in energy of the accumulator (Fig. 2, b) and the dependence of the discharge degree (Fig. 2, c), an increase in the corresponding values is observed. From 2000 s to 7600 s, the stage of maneuvering under load continues. During this stage, the power source is energy storage, so the energy and the degree of charge of the energy storage are reduced. From 7600 s to 9600 s, traffic continues from the transshipment point to the crushing plant. During this interval, stages of intensive reduction of energy and the degree of charge of the accumulator are observed. This is caused by the consumption of energy from the storage to compensate for the power limitation of the input converter. At the same time, electrodynamic braking is carried out at this stage, which leads to an increase in energy in the storage device. From 9600 s to 11000 s, there is unloading at the crushing plant, where energy is only consumed from the accumulator.

In general, energy storage is discharged from 80% to 44% because the capacity of the battery exceeds the energy required for movement. This is related to the characteristics of the cells selected for the storage device. On the other hand, with this type of discharge, one charge will be enough to carry out two cycles of movement.

The duration of one movement cycle is about 3 hours. Assuming that 6 cycles of movement are carried out during the day, the authors got that there should be three charging of the energy storage. Let the locomotive work for 350 days during the year. Then there will be about 1000 cycles per year. According to the information of the cell manufacturer [32], after 8000 discharge/charge cycles, the initial capacity of the cell practically does not change. Therefore, the duration of use of the storage device can be estimated at 8 years.

Conclusions. A mathematical model was developed and the simulation of energy exchange processes in the traction system of a mining locomotive equipped with on-board energy storage was carried out. The mathematical model combines the model of train movement along the railway section and during maneuvering and the model of energy exchange with an onboard energy storage device. The parameters of the Toshiba SCiB 20Ah-HP cell-based energy storage device have been defined. It has been determined that the energy consumption during the work cycle is about 200 kWh, and the storage battery charge is reduced by 36%. The storage life is estimated at 8 years.

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Моделювання роботи бортового накопичувача енергії у тяговій системі кар'єрного локомотиву

Розглянуто шляхи оновлення рухомого складу кар'єрних залізниць та визначені основні способи застосування накопичувача енергії на локомотиві для кар'єрних залізниць. Розроблено математичну модель, яка включає модель руху поїзда по ділянці залізниці та упродовж маневрування і модель енергетичних процесів у тяговій системі з бортовим накопичувачем енергії. Виконано моделювання у циклі, який включає рух від дробарної фабрики до пункту перевантаження з порожніми думкарами, маневрування при навантаженні, рух від дробарної фабрики до пункту перевантаження з навантаженими думпкарами та маневрування при розвантаженні. При моделюванні враховано обмеження споживаної потужності на рівні 4000 кВт. Визначено параметри накопичувача енергії, для якого обрані комірки Toshiba SCiB 20Ah-HP cell. Потужність накопичувача енергії складає 3600 кВт, енергоємність – 414 кВт·год. Запропоновано застосування модулів для формування накопичувача енергії. Визначено, що споживання енергії за цикл роботи при обраному алгоритмі енергетичного обміну з урахуванням електродинамічного гальмування складає близько 200 кВт·год, а зменшення заряду за цикл руху становить 36%. Термін служби накопичувача енергії з вибраними комірками оцінюється у 8 років.

Ключові слова: *локомотив, рухомий склад, моделювання, накопичувач енергії*

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Determination of rational parameters of the logistics chain in the process of customer service in international transportation

In this paper, we propose technological principles for determining rational parameters of the supply chain in order to establish a balance between demand and supply for goods in the chain links under conditions of variable demand and optimisation of total costs for all cargo delivery participants, which will affect the final cost of goods to customers. For the experimental research of the supply chain functioning, the forecast values of demand were determined based on the study of demand trends. As a result of the research conducted using mathematical modelling, regularities of the influence of supply chain parameters on the total costs of delivery participants have been established and rational parameters of the supply chain for consumer goods customers in international connections have been determined, minimising additional costs and ensuring a minimum level of total costs. The positive results of the economic effect estimate demonstrate the effectiveness of the proposed solutions.

Keyword: *supply chain, batch size of the cargo, delivery period, total costs, economic effect*

Introduction. The development of the supply chain management concept is driven by the need to coordinate and regulate the activities of cargo delivery participants under conditions of uncertainty. This is due to a significant level of complexity arising from the presence of a large number of links (participants), technological operations, and various flows. As the number of connections increases, the vulnerability of supply chains also increases, leading to higher costs and, consequently, to an increase in the final price of the product and a decrease in its competitiveness in the market. Guided by the concept of the 'ideal order,' logistics companies face the challenge of an imbalance between demand and supply at different points in the chain, resulting in additional costs and a decrease in the level of service quality. [1].

With the onset of military actions in Ukraine, most logistic chains were disrupted. There was a relocation of production capacities from the eastern regions of Ukraine, ongoing destruction of infrastructure, and other challenges, necessitating the use of new approaches to build flexible supply chains for goods from EU countries to Ukraine capable of responding to external threats and changes. According to data from the Transport Company "Neolit Logistics" (TC), one of the most demanded directions for the import of goods among customers is Germany-Ukraine. In this direction, a large share of imported goods consists of consumer goods. Among the urgent problems in organizing deliveries, company managers identify interruptions in supplies to Ukraine due to discrepancies in delivery times and excessive waiting times at border crossings for transport vehicles. These issues lead to failures in meeting agreed delivery times and the occurrence of associated additional costs.

All of this underscores the relevance of searching for approaches to optimizing the functioning of the logistics supply chain by determining rational parameters, batch sizes, and delivery periods to establish a balance between demand and supply in the chain links and reduce additional costs associated with undersupply or the formation of excess inventory at customer premises.

Analysis of recent research and problem statement. An important aspect of logistics system activity is maintaining inventory levels that ensure the uninterrupted supply of all units with the necessary material resources while meeting the economic requirements of the entire material flow process. The author [2] believes that logistics research should consider an integrated system of material, information, and financial flows within an enterprise, which are combined into a unified logistics flow.

The works [2-15] are dedicated to the formation of supply chains and optimisation of their parameters. Taking into account the existing approaches and methods, they can be grouped in the following directions:

– formation of inventory management systems;
– design of logistic systems;
– design of delivery systems in supply chains;
– development of models for the operation of transport and production complexes;
– formation of terminal systems, etc.

A common advantage of most of these approaches is that the authors use stochastic optimisation models and consider the random nature of technological processes. However, some models are complex to implement and are not universal, meaning they cannot be easily supplemented and expanded for specific conditions.

Improving the cargo delivery process to increase its efficiency requires solving a wide range of optimisation tasks by determining optimal connections between suppliers and consumers. From the perspective of a logistic approach, the efficiency of the cargo delivery process is determined by three factors: costs, speed, and continuity.

The logistic system should be organised in such a way that its total costs remain at a minimum level during the delivery process. Speed is related to the qualitative indicators of transport services and depends on transport costs. When designing a delivery system, it is necessary to strike a balance between speed and cost, as increasing the level of service quality leads to increased costs. On the other hand, the faster the transportation, the less time stocks are spent in transit and are unavailable for use. The continuity of transportation depends on the delivery period. Insufficient continuity of the delivery process leads to the need to create safety stocks to prevent unforeseen disruptions in production and sales processes. At the same time, the formation of excess stocks in the warehouses of the delivery process leads to additional costs, which affects the cost of the final product cost. The quality level of the delivery process has a significant impact on the activities that are sensitive to the time factor. Therefore, a balance between costs and quality of transportation is a necessary condition to choose logistic service technology and to manage it in supplies of raw materials and finished products, especially in international connections.

As a criterion of efficiency, most commonly used when optimising logistic chain parameters is the cost indicator and its derivatives (cost price, adjusted costs, etc.). [2-3, 6-7, 9-11]. The international logistic service aims to minimise total costs in resource movement management by optimising the operation of the logistic system from the moment of selecting a supplier to the after-sales service, focussing on obtaining and using synergistic dependencies and effects [9].

The construction of cargo flow distribution channels and the distribution network system in international delivery significantly affect the supply costs to the end consumer. Among the economically justified methods for quickly replenishing stocks are strategies for placing distribution warehouses near sales markets and production facilities. When forming a delivery system in the supply chains of small batches of goods in international connections, the most advantageous option is to use terminal systems [11].

As a result of the analysis of the current state of the problem, the shortcomings and advantages of existing methods for determining rational parameters of supply chains when delivering goods to customers in international connections were identified, which necessitate the development of technological foundations for determining rational parameters of the supply chain, batch size, and delivery period of goods to customers in international connections in order to maintain a balance between demand and supply in the chain links and reduce additional costs associated with waiting for delivery or the formation of excess inventory.

Purpose and objectives of the study. The purpose of the research work is to increase the efficiency of logistic services for cargo owners in international connections by determining the rational parameters of the supply chain. The object of the study is the process of delivering consumer goods to customers in international connections; the subject of the study is the influence of supply chain parameters on the total costs of delivery participants of consumer goods when serving cargo owners.

To achieve this purpose, the following tasks need to be solved: to analyse the current state of determining the rational parameters of the supply chain for customers in international connections; to form a model for determining rational parameters of the supply chain; to conduct experimental research; to analyse the research results.

Materials and methods of the study. The object of research has its own peculiarities related to the supply system, the organisation of the freight flow distribution system in the supply chain, the location of terminals and distribution centres, the distribution of their service area, the density and form of work of customers and the retail network in different regions of Ukraine. The process of supplying goods to the end consumer is a complex process and represents a multilevel distribution channel (Fig. 1), which determines the final price of the product in the retail trade network.

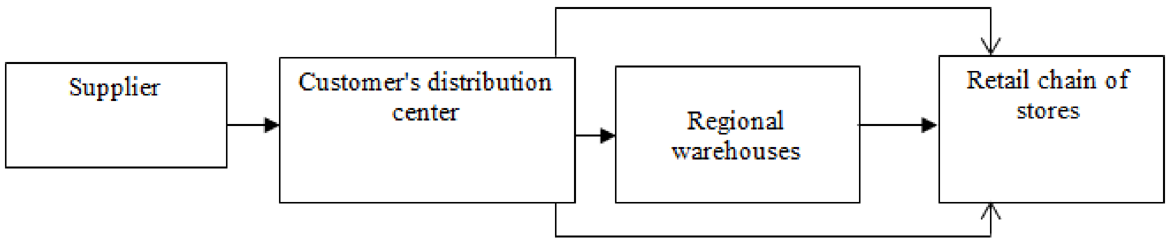

Fig. 1. **Structure of the cargo flow distribution channel in the customer supply chain**

The supply chain is characterised not only by its scheme, but also by a specific technology. Therefore, it can be said that the structural scheme determines the efficiency of the system's operation (Fig. 2). The manufacturer must supply the customer with products within the contractually agreed period. In case of a product shortage, safety stock is used in the distribution centre, which can lead to a disruption in product delivery to consumers in the region. In such a case, the customer incurs losses.

The problem statement for determining the rational parameters of the supply chain includes formalisation of the efficiency criterion, determination of controllable parameters, the change of which will affect the process efficiency, development of the process model (mathematical), determination of the system of constraints and assumptions regarding conditions, requirements, and capabilities.

The efficiency of the supply chain operation is advisable to assess using an economic criterion - supply costs for a certain period, as this indicator significantly affects the final product cost. Value indicators of the elements of the supply process and the total demand for the planning period are established as parameters of external influence.

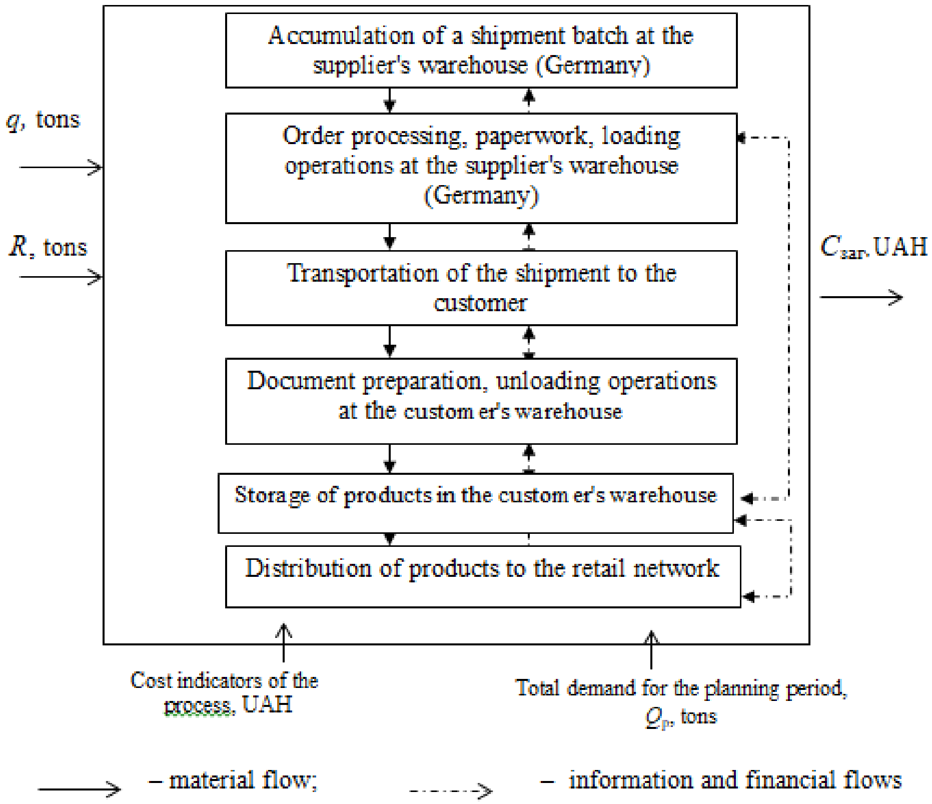

Fig. 2. **The structural scheme of the research object**

The complexity of the channel of distribution of freight flow in the supply chain of consumer goods to the customer in international connections requires consideration of the interests of all participants in the delivery process. According to the approach proposed in [11], it is proposed that the efficiency criterion should be considered as the total costs (C_{tot}) for the entire supply period of product (T). In this case, the target function is as follows

$$C_{tot} = f\left(q, R, C_1, t_1, C_2, t_2, C_R, Q_p, T\right) \rightarrow min. \qquad (1)$$

where q – batch size, tons;
R – stock of finished products at the customer at time, t_1, tons;
T – period during which the supply is made, months;
Q_p– total demand for the planning period, tons;
C_R – order processing cost associated with document processing, receipt and delivery, transportation of the batch of cargo, UAH;
C_1– cost of storing 1 ton of product at the customer per month, UAH/month$
C_2 – losses incurred by the customer in case of undersupply of 1 ton of product, UAH/month.

The input parameters of the model are the batch size (q, tons) and the stock of finished products at the customer at time t_1 (R, tons); the output parameter is the total costs ($C_{заг}$, UAH) for the entire period of product supply T; the parameters of the external environment are the value indicators of the process (C_1, C_2. C_R) and the total demand for the planning period (Q_p, tons). Some indicators are uncontrollable, while others are controllable, and their rational values need to be determined.

Fators C_1, t_1, C_2, t_2, C_R, Q_R are uncontrollable, while others are controllable, and their rational values (C^*_{tot}, q^*_{rat}, R^*_{rat}, t^*_{Rrat},) are need to be determined.

The defined function has a system of restrictions and assumptions. Based on the research goal set in the paper, the task of optimising the parameters of the supply chain to the customer in international connections should be addressed. It is proposed to consider the delivery process from the distribution centre in Germany (Berlin) to the distribution centres located in Ukraine. Thus, the system of restrictions and assumptions is as follows

$$\begin{cases} T = 12, month; \\ 380 \le Q_p \le 820, tons; \\ L_{del} = 1300, km; \\ 3 \le R \le 30, tons; \\ 8 \le q \le 28, tons; \\ g > 0, tons; \\ t_1 > 0, hours. \end{cases} \quad (2)$$

Improving the delivery process of goods in the supply chain aims to minimise logistic costs throughout the lifecycle of the logistic system, taking into account the system's ability to adapt to possible changes under the influence of external factors. Let's present the total costs for the planned customer service period in the form of a mathematical model [11].

The number of batches for the planned period (year) is determined

$$g = \frac{Q_p}{q}. \quad (3)$$

Frequency of batch delivery to the customer

$$t_R = \frac{T}{g} = \frac{T \cdot q}{Q_p}. \quad (4)$$

Exceeding the demand value over the stocks is acceptable.

The time interval during which a certain level of R stock will accumulate is

$$t_1 = \frac{R}{q} \cdot t_R. \quad (5)$$

The time interval when there is a shortage of stocks is equal to

$$t_1 = \frac{q - R}{q} \cdot t_R. \quad (6)$$

The average stock during time t_1 is equal to

$$\bar{R} = \frac{R}{2}. \quad (7)$$

Storage costs for the entire time t_1 amount to

$$C_{st} = \frac{R}{2} \cdot C_2 \cdot t_1. \qquad (8)$$

The average level of undersupply (exceeding demand over stock level) during time t_2 is calculated as follows

$$q > R = \frac{q - R}{2}. \qquad (9)$$

The losses incurred by the customer due to the shortage of products during time t_2 amount to

$$C_{loss} = \frac{q - R}{2} \cdot C_2 \cdot t_2. \qquad (10)$$

The target function for inventory management can be represented as a mathematical model

$$C_{tot}(q, R) = \left(\frac{R}{2} \cdot C_1 \cdot t_1 + \frac{q - R}{2} \cdot C_2 \cdot t_2 + C_R \right) \cdot \frac{Q_R}{q} \rightarrow min. \qquad (11)$$

Taking into account the described dependencies for t_1, t_2 , t_R, we obtain

$$C_{tot}(q, R) = \frac{R^2}{2 \cdot q} \cdot C_1 \cdot T + \frac{(q - R)^2}{2 \cdot q} \cdot C_2 \cdot T + C_R \cdot \frac{Q_R}{q} \rightarrow min. \qquad (12)$$

The solution to the problem lies in finding the extremum of the target function (9), which is found by differentiation, allowing us to find models to determine rational values of inventory indicators.

Thus, the rational values for the parameters are as follows:

– batch size

$$q^*_{rat} = \sqrt{2 \cdot \frac{Q_p \cdot C_R}{T \cdot C_1}} \cdot \sqrt{\frac{C_1 + C_2}{C_2}}; \qquad (13)$$

– frequency of batch delivery to the customer

$$t^*_{Rrat} = \sqrt{2 \cdot \frac{T \cdot C_R}{Q_p \cdot C_1}} \cdot \sqrt{\frac{C_1 + C_2}{C_2}}; \qquad (14)$$

– minimum costs

$$C^*_{tot} = \sqrt{2 \cdot Q_p \cdot T \cdot C_1 \cdot C_R} \cdot \sqrt{\frac{C_2}{C_1 + C_2}}.. \qquad (15)$$

Thus, a mathematical model has been developed to determine the rational technology of cargo delivery in supply chains. It is possible to conduct experimental studies to determine the rational delivery parameters that will ensure the minimum total costs of the process participants.

In order to conduct experimental studies, primary information was collected at the enterprise TC "Neolith Logistics", which provides transport and forwarding services to customers, particularly in international communication. A significant client of the TC is a wholesale trading network in Ukraine. According to the company's data for the last three years, a significant portion of cargo volumes (consumer goods) is imported from Germany (distribution centre in Berlin) to Ukraine to the customer's distribution centre located in Vinnitsa. From distribution centres, the goods are distributed to regional warehouses, from where deliveries to the retail network occur twice a week. Delivery is carried out by motor transport of carrier enterprises with which TC "Neolith Logistics" has cooperation agreements. Tarpaulin-sided trucks are used for the transportation of consumer goods. Monthly supply plans are drawn up according to orders and TC employees search for available transport from partner companies to transport batches of goods from Germany to Ukraine on specified dates. Shipments of cargo batches from the distribution centre in Germany to distribution centres in Ukraine are made every Sunday along established routes. The route length is 1300 km, and the average shipment volume is 18.0 tons, with a frequency of twice a month. The further distribution of goods to the retail network of stores from the distribution centre is carried out through both regional warehouses and directly to the retail network. The volume of cargo transport in tons is planned based on the turnover plan of the store network. Supply to the retail network from regional warehouses is carried out according to the daily schedules of deliveries and distribution routes of the mobile fleet. For supply to the retail network in the regions, the mobile fleet of local carrier enterprises is involved.

The goal of determining the optimal parameters of the supply chain is to maintain a balance between demand and supply at the links of the chain. To model dynamic processes, it is necessary to identify the main trends in their development. Therefore, an important stage is the qualitative planning of the transport process for the future period based on the study of demand change trends.

Special forecasting methods include building dynamic series, based on which forecast values of the process development can be determined, taking into account the regularities of previous periods. To describe the trend of change in demand, we propose using least squares. To choose the type of function as alternatives, we suggest considering linear, hyperbolic, and parabolic functions.

The determination of the components of the system of equations is carried out based on the initial data on the volumes of orders for the delivery of consumer goods to the distribution centre of the customer – a trading company located in Vinnitsa, by months for the year 2023 according to the data of the transport company "Neolith Logistics", which serves the customer on a permanent basis.

The determination of the coefficients of all three trend models is solved using systems of normal equations, which are constructed separately for each model.

By the criterion of assessing the adequacy of trend models, the minimum sum of squares of deviations of forecast values from empirical ones, we choose the hyperbolic model, since according to this model, the sum of squares of demand deviations has the lowest value (7.94047 tons). Therefore, it is the hyperbolic trend model that determines the forecast demand values for the year 2024.

The results of the calculations of forecast demand values for 2023 are presented in Table 1.

Table 1. **Results of calculations of forecast demand values for the year 2024**

Month	Demand, tons	Month	Demand, tons	Month	Demand, tons	Month	Demand, tons
1	37,51	4	37,53	7	37,54	10	37,55
2	37,51	5	37,53	8	37,54	11	37,55
3	37,52	6	37,53	9	37,54	12	37,55

The total expected demand for the delivery of consumer goods from Germany to Ukraine for 2024 is 488 tons.

The values of the input parameters for modelling according to the proposed mathematical model are given in Table 2.

Table 2. **Input parameters of the model**

Indicators	Unit of measurement	Value of indicators
Period during which delivery is made	month	12
Order processing cost	UAH	300
Kilometre tariff	UAH /km	[20;38]
Cost of storing 1 ton of cargo at the consignee's warehouse	UAH /month	1800
Losses incurred by the customer in case of non-delivery of 1 ton of cargo	UAH /month	1300
Batch size	tons	[8;20]
Reserve cargo stock in the warehouse	tons	[3;30]

The results of calculations of the efficiency criterion at the minimum values (q_{min}=8 tons; R_{min}=5 tons), average values (q_{mid}=14 tons; R_{min}=5 tons) and maximum values (q_{max}=20 tons; R_{max}=25 tons) of the input parameters are graphically shown in Fig. 3 as dependencies of the components of the efficiency criterion and the total costs according to the size of the shipment batch.

Analysing the calculation results, the following conclusions can be made: at the minimum level of input parameter values (q_{min}=8 tons; R_{min}=5 tons), the maximum value of the efficiency criterion and the costs of order processing and the level of customer losses due to nondelivery of products are observed. Thus, the interval of time when there is a shortage of stocks exceeds 2 days, which indicates supply disruptions and a demand-supply imbalance in the customer's chain in the supply chain.

This, in turn, leads to additional costs associated with customer losses. Also, there is a high level of order processing costs, the lion's share of which consists of transportation costs since at the minimum shipment batch size, it is necessary to make the maximum number of shipments, 61 units over a distance of 1300 km, which is economically impractical.

At the maximum level of the values of the input parameters (q_{max}=20 tons; R_{max}=25 tons), an increase in the costs of storing goods in the distribution warehouse is observed since supply exceeds demand, and intensive accumulation of stock levels occurs. Also, there is a slight increase in order processing costs, but compared to the minimum level of input parameter values, they are lower by 325050 UAH per year.

At the average values of the input parameters, the efficiency criterion reaches a minimum, mainly due to a decrease in order processing costs. Also, at a shipment batch size of 14 tons, the lines of functions of storage costs of goods and the sum of customer losses associated with nondelivery intersect. This indicates the presence of a demand-supply balance in the chain links, precisely at a shipment batch size of 14 tons.

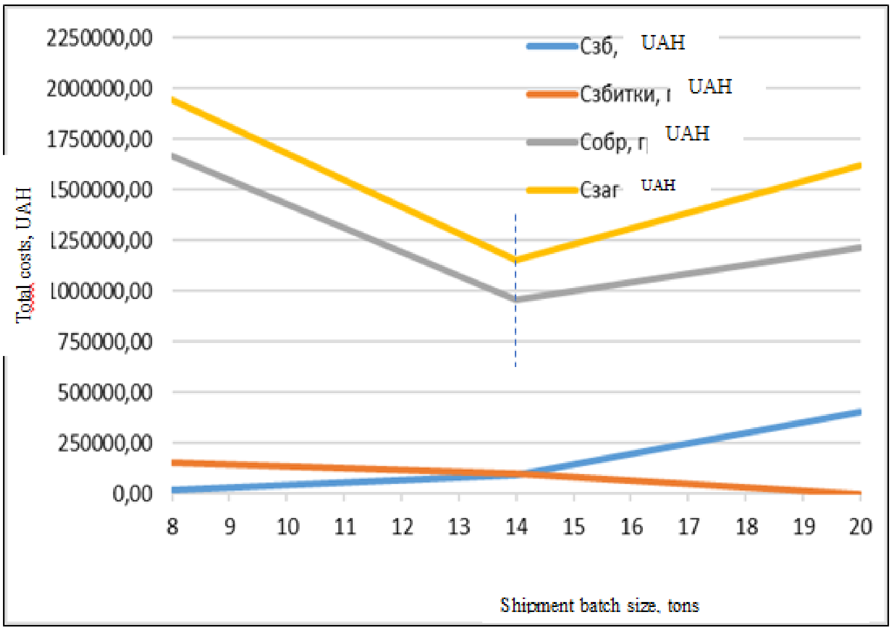

Fig. 3. **Dependence of the components of the efficiency criterion and total costs on the size of the shipment batch at different levels of input parameters**

Thus, it was determined that the minimum level of total costs, amounting to 115196,0 UAH, is achieved when supplying a rational batch size of 14 tons to the customer of TC "Neolith Logistic" in the direction of Germany - Ukraine with a delivery period 3 times a month.

The effect associated with the total cost of delivery, is determined by the following formula

$$E = C_{tot}^{min(max)}(q_{min(max)}, t_{Rmin(max)}) - C_{tot}^{*}(q_{rat}^{*}, t_{Rrat}^{*}) \qquad (16)$$

where $C_{tot}^{min(max)} = \left(q_{min(max)}, t_{Rmin(max)}\right)$ – the total cost total costs at minimum and maximum values of input parameters, UAH;

C_{tot}^{b} – the total costs at rational values of input parameters, UAH.

Results of calculations of the economic effect are given in Table 3.

Table 3. **Results of calculations of the economic effect**

Indicators	Value of indicators		
	Minimum	Rational	Maximum
Total costs of supplying products to customers, UAH	1946850,0	1155196,0	1621800,0
Economic effect, UAH	E_1=791654,0		E_2=466604,0

The results of the economic effect calculation demonstrate the effectiveness of the proposed solutions for determining the optimal size of the cargo batch and the delivery period to customers of TC Neolith Logistic in the direction of Germany - Ukraine. This is achieved while maintaining the balance of supply and demand and reducing the likelihood of additional costs associated with shortages or excessive stocks, which would impact the final cost of goods.

When comparing the total cost of delivery with rational supply chain parameters with the total cost at the minimum and maximum levels of variation of input parameters, positive values were obtained $E1$=791654,0 UAH and $E2$=466604,0 UAH, which indicates the effectiveness of the solutions proposed.

Conclusions. In this paper, propose technological principles for determining rational parameters of the supply chain in order to establish a balance between demand and supply for goods in the chain links under conditions of variable demand and optimisation of total costs for all cargo delivery participants.

Analysis of the current state of determining rational parameters of the supply chain with service of customers in international connections has revealed the relevance of the chosen research direction. The drawbacks and advantages of existing problem-solving methods have been identified based on the results of studying literary sources. Existing approaches and methods have been grouped into the following directions: inventory management system formation, logistic system design; delivery system design in supply chains; development of functioning models for transport-production complexes, terminal system formation, and so on. Based on the results, the object and subject of the research have been characterised and the purpose and objectives of the study have been formulated.

The input parameters, output parameter, external environmental factors, system elements, and relationships between them have been determined based on the formed structure of the research object. To determine the nature of the influence of controlled parameters on the efficiency of the functioning process of the research object, the method of mathematical modeling has been chosen. A mathematical model has been developed to determine the rational parameters of the supply chain - the cargo batch size and the delivery period to customers - at which the efficiency criterion value will be minimized

In order to conduct experimental studies of the supply chain functioning on the example of customer service at TC “Neolit Logistic”, it was important to conduct high-quality planning for the future period based on the study of demand trends. Taking into account the complexity of studying trends, the method of dynamic series construction has been chosen for demand forecasting. The total forecast demand, determined by the hyperbolic model as the most adequate model for forecasting, based on the criterion of minimal sum of squared deviations, is 488 tons.

Based on the results of experimental studies, the nature of the impact of model input parameters on the efficiency criterion has been determined at different levels of controlled parameters, and rational values of supply chain parameters have been identified. Specifically, the minimum level of total costs is achieved with the supply of a rational cargo batch size of 14 tons to the customer TC "Neolit Logistic" in the direction of Germany - Ukraine, with a delivery period of 3 times a month.

The positive results of the calculation of the economic effect testify to the effectiveness of the solutions proposed in the research work.

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Визначення раціональних параметрів ланцюга постачань при обслуговуванні замовників у міжнародному сполученні

Логістичні компанії постійно знаходяться у пошуку раціональних рішень при організації доставки вантажів у міжнародному сполученні, що дозволяли б досягнути балансу між попитом та пропозицією на товари в ланках ланцюга та зменшити додаткові витрати, пов'язаних із очікуванням поставок або зі зберіганням надмірних запасів. В роботі вирішена задача підвищення ефективності логістичного обслуговування вантажовласників у міжнародному та запропоновано технологічні основи з визначення раціональних параметрів ланцюга постачань з метою встановлення балансу попиту та пропозиції на товари в ланках ланцюга в умовах мінливого попиту та оптимізації сумарних витрат усіх учасників доставки вантажів, що матиме вплив на кінцеву вартість товару у замовників. Для вирішення поставленої задачі використано системний підхід, методи математичного моделювання та прогнозування. Для проведення експериментальних досліджень, враховуючи складність вивчення тенденцій, для прогнозування попиту обрано метод побудови динамічних рядів. Для заданих умов функціонування ланцюга постачань товарів у міжнародному сполученні визначено характер впливу вхідних параметрів моделі на критерій ефективності при різних рівнях керованих параметрів та визначено раціональні значення параметрів ланцюга постачань, при яких досягається мінімальний рівень сумарних витрат на доставку вантажів. Про ефективність запропонованих рішень свідчать позитивні результати розрахунку економічного ефекту.

Ключові слова: *логістичний ланцюг, розмір партії вантажів, період постачання, сумарні витрати, економічний ефект*

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Theoretical assessment of the distribution of dynamic interaction forces of the "rolling stock-track" system along the length of subway railway switches

Abstract. *One of the peculiarities for switch operation is the increased level of force interaction between the bearing elements of the switch and the rolling stock chassis, which causes increased requirements for strength, stability, reliability and durability of switches. Accordingly, to assess the strength of structures, it is necessary to know the magnitude of the forces acting on them, which can be determined experimentally or by theoretical calculations. In the case of tunnel sections of subways, experimental studies are extremely difficult to organize and conduct, so only theoretical methods are an alternative. This study presents the results of theoretical calculations of the elastic-dynamic characteristics for railway switches used in tunnel sections of subways. Practical calculations of the stiffness of rail threads and the modulus of elasticity of the sub-rail base were performed, and dependencies of the distribution of elastic-dynamic parameters along the length of railway switches were obtained. On their basis, the forces of interaction with the subway rolling stock were determined and their distribution along the length of the railway switch was analyzed. The obtained data can serve as a prerequisite for checking the strength of structural elements.*

Keywords: *railway switches, sub-rail base, stiffness, elastic modulus, elastic-dynamic track parameters, dynamic forces, dynamic deflections, stresses.*

Introduction. Scientific studies of the operation of railway switches in interaction with rolling stock are always relevant, as they provide information on the stress-strain state of the railway switches structure and the permissible speeds of trains, both on the main and side tracks. Compared to a conventional track, the operating conditions of railway switches structures under rolling stock wheels are much more complicated.

The design of railway switches and their operating conditions differ significantly from conventional track, so a number of issues arise during their design, modernization, and operation that require engineering solutions [1]. In particular, it is necessary to take into account the relevant design features of railway switches that cause a variety of dynamic effects on its elements [2-6].

In subways, the operation of railway switches differs from that of mainline railways as the intensity of train traffic is much higher with lower axial loads. Also, in the tunnel sections of subways, the operation of railway switches differs from that of mainline railways due to the peculiarities of the tunnel structure design. Therefore, it is very difficult and, in some cases, almost impossible to take into account the whole variety of force actions on the railway switch elements and the peculiarities of their support on the sub- railway switch base. Such circumstances require that all the features of the interaction between rolling stock and railway switches on subway tracks are taken into account in the calculations and an adequate calculation methodology is applied that would sufficiently reflect the actual operation of the railway switches structure in interaction with rolling stock and at the same time would be brought to engineering application [7].

Analysis of the latest research and problem statement. The long-term and safe operation of railway switches depends, on the one hand, on the magnitude of the forces exerted by the wheels of the rolling stock on the track, and, on the other hand, on the strength of the structure [3-5]. However, most studies on this problem consider only individual parts of railway switches, such as a crosspiece or an arrow [4, 5], and a comprehensive assessment of the dynamic impact along the entire length of the switch structure has not yet been performed. And in the few works [3] that consider the variability of the switch structure along its length and evaluate the force interaction between the rolling stock and railway switch, the adopted mathematical model is not sufficiently demonstrated and does not give sufficiently complete results, and the same emphasis is placed on the study of the stress-strain state of the railway swith sleepers. In other words, the distribution problem of dynamic forces along the length of railway switch has not been completely solved and remains relevant.

Meanwhile, the forces of interaction between track elements and rolling stock largely depend on the stiffness of the so-called elastic-rigid track parameters, which include: the masses of track structures involved in the interaction process, as well as viscous (dissipative) and elastic interconnections between individual interacting masses. When calculating the forces of interaction between track elements and rolling stock using modern computational methods and system modeling consisting of a series of sequential masses connected by elastic and dissipative links, one of the most critical aspects is determining the elastic-stiffness parameters of the track. These parameters, also known as the calculated mechanical parameters of the track, play a crucial role in computational schemes.

In general, research on the stiffness of track structures has been conducted by numerous researchers in various countries around the world, including the United Kingdom [8], France [9], Germany [10], Sweden [11], Spain [12], Slovakia [13], China [14-17], and others.

According to the results of various studies, the vertical stiffness of the track for railway switches on wooden beams ranges from 30,000 kN/m to 11,000 kN/m, and for switches on reinforced concrete beams it ranges from 60,000 kN/m to 13,000 kN/m. In the paper [13], the author notes that with very stiff supports, the vertical stiffness can reach 480000 kN/m. In general, the analysis of the review of sources shows that in various studies, information on the design characteristics of the track within railway switches obtained by experimental methods is difficult to use in practical calculations for specific structures due to a rather large difference in results. This situation arises due to the fact that the results were obtained for specific structures that were operated under specific operating conditions. Therefore, such data cannot be applied to other different structures, for example, of another modification or with other geometric parameters. In this case, it is more correct to determine the track characteristics by calculation methods, if such methods are sufficiently reliable and close to the actual results.

Research conducted by national scientists [1, 18], which was carried out at different times for track structures on wooden and concrete sleepers with various rails and fastenings, can be shown in the form of table 1.

Table 1. **Stiffness of rail thread on cap $\beta_{y(midd)}^{head}$ and sole $\beta_{y(midd)}^{base}$ and the horizontal cross-sectional modulus of elasticity of the sub-rail base U_y for different track constructions**

Sleepers	Type of rail	Type of fastenings	Horizontal cross-sectional stiffness of rail thread, kN/mm		the horizontal cross-sectional modulus of elasticity of the sub-rail base U_y, MPa if only H (P=0)
			$\beta_{y(midd)}^{head}$	$\beta_{y(midd)}^{base}$	
Concrete	R65	KB	from 17 to 23	from 37 to 64,9	10,9
		ZHB	from 8 to 12	from 19,5 to 40	19,7
Wooden	R65	D0	from 16 to 22	from 32 to 48	from 22 to 24,0
	R50	D0	from 12,6 to 13,1	from 25,2 to 27,6	from 19 to 24,0
	R43	D0	from 10,9 to 12,1	from 21,8 to 24,2	from 18 to 24,0

The methodology for determining the stiffness parameters of rail tracks using theoretical methods [1] was developed by Dr. Eng. Prof. E. I. Danilenko in the mid-1990s. Subsequently, from 1995 to 2000, during experimental studies of railroad railway switches on wooden and concrete sleepers, it demonstrated fairly reliable convergence with experimental data. The obtained results were reflected in regulatory and technical documents [18].

Despite the extensive research on the elastic-deformation parameters of railway tracks, there are very few works dedicated to railroad railway switches, and even fewer to switches installed in subways. A similar situation is observed regarding the assessment of the force impact on railroad railway switches.

Thus, this study aims to investigate the interaction forces within the area of a railroad railway switch, depending on changes in the elastic-dynamic parameters of the sub rail base along the length of the railway switch. This is the first time that scientific research in this setting has been performed for switches laid in subway tracks.

The purpose and objectives of the research. The main objective of this study is to assess the power load of railway switches for subway operating conditions.

To be able to theoretically solve this problem, in accordance with the existing methodology for calculating track strength [18], it is necessary to know the track structure, stiffness parameters of the sub rail base and characteristics of the rolling stock. While the stiffness parameters are well studied for conventional track construction, there is no experimental data on these characteristics for subway railway switches. It is quite difficult to organize experimental studies in subway conditions. Therefore, we propose theoretical approaches to solve the following problems.

Thus, the first task of this study, performed for a switch laid in a tunnel section of the subway, is to theoretically determine the elastic and dynamic parameters, taking into account the fact that at a relatively short length of the switch track, its structure and characteristics of the subgrade base undergo significant changes. And the second task, which is solved on the basis of the previous one, is to establish the nature of the distribution of dynamic forces and stresses in the rails and dynamic deflections along the length of the switch, which will further serve as the basis for assessing the strength of individual structural elements, taking into account the specifics of subway conditions.

Research materials and methods. The strength characteristics of railway switches affect the safety of train traffic and the permissible speed level. Strength assessment for a known structure is possible if the forces acting on it are known.

For the theoretical determination of dynamic interaction forces, we can use well-known rules [18], which can be adapted to solve the problem at hand. In this case, we assume the following starting points:

1. Each of the two rails of the track is considered as a beam of infinite length with a constant cross-section, freely resting on a solid equiaxed base or on separate point equiaxed supports.

2. The main calculation of the rail is performed for the action of vertical forces; vertical forces are assumed to be applied in the plane of symmetry of the rail, and the rails of both strands are assumed to be equally loaded.

3. Horizontal longitudinal forces are taken into account by appropriate selection of permissible stresses. The permissible physical stresses are the permissible bending stresses in the rails during endurance service.

4. The static calculation of a rail as a beam on an elastic base is based on the hypothesis of a linear relationship between the pressure per unit area of the base (*p*) and the elastic settlement of the base (*Z*), which is defined by the equation:

$$p = C_{ball.} \cdot Z, \tag{1}$$

where p – pressure per unit area of the base (equal to the reactive resistance of the elastic foundation settling);
Z – elastic beam settling;
$C_{ball.}$ – the elasticity characteristic of the base, which is called the ballast's elastic compression ratio, or "bed ratio".

5. In practical engineering calculations, the track structure is designed to withstand dynamic wheel loads.

The elastic bending line of a beam under dynamic vertical load is taken as the elastic bending line of a beam under static load, which is numerically equal to the value of the dynamic force at a given time.

6. The influence of oscillations in the wheel-gauge system and the influence of irregularities on the track and wheel are taken into account by the inertial forces arising from the interaction of the specified system, which arise in the system in addition to the action of static forces.

The resultant of all vertical force components transmitted by the design wheel to the rail is taken at its maximum probable value $P_{calc} = P_{dyn}^{max}$ as a statistical set of random components with a probability level F=0,994 (with a normalizing factor λ=2,5).

7. The effect on the rail thread of all other wheels of the carriage is taken into account by loading the lines of influence of moments M and lateral forces Q with the wheel load system P_{dyn_i} and determining the equivalent loads P_{eq}^{I} i P_{eq}^{II}.

8. In practical engineering calculations, it is noted that the maximum probable dynamic wheel load acts in the design cross-section of the rail (i.e., the section where the stressed state is determined) $P_{calc.} = P_{dyn}^{max}$, and the influence of neighboring wheels is taken in the form of their average dynamic loads $\bar{P}_{dyn_i}$, taking into account that the maximum dynamic pressure of the design wheel does not coincide with the maximum pressure of adjacent wheels.

9. It is considered that the railway track and rolling stock are in a serviceable condition, which corresponds to maintenance standards.

The greatest difficulty for theoretical calculation methods is the determination of variable values of track stiffness and elastic modulus of the sub rail grade within the length of the railway switch. The theoretical solution of this problem in the vertical direction is carried out in stages: first of all, considering the track structure as a beam resting on separate elastic supports, and the work of each support (sleeper or beam) under the influence of loads transmitted from the rails should be considered as the work of a beam of limited length resting on a continuous equiaxed "Winkler" base (Fig. 1).

The solution approach for the mentioned problem for railway switches undoubtedly depends on the considered arrangement scheme of rail threads on elastic supports of the base. However, in general, the algorithm for solving the problem under consideration will be common for all arrangement schemes of rail threads and can be presented as a generalized sequence of calculating the stiffness parameters of the track within the railway switches:

1. Determination of the elastic deflections of the sub-rail supports under the influence of unit forces applied at the sub-rail cross-sections. In cases where multi-threaded rail schemes are considered, the calculation is performed taking into account the influence of loaded and unloaded rail threads.

2. Determination of the total point stiffness of the sub-rail base as a multi-layered structure, taking into account the design features of the sub-rail base;

3. Determination of the vertical modulus of elasticity of the sub-rail base, considering the distribution diagram of ties (sleepers);

4. Determination of the total stiffness of the rail threads working together with the sub-rail base; for multi-threaded constructions, the calculation is performed considering the influence of unloaded threads and the specific structural arrangement (i.e., the stiffness of each thread).

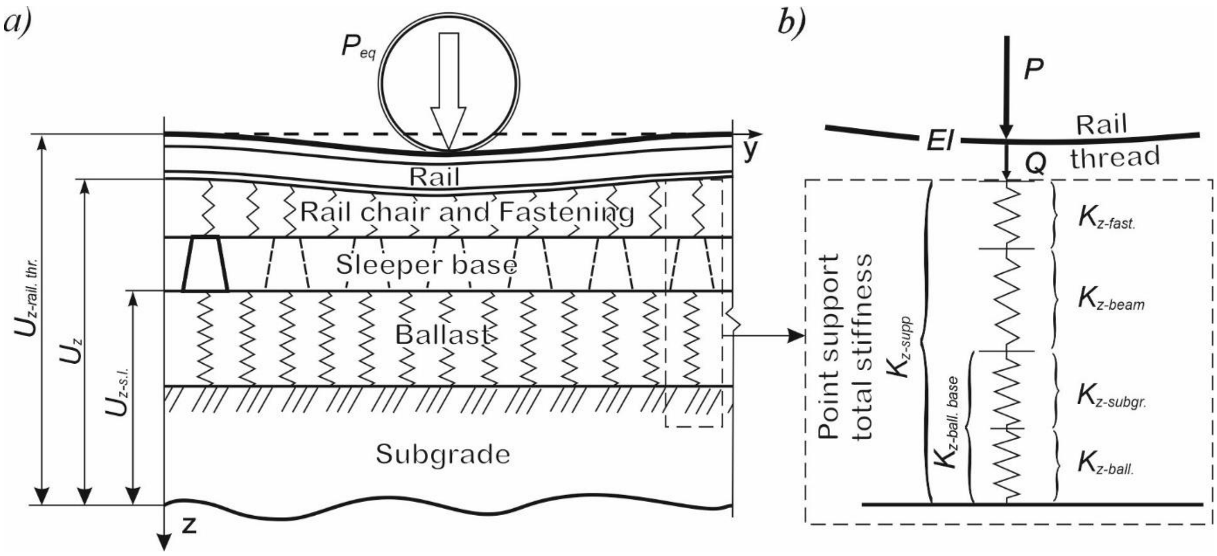

Fig. 1. **Mechanical model of elastic track operation: *a* - as a multilayer structure; *b* - as a single point support under the rail**

According to the research [19], the sequence for determining the elastic-dynamic characteristics of railway switches can be presented as the following algorithm, which can be conveniently implemented as a computer program:

1) Input of initial data for a particular cross-section of the railway switch: length L, height h, width b of the beam; points of load application Q relative to the beginning of the beam a_i; elastic moduli E_i and moments of inertia I_i of the beam and rails; beam bedding factor $C_{ball.}$ and distance between beam axes l_i; area of the substrates ω and modulus of elasticity at compression of the beam E_{st}; stiffness of fasteners K_{fast}; values of vertical dynamic interaction forces P^{dyn};

2) Calculation of elastic deflections of sub-rail supports under the action of unit forces applied in sub-rail sections as beams lying on a continuous equally elastic base by the method of initial parameters from solving a differential equation:

$$EI\frac{d^4Z}{dx^4} + C_{ball.}bZ = \sum_1^n Q_i\eta_i(x - a_i). \tag{2}$$

The deflections in the characteristic cross-sections Z_i and the bending coefficient α of the beam are determined;

3) Determination of the total point stiffness of the sub-rail base as a multilayer structure:

- the stiffness component is determined, which takes into account the bending of the beam and depends on the elastic subsidence of the ballast layer and subgrade under the beam:

$$K_{z-ball.base} = \frac{C_{ball.}\cdot\alpha\cdot l\cdot b}{2}; \tag{3}$$

- the stiffness component is determined, which depends on the compression performance of the beam in the sub-rail section:

$$\frac{1}{K_{z-beam}^{compr}} = \frac{h\left(\frac{1}{\omega_i}+\frac{2}{\alpha \cdot l \cdot b}\right)}{2 \cdot E_{ball.}^{compr}}; \tag{4}$$

- the value of point stiffness (pliability) is determined:

$$\frac{1}{K_{z-supp.}} = \frac{1}{K_{z-ball.base}} + \frac{1}{K_{z-beam}} + \frac{1}{K_{z-fast.}}; \tag{5}$$

4) Determination of the vertical modulus of elasticity of the sub-rail base, taking into account the layout of the beams:

$$U_z = \frac{K_{z-supp.}}{l_i}. \tag{6}$$

5) Calculation of the equivalent moment of inertia of the design rail thread $I_{in(red.)}$, operating in bending in the vertical plane, taking into account the influence when operating in bending both the loaded thread and the unloaded other threads.

$$I_{in(red.)} = I_{in(calc)} + \sum_{n=1}^{n=m} k_{n(infl.)} \cdot I_{n(unload.)}. \tag{7}$$

6) Determination of the total stiffness of rail threads working together with a sub-rail base:

$$K_{z(rail.thr.)} = \sqrt[4]{64 \cdot E_{st} \cdot I_{in(red.)}} \cdot \sqrt[4]{U_{zi}^3}. \tag{8}$$

7) Calculation of vertical dynamic interaction forces $P^{дин}$;
8) Determination of dynamic deflections in a specific cross-section for a given rail thread:

$$Z_{rail.}^{dyn} = \frac{P_i^{dyn}}{K_{z(rail.thr.)}}. \tag{9}$$

9) Printing out the calculation results: U_z, $K_{z(rail.\ thr.)}$, $Z_{rail.}^{dyn.}$.

In this way, the task is structured and becomes practical. For each stage, more detailed block diagrams were developed and calculation programs were compiled.

According to the above algorithm, we calculated the stiffness parameters of the track using 1/9 grade steel for the P50 railway switch on wooden beams and crushed stone ballast laid in the tunnel section of the subway.

The peculiarity of solving this problem is that the length of the railway switches varies along the length of the beams, the number of rail threads, and the parameters of the cross-sections of the bearing elements. Therefore, the calculation was based on beams of all standard sizes, which are sequentially placed from the railway switch to the cross section.

The results of the calculations of the stiffness characteristics are summarized in Table 2, and a graphical representation of the results is shown in Fig. 2.

For railway switches with wooden sleepers, there are practically no analogs for theoretical determination of stiffness characteristics along the entire length, so the obtained results are of scientific and practical interest.

Overall, the following patterns of stiffness distribution along the length of the railway switch are observed:

- the stiffness characteristics of the inner rail thread have higher values along almost the entire length than those of the outer rail thread;

- there is a significant increase in stiffness within the cross section;
- there are stiffness increase in places of change in the standard sizes of switch beams, and they have higher values for the outer rail thread compared to the inner one;
- there is a local increase in stiffness at the root of the point, which is explained by the peculiarities of their design, while it should be noted that the calculations did not consider the beams placed along the length of the points, so the graphs do not show stiffness increase within the length of the points;

Table 2. **Stiffness characteristics of railway switches type P50 grade 1/9 for subway conditions**

№ beam	U_z, MPa ixternal	$U_{z,}$ MPa internal	K_z, kg/cm ixternal	K_z, kg/cm internal	$K_{ball.\ base}$, kg/cm ixternal	$K_{ball.\ base}$, kg/cm internal	$K_{rail.\ thr.}$, kg/cm ixternal	$K_{rail.\ thr.}$, kg/cm internal
0	38,57	38,57	20058	20071	44114	44169	62812	62844
1	35,05	35,05	21032	21032	48282	48282	58463	58463
19	37,94	38,4	20866	21121	47546	48679	73668	74283
20	38,94	39,54	20831	21156	47391	48839	72518	73785
26	39,39	41,1	20362	21234	45378	49191	70512	74537
27	47,48	48,25	20889	21231	47649	49181	81196	84115
33	37,24	39,23	20295	21379	45098	49855	64525	71356
34	38,24	39,28	20841	21405	47437	49974	65790	71700
38	37,33	39,49	20342	21521	45292	50514	62627	72662
39	38,26	39,5	20850	21523	47474	50526	64441	71993
41	37,84	39,58	20624	21571	46492	50751	62435	74000
42	38,46	39,56	20963	21562	47973	50707	63134	74363
45	39,59	44,44	22965	25773	47742	50776	73286	104624
46	39,91	44,42	23146	25764	48409	50748	73597	105356
50	47,12	58,94	20733	25932	46965	51023	74967	111262
51	37,55	46,21	21029	25876	48268	50839	63214	92688
63	38,69	39,60	21086	21582	48524	50800	63577	72804

The obtained distribution of the stiffness characteristics of railway switches along its length allows us to conclude that it is necessary to conditionally divide the railway switch into separate zones within which the stiffness parameters include similar components, in particular:
- the front overhang of the frame rails, where the railway switch design differs little from the conventional track;
- the point area, where the overall stiffness includes the effects of the frame rails, points, switch pads and shoes;
- connecting part, is essentially a four-threaded track structure with two loaded and two unloaded rail threads.
- the cross section, which in turn has sections with four rail threads, where counter rails are mounted near the outer threads, and in the middle part the inner threads cross the cross section, which has a variable cross-section and corresponding bending stiffness;
- the cross section, within which the four-threaded railway switch structure gradually transitions to two directions of the conventional track.

The obtained calculation results indicate that for such a multi-threaded construction as a railway switch, the distribution of stiffness characteristics along the length depends on many factors, but the greatest impact comes from the stiffness of the rail threads and the density of the beams. Thus, the presence of counter rails, a strong cross section and carriages result in significant increases in overall stiffness and elastic modulus. Slightly smaller increases in stiffness are caused by densely stacked beams.

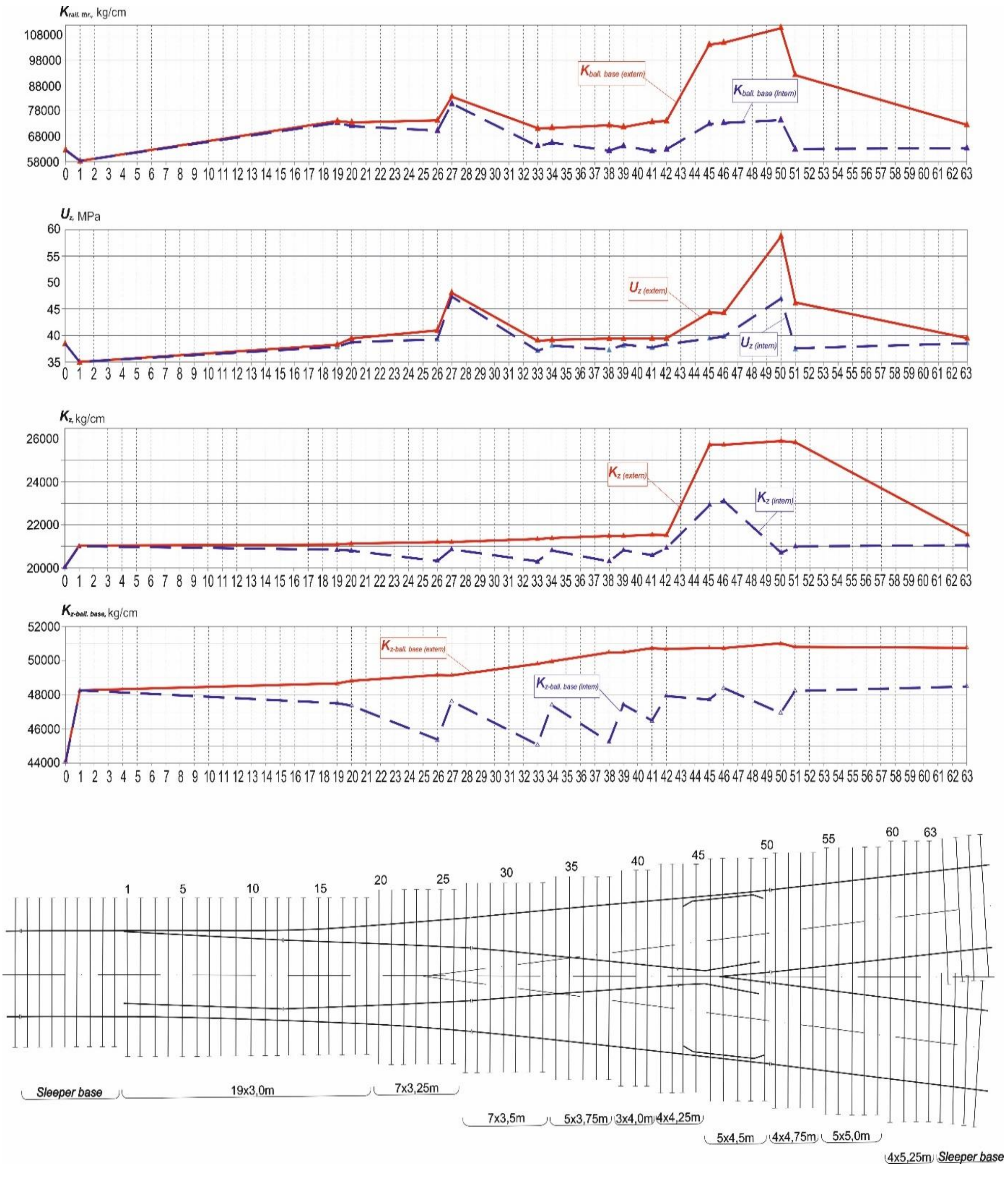

Fig. 2. **Distribution of the stiffness characteristics of a railway switch type P50, grade 1/9, on wooden beams along the length**

Due to the change in the position of vertical loads along the length of the switch beams and the influence of unloaded rail threads, the nature of the change in stiffness parameters along the outer and inner rail threads differs.

The results obtained are a prerequisite for further determining the dynamic forces transmitted from the wheel to the rail elements of the railway switch.

The calculated dynamic load is taken as the maximum probable value from the combination of the effects of constant static and variable dynamic forces in accordance with [18].

The algorithm for determining dynamic interaction forces can be presented in the form of a flowchart shown in Fig. 3.

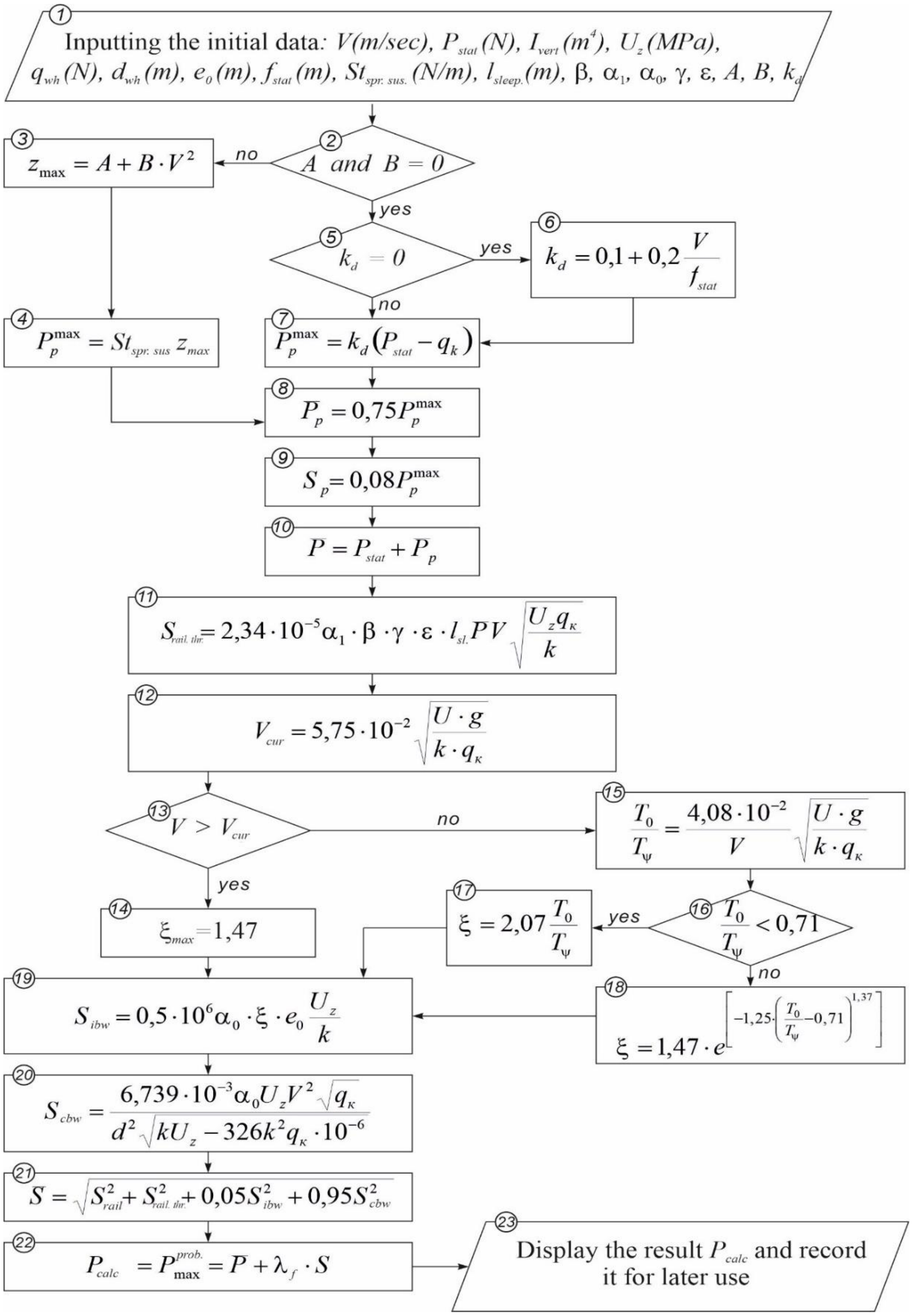

Fig. 3. **Algorithm for calculating dynamic forces**

The above algorithm was implemented in the form of a computer program, and the results of calculations of vertical dynamic forces, stresses in rails and dynamic deflections of rail threads when moving along a subway railway switch are summarized in Table 3 and graphically displayed in Fig. 4.

Table 3. **Vertical dynamic forces and dynamic deflections for a railway switch of type P50, grade 1/9, for subway conditions**

№ бруса	$Z_{dyn,}$ mm ixternal	$Z_{dyn,}$ mm internal	$P_{dyn,}$ кN ixternal	$P_{dyn,}$ кN internal	$\sigma_{head-edge,}$ MPa ixternal	$\sigma_{head-edge,}$ MPa internal	$\sigma_{base-edge,}$ MPa ixternal	$\sigma_{base-edge,}$ MPa internal
0	1,77	1,77	110,55	110,55	97,53	97,53	89,69	89,69
1	1,958	1,958	113,46	113,46	102,14	102,14	93,93	93,93
19	1,815	1,8	111,87	112,0	99,09	98,99	91,13	91,03
20	1,77	1,752	111,39	111,56	98,15	98,02	90,27	90,14
26	1,742	1,692	110,61	111,05	97,2	96,82	89,39	89,04
27	1,477	1,461	108,43	108,59	91,84	91,69	84,46	84,33
33	1,834	1,77	111,43	111,98	99,02	98,56	91,07	90,64
34	1,801	1,768	111,71	111,99	98,79	98,55	90,85	90,63
38	1,831	1,762	111,46	112,05	99,0	98,51	91,05	90,59
39	1,8	1,761	111,71	112,05	98,78	98,5	90,85	90,59
41	1,814	1,759	111,59	112,07	98,88	98,49	90,93	90,57
42	1,795	1,76	111,77	112,07	98,74	98,49	90,8	90,58
45	1,787	1,653	113,84	115,18	100,15	99,17	92,09	91,2
46	1,777	1,654	113,94	115,18	100,08	99,18	92,04	91,21
50	1,484	1,276	108,36	110,54	91,91	89,90	84,5	82,68
51	1,836	1,596	112,26	114,68	99,66	97,88	91,65	90,01
63	1,786	1,758	111,83	112,08	98,68	98,48	90,75	90,57

The obtained calculation results reveal the following patterns in the distribution of dynamic force levels along the length of the railway switch:

- stiffness significantly influences the level of dynamic forces. Increased stiffness leads to a reduction in dynamic forces, stresses, and deflections of the rail threads;
- for the inner and outer rail threads, the forces along almost the entire length have insignificant differences, except for the cross section (for which a different calculation method is used. Within the cross section, the level of dynamic forces should additionally be taken into account due to the presence of vertical irregularities);
- in places of stiffness increases, the forces are higher along the outer rail thread than along the inner rail thread;

Conclusions. The structural peculiarities of a railway switch demand a differentiated approach to assessing the force dynamics depending on the position of the moving load along the length of the railway switch.

The specific design features of railway switches necessitate a differentiated approach to evaluating their force loading and deformability. Therefore, it is advisable to introduce a conditional division of the railway switch into sections, within which the force dynamics exhibit similar characteristics.

For certain parts of the railway switch in the front overhang of the frame rails, on the connecting tracks and in the crossover zone, i.e. in those areas of the railway switch where there are no structural irregularities on the rolling surface, the dynamic forces of interaction between the wheel and rail can be determined using a standard methodology for calculating track strength. However, in the areas of irregularities on the switch and cross section, other approaches, including mathematical modelling methods, should be used to determine the vertical dynamic forces.

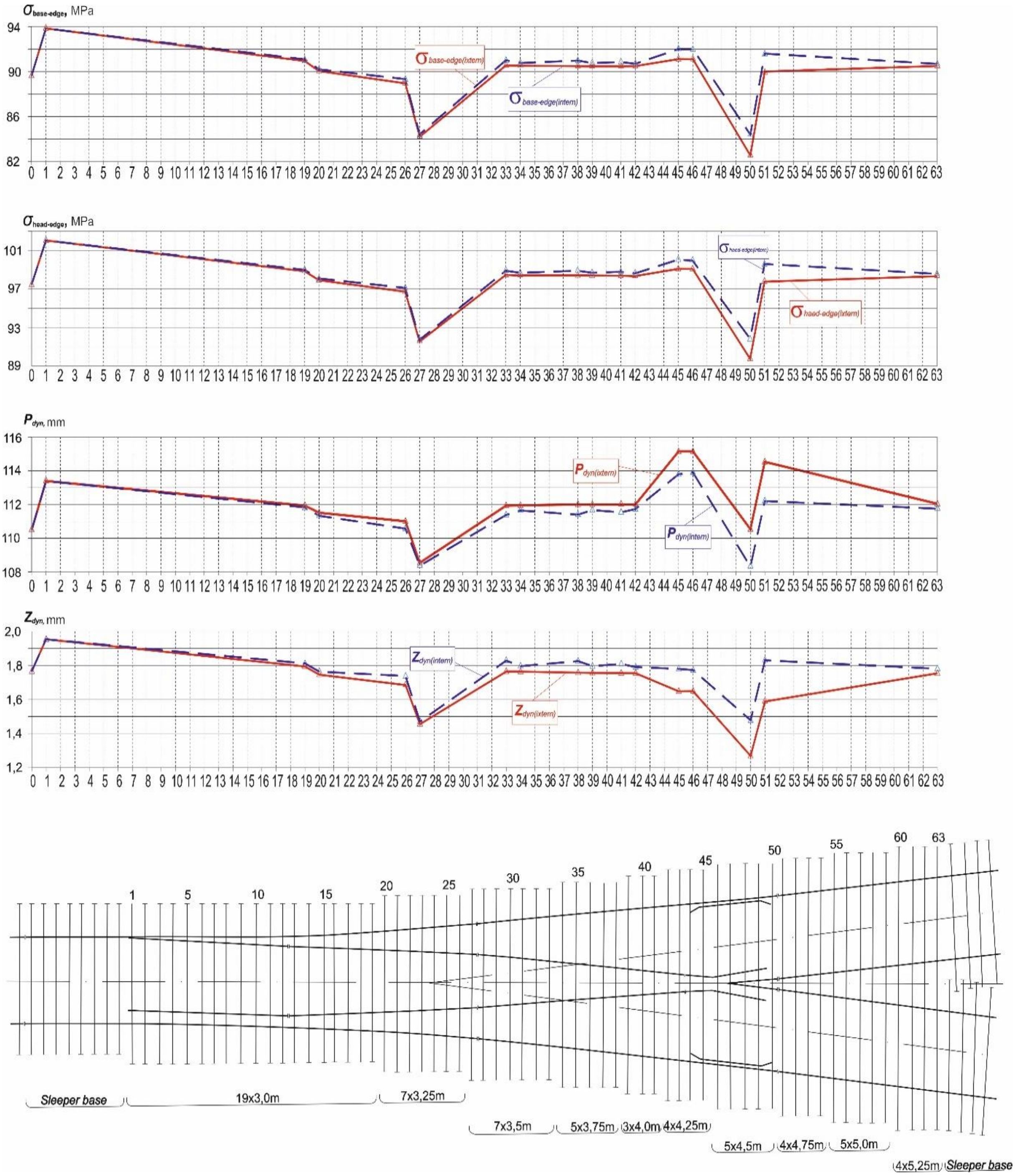

Fig. 4. **Distribution of dynamic forces, stresses in the rails and dynamic deflections of the railway switch of the P50 grade 1/9 on wooden beams along its length**

It is proposed to establish the basic stages of assessing the power load of a railway switch along its length.

1. The railway switch is divided along the length into sections: pre-point, point, connecting, crossing, and post-crossing.

2. For each part, taking into account the design parameters, geometric, inertial, elastic and other design data are determined.

3. Stiffness parameters of the track within each selected part of the railway switch are calculated.

4. On the parts of the railway switch where its design is similar to a conventional track, vertical dynamic forces are calculated according to the algorithm shown in Fig. 3 algorithm.

5. Within the point and cross parts, with known forms of irregularities on the rolling surface, mathematical models of interaction between the rolling stock and track system in the vertical plane are developed and the corresponding dynamic forces are determined based on their implementation.

6. On the basis of the obtained results of power loading, the stress state of the corresponding elements of the railway switch is determined.

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Теоретична оцінка розподілу динамічних сил взаємодії системи «рухомий склад-колія» по довжині стрілочних переводів метрополітенів

Анотація. *Однією з особливостей роботи стрілочних переводів є підвищений рівень силової взаємодії несучих елементів переводу з ходовими частинами рухомого складу, що викликає підвищені вимоги до міцності, стійкості, надійності та довговічності стрілочних переводів. Відповідно для оцінки міцності конструкцій потрібно знати величину діючих на них сил, які можна визначати експериментально або теоретичними розрахунками. У випадку тунельних ділянок метрополітенів експериментальні дослідження вкрай складно організувати та провести, тому альтернативою є лиш теоретичні методи. У даному дослідженні представлені результати теоретичного розрахунку пружнодинамічних характеристик для стрілочних переводів, що експлуатуються в тунельних ділянках метрополітенів. Виконано практичні розрахунки жорсткості рейкових ниток та модуля пружності підрейкової основи й отримано залежності розподілу пружнодинамічних параметрів по довжині стрілочних переводів. На їхній основі визначені сили взаємодії з рухомим складом метрополітену та проаналізовано їх розподіл по довжині стрілочного переводу. Отримані дані можуть служити передумовою для перевірки міцності конструктивних елементів.*

Ключові слова: *стрілочні переводи, підрейкова основа, жорсткість, модуль пружності, пружно-динамічні параметри колії, динамічні сили, динамічні прогини, напруження.*

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Research on graphic data formats for compact representation and comparison of images

This article investigates common methods of lossy and lossless compression of graphic information. The advantages and disadvantages of compression methods are identified as a result of the research. A comparative analysis of the main capabilities of graphic information compression methods is conducted. The relevance lies in the efficient transmission, processing, and storage of graphic information, as large data volumes require increased network bandwidth and significant resources for data storage. The practical significance lies in solving the task of effectively reducing data sizes by applying well-known compression methods. Based on the study of graphic data formats, the development of algorithms for the computational scheme of "precise" processing of halftone images for pattern recognition is presented. Such a scheme rewrites a multigradient image into a three-level representation and implements a balancing procedure, which allows forming image features in a more compact form and computing the correlation function faster. The effectiveness of using developed methods of compact image representation with correlation comparison of balancing curves is demonstrated compared to traditional correlation comparison of images.

Keywords*: image, compression, lossy, lossless, three-level representation, balancing, correlation function.*

Introduction. The problem of transmitting large volumes of graphic information via communication channels continues to be topical. The existing methods of coding graphic information begin to be replaced by more complex and effective methods based on analyzing the content side of information about objects and phenomena in images. In contrast to formal description, which weakly takes into account their specificity. Such methods of information representation better reproduce the semantics of objects of the corresponding subject area.

Images such as maps, diagrams, blueprints, etc., which are structured, are not processed too efficiently by existing image coding methods. Since they are characterized by internal correlations which are strongly and selectively related to their ordered and organized structure. Therefore, the lack of taking into account this structure leads to a decrease in the compression performance of graphic information, which determines the effective bandwidth of communication channels, as well as to a decrease in the performance of coding and decoding procedures.

In this connection the problem of development of computer methods of representation and coding of graphic information, which would take into account the specificity of graphic images, as well as increase the level of efficiency of their representation in telecommunication systems, becomes urgent.

Currently, there are quite a few methods for compact representation of graphic information. The basis of any data compression methods lies in utilizing the inherent redundancy of the original information. Compression methods for graphic information are developed to reduce the volume of the original information using either lossless or lossy transformations. Thus, such methods are divided into lossy compression and lossless compression [1]. Common standard methods and their combinations do not give clear answers about which of them are the best. Everything depends on the specific requirements for the reconstructed post-compression image, the available hardware and software support [2].

Lossy compression is the transformation of input data into output data that reproduce the external characteristics of the input data with a difference in volume. The degree of similarity between input and output data is determined by the degree of correspondence of certain properties of the image represented by a given information stream. Lossy compression methods allow for significantly higher compression ratios. However, this leads to distortion of the output image and deterioration in its quality. Therefore, when comparing different compression methods, the quality of image reconstruction must be taken into account. Lossy compression is most commonly used for multimedia data, especially for streaming data transmission and telephony. Lossy methods are typically applied to compress images and audio [1, 3].

Lossless compression is the transformation of input data into output data where the encoded information can be recovered with bit accuracy. Lossless compression methods are used to reduce data size. By employing these methods, it is possible to accurately reconstruct the original data. For each type of digital information, there are typically specific lossless compression methods. The result of lossless compression is always a reduction in the volume of the output information stream without altering its informativeness, i.e., without loss of information structure. Lossless compression methods are used in areas where data accuracy and transmission speed between system nodes are crucial. For instance, in scientific and medical applications where information loss is unacceptable or where image noise itself is the primary information. Its practical significance lies precisely in its hardware implementation. Such encoders are used in security systems, data collection systems, satellite, underwater, and other surveillance systems, as well as in astronomical instruments and telescopes [4].

Analysis of recent research and problem statement. Initially, conventional methods used in backup systems and in the creation of distributions were first applied for image compression. These algorithms compressed information without alteration. Large companies utilized compression methods for storing vast amounts of data. With the advent of the internet, there arose a need to improve existing compression methods, as channel bandwidth was extremely narrow [1]. Therefore, formats such as ZIP, GIF, and PNG were developed. The first successful archiver, ARC, allowed compressing multiple files into an archive, and its outputs were open. ARC used a modified LZW method. With the advancement of computer technology, the DEFLATE method replaced the LZW method. Among the new features was the ability to split the archive into volumes. This version is still widely used despite its venerable age. The GIF (Graphics Interchange Format) image format supports lossless image compression and is limited to a palette of 256 colors. It remains popular, especially due to its support for animation. Currently, DEFLATE is the most popular compression algorithm. As new classes of images are increasingly used, old methods no longer meet compression requirements. This led to the creation of a new type of algorithms - lossy compression algorithms [5]. Typically, the compression ratio, and thus the level of quality loss, can be specified in them. This achieves a compromise between image size and quality. One of the significant problems of image compression is the lack of adequate criteria for evaluating quality loss because the quality may deteriorate at any stage of processing (during digitization, when converting to a limited color palette, when converting to another color representation system for printing, during lossy compression).

It is known that almost all graphic information subjected to compression is intended for further analysis by humans. It is best to assess image quality loss visually, using sight. Compression is considered excellent when it is visually impossible to distinguish between the original image and the one restored after compression. It is considered normal when the original and the restored image after compression can only be distinguished by comparing the two images.

In practice, even with excellent preservation of quality, regular specific changes may be introduced into the images. Therefore, lossy compression methods are not recommended for compressing images that will subsequently need to be printed with high quality or processed by image recognition programs [6]. Unpleasant effects with such images may arise even with simple scaling [7-9].

Aims and Objectives of the Research. Today, an important task in communication systems is the effective transmission and preservation of images due to the large sizes of graphic images requiring significant storage resources. The application of image compression methods, which involve reducing the file size, addresses this issue. There are many developed methods for compressing graphic information, including methods focused on compression and decompression, as well as methods focused on the degree of compression. Typically, such methods are developed for specific types of graphic information. Therefore, to analyze different image compression methods, it is necessary to know which class of images to focus on (monochromatic, halftone, color, images with continuous tone, discrete-tone images, images with large areas of one color). Thus, it is difficult to delineate and compile a universal description of known methods. This can only be done for typical methods under the condition of using typical methods on typical platforms [9].

The scientific novelty lies in the development of a method of generalized spatially connected dissection of image parts. On the basis of which comparison functions are calculated, including correlation, which allows the implementation of the method of image segmentation and compact representation. The considered methods of image representation make it possible to determine the list of quality parameters of the system functioning, to create evaluation criteria adapted to the complex nature of quality parameters; to estimate the computing power required to implement the optimal structure of a computer network.

Materials and Research Methods. Among the main lossless compression methods are the RLE method, the LZW method, the Huffman method, the JBIG method, the Lossless JPEG method, and the DEFLATE method. Let's consider them in more detail.

1. RLE Method (Run Length Encoding) **-** is one of the oldest and simplest compression methods. This method is easy to implement as it does not require additional memory during compression /decompression. The method is oriented towards images with a small number of colors or images with larger color areas that are repeated. RLE has high speed and does not require additional memory during compression. However, RLE has a low compression ratio. This method is effective for compressing raster tonal images (BMP, PCX, TIFF) as they contain long series of repeated byte sequences [1, 3, 9]. The main advantage of RLE is its lower computational complexity with simpler encoding and decoding stages, facilitating faster implementation compared to other encoding methods for better distortion-free compression [10].

2. LZW Method (Lempel-Ziv-Welch) - is a universal lossless compression method aimed at 8-bit images. Compression is achieved by identical byte subsequences in the stream. The compression process is relatively simple: characters in the input stream are read sequentially, and it is checked whether such a string exists in the created string table. If the string exists, the next character is read, and if the string is absent, the code for the previous found string is entered into the stream, the string is entered into the table, and the search begins again. LZW is universal, as its variants are used in common archivers. It is implemented in GIF, TIFF, and TGA formats. The main drawback of this method is its low compression ratio compared to two-stage coding schemes [1, 3, 9].

3. Huffman Method **-** is a classic method for compressing information, applicable to text files, where text symbols are replaced by strings of bits of different lengths, ensuring a unique construction of a code with the lowest average number of symbols per letter for a given distribution of probabilities among the characters. The Huffman method is practically not applied to images in their pure form but is usually used as one of the compression stages in more complex schemes. It is the only method that does not increase the size of the output data in the worst case (if we do not consider the need to store the recoding table along with the file) [1, 3, 9].

4. DEFLATE Method based on a combination of LZW (Lempel-Ziv-Welch) and Huffman algorithms. The DEFLATE method is quite simple to implement, fast, and widely used in software. The disadvantage of the method is the low coding efficiency of small data volumes. Compared to RLE, LZW, and Huffman methods, the DEFLATE method is optimal in terms of loss quality ratio. Therefore, it is advisable to develop a new approach to image compression based on the DEFLATE method using a preprocessing stage. At this stage, data should be prepared, firstly, with repeated fragments and, secondly, with a large number of identical pixels in the image. The preprocessing stage may include the following main algorithms: background color determination; determination of image presence; analysis of the possibility of separating image fragments; bringing fragments to a rectangular form; direct processing of image fragments. Additionally, increasing the compression ratio is possible by selecting a color model. Since the DEFLATE algorithm compresses by the frequency of pixel appearance in the image, it is advisable to use a color-difference model, in which two color components have a reduced dynamic range of data for image fragments with homogeneous rows [3].

Table 1. **Comparison of the main characteristics of lossless graphic information compression methods**

Method name	Main characteristics of the method	Advantages and disadvantages of the method
RLE Method (Run Length Encoding)	The essence lies in encoding repetitive color values.	*Advantages:* simple to implement, useful for redundant data such as images with a large number of pixels.
		Disadvantages: compression leads to an increase in file size.
LZW (Lempel-Ziv-Welch method)	Repetition of homogeneous color sequences	*Advantages*: simple to implement, high compression speed, does not require additional memory.
		Disadvantages: low compression ratio
Huffman Method	Differing color occurrence frequencies	*Advantages:* high compression speed, relevant for text files, ensures unambiguous construction of a code with the smallest average number of symbols per letter for a given distribution.
		Disadvantages: practically not applicable to images in their pure form
DEFLATE	Compression occurs due to the sharp frequency of appearance of pixels in the image and their homogeneous rows.	*Advantages:* simple to implement, fast, widely used in software.
		Disadvantages: low efficiency of encoding small data volumes
JBIG	Compression of one-bit black-and-white images	*Advantages:* allows control over the order of splitting the image into bit planes, the width of the strips in the image, and scaling levels (enabling viewing of the image through reduced copies).
JBIG	Compression of one-bit black-and-white images	*Disadvantages:* reduction in compression ratio with increased levels of noise in the input data
Lossless JPEG	Targeted at full-color 24-bit and 8-bit images without a palette	*Advantages:* universal
		Disadvantages: low compression ratio (when compressing lossless images)

5. *JBIG Method (Joint Bi-level Experts)* was developed by the ISO Joint Bi-level Experts Group specifically for compressing one-bit black-and-white images (e.g., for faxes or scanned documents) and can be applied to both 2-bit and 4-bit images, dividing them into separate bit planes. Like the Huffman method, the JBIG method uses short chains for common symbols and long chains for rare ones. However, unlike it, the JBIG method uses sequences of symbols. JBIG allows controlling the order of breaking the image into bit planes, the width of strips in the image, and scaling levels. The latter allows for easy orientation in a database of large-sized images by first viewing their reduced copies. Adjusting these parameters allows for gradually unpacking the image on the screen when receiving the image over the network or any other channel with a bandwidth significantly lower than the processor's capabilities,

enabling the operator to analyze the picture long before the decompression process is completed. A characteristic feature of JBIG is a sharp decrease in compression ratio with increasing noise levels in the input image [1, 3, 9].

6. Lossless JPEG Method was developed by a group of photography experts (Joint Photographic Expert Group). JPEG-LS is based on the LOCO-I compression method. It significantly differs from the JPEG and JPEG2000 methods, although the name is similar. Unlike JBIG, Lossless JPEG is oriented towards full-color 24-bit and 8-bit images without a palette (in grayscale). It represents a special implementation of JPEG without loss. JPEG includes two compression methods - lossless and lossy. This method is recommended for use in systems with fairly limited resources, such as space stations or web cameras. The JPEG-LS method consists of three main execution stages: modeling, prediction, and encoding. Its main difference from other algorithms is the prediction module and context work [1, 3, 4, 9]. To compare lossless graphic compression methods, let's consider Table 1.

Therefore, the aforementioned lossless information compression methods are universal and cover all types of images, but they have too small compression ratios. Using one of the lossless compression methods can provide approximately a two-fold image compression, although this largely depends on the characteristics of the image. Lossy compression methods are the most effective, but they also require evaluation based on the criteria mentioned above, as reproduction methods are crucial for ensuring rational reproduction of the original (analog or digital) with a full set of color and tone characteristics [3, 9].

Therefore, let's analyze the main lossy graphic information compression methods. Among the main lossy compression methods are the JPEG method, the JPEG 2000 method, the fractal method, and the Wavelet (recursive method). Let's consider them in more detail.

1. JPEG Algorithm - one of the most widespread and powerful methods. Today, it is the standard for full-color images. It operates on 8x8 blocks where brightness and color change relatively smoothly.

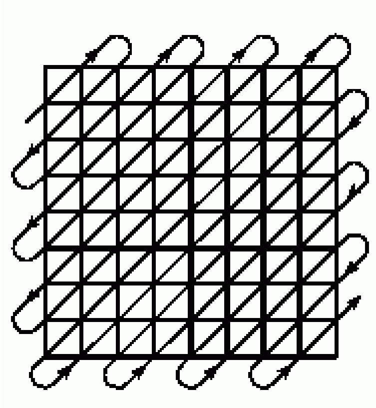


Fig. 1. **Image area 8x8**

As a result, when decomposing the matrix of such a region into a double row by cosine, only the first coefficients turn out to be significant. Compression in JPEG is achieved due to the smoothness of color changes in the image [3, 8, 9].

The method covers full-color 24-bit images (24 bits per pixel) or grayscale images without sharp color transitions (photographs). Symmetry: 1 [3, 9].

The compression algorithm scheme according to the JPEG standard is shown in Fig. 2.

Compression of images according to the JPEG standard involves the following sequence of steps:

1) The color image is converted from the RGB space to the YCrCb space.

In images of the RGB format, there is a significant correlation between the color components. The components R, G, and B are transformed into the Y component and two chrominance components U and V, in the YUV format, where Y is the luminance signal, and U and V are the chrominance difference signals.

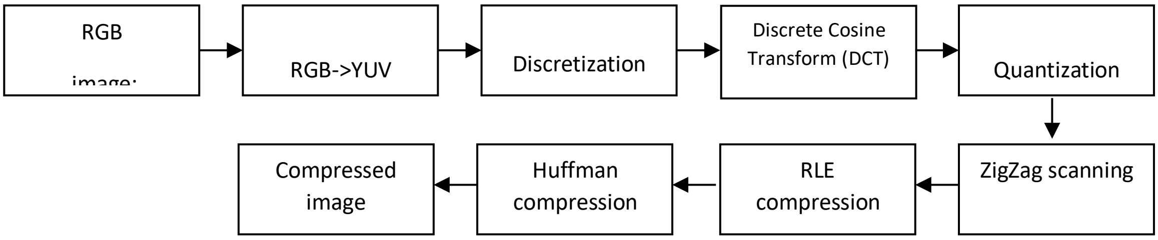


Fig. 2. **Scheme of the JPEG image compression algorithm**

The transformation is performed from pixel to pixel using the following formulas:

$$Y = 0.3 \cdot R + 0.59 \cdot G + 0.11 \cdot B; \tag{1}$$

$$U = -0.15 \cdot R - 0.29 \cdot G + 0.44 \cdot B; \tag{2}$$

$$V = 0.62 \cdot R - 0.52 \cdot G - 0.1 \cdot B, \tag{3}$$

where *R*, *G*, *B* are the color signals of the image (red, green, and blue respectively).

Representation of a color image in the *YUV* system allows exploiting the characteristics of human visual perception, which has low sensitivity to color accuracy [1, 8].

2) The color image is divided into large pixels. Pixels of each color component are assembled into 8 × 8 blocks, called data units;

3) Discrete cosine transformation (DCT) is applied to each data unit, resulting in 8 × 8 blocks of frequency data units (to reduce data redundancy in the image);

4) Quantization of each DCT block coefficient: each of the 64 frequency components of the data units is divided by a special number called the quantization coefficient (QC), which is rounded to an integer. Implementing DCT is the most challenging aspect. The encoding process using DCT involves dividing the image into 8x8 blocks (for encoding color images, each component is processed independently).

Within each block, a two-dimensional DCT is performed according to the expression:

$$F(u,v) = \frac{1}{4} \cdot C(u) \cdot C(v) \cdot \sum_{i=0}^{7} \sum_{j=0}^{7} cos\left(\frac{(2 \cdot i + 1) \cdot u \cdot \pi}{16}\right) cos\left(\frac{(2 \cdot j + 1) \cdot v \cdot \pi}{16}\right), \tag{4}$$

where $C(x) = \begin{cases} \frac{1}{\sqrt{2}} & x = 0 \\ 1 & x <> 0 \end{cases}, x = 0,...,u,v - 0,1,2,...,7.$

When decoding, the inverse discrete cosine transform (IDCT) is computed:

$$F(i,j) = \frac{1}{4} \cdot \sum_{i=0}^{7} \sum_{j=0}^{7} C(u) \cdot C(v) \cdot F(u,v) \cdot cos\left(\frac{(2 \cdot i + 1) \cdot u \cdot \pi}{16}\right) cos\left(\frac{(2 \cdot j + 1) \cdot v \cdot \pi}{16}\right), \tag{5}$$

where i, j – 0,1,2 … 7.

5) Encoding the resulting coefficients using static Huffman coding: all 64 quantized frequency coefficients of each data unit are encoded using a combination of RLE and the Huffman algorithm. At the static encoding stage, besides the Huffman algorithm, the JPEG specification allows the use of other methods to reduce information volume, such as arithmetic coding QM.

6) In the final step, a header with the JPEG parameters used is added, and the results are output to a compact file. The compression ratio is set by the user from 2 to 200, although in practice, the compression ratio does not exceed 20-25 [3, 8, 9].

JPEG has its peculiarities. The most well-known are the "Gibbs effect" and the division of the image into 8x8 squares. The former manifests itself at the sharp boundaries of objects, creating a kind of "halo." Dividing into squares occurs when too high a compression percentage is specified for a particular image. A drawback of the JPEG method is also that horizontal and vertical stripes on the display are often not visible and may only appear as moiré when printed. For this reason, JPEG is not recommended for use in printing at high compression ratios. However, when rational compression limits and dithering algorithms are applied, it can be considered as a compression option to reduce the file size of full-color images in original layouts for publications that will be printed [1].

2. JPEG 2000 Method. Developed by the same group of experts in the field of photography as JPEG. The scheme of compressing images according to the JPEG2000 standard is presented in Fig. 3.

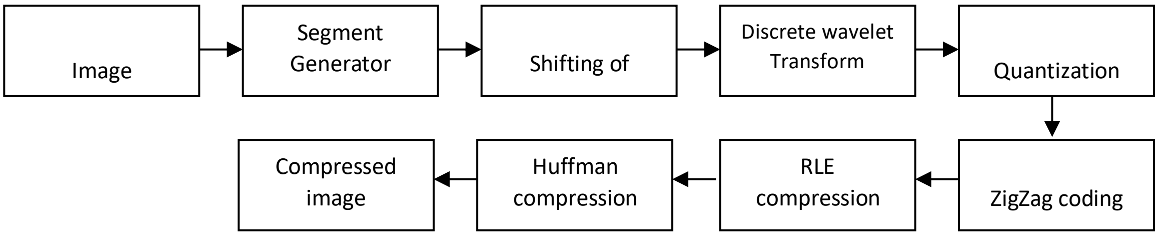


Fig. 3. **Compression scheme for JPEG2000 images**

The scheme of the JPEG 2000 algorithm is very similar to the basic JPEG scheme. The differences are as follows:

- instead of discrete cosine transform (DCT), discrete wavelet transform (DWT) is used;
- arithmetic compression is used instead of Huffman coding;
- the algorithm includes quality management for image regions from the beginning;
- explicit sampling of the U and V components after color space transformation is not used because DWT can achieve the same result, but slightly better.

Thus, when implementing the JPEG 2000 algorithm, unlike the JPEG algorithm, we obtain:

- improved image quality with significant compression;
- support for lossless compression. This allows the use of JPEG for compressing medical images, in printing;
- support for compression of one-bit (2-color) images. In JPEG, when compressing a 1-bit image, it increased by 8 times. Then an attempt was made to compress, often less than 8 times. Now JPEG 2000 can be recommended as a universal method;
- at the JPEG 2000 format level, transparency is supported. When creating web pages, now you can apply a transparent background not only in GIF but also in JPEG 2000. In addition, not only 1-bit transparency (transparent / opaque pixel) is supported, but also a separate channel, allowing for a smooth transition from an opaque image to a transparent background [8, 9].

3. The fractal method is a mathematical process of encoding rasters containing real images into a set of mathematical data describing the fractal properties of the image. The method is based on the fact that all natural and most artificial objects contain redundant information in the form of repeating patterns (fractals) [11]. The method relies on representing the image in a compact form using coefficients of iterated function systems (IFS). IFS translates one image into another. The transformation applies to points in three-dimensional space (x-coordinate, y-coordinate, brightness) [3, 8, 9, 11]. In other words, it involves searching for self-similar areas in the image. The method utilizes systems of domain and range blocks of the image, square-shaped blocks covering the entire image [12]. According to this method, the image is divided into numerous non-overlapping range sub-images, and numerous non-overlapping domain sub-images are determined. For each range block, the encoding algorithm finds the most suitable domain block and an affine transformation that maps this domain block to the given range block. The structure of the image is reflected in the system of range blocks, domain blocks, and transformations [3, 8, 9].

The process of fractal compression begins with taking two identical instances of the image – A and B, one of which is divided into non-overlapping blocks (range areas), while the other is provided with a set of domains that may overlap.

After this, the most appropriate domain is selected for each rank region. The numbers of domains used for encoding each rank region are recorded in a file. The compressed image file contains a header with information about the location of rank regions and domains.

Fractal compression is an asymmetric process. Compression takes much longer than decompression. This characteristic makes it effective for images that are continuously decompressed but rarely compressed. Therefore, the fractal method is suitable for use in image databases. There is a significant amount of research by foreign scientists dedicated to optimization issues of digital image fractal compression. One notable work discusses the method of fractal image compression using spatially sensitive hashing. However, little attention has been paid to optimization methods of fractal compression that would have equally high characteristics of compression ratio and quality of the restored image. The question of constructing fast fractal compression methods remains particularly relevant today [11].

Thus, after analyzing the features of the fractal compression method, it has been determined that it is capable of providing the best balance between compression ratio and quality of the restored image. The method has good prospects for further development. During the transformation of ordinary raster images into fractal ones, there is the possibility of scaling the fractal image without introducing artifacts or losing details, as is typical for raster images [11]. The advantages of the fractal method lie in its high compression ratios, speed of inverse transformation, and the possibility of further structural analysis of the image. However, the compression results depend on the principles of selecting basic elements and domains, and the compression ratio depends on the repetitiveness of the basic elements. The algorithm is oriented towards full-color images and grayscale gradations. Fractal compression is implemented in the FIF format [1].

The main drawback of the fractal method is its low compression speed. This is because to obtain high-quality images, each rank region requires iterating through all domain blocks, and for each domain block, at least eight affine transformations are required. This problem is only partially solved. Due to the noted drawbacks, this method is relatively rarely applied in practice.

The process of fractal transformation is asymmetric. That is, image reconstruction occurs much faster than compression. Therefore, researchers have opportunities to improve efficiency and search for other optimization methods for fractal encoding [11].

4. Wavelet-Recursive Method. Wavelet compression involves the utilization of wavelets, which are defined only in a portion of the argument domain and can be considered as replicas of a single basic function that differ in scale and position. The method's concept lies in storing in a file the difference between the average values of neighboring blocks in the image, which typically tend to be close to 0 [1, 9]. This method is oriented towards compressing color and grayscale images with smooth transitions, making it ideal for images like X-ray snapshots. Today, experts identify several advantages of wavelet compression compared to methods based on discrete cosine Fourier transformation, which is used in JPEG. In modern image compression methods, wavelet compression allows for a significant increase (up to two times) in the compression ratio of grayscale and color images while maintaining visual quality compared to previous-generation methods [1, 3, 8].

Wavelet transformation has found wide application in image processing tasks (language, satellite images, X-rays), pattern recognition, and the study of crystal and nano-object surface properties [13]. Wavelet transformations are used in medical diagnostics to compress images with minimal information loss required for diagnosis. Wavelet transformations are more sophisticated compared to Fourier transformation. The goal of new methods for analyzing medical signals is to automatically establish a correct diagnosis in the absence of a doctor or in cases of insufficient qualification, thereby increasing the likelihood of diagnosing diseases at early stages [14].

The coefficients of continuous wavelet transforms contain information about the energy of individual components of the electrocardiography signal and the time of their appearance. This allows for simultaneous investigation of the slow and fast dynamics of changes in the cardiac signal over time.

One advantage of this method is its ability to easily implement the gradual "unveiling" of an image when transmitting it over a network. Additionally, since we essentially store a reduced copy of the image at the beginning, it simplifies its display in the header. Unlike JPEG and fractal algorithms, this method does not operate in blocks, such as 8x8 pixels. More precisely, we operate in blocks of 2x2, 4x4, 8x8, and so on. However, because we store coefficients for these blocks independently, it is relatively easy to avoid splitting the image into mosaic squares [8].

In recent years, wavelet transformation has become known as a powerful tool for image compression. Various approaches related to wavelet-based encoding are well-known. The effectiveness of transformation encoding essentially depends on compressing energy with two-level wavelet transforms [13, 15]. The creation of a new system of "wavelet" functions has revolutionized the theory of signal processing and storage, allowing information to be compressed by 100-150 times without significant loss of quality. This is the main purpose and achievement of using wavelet transforms.

Therefore, by analyzing the main characteristics of lossy compression methods for graphic information [16, 17], we present the comparison results in Table 2.

Table 2. **Comparison of the main characteristics of lossy compression methods for graphic information**

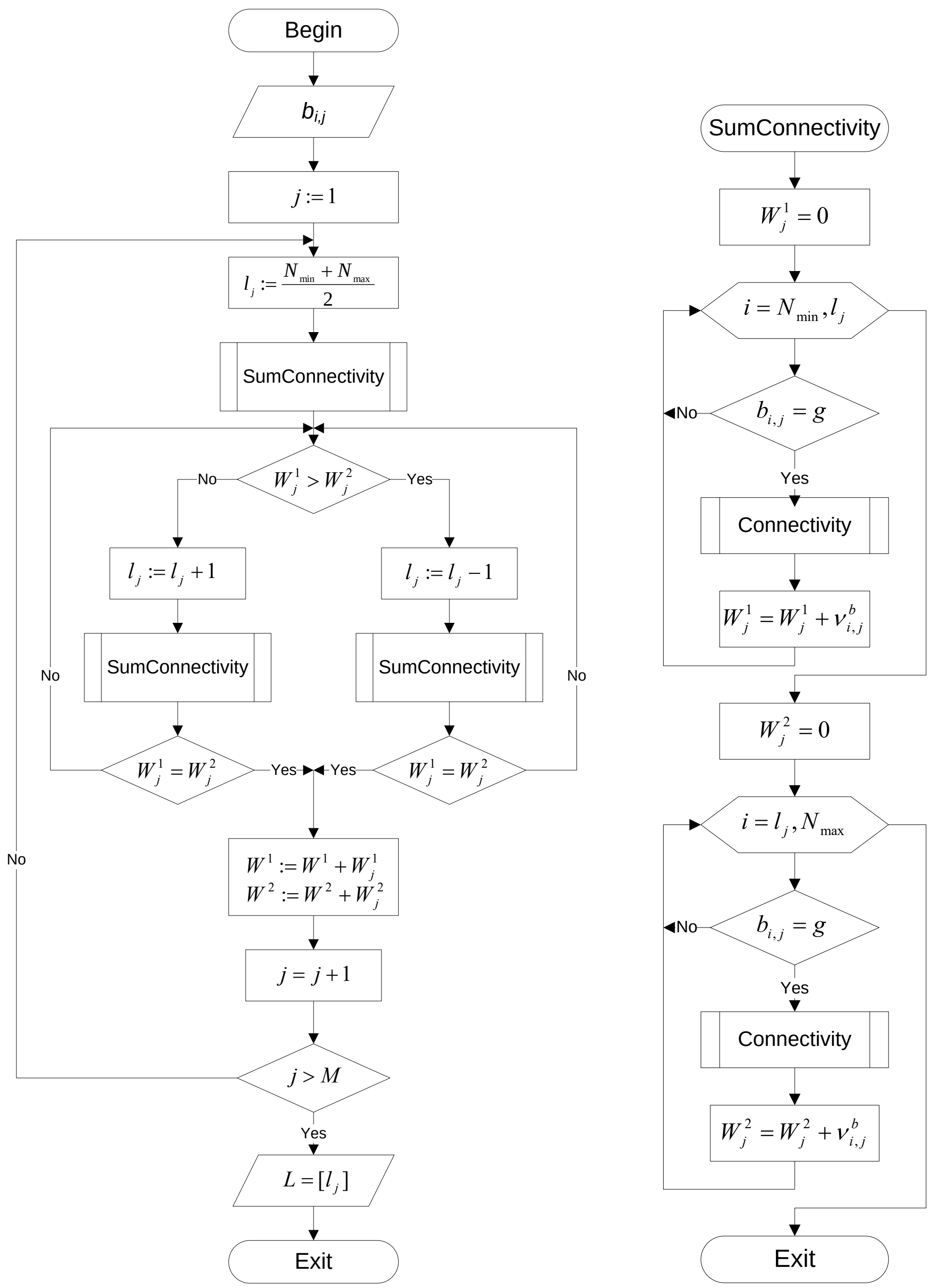
Method name	The main characteristics of the method	Advantages and disadvantages of the method
JPEG	Absence of sharp boundaries	*Advantages:* Good quality of the restored image
		Disadvantages: Gibbs effect. Lack of automatic conversion for multiple cases
JPEG 2000	Absence of sharp boundaries	*Advantages:* Improved image quality with significant compression, support for lossless compression, support for compression of binary (2-color) images
JPEG 2000	Absence of sharp boundaries	*Disadvantages:* Absence of automatic conversion for multiple cases
Fractal method	Full-color images and grayscale gradations	*Advantages:* High compression ratio, high speed of inverse transformation, possibility of further structural analysis of the image, smaller size of physical data used to record fractal codes compared to the initial raster data.
		Disadvantages: Low compression speed, which makes the method relatively rare in application
Wavelet (recursive compression)	Compression of color and grayscale images with smooth transitions	*Advantages:* Ability to compress information without significant loss of quality
		Disadvantages: Their relative complexity

Development of algorithms for compact image representation. Based on the developed preprocessing model [18, 19], let's create an algorithm. The images to be processed are provided as files in PCX or BMP graphic formats. To represent the image as a matrix of pixel brightness values, we will create a procedure for reading the file and decoding data from the PCX format. Information about the image size and the number of brightness levels is also extracted from the image file. After decoding the data, we obtain a brightness matrix. $A = [a_{i,j}]$. Next, the image is prepared. We find the average brightness value of all elements in matrix A of the image.

$$\bar{a} = \frac{1}{N \cdot M} \cdot \sum_{i,j} a_{ij}. \quad (6)$$

Next, we determine the array of differences between each element and the average value of the image.

$$r_{ij} = a_{ij} - \bar{a}. \quad (7)$$



a) b)

Fig. 4. **The algorithm for equalization block diagram**

Threshold δ, satisfying the condition $N_t^{(1)} = N_t^{(-1)} = N_t^{(1)}$ is found in this way. A search is conducted for brightness values t, and it is assumed that $\delta=t$, $t=\epsilon(0\ldots t_{max})$, where t_{max} - is the maximum value of brightness levels for the given image. Next, all elements of the array $R=\lfloor r_{ij} \rfloor$ are compared with the threshold δ. This takes into account the number of elements classified as $N_t^{(1)}, N_t^{(-1)}, N_t^{(0)}$ and calculates the value of the variable $maxP_t = N_t^{(1)} \cdot N_t^{(-1)} \cdot N_t^{(0)}$ for every value t. So the value of t for which the variable $MaxP$ takes the maximum value is chosen as the threshold δ.

To find the elements of the prepared image, we will use the obtained threshold δ. Then,

$$\begin{cases} \text{If } R_{i,j} > \delta, \text{ то } b_{i,j} = 1; \\ \text{If } R_{i,j} < -\delta, \text{ то } b_{i,j} = -1; \\ \text{If } R_{i,j} \le |\delta|, \text{ то } b_{i,j} = 0; \end{cases} \quad (8)$$

Thus, a matrix of elements $B=[b_{i,j}]$ is formed.

According to the mathematical model [18], we will develop an algorithm for the formal description of image parts (Fig. 4).

Let's compose a procedure for reading the preprocessed image represented by a matrix. $B=[b_{i,j}]$. Balancing by connectivity is carried out as follows. The balancing curve point is set in the middle of the column section where balancing occurs.

$$l_j := \frac{N_{min} + N_{max}}{2}. \quad (9)$$

Next, the SumConnectivity procedure is called (Fig. 4, b), in which the total connectivity values in the column are calculated from the beginning to the dividing point W_j^1 and from the dividing point to the end of the column W_j^2.

$$W_j^1 = \sum_{i=N_{min}}^{l_i} v_{i,j}^b, \quad W_j^2 = \sum_{i=l_i}^{N_{min}} v_{i,j}^b. \quad (10)$$

The connectivity values of the preparations are separately determined for zero, unitary, and minus unitary preparations g=(-1, 0, +1). The connectivity of individual preparations is computed as follows: adjacent elements of the preparation under consideration are iterated over, and the connectivity of this preparation is taken as equal to the number of elements that are also preparations for them, the connectivity value is found $b_{i,j}=g$.

Total connectivity values obtained W_j^1 and W_j^2 are being compared: if $W_j^1 > W_j^2$, then the point of the balancing curve is lowered by one step. At the same time, if the element $b_{i,j}$, is equal to g, then its connectivity $v_{i,j}^b$ is found and $W_j^1 = W_j^1 - v_{i,j}^b$, $W_j^2 = W_j^2 + v_{i,j}^b$. This operation is performed until equality is achieved $W_j^1 < W_j^2$.

If $W_j^1 = W_j^2$, then the described procedure takes place in reverse order. Similar operations are performed for the following columns. After that, the obtained connectivity values are added up. $W_\Sigma^1 = \sum_{j=1}^{M} W_j^1$, $W_\Sigma^2 = \sum_{j=1}^{M} W_j^2$.

In addition to the values of connectivity W_j^1 and W_j^2 the coordinates of each point of the balancing curve are also recorded.

Next, the balancing of the area of the image below the dividing curve takes place. Here, the lower boundary is the initial row of the prepared image, and the upper boundary is the array with the coordinates of the curve points from the previous balancing. Afterward, balancing occurs, according to the provided algorithm, for the area above the dividing curve. In this case, the lower boundary is the array with the coordinates of the dividing curve points, and the upper boundary is the last row of the prepared image.

Following the described algorithm, the prepared image is divided both vertically and horizontally. During implementation on the computer, image processing was done sequentially – first, the processing of the initial image occurred, and its balancing curves were saved in the array $arsi_{i,j}$. The correlation coefficients were found after finding the balancing curves for the second image.

In the table 3, the estimation of the execution time of the "exact" scheme of image processing with the correlation comparison of the balancing curves and the estimation of the time for the traditional correlation comparison of images are given [20].

Table 3. **Execution time of the "exact" image processing scheme with correlation comparison of balancing curves**

Image size	Computation time, msec				
	Balancing horizontally for 1 field of preparations	Balancing vertically and horizontally for 1 field of preparations	Balancing vertically and horizontally for 3 fields of preparations	Three steps of balancing vertically and horizontally for 3 fields of preparations	Evaluation of traditional image correlation comparison time
100×100	5	20	110	220	770
128×128	10	110	220	390	1320
200×200	110	110	500	880	3130
256×256	110	220	660	1320	4730

Comparative analysis of Table 3 shows that: if one equalizing curve is used for image recognition, the time savings of the developed method compared to the traditional one will be 43 times. If two equalizing curves are used for image recognition, the time savings of the developed method compared to the traditional one will be 22 times. If six equalizing curves are used for image recognition, the time savings of the developed method compared to the traditional one will be 7,2 times. If eighteen equalizing curves are used for image recognition, the time savings of the developed method compared to the traditional one will be 3,6 times. This algorithm allows you to process images in real time, like similar methods [21-23].

According to the presented algorithms, a program was developed and used to evaluate the performance of the compact image representation and comparison method. The conventional correlation comparison of images was done pixel by pixel. Therefore, as the dimensionality of the images increases, the correlation comparison time increases significantly (Fig. 5).

The results given in the table have relative values. Since the absolute values depend on the performance of computer systems on which the given algorithms will be realized. And also the results depend on the software implementation, which can be optimized for a particular hardware structure.

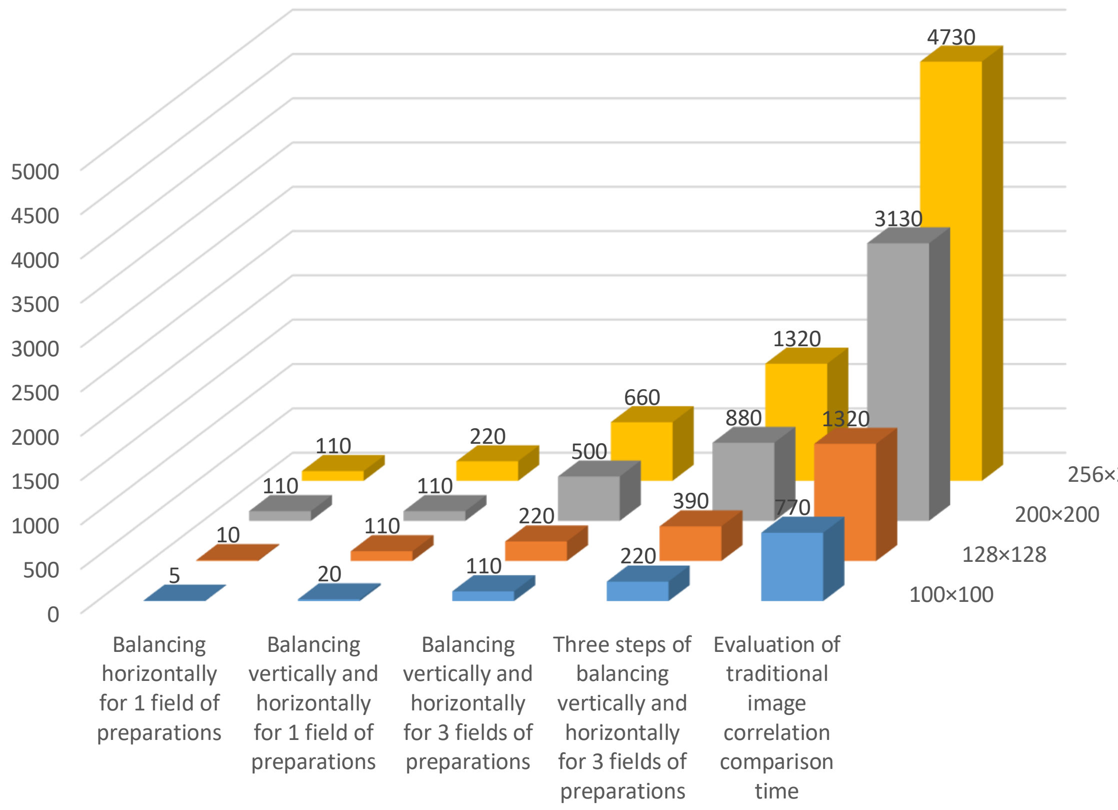


Fig. 5. **A comparison chart of the execution time of an "exact" image processing scheme with a correlation comparison**

Conclusions. The research has shown that the main requirements for universal methods of compact image representation include high compression ratio, quality of compressed images, compression/ decompression speed, and consideration of individual image characteristics.

We believe that among the researched methods, the fractal method of lossy compression is the most promising for further development, improvement, and practical application in computer technologies. It has several unique features and advantages: image reconstruction is much faster, noticeable artifacts at color transitions are reduced, the method can be used for compressing images intended for high-quality printing, and image scaling is possible.

Algorithms have been developed that implement an "accurate" image processing scheme, within which a multi-level image representation is carried out, and an equalization procedure is implemented, allowing for a more compact representation of image features and faster computation of the correlation function. It has been shown that the method of equalization of halftone images within the "accurate" processing scheme and excessive equalization in four directions, compared to the traditional method of correlation image processing, allows reducing the image recognition time for different numbers of equalizing curves from 3.6 to 43 times.

The algorithms for describing the information fields of an image in the form of a spectrum of spatial connectivity of its constituent elements are presented. Based on this concept, a method of generalized spatially connected dissection is proposed, on the basis of which comparison functions are calculated, including the correlation function, which allows the implementation of the method of image segmentation and their compact representation.

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Дослідження графічних форматів даних для компактного представлення і порівняння зображень

В статті проводиться дослідження поширених методів стиснення графічної інформації із втратами та без втрат. В результаті дослідження виділено переваги та недоліки методів стиснення. Здійснено порівняльний аналіз основних можливостей методів стиснення графічної інформації. Актуальність полягає в ефективній передачі, обробці та збереженні графічної інформації, оскільки великій обсяг даних вимагає збільшення пропускної здатності мереж і значних ресурсів для зберігання даних. Практичне значення полягає у вирішенні завдання ефективного зменшення розмірів даних шляхом застосування відомих методів стиснення.

На основі дослідження графічних форматів даних приводиться розробка алгоритмів обчислювальної схеми «точної» обробки напівтонових зображень для розпізнавання образів. Така схема здійснює переопис багатоградаційного зображення в трирівневе подання і реалізує процедуру урівноваження, що дозволяє в більш компактному виді формувати ознаки зображення і швидше обчисляти кореляційну функцію. Показано ефективність використання розроблених методів компактного подання зображень із кореляційним порівнянням урівноважуючих кривих перед традиційним кореляційним порівнянням зображень.

Ключові слова: зображення, стиснення з втратами, перетворення, трирівневе подання, урівноваження, кореляційна функція.

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