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Основная тематическая направленность журнала: материалы о научно-технических, организационных, экономических, экологических, правовых проблемах, истории, состоянии и перспективах развития транспортного комплекса стран БРИКС; о взаимодействии стран БРИКС по вопросам транспортного обеспечения и сотрудничества с другими государствами, мировыми транспортными системами, а также о подготовке персонала всех уровней для транспортной отрасли и развитии в данной сфере сотрудничества образовательных учреждений и транспортных предприятий разных стран.

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Review article
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Railways of India. An important stage of modernization is completed — unification of track width

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ABSTRACT India, the Republic of India is a country of one of the world's oldest civilizations, the largest state in the world by population — 1.42 billion people (end of 2022), occupying an area of over 3 million square kilometers. India, which has accelerated the pace of its socio-economic development in recent decades, is playing an increasingly important role in the international arena every year, including as one of the BRICS organizers. The state railways of India are managed by the Ministry of Railways of India represented by Indian Railways (99 % of the country's railway network) and are, despite the dominance of motor transport, remain one of the main modes of transport. During the year, the railways of India transport more than 8 billion passengers (2nd place in the world after Japan), the staff of the railways of India will amount to 1.2 million people (the 7th employer in the world). Railway transport in India is developing intensively, in recent years, work has been intensified on the organization of high–speed traffic on a number of lines of existing railways, the first high-speed railway line Mumbai — Ahmedabad is being built with a normal gauge of 1435 mm with a length of 508 km, designed for a maximum train speed of 350 km/h. The authors of the article have repeatedly visited India, visited various railway enterprises, railway educational institutions — universities and institutes, met with industry leaders at the Ministry of Railways of India, traveled along the country's railways along a number of routes with a total length of about six thousand km.

KEYWORDS: railway transport of India; history of transport; narrow-gauge; standard; broad-gauge railways; modernization; electrification; high-speed railways

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Обзорная статья

Железные дороги Индии. Завершается важный этап модернизации — унификация ширины колеи

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АННОТАЦИЯ Республика Индия — страна одной из древнейших мировых цивилизаций, крупнейшее по населению государство мира — 1,42 млрд человек (конец 2022 г.), занимающее территорию свыше 3 млн км^2. Индия, ускорившая в последние десятилетия темпы социально-экономического развития, с каждым годом играет все большую роль на международной арене, в том числе и как один из организаторов БРИКС. Государственные железные дороги управляются Министерством железных дорог Индии в лице компании Indian Railways (99 % железнодорожной сети страны) и, несмотря на доминирование автомобильного транспорта, остаются одними из основных перевозчиков. За год железные дороги Индии транспортируют более 8 млрд пассажиров (второе место в мире после Японии), персонал железных дорог Индии составляет 1,2 млн человек (седьмой работодатель в мире). Железнодорожный транспорт Индии развивается, в последние годы активизированы работы по организации скоростного движения на ряде линий существующих железных дорог, строится первая высокоскоростная железнодорожная магистраль Мумбаи (*Mumbai*) – Ахмедабад (*Ahmedabad*) нормальной колеи 1435 мм длиной 508 км, рассчитанная на максимальную скорость движения поездов 350 км/ч.

Авторы неоднократно бывали в Индии, посещали различные железнодорожные предприятия, железнодорожные учебные заведения — университеты и институты, встречались в Министерстве железных дорог Индии с руководителями отрасли, совершили поездки по железным дорогам страны по ряду маршрутов общей протяженностью около 6000 км.

КЛЮЧЕВЫЕ СЛОВА: железнодорожный транспорт Индии; история транспорта; узкоколейные; стандартные; ширококолейные железные дороги; модернизация; электрификация; высокоскоростные железные дороги

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THE BIRTH OF RAILWAY TRANSPORT IN INDIA

The first railway projects in India, then a British colonial possession, appeared early by world standards — in 1832. It was rather about creating industrial railways to transport construction materials and minerals. In 1837 the first industrial railway, the Red Hill Railroad, 25 km long, was opened in Madras [1] built by an English engineer and entrepreneur Sir Arthur Thomas Cotton (1803–1899)[1]. Arthur Cotton built canals, dams and railways and was interested in railways as a means of facilitating the delivery of construction materials to sites. To this end he built another Godavari Dam Construction Railway in 1845 to build a dam on the Godavari River [2].

In the 1840s several attempts are made to build public railways. In 1845 the Madras and East India Railway Companies are set up. The former failed and failed to start construction, was dissolved and re-established in the 1850s. The East India Railway Company was more successful and in 1851 a survey from Calcutta to Raniganj Raniganj began, which identified a crossing point for the Son River, the largest tributary of the Ganges River [2].

Many difficulties arose during the organisation of the construction. The delivery of nearly all necessary materials, including rails, fasteners and rolling stock was carried out from England by sailing ships. It was a long voyage around the Cape of Good Hope and the Suez Canal was not opened until 1869. Wood for sleepers was sourced from Nepal and some spruce sleepers were brought from the Baltic Sea coast, with sleepers being treated with creosote in England. The first section from Howrah to Benares, 37 km long, was opened on 15 August 1854[2].

The beginning of the modern public railway network is associated with the construction of a 33.8 km long railway between Bori Bunder (Bombay, now Mumbai) and Thane [3, 4], on which the first passenger train passed on 16 April 1853. This was a section of the future Great Indian Peninsula Railway (GIPR). The railway was built with a track gauge of 5ft and 6in (1676 mm).

The country's largest railway station, Chhatrapati Shivaji Maharaj Terminus (Chhatrapati Shivaji Terminus, CSMT)[3] which is located on the site of the former Bori Bunder station in Bombay (now Mumbai), is a reminder of that momentous occasion. The building was built between 1878 and 1888 by the British architect Frederick William Stevens[4] (1847–1900), High Victorian Gothic design based on late medieval Italian models [5]. The terminal has become one of the symbols

[1] Arthur Cotton is the builder of many hydraulic structures — irrigation canals and dams in India — has earned the grateful memory of Indians, which is kept in the states of Andhra Pradesh and Tamil Nadu. A museum dedicated to his work has been opened in Rajamahendravaram. Arthur Cotton was persecuted and harassed by the British administration, which did not maintain his loyal relationship with the locals. In recognition of Cotton's contribution, a new dam on the Godavari River, built in 1982, was named after him by the decision of Indian Prime Minister Indira Gandhi.

[2] East Indian Railway Company. URL: https://en.wikipedia.org/wiki/East_Indian_Railway_Company

[3] Formerly Victoria Terminus, the name was changed in 1996.

[4] Frederick William Stevens (1847–1900) is the author of other famous architectural creations: The former Royal Alfred Sailors' Home, Bombay (1872–1876), Municipal Corporation Buildings, Bombay (1888–1893), The Flora Fountain, Bombay (1869) together with Scottish sculptor James Forsyth (1827–1910) etc. URL: https://victorianweb.org/art/architecture/stevens/index.html

Fig. 1. Chhatrapati Shivaji Terminus Railway Station (CSMT)), Mumbai. Photo by the authors. 2016

of Bombay-Mumbai and was inscribed on the UNESCO World Heritage List in 2004[5] (*Fig. 1–4*).

The railway station is being carefully preserved and renovated to improve the passenger experience, while preserving all the important historical architectural and planning features. In recent years, air-conditioned waiting rooms, modern ticket offices and an expanded list of additional services provided to passengers have been built.

The station houses the Chhatrapati Shivaji Terminus Heritage gallery (*Fig. 5–9*). Visitors can explore the preserved state rooms of the station and the numerous stands and exhibits relating to the history of the station and the Indian Railways from the 1930s to the present day.

In 2009, a memorial was unveiled at Chhatrapati Shivaji station, which is sacred to the people of India (*Fig. 10*) to commemorate the tragic events of November 26, 2008, when a number of Mumbai facilities, including this station, were attacked in a terrorist attack that resulted in numerous casualties.

THE KEY ISSUE IN CREATING RAIL TRANSPORT: THE CHOICE OF TRACK GAUGE

To understand how entrepreneurs, engineers, planners and builders who built the first railways in India and then formed its railway network came to the decision to use the 1676 mm gauge as the main gauge in the country, while several narrow-gauge railways were also built, it is necessary to make a brief excursus into the history of the first decades of railway transport in Great Britain. The early days of railway construction in this country, the technical solutions adopted, the construction and operational parameters have had a major influence on the creation of railway transport in almost every country in the world. They influenced the

Fig. 2. CSMT. Distribution hall. Photo by the authors. 2016

[5] World Heritage — natural or man-made sites that UNESCO considers a priority for conservation and promotion because of their special cultural, historical or ecological significance.

Fig. 3. CSMT. Common waiting room. Photo by the authors. 2016

establishment and development of railways in India, which had been under colonial dependence on Britain for a long period of time. The country's railways, built for the most part by British entrepreneurs and engineers, were a reflection of the situation in the metropolis, a "crooked mirror" that in many cases exaggerated negative phenomena.

It is well known that the choice of gauge for a railway is one of the fundamental factors determining the scope and cost of construction works and the most important parameters for future operation, including maximum speed, carrying capacity and operating costs.

In the early decades of public railways, engineers and planners in various countries, especially in the home of railways in England, experimented with gauges. As the sources of those years indicate, most of them, and practically the entire community of entrepreneurs and engineers and government officials, until the mid-1830s considered each railway project as an isolated transport enterprise, based on its specific practical and commercial purposes in a given location, in connection with other facilities — mines, mines, factories, ports. Few foresaw that road railways, especially in the initial period of construction of the first of them, would in the foreseeable future come together, much less merge into a nationwide network.

In England, for example, by the beginning of XIX century there was a well-developed network of canals to ensure national transport tasks, and the length and condition of highways were improving year by year. Railways, mostly with cast-iron rails,

Fig. 4. CSMT. Men's Lounge for 1st and 2nd class passengers. Photo by the authors. 2016

Fig. 5. CSMT. Museum of Indian Railways. Layout of the Chhatrapati Shivaji Terminus. Photo by the authors. 2016

Fig. 6. CSMT. Terminus Parade Gallery. Photo by the authors. 2016

Fig. 7. CSMT. Parade Hall for official delegations. Photo by the authors. 2016

Fig. 8. CSMT. Museum of Indian Railways. Model of a late 19th century Indian Railways mix-type passenger car. Photo by the authors. 2016

were designed for local transportation purposes of cargo delivery to ports or from ports to industrial plants, intrafactory transportation and delivery of materials to construction sites. There was practically no passenger transport on the rail tracks.

Only after Liverpool-Manchester railway (1830) and Great Western Railway (1838) were built, and titans of engineering and building such as George Stephenson (1781–1848) and Isambard Kingdom Brunel (1806–1859) and some other figures entered the field of railway transport, a wide circle of businessmen, representatives of government structures and then society as a whole, saw opportunities and prospects of new type of transport — the railway. The leading figures of the transport industry and industry began to realise the consequences of disorderly development of railways. First of all, this concerned the main and at that time defining parameter for the possibility of unit-

Fig. 9. CSMT. Museum of Indian Railways. Model of an Indian railway steam locomotive from the late 19th century. Photo by the authors. 2016

Fig. 10. CSMT. Memorial to the tragic events of 26 November 2008, Mumbai. Photo by the authors. 2016

ing the railways into a single national network — the width of the gauge[6].

In the late 1830s and early 1840s a social-economic phenomenon called British Railway Mania of the 1840s[7] broke out in Britain — the Battle of the Gauges or Gauge Wars. Among engineers, builders, railway workers and businessmen, two principled approaches to further railway construction emerged. The ideas of these engineering approaches also spread to broader social circles, with adherents of one and the other emerging amongst different sections of society, professions, journalists, politicians.

From the two different approaches to railway construction, it is possible to identify those who advocate "narrow gauge" — any gauge narrower than 4ft 8 and 1/2 inches (1435 mm) — and those who advocate "broad gauge" — broader than 1435 mm. The exponent of the technical and economic ideas of the former was the great engineer and entrepreneur George Stephenson[8]. The second line was represented by the equally great and successful engineer and entrepreneur Isambard Kingdom Brunel, who built the Great Western Road with a track gauge of 7 feet and 1/4 inch (2140 mm)[9].

Broad gauge advocates argued that they could deliver higher speeds, more comfortable travel conditions for passengers, greater capacity through larger rolling stock and, most importantly, that they were safer and more reliable.

The narrow-gauge advocates assured other people that they could provide almost the same high speed and carrying capacity on their railways, and, with figures in their hands, proved considerable savings in the construction of 1435 mm gauge railways and their rolling stock as compared with broad gauge.

In the early years of the Great Western Railway's operation its trains reached higher speeds than the Stephenson gauge, but by the end of the 1840s the speeds were virtually identical.

By this time, more than two dozen gauge sizes were in operation in the UK, ranging from 600 mm[10] and up to 2140 mm on the Great Western Railway[11] (*Fig. 11*).

In the 1840s, a paradoxical situation developed in Britain: as the length of railways in the kingdom increased, it became increasingly inconvenient for passengers and shippers. At the junctions of different rail gauges, there are obstacles to travel, to transport goods in direct services, and to ensure "Seamless Traffic".

[6] Nowadays, apart from this technical parameter, other parameters are important which determine the possibility to combine different railways for a single operation, besides the dimensions of the rolling stock and the proximity of the structures, such as the electrical supply system on electrified railways, the characteristics of fixed and train devices of railway automation, telemechanics and several others, but at that time the gauge was the most important.

[7] Railway mania — "financial pyramid schemes", "financial bubbles" in the stock market of the United Kingdom of Great Britain and Northern Ireland in the 1840s, associated with the construction of new railways. As the share price of the railway companies increased, speculators invested more money in them, which further increased the share price until the share price collapsed. The mania reached its peak in 1846, when 263 parliamentary acts were passed to create railway companies.

[8] The 4ft 8in1/2inch (1435 mm) track, which later became standard in many countries, was suggested by George Stephenson. It is often referred to as the "Stephenson gauge".

[9] Originally 7ft (2134 mm), later widened to 7ft and 1/4 in (2140 mm). In 1854, after merging with several other railways, the Great Western Railway was "re-stitched" to what had by this time become the standard gauge of 1435 mm.

[10] The Wells and Walsingham Light Railway in Norfolk England has the world's narrowest gauge of 10 and 1/4 inches (260 mm) of public railways in continuous commercial operation (established by an Act of Parliament in the UK) at 6.4 km.

[11] The broadest track gauge in the world is that of the currently active toothed track of the Krasnoyarsk Hydroelectric Power Station ship-lift in Russia — 9000 mm (29 ft 6 in + 5/16 in). A number of sources indicate the use of 8 ft (2439 mm) broad track in the early twentieth century on a timber road in Oregon, USA, but conclusive evidence has not yet been found.

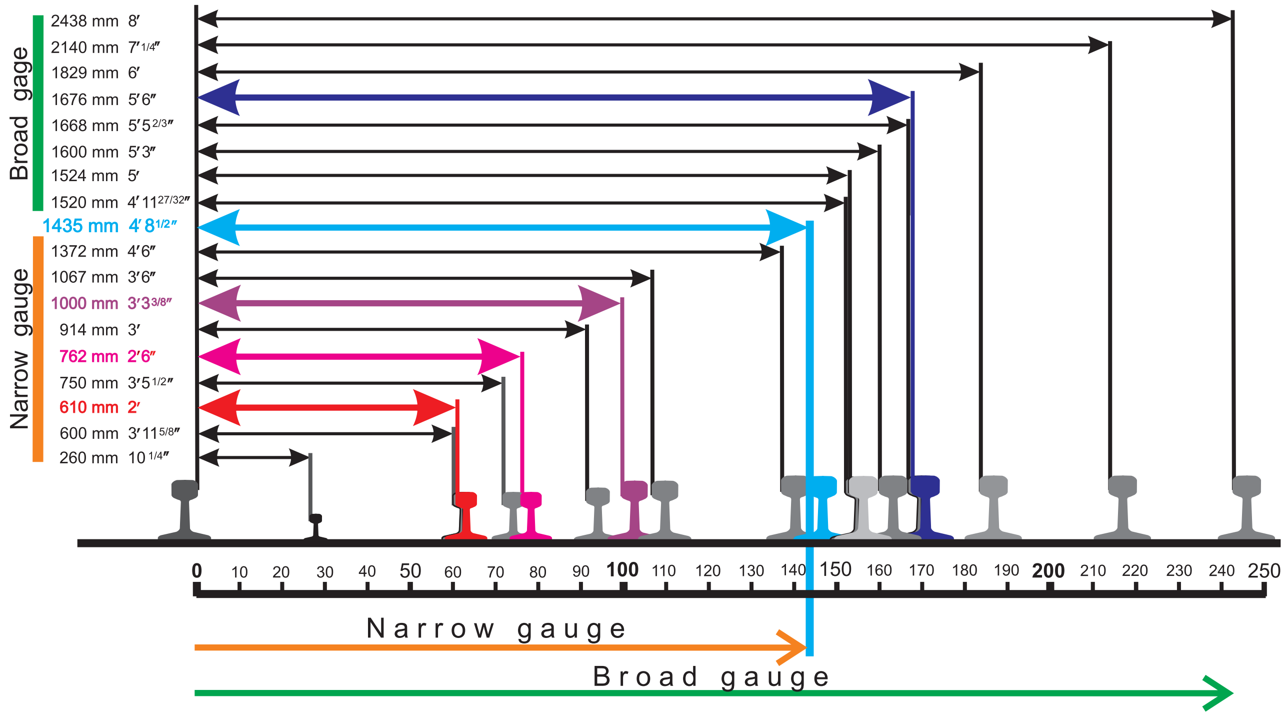

Fig. 11. Examples of different track gauges common on the world's railways. The narrowest and broadest gauge in regular commercial use are shown. Bold coloured lines indicate gauge types used in India. The rail profile is shown conventionally and does not refer to the types of specific gauge. Reconstruction by the authors from open sources. 2023

The "Gauge War" involves railway professionals, business people, the press, politicians, and, increasingly, the general public — passengers and shippers — who experience the problems of operating stations at the junctions of different gauge railways. Newspapers have published cartoons on these subjects [6] (*Fig. 12*).

Queen Victoria was definitely not amused. Whenever she travelled from her estate on the Isle of Wight to her castle at Balmoral, she encountered the inconvenience of twice changing trains, once at Basingstoke and again at Gloucester. She had no choice: even royalty was obliged to mind the gap between railway tracks of different gauges [6].

The situation at the transfer stations threatened passengers every day with complete chaos, delayed trains, lost luggage [6] (*Fig. 13*).

However, neither Stephenson's supporters nor Brunel's supporters gave up. The construction of railways with different gauges continued in Britain. Different ways of solving the problem were proposed: using auxiliary rolling stock to carry wagons on a different gauge — Rollbock and Transporter wagon, which gained some popularity, construction of tracks with dual gauge — three or four rails (dual gauge), attempts to create rolling stock, which could switch from one gauge to another (variable gauge system). In 1845, I. Brunel suggested to carry goods in big boxes — container. The system, later called containerization, made it easier to move goods from one wagon to another. None of these proposals fundamentally solved the problem of fragmented railways.

In 1845, a Royal Commission was set up to study the question of gauge and make recommendations. After numerous surveys, technical and economic comparisons, and expert hearings, including George Stephenson and Isambard Kingdom Brunel, the Commission prepared the Railway Regulation (Gauge) Act 1846,

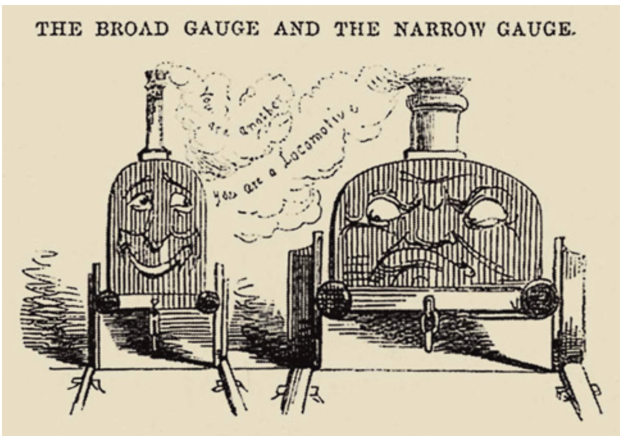

Fig. 12. A caricature in the spirit of today's Thomas the steam locomotive. The meeting of locomotives of different track gauges clearly shows: the designers of broad-gauge railway rolling stock had more scope for implementing their technical ideas. Cartoon by Angus Reach, 1845 © Lordprice Collection/Alamy

Fig. 13. J.H. Townshend, Break of Gauge at Gloucester, 1846, Illustrated London News, 6 June 1846

which was passed by the British Parliament and approved by Queen Victoria on 18 August 1846[12].

The Act further required railways in Britain to be built with gauges of 4 ft 8 and 1/2 inches (1435 mm), and in Ireland 5 ft 3 inches (1600 mm). Importantly, for the first time the Act defined "railway gauge" as "the distance between the inner surfaces of two running rails"[12]. In the UK, and elsewhere, some experts have found it useful to refer to the gauge as the distance between the axes of the rail heads, leading to confusion.

But the law did not prohibit the continued operation of the railways already built with different gauge, nor did it permit the construction of new railways with different gauge, provided that the project was approved by Parliament. In other words, the status quo of "different gauge" railways was maintained for many years. Proponents of broader or narrower gauge lobbied parliament for the decisions they wanted, and construction continued on a variety of railways, including the broad-gauge Brunel line.

The Great Western Railway was "converted" to the Stephenson gauge, later to be called the standard-gauge railway, a more or less complete unification of the British railway network with a single gauge of 1435 mm only occurred in 1892 (track gauge conversion).

Railways in India were built with different gauges depending on decisions of particular entrepreneurs and design engineers, often with immediate interests of businessmen clashing with regional or national ones. The battle of the gauge in all its negative manifestations is unfolding in India.

In India, the gauge used was 2 ft (610 mm); 2 ft and 6 in (700 mm); the standard gauge was 2 ft, 8 in and 1/2 in (1435 mm); and the broad gauge was 5ft and 6 in (1667 mm). There is conflicting information in published sources about the gauge of the same railways. Apart from gauge, the British builders of India's first railways, like all other countries, experimented with track designs and other technical devices in an effort to keep construction costs as low as possible. For example, the Godavari Dam Construction Railway and a number of other early railways used peculiar rails with a wooden backing and iron strips to create a rolling surface for the wheels. To do this, they would take a 6–7 inch (15–17 cm) diameter dulled teak logs 20 feet (8.09 m) long and tap them to a narrow, flat surface, onto which a 1/2 inch wide and 1/2 inch thick iron strip would be screwed. The resulting "rail" was laid in the track on wooden sleepers. The author of one note notes that the cost of such rails was "negligible"[13].

All kinds of experiments aimed at reducing capital investment in construction, reducing the cost of construction materials, while possibly using cheap labour, have resulted in the creation of unique transport systems in India — single-rail (monorail) railways of the so-called outrigger type, known as the Ewing System[14]. In the first decade of the twentieth century, more than 10 such railways were built in India with a total length of about 500 km. One of them, Patiala State Monorail Trainways (PSMT) with a total length of several lines of about 80 km was constructed in 1907 in the city area and operated until the mid-1920s.

On the railways of this system, only one metal running rail (cast iron, iron or steel) was laid in the track, on which the grooved (dual ridge) wheels of the rolling stock were supported. To maintain equilibrium, the rolling units were equipped with a kind of outriggers with wide steel wheels, which rolled on a compacted earth track, laid parallel to the rail. The wheels on the rail carried about 70–80 % of the load of the locomotive or wagon, the rest being carried by the outrigger.

The single-rail track reduced the need for metal for the track by half. The cheap labour of local diggers kept the compacted dirt track for the outrigger wheels in good condition, and in some cases this track was paved with stone within stations.

A small section of Patiala State Monorail Trainways is now reproduced in the National Rail Museum, New Delhi (*Fig. 14*). It features a dismantling of the pre-

[12] An Act for regulating the Gauge of Railways. 18th August 1846. URL: https://www.irishstatutebook.ie/eli/1846/act/57/section/1/enacted/en/html

[13] Godavari Dam Construction Railway. URL: https://wiki.fibis.org/w/Godavari_Dam_Construction_Railway

[14] In 1895 the English entrepreneur W.J. Ewing, working in Bengal, India, patented the monorail system proposed by William Thorold of Norwich in England in 1868.

Fig. 14. Patiala State Monorail Trainways National Rail Museum, New Delhi[15]

served original monorail rolling stock, including a unique steam locomotive[15].

ESTABLISHMENT OF COMMON RAILWAYS IN INDIA

Today, India's railways are the fourth longest in the world (67.900 km) after the USA (148.7)[16], China (109.7)[17] and Russia (85.5)[16], India, meanwhile, operates the largest railway network in the world on the broadest gauge currently in operation — 5 feet and 6 inches (1.676 mm) (see table). This gauge was first used in Scotland on two small railways built in the 1830s. This was a time of many experiments in railway construction in the context of the "Battle of Gauges". The builders of the first Scottish railway chose a gauge of 1676 mm, probably out of a desire to be in the "golden mean" between Stephenson's standard 1435 mm gauge and Brunel's extra broad 2140 mm gauge[18].

In India in the 1830s and 1840s, echoes of the battle of the gauge battles that were taking place in the metropolis reached the country. In response to a variety of sentiments, entrepreneurs, engineers and local colonial authorities opted for a Scottish gauge of 1676 mm for the first main line railway in India. Railway builders in several other countries of the region — Pakistan, East Pakistan (Bangladesh), Nepal, Sri Lanka, the island of Ceylon[19].

In the metropolitan area, not much time had passed since the Gauge Act was passed in 1846 and, as shown above, there was in fact still considerable confusion about how to determine the optimum gauge in practice. Similar processes have taken place in other countries. In the North American United States (USA), no fewer than a dozen different gauge sizes were being built, with the Stephenson gauge of 1435 mm and the five-foot gauge of 1524 mm dominating. Russia, a future great railway power, experimented with a broad gauge of 6 feet on its first public railway, the Tsarskoselskaya. The American five-foot gauge (1524 mm) was adopted when the construction of the main line between Saint Petersburg and Moscow was decided, and later became the standard gauge in Russia, later to be called the Russian gauge.

With the establishment of the Great Indian Peninsula Railway in India in 1849, it was decided that the Indian railway network would develop with a track gauge of 1676 mm. Many historical publications have pointed out that the choice of a broader track (1435 mm) in India was based on the belief of many experts at the time that a broader track would be more resistant to possible damage under the harsh conditions of the Indian peninsula, especially the long monsoon rains and the hot climate.

Despite the decision to build 1676 mm broad gauge mainline railways in India, numerous metre gauge railways and smaller gauges — 762 mm and 610 mm — were constructed throughout the 19th century and early 20th century[20] [7]. Entrepreneurs tried in every way to reduce the cost of building railways. At the same time, even the construction of one-metre gauge railways seemed to many of them to be too expensive. As has already been noted, often projects to build narrow-gauge railways, for which powerful lobbyists had per-

[15] Delhi: India's oldest monorail comes back to life, to chug every Thursday. URL: https://www.hindustantimes.com/delhi-news/delhi-india-s-oldest-monorail-comes-back-to-life-to-chug-every-thursday/story-pRQRDdKcFDCaLXP8uhY8DO.html

[16] International Union of Railways data, which we consider to be the most trustworthy / Railway Statistics Synopsis 2022 edition. Paris: UIC, 2022. URL: https://uic.org/IMG/pdf/uic-railway-statistics-synopsis-2022.pdf

[17] US and Chinese railways use a standard gauge of 1,435 mm for almost their entire length, while the Russian Federation's railways use a gauge of 1,520 mm, established in the 1970s.

[18] Today it is difficult to establish the true reasons why the Dundee and Arbroath Railway (1836–1947) and the Arbroath and Forfar Railway were built with a gauge of 1667 mm. Subsequently they were "converted" to a standard gauge of 1435 mm.

[19] The 1676 mm gauge is currently used in Argentina, Chile, on the Bay Area Rapid Transit (BART) urban passenger rail line in San Francisco. In the past, railways with this track gauge, further "converted" to a standard of 1435 mm, were operated in Canada and the USA.

[20] The 1000 mm broad track was first used in Belgium and France and in cities in Germany and other European countries. Subsequently, in most European countries it was "re-stitched" to a standard gauge. However, the one-metre gauge has survived and is in use in many countries in Africa and Asia. According to various estimates, the length of railways with such track in the world is about 80 thousand km, it is also used as a tramway in more than 50 cities around the world.

Table

Operational length of railways in India

<table>
<tr><th rowspan="4">Years</th><th colspan="8">Track gauge, mm</th><th rowspan="4">Total operational length</th></tr>
<tr><th colspan="2">1676</th><th colspan="2">1000</th><th colspan="2">762</th><th colspan="2">610</th></tr>
<tr><th colspan="8">1 – operational length, km, 2 – percentage of the operational length of the network</th></tr>
<tr><th>1</th><th>2</th><th>1</th><th>2</th><th>1</th><th>2</th><th>1</th><th>2</th></tr>
<tr><td>1956–1957 [8]</td><td>25 842</td><td>47.0</td><td>24 654</td><td>44.9</td><td>3 886</td><td>7.0</td><td>577</td><td>1.0</td><td>54 959</td></tr>
<tr><td rowspan="3">2022*</td><td rowspan="3">65 093</td><td rowspan="3">95.7</td><td rowspan="3">1655</td><td rowspan="3">2.5</td><td colspan="4">Narrow gauge 762 + 610 mm</td><td rowspan="3">68 193
According to UIC – 67 956[16]</td></tr>
<tr><td>1</td><td colspan="3">2</td></tr>
<tr><td>1294</td><td colspan="3">1.91</td></tr>
<tr><td colspan="10">* India Brand Equity Foundation (IBEF). URL: https://www.ibef.org/industry/railways-presentation</td></tr>
</table>

suaded both the local authorities and London to grant permission, conflicted with the transport needs of the country. By the end of the 19th century India's railway network, like Britain before it, had numerous junctions where goods and passengers had to be reloaded and interchanged. The Indian railway network at the beginning of the twentieth century was a patchwork of different gauges: broad (1676 mm), one-meter and narrow gauges, with numerous junctions and transfer platforms.

MODERNISING INDIA'S RAILWAYS WITH INDEPENDENCE

Great Britain had left India with a dire railway legacy of a network of backward infrastructure and scattered sections of railways of various gauges. While the metropolis had a unified network of standard gauge mainlines by the early 1890s, the situation in India at the time of India's independence in 1947 was dire in terms of nationwide operations. The length of India's railways by the 1950s was about 55.000 km [8], placing it seventh in the world after the USA (350.000 km)[21], USSR (120), France (40.9), Great Britain (30.60), and Germany (30.5) [8]. Technical armament of Indian railways was one of the lowest in the world for a network of such length, in the vast expanses of India railway stations of different gauges were comparable with rapids on navigable rivers. Of the 54,500 km operational length, 47 % had 1667 mm broad track gauge; 44 % had meter track gauge and about 9 % had narrow gauge (762 mm and 610 mm gauge railways)[22] [8].

For several decades in the second half of the twentieth century, the process of interconnecting India's network on the basis of 1676 mm broad gauge railways, important for improving railway operations, developed very slowly. Both the country's leadership and the railway community were well aware of the need for it. However, the stated objective required enormous expenditures at the national scale for reconstruction, and sometimes practically new construction of railways when they were converted from the narrow gauge to the standard broad gauge accepted in the country. In many cases it was a question of constructing a new earthwork, artificial structures, laying new track structure and replacing rolling stock compatible with a broad track gauge of 1676 mm. This landmark reconstruction required political will and a unified approach at various levels of government, as well as unity in dealing with the many tasks of various social groups, associations of businessmen, industrialists, builders.

Ten years after independence, the task of creating a single "seamless" railway network was far from being achieved. Within a decade, many new metre gauge railways had been built and some of the narrower gauge roads had been reconstructed to metre gauge.

The revolutionary decision to carry out systematic work to unify the Indian railway network on the basis of converting ("re-building") railways with a gauge of already 1676 mm (meter gauge, 762 mm and 610 mm) into 1676 mm gauge mainlines was taken on April 1, 1992 by a program called Unigauge[23] [7], A timetable was approved for the transformation of individual railway lines, railway sections and railway junctions into

[21] The maximum operational length of the US railways reached 409,100 km in 1916, after which they steadily declined.
[22] Figures published in 2023 by the Ministry of Railways of India differ slightly from the above, but within 1–2 percent (Project Unigauge. URL: https://en.wikipedia.org/wiki/Project_Unigauge; What is project Unigauge. URL: https://www.railnewscenter.com/what-is-project-unigauge/railway-employee/
[23] What is project Unigauge. URL: https://www.railnewscenter.com/what-is-project-unigauge/railway-employee/

a unified network of 1676 mm gauge. Several narrow-gauge railways are to be eliminated and their freight and passenger flows transferred to the new broad-gauge lines.

The progress of the Unigauge programme to date is significant. In 2022, the operational length of the broad-gauge railway network in India was 65.094 km or 95.7 % of its total length.

Under the Unigauge programme, a specific list of metre and narrower gauge railways with a total length of about 500 km has been drawn up and approved as a national historical and cultural heritage as well as a UNESCO World Heritage Site in India. They and the rolling stock for them, as well as railway buildings of various industrial uses and railway stations, are not subject to alterations and conversions and are preserved and maintained in their historical form.

CONCLUSION

Railway transport in India, from the construction of the first railways in the 1830s until the country's independence in 1947, developed as part of the colonial policy of the metropolis to enslave the country and plunder its national wealth. The British colonisers did this in the cheapest way possible, without creating high-tech national enterprises and without taking into account the interests of the colonial territories.

In the development of rail transport in India, this was evident in the construction of railways by the colonial authorities in the cheapest way possible, almost universally to the detriment of national interests, without any aspiration to create a unified railway network, with the 1676 mm broad gauge adopted as standard in the country.

The result of this policy was the formation of a fragmented agglomeration of railway lines by the mid-20th century. In India, a fragmented agglomeration of railway lines and local sections of railways of different gauges with numerous junctions and reloading stations, which hindered freight and passenger transportation at a significant cost of transport operations.

Only after national independence did the modernisation of the railways begin. Preparatory work was carried out over several decades, and the national Unigauge programme, adopted in 1992, brought the first phase of rail modernisation closer to completion. Today, more than 95% of the total length of India's railways is a unified gauge system with a gauge of 1667 mm.

This opens broad prospects for a technological renewal of all railways, based on the completion of electrification, the unfolding construction of high-speed railways and the digitalisation of rail transport.

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Influence of financing water protection measures in the field of transport on water quality of water bodies

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ABSTRACT Transport is a major water consumer and source of environmental pollution, including water resources. In order to preserve and improve water quality in water bodies at industrial and transport enterprises, including railway enterprises, water protection measures entailing permanent significant funding are required.

The study is aimed to develop a methodology for determining dependence of water quality of the water body on the real financing of water protection measures; theoretical justification of the choice of water quality of the water body from the quality of wastewater (WW) of water users, discharging them into the water body and amount of financing of water protection measures.

The solution of the task of determining the best water quality in a water body under limited financing of water protection measures and rational distribution of financial resources between water users, including transport infrastructure objects, is proposed.

Financing of water protection measures in Russia is less than abroad and has been decreasing over the last three decades. The limits for pollutant concentrations in pollutant discharges into water bodies and water disposal systems in Russia are often set very strict, sometimes more stringent than those for drinking water, which leads to unjustified spending of investment costs.

It is pointed out that at present in Russia market relations in the field of nature and, in particular, water use have not been formed. The basic difficulties at realization of these relations in our country are designated.

When using the proposed methodology, the rational quality of water resources of water users by limiting pollutants and the rational distribution of funds for water protection measures among water users within the limited amount of financing are determined. The extent to which water quality in a water body changes is also determined. The possibility of practical application of the proposed methodology is considered.

KEYWORDS: financing of water protection measures; water quality; water body; water user; transport infrastructure; water purity index; pollution concentration; environmental performance index; maximum permissible discharge

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Научная статья

Влияние финансирования водоохранных мероприятий в сфере транспорта на качество воды водных объектов

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АННОТАЦИЯ Транспорт является крупным водопотребителем и источником загрязнения окружающей среды, включая водные ресурсы. Для сохранения и улучшения качества воды в водных объектах на промышленных и транспортных предприятиях, в том числе железнодорожных, необходимо проводить водоохранные мероприятия, которые требуют постоянного значительного финансирования.

Цель исследования — разработка методики определения зависимости качества воды водного объекта от реального финансирования водоохранных мероприятий; теоретическое обоснование выбора состояния качества воды водного объекта от качества сточных вод (СВ) водопользователей, сбрасывающих их в водный объект, и от объема финансирования водоохранных мероприятий.

Предложено решение задачи определения наилучшего качества воды в водном объекте при ограниченном объеме финансирования водоохранных мероприятий и рациональном распределении финансовых средств между водопользователями, в том числе объектами транспортной инфраструктуры.

Финансирование водоохранных мероприятий в России меньше, чем за рубежом, за последние три десятилетия оно снижается. Предельные нормы концентраций загрязняющих веществ (ЗВ) в СВ при сбросе их в водные объекты и в системы водоотведения в России часто устанавливаются очень жесткие, иногда более жесткие, чем к питьевой воде, что ведет к неоправданному расходованию инвестиционных затрат.

Указано, что в настоящее время в России не сформировались рыночные отношения в области природо- и, в частности, водопользования. Обозначены основные трудности при реализации этих отношений в нашей стране.

При использовании предложенной методики определяется рациональное качество СВ водопользователей по лимитирующему ЗВ и рациональное распределение финансовых средств на водоохранные мероприятия между водопользователями в пределах ограниченной суммы финансирования. Устанавливается также, насколько изменяется качество воды в водном объекте. Рассмотрена возможность практического применения предложенной методики.

КЛЮЧЕВЫЕ СЛОВА: финансирование водоохранных мероприятий; качество воды; водный объект; водопользователь; объекты транспортной инфраструктуры; индекс чистоты воды; концентрация загрязнений; индекс экологической эффективности; предельно допустимый сброс

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INTRODUCTION

Transport, like industry and energy, is a major water consumer and source of environmental pollution, including water resources [1].

In the XIX — beginning of the XX century, water supply facilities were crucial for the organization and successful operation of the transportation process under steam traction. In the subsequent period, with the transition of railway transport to other types of traction, water continues to be used for domestic, industrial purposes, large volumes of water are consumed when washing rolling stock, containers (including tanks of cisterns that carry various liquids), as well as at firefighting facilities of transport infrastructure. At the moment, issues related to drainage and treatment of wastewater (WW), rational use and protection of water resources are of paramount importance for rail transport facilities, as well as for other industrial sectors.

In order to preserve and improve water quality in water bodies at industrial and transport enterprises, including railway enterprises, water protection measures need to be implemented, which require constant and significant funding. In the Transport Strategy of the Russian Federation to 2030 with a forecast for the period up to 2035[1], Federal Law No. 416-FZ “On Water Supply and Sanitation”[2], other existing documents usually do not provide economic justification for strict regulatory requirements on the discharge of waste water into water bodies. As a result, practically all water users become hostages to the current situation, as there are insufficient financial resources to meet the required standards.

Relative investment in environmental protection (EP) in Russia is significantly lower than in some other countries (*see Table*).

From 1990s till present, the situation with regard to water protection measures in the Russian Federation has deteriorated (*Fig. 1*). From 1992 to 2020, according to the Russian Statistical Yearbook 2022 [1], indicators such as the relative investments in fixed capital aimed at protecting water resources, the commissioning of sewage treatment plants and the implementation of water recycling systems are decreasing.

[1] Transport Strategy of the Russian Federation until 2030 with a forecast for the period until 2035 (approved by the Decree of the Government of the Russian Federation dated 27.11.2021 No.3363-r).
[2] Federal Law No. 416-FZ dated 07.12.2011 on Water Supply and Sanitation. Moscow, ConsultantPlus, 78 p.

Table

Environmental protection costs [2]

Country	% of GDP	GDP, $ billion in 2017	EP costs, $ billion	Territory, thousand km²	Investment per unit area, thousand $/km²
Russia	0.9	3807	34.3	17 125	2.00
France	1.0	2983	29.8	552	54.0
Germany	0.7	4377	30.6	358	85.6
UK	0.7	3022	21.2	242	87.4
Japan	1.3	5194	67.5	378	179

Despite the lack of funding for water protection measures, the maximum permissible concentrations (MPC) of pollutants in wastewater, including from transport infrastructure, when discharged into wastewater disposal systems and water bodies in Russia are often set very high, sometimes more stringent than for drinking water (*Fig. 2*), which leads to unjustified investment costs.

RESULTS OF THE STUDY

At present, the Russian Federation has not yet established market relations in the field of nature and, in particular, water use. There are a number of difficulties in the implementation of these relations in our country, the main ones being:

- there is no legal basis for regulating such relationships;
- financing opportunities for water protection measures, as a rule, do not allow achieving the required values of maximum permissible discharges (MPD)

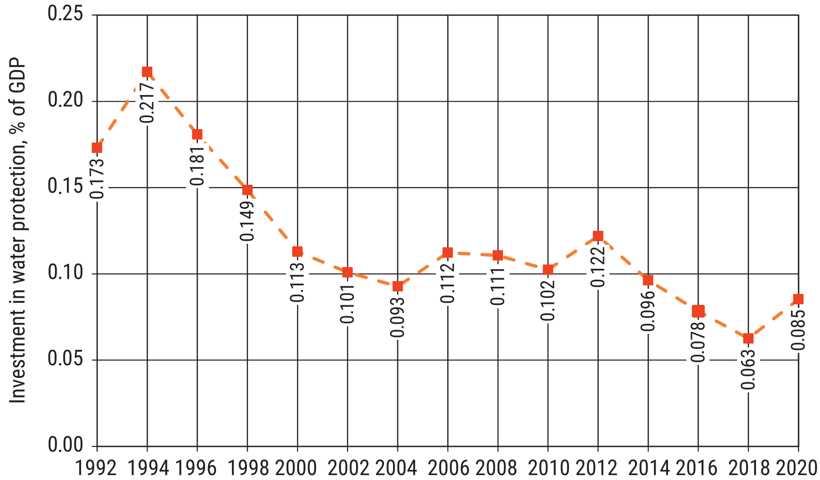

Fig. 1. Investment in water protection, % of GDP
Water protection measures in the Russian Federation in 1992–2020

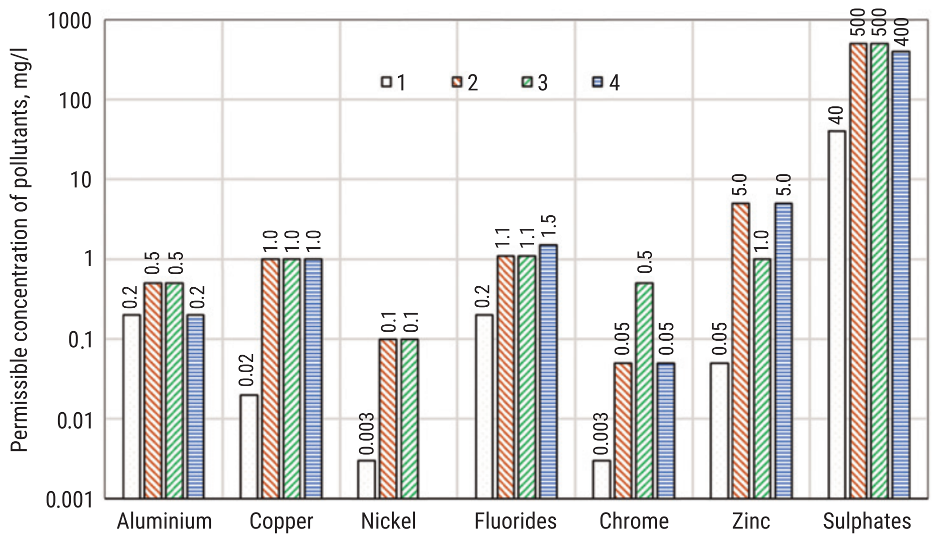

Fig. 2. Permissible concentrations of pollutants: *1* — in industrial wastewater in Saint Petersburg; *2* — in drinking water; *3* — in domestic and drinking water bodies; *4* — in drinking water according to the recommendations of the World Health Organisation (WHO)

of pollutants in the required time; this obliges either to significantly increase financing of environmental protection measures to the detriment of other economic activities, or to reduce requirements to the quality of waste water discharged into water bodies in accordance with our capabilities. Over the last decade, new less stringent requirements for permissible pollutant discharges have been established abroad in comparison with previously existing ones, taking into account real possibilities of financing. These actions made it possible to implement market mechanisms in environmental protection activities to the full extent;

- there is no substantiated methodology for determining permissible pollutant discharges into urban wastewater networks, depending on MPC of pollutants discharged into water bodies, which often leads to a paradoxical situation: in many cases, the requirements for wastewater discharged by water users into urban wastewater networks are stricter[3, 4], than MPC of pollutants in water bodies or drinking water indicators (SanPiN[5] and WHO recommendations);
- there is no methodology for changing the quality of water in a water body depending on the amount of investment in water protection measures in the basin of the water body.

Let us consider the latter circumstance in more detail.

Suppose that for a group of water users of one water basin it is necessary to choose a rational way of financial allocation and at the same time to obtain the highest possible water quality of a water body, which under a certain background pollution depends on WW quality of water users [3].

Fig. 3 shows a graphical interpretation of the solution to the problem.

A general criterion for water quality of a water body can be the water purity index I_p [4], which for the i-th pollutant is determined by the formula

$$I_p = \sum_{j=1}^{n} \frac{\text{MPC}_j}{C_j}, \qquad (1)$$

where MPC_j and C_j — respectively the maximum permissible concentration and the actual concentration of the j-th pollutant.

Water users aim to find the maximum function $I_p(I_i)$, where I_i —WW purity index of the i-th water user.

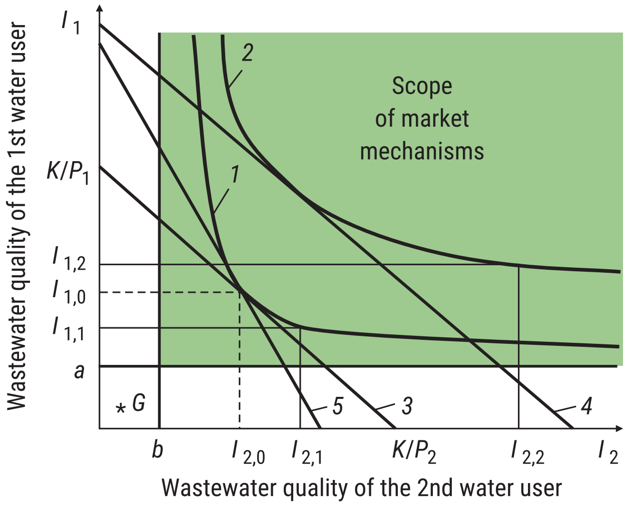

Fig. 3. Graphical interpretation of the solution to the water quality condition selection problem for two water users: *1* — function level curve $I_p = f(I_1, I_2) = \text{const}_1$; *2* — new function level curve $I_p = f(I_1, I_2) = \text{const}_2$ with increased funding opportunities; *3* — the old line of budgetary restraint $P_1 \cdot I_1 + P_2 \cdot I_2 = K$; *4* — a new line of budgetary constraint while maintaining the price ratio of I_1 and I_2; *5* — a new line of budgetary constraint when the price ratio changes I_1 and I_2

Since water users are often limited in funds, they can spend part of this money in order to invest it in improving WW quality of one water user, and another part in improving the WW quality of another water user, etc. Suppose also that P_i — the price of improving the “quality unit” of WW of the i-th water user.

In general terms, the challenge facing water users in a water basin can be formulated as follows

$$I_p(I_i) \to \max; \qquad (2)$$

$$\Sigma(P_i \cdot I_i) \le K; \qquad (3)$$

$$I_i \ge 0. \qquad (4)$$

In order to visualise the condition of the problem, let us assume that the water quality of a water body needs to be selected for two water users. Let us denote WW quality of one water user I_1, that of the second one — I_2. P_1 should be paid for the improvement of the first water user’s WW (i.e. P_1 — the price of a “quality improvement unit” of WW of the first water user, and for the improvement of the second water user’s

[3] Bezpamyatnov G.P., Krotov Yu.A. Maximum permissible concentrations of chemical substances in the environment: handbook. Leningrad, Chemistry, 1985;528. (In Russ.).

[4] Guidelines for drinking water quality control. Volume 1. Recommendations. Geneva, World Health Organisation (WHO), 1986;126.

[5] SanPiN 2.1.3684-21. Sanitary and epidemiological requirements for the maintenance of urban and rural settlements, water bodies, drinking water and potable water supply, atmospheric air, soils, living quarters, operation of industrial and public buildings, organization and conduct of sanitary and anti-epidemic (preventive) measures. Moscow, 2021;66. (In Russ.).

WW, P_2 should be paid. In this case, the task can be expressed as follows

$$I_p(I_1, I_2) \to \max;$$
$$P_1 \cdot I_1 + P_2 \cdot I_2 \leq K;$$
$$I_1 \geq 0; \quad I_2 \geq 0.$$

Let's assume that $I_{1,0}$ and $I_{2,0}$ — is an optimal solution of problem (2)–(4), the constant a defines the minimum permissible level of WW of the first water user (MPD_1), which depends on MPC of pollutants in water of the water body; the constant b defines the minimum permissible level of WW of the second water user. The I_p functions in this case can be calculated as follows

$$I_{p1} = f_1(a, b, P_1, P_2, K); \tag{5}$$
$$I_{p2} = f_2(a, b, P_1, P_2, K). \tag{6}$$

The constants a and b set the lower limits for the quality of the WW of water users (MPD_1 and MPD_2).

Demand for WW quality of water users and, consequently, water bodies is functionally related to the prices for WW quality improvement of each water user and the financial possibilities of each water user.

Function level line $I_p = f(I_1, I_2)$ indicates all points I_1 and I_2, for which the following equation is fulfilled $I_p = f(I_1, I_2)$ = const (i.e. the value of the criterion is the same for these points). If we take another point, for example $I_p = f(I_{1,1}, I_{2,1})$, lying on this curve, the value of the criterion will not change, i.e. $I_p = f(I_{1,1}, I_{2,1}) = f(I_{1,0}, I_{2,0})$, However, it will cost more to ensure $I_{1,1}$, $I_{2,1}$ for water users.

A change in K value results in a parallel shift of the budget constraint line. A change in the price ratio changes the slope of the budget constraint line (see *Fig. 3*).

This problem has a solution only if $P_1 \cdot a + P_2 \cdot b \leq K$, i.e. in the first place, it is necessary to ensure WW quality at the minimum permissible level, and then to spend the remaining funds for additional water quality improvement. If the financial resources of natural resource users K exceed the minimum allowable value, the remaining part is divided according to the type of dependence (2): $I_p = f(I_1, I_2)$. If water users have only had enough to ensure that the quality of WW is at a minimum acceptable level, i.e. $P_1 \cdot a + P_2 \cdot b = K$, they have no choice but to choose this particular set. The cost ratios of ensuring quality of WW of the water users, which determine the slope of lines 4 and 5, have no influence on this choice.

The water quality choice area of a water body, which depends on the quality of WW of water users, can be divided into three zones (see *Fig. 3*):

- quality of WW of water users above the maximum permissible values MPD_i (lines a and b) — the scope of market mechanisms;
- quality of WW of water users is equal to the maximum permissible values (lines a and b) — lines of administrative regulation;
- quality of WW of water users cannot be ensured for one reason or another (e.g. financing conditions) — an area of uncertainty.

The peculiarity of the current state of water use in Russia is that the allocated amount of funds K, as a rule, is insufficient even to ensure the quality of discharged to water bodies at the minimum acceptable level, i.e. the necessary condition of the market mechanism according to the formula (3) is not met, there is no possibility to maneuver financial resources.

In order to meet the current MPC standards for pollutants in wastewater discharged into water bodies in our country, it is necessary to increase significantly funding for water protection measures.

It should be borne in mind that these costs are minimal and sufficient only to meet the regulatory requirements for the quality of waste water discharged into water bodies. For normal functioning of water protection relations under market economy conditions (providing some freedom of choice), they should be several times higher.

At present, Waste water quality of the majority of water users in the Russian Federation (and, accordingly, of water bodies) can be conditionally characterized by the position of point G in *Fig. 3*.

In this regard, the view of some experts that a system of penalties can be progressive in our conditions in the field of drainage and protection of water resources is untenable. It can be so only if it serves as an incentive to introduce new technologies, if the natural resource user has a choice: to improve production or pay a fine. At present, water users have no such alternative.

CONCLUSION

Relative financing of water protection measures in the Russian Federation is considerably lower than in foreign countries, and has been declining in our country over the past three decades.

The limits for concentrations of pollutants in WW when discharged into water bodies and water disposal systems in Russia without economic justification are often set very strict, sometimes more stringent than for drinking water, which leads to unjustified expenditure of investment costs.

The authors propose a methodology for determining the dependence of water quality of a water body on the actual financing of water protection measures.

Consideration is given to the practical application of the proposed methodology.

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On some mechanical characteristics of the ballast in assessing the stress-strain behaviour of railway tracks

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ABSTRACT On the basis of recent research, a review has been carried out on the experimental determination of the mechanical parameters of the materials used as ballast material. Considerable attention is given to the well-founded selection of input data for the calculation, i.e. quantitative characteristics of the elastic properties of the materials used to form the ballast layer, which is treated as a continuous medium. It appears that this approach makes it possible to assess correctly the influence of grain (grain size distribution) distribution, ballast layer thickness and material type on the stability of a railway track to vertical and horizontal disturbances. The data of this review show that material properties and particle size have a significant impact on elastic moduli and in finite-element modelling of static strength problems, grain-size distribution and material properties are only taken into account through these moduli. Experimental results show a non-linear dependence of the elastic moduli on the stress behaviour of the ballast prism, which is related to a densification of the medium in compression. However, it is established that, after a sufficiently large number of loading cycles, the medium can be treated as linearly elastic. In general, the results of the research allow establishing requirements for damping, geometric and granulometric parameters of the ballast prism.

KEYWORDS: ballast layer; ballast materials; grain size distribution; compression; linear-elastic medium

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Научная статья

О некоторых механических характеристиках балласта при оценке напряженно-деформированного состояния железнодорожного пути

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АННОТАЦИЯ На основании зарубежных публикаций проведен обзор по экспериментальному определению механических параметров материалов, используемых в качестве балластного материала. Данные этого обзора показывают, что свойства исходного материала и размеры частиц оказывают влияние на упругие модули и при конечно-элементном моделировании статических задач гранулометрический состав и свойства материала учитываются лишь через модули. Экспериментальные результаты показывают нелинейную зависимость модулей от напряженного состояния, что связано с уплотнением среды при сжатии. Однако указывается, что после достаточно большого числа циклов нагружения можно считать среду линейно-упругой.

КЛЮЧЕВЫЕ СЛОВА: балластный слой; балластные материалы; гранулометрический состав; сжатие; линейно-упругая среда

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INTRODUCTION

The ballast layer, as an element of the track structure, significantly predetermines durability of the track as a whole, serviceability of the subgrade and scope of maintenance and repair works.

Existing semi-empirical path calculation methods give a linear dependence of deformation (deflection) on the speed of the vehicle in a fixed section. However, experiments show that this dependence is valid only at low speeds (up to 100–150 km/h). At higher speeds this dependence becomes non-linear and gives a significant divergence from theory.

The interaction of the track and rolling stock at different speeds is determined by force interaction between wheel and rail, in which a great role is played by static and dynamic properties of the ballast prism. In general, the calculation of this interaction is related to the solution of a dynamic problem in elasticity theory. In fact, one should consider the oscillation of an elastic volume under the influence of external forceful disturbances. Taking into account wave processes in such systems as "vehicle-track" is a difficulty, which, on the one hand, is related to the correct setting of appropriate boundary conditions, on the other hand, with a reasonable choice of physical and mechanical properties of the ballast material, which are put in the mechanical-mathematical model of the deformation of the track.

MATERIALS AND METHODS

The ballast for the upper part of the track is a granular material designed to distribute the load applied by the moving train evenly. The ballast consists of particle elements between 20 and 60 mm in size. Today it is generally accepted that high quality ballast must have well defined particles, high density, high shear strength, high rigidity, high resistance to abrasion, uneven surface and minimum number of cracks and inclusions [1–4]. Many properties of the ballast will change under dynamic loading due to ballast discolouration, deformation and contamination. Ballast contamination causes reduction in drainage capacity, hydraulic erosion, reduced stability due to sliding particles, wear on the bottom of the track and track damage due to increased water pressure (during rain) in the pores between the particles in the ballast.

This raises the need to improve drainage and strength properties, which are in a sense contradictory. It is first necessary to consider physical and mechanical properties of the ballast and how to mechanically and mathematically model the behaviour of the railway track.

The simplest model of track is a sleeper as a bar on an elastic base under the impact of a concentrated load acting from the side of the wheel. The resilient bed must take account of the stiffness of the sleepers, ballast and track bottom (earth, etc.). The values for the elasticity modulus of the rail support are derived from the results of field tests of the track sections under operating loads. It is defined as the specific force (acting per unit of rail length) per unit of track deflection

$$U = \frac{1}{4}\left(\left(\frac{P}{\delta}\right)^4 \frac{1}{EI}\right)^{1/3}, \quad (1)$$

where P is acting load (force); δ is deflection of the rail under the point of load application; E is Young modulus of rail steel; I is moment of inertia of rail cross-section.

More complex analytical track models represent rails and sleepers as bars resting on a multi-layer base that includes a ballast layer and soil. These models include computer programmes such as ILITRACK (1975), MULTA (1978), GE-OTRACK (1980, 2000), KENTRACK (1986), RAIL (2004). Finite element models have also been developed based on one-, two- and three-dimensional representations of track elements. In the last fifteen years, calculation programmes based on combined boundary and finite element methods have been widely used [5-8].

There are two main problems associated with the physical and mechanical properties of ballast:

- determination of maximum elastic deformations and deflections caused by wheel loads;
- accumulation of plastic deformations as a result of repeated characteristic loads.

The concept of elastic recovery modulus (unloading-loading modulus) Eur is used to describe the behaviour of the ballast under repetitive loading conditions. The elastic recovery modulus is defined as the ratio of the deviator of repetitive stresses to the restored part of the axial strain [9]. The most commonly used expression for this modulus is

$$E_{ur} = Kp_r \left(\frac{\sigma_3}{p_r}\right)^n, \quad (2)$$

where K, n are material constants determined by tests; p_r is reference pressure; δ_3 is primary stress.

In [10], on the basis of in-situ experiments, the authors state that the elastic recovery modulus of the ballast layer under given loading conditions is one of the most important factors influencing the value of stress deviation at the soil-ballast boundary. With a minimum ballast layer thickness of 0.3 m, the stress-deviation stresses are maximal at the end of the sleeper and minimal at the centre of the sleeper. An increase in ballast thickness from 140 to 550 MPa results in a 35 % decrease in the stress-deviation stress at the ground near the end of the sleeper.

It was also established that the elastic recovery modulus has the greatest influence on the deflection of sleepers under the wheels. GEOTRACK software was used to determine the average deformation of the ballast in the vertical direction. The average deformation was calculated as the ratio of the difference in displacement of the upper and lower surfaces of the ballast to the initial thickness of its layer. If E_{ur} is reduced from 689 to 55 MPa, the deformation of the ballast is increased by a factor of 9. Based on the results of these studies, the modulus of elasticity of the base U (1) was estimated to increase by 20 % with an increase of E_{ur} within the specified limits.

In order to investigate the residual deformation in ballast, three-axial compression tests must be carried out on special stabilometers under repeated loading. The tests carried out by many researchers in the last 30 years showed that there is a limit for the ratio of stress deviator of cyclic failure to the value of stress deviator of static failure

$$K_c = \frac{(\sigma_1 - \sigma_3)_{cf}}{(\sigma_3 - \sigma_3)_f},$$

where σ_1, σ_3 are primary stresses.

If the cyclic stresses are less than $K_c(\sigma_1 - \sigma_2)_f$, the residual strain of the ballast test piece converges to a constant value for that material. The ballast test piece then behaves as a quasi-elastic material. If the above-mentioned limit is exceeded, the cyclic and plastic strain is increased almost linearly from cycle to cycle and the test piece fails within a short time [11]. Different data are given in the literature regarding the value. Thus, K_c = 0.8 according to the results obtained in [11] and K_c = 0.6 according to the publication [12].

Several expressions have been proposed for the estimation of permanent strain in ballast caused by repeated loading.

The Office of Research and Testing of the International Union of Railways (ORE of IUR) suggests using the formula [13]

$$\varepsilon_N = 0.082(100n - 38.2)(\sigma_1 - \sigma_3)^2(1 + 0.2 \log N), \quad (3)$$

where ε_N is plastic strain after N cycles of loading; n is initial porosity of the test piece; $\sigma_1 - \sigma_3$ is stress deviator.

In paper [14] it is suggested to determine ε_N as follows

$$\varepsilon_N = \varepsilon_1(1 + C \log N), \quad (4)$$

where C is constant of the material, C = 0.2–0.4.

Equations (3) and (4) show that plastic strain in any cycle ε_N can be calculated as a function of the number of applied cycles N or of the plastic strain after the first loading cycle ε_1, irrespective of the state of stress and degree of compaction of the test piece. The value ε_1 can be determined by the formula

$$\varepsilon_1 = \varepsilon_a - \varepsilon_{ur}, \quad (5)$$

where ε_a is axial strain from the stress deviator $\sigma_1 - \sigma_3$; ε_{ur} is recoverable deformation during unloading. Deformation ε_a is determined from the ratio

$$\varepsilon_a = \frac{(\sigma_1 - \sigma_3)/E_i}{1 - \dfrac{(\sigma_1 - \sigma_3)(1 - \sin\varphi)R_f}{2(c\cos\varphi + \sigma_3 \sin\varphi)}},$$

$$(\sigma_1 - \sigma_3)_f = R_f(\sigma_1 - \sigma_3)_{ult},$$

where E_i is initial tangential elasticity modulus of the ballast; φ is internal friction angle; R_f is the ultimate fracture ratio, is always less than 1 and is largely independent of σ_3; c is coupling; $(\sigma_1 - \sigma_3)_f$ is compressive strength (fracture stress difference obtained in triaxial tests); $(\sigma_1 - \sigma_3)_{ult}$ is asymptotic value of the stress deviation derived from the test results.

The level of stresses in the ballast layer depends not only on the magnitude of the applied loads but also on the resistance to them from sleepers, fasteners and ballast layer parameters. Numerous field experiments have demonstrated that the speed of a train significantly affects the magnitude of the stresses exerted in the ballast. The maximum vertical dynamic stresses in Hannover–Wurzburg line were measured [11]. When the speed of a train is increased from 150 km/h to 300 km/h, the maximum vertical stresses were 70 and 100 kPa, respectively. The authors [11, 14] defined the dynamic factor as the ratio of the dynamic stress in the ballast to the static stress. Its value was equal to 1.7 when the speed changed from 150 to 300 km/h. It has been reported that stresses on the sleeper-ballast soil interface for heavy-load trains can reach a value of 450 kPa at a speed of 170 km/h [11].

The horizontal stresses have been measured [15] and are not as significant as the vertical stresses. The maximum value is 90 kPa at a speed of 150 km/h and a vertical load of 140 kN.

The value of the elastic modulus in the full compression test can be obtained from the expression for generalized Hooke's law

$$E = \frac{\partial\sigma_a}{\partial\varepsilon_a} - 2\nu\frac{\partial\sigma_3}{\partial\varepsilon_a}. \quad (6)$$

where $\partial\sigma_a$, $\partial\varepsilon_a$ is change in axial stress and strain respectively; $\partial\sigma_3$ is change of volumetric stress; ν is Poisson ratio.

Since in full-compression tests there is no change in the volumetric stress and the measurement data is recorded at discrete points in time, formula (6) takes the form of

$$E = \frac{\Delta\sigma_a}{\Delta\varepsilon_a}. \quad (7)$$

Since soil and ballast do not behave linearly under loading and unloading, several possible ways of determining the modulus of elasticity of ballast can be suggested. The following interpretations of "elastic moduli" are currently known:

1. The initial tangential elastic modulus, defined as the initial slope of the stress-strain curve [16].

2. The modulus of loading-unloading (recovery) is defined as the ratio of the stress deviator of all-round compression to the corresponding strain at the end of the loading-unloading cycle [17]. This modulus was originally used to evaluate the elastic behaviour of soils under cyclic loading.

3. Secular modulus, defined as the ratio of half of the maximum stress deviator to the corresponding strain [18].

All of the above moduli can be determined by statistical processing of the experimental data and are represented in the form of the formula

$$E/p_r = K(\sigma_3/p_r)^n, \quad (8)$$

where p_r is the reference pressure, usually taken as 1 kPa. To find K and n from relation (8) we obtain

$$\lg(E/p_r) = \lg K + n\lg(\sigma_3/p_r). \quad (9)$$

The linear regression analysis is then applied to the experimental data and the dependence of E/p_r on σ_3/p_r is plotted, from where the K and n coefficients are found. The dependence of these values on bulk stresses, particle size and ballast material can be investigated.

The values of elastic moduli for different materials may have different dependencies on the particle size of the ballast. It is possible to trace such dependencies for limestone, basalt and granite from research material [19–21]. Due to limited and often inconsistent experimental data, further tests are required in order to draw definitive conclusions. Ballast used in railways consists of different particle sizes. GOSTs and national regulations regulate the use of a particular type and size of particles.

Granite ballast

In [20] data on tests of dry granite ballast particles of two sizes as well as mixtures of these particles are given:

a) fine particles (20 mm diameter) by volume as much as the larger fraction (50 mm) and the fine particles were placed on top;

b) the fines placed on top have a volume equal to 1/3 of the volume of the coarse fraction;

c) the fines placed on top are 2/3 the volume of the coarse fraction;

d) the fines placed on top were 1 and 2 layers.

The tests were carried out under cyclic loading until 105 cycles were reached. From the test results, the authors concluded that the values E_{ur} and E_i for all particle sizes increased as the volumetric stress increased during the test. Particles with a small cross-sectional area and lower porosity had higher modulus value E_i than larger particles. Modulus values E_{ur} are increased with increasing number of load cycles for fine and coarse ballast. The same tendency was observed for ballast types (a) to (d) above. The modulus values E_{ur} for cases (a) to (c) were about 30 % higher than for ballast of only coarse particles. The values of E_{ur} for case (d) were roughly the same as for ballast of only coarse particles at pressures of 40 and 90 kPa.

The results are summarised in *Table 1*. The conclusion to be drawn from this study is that a ballast prism consisting of two layers of different particle sizes has a higher shear strength and load-displacement modulus than a ballast of the same particle size.

Limestone ballast

Estimates of elastic moduli from triaxial tests of limestone ballast are given in [19]. The results were obtained on test pieces of five sizes. Test peices L-2.36 consisted of 2.39–4.75 mm ballast particles; L-4.75 had ballast particle sizes of 4.75–9.5 mm and L-9.5 had ballast particle sizes of 9.75–19 mm. The following formulas can be proposed to determine the parameters required for the estimation of the modulus E_{ur} as a function of the particle size

$$n = 0.5624D^{-0.1655}, \quad R = 0.403;$$

$$\lg K = 4.102D^{0.0464}, \quad R = 0.619,$$

Table 1

Strain and initial modulus values of the granite ballast

Average diameter particle diameter, mm	Pressure, kPa	E_i, MPa	E_{ur}, MPa 10^2 cycles	E_{ur}, MPa 10^3 cycles	E_{ur}, MPa 10^4 cycles	E_{ur}, MPa 10^5 cycles
50	40	55	208	244	290	292
50	90	55	292	323	358	368
50	140	81	354	377	388	401
20	40	33	302	388	489	529
20	140	228	563	672	737	818
20	240	–	1327	1533	1596	1949
20 (1/3 of the volume)	40	72	251	298	305	370
20 (1/2 of the volume)	40	71	280	303	364	376
20 (1/2 of the volume)	90	–	368	411	466	493
20 (2/3 of the volume)	40	44	234	297	293	394
20 (1 layer)	40	36	207	219	267	287
20 (2 layers)	40	46	186	236	256	299
20 (1 layer)	90	–	282	300	321	345

where R is coefficient of determination; D — average particle size. Note that the values of n obtained in the tests are higher than those predicted by Hertz contact theory (n = 0.333).

To estimate modulus E_i of dry ballast depending on particle size the following values were obtained

$$n = 0.6006D^{-0.021},\quad R = 0.938;$$
$$\lg K = 3.5065D^{0.0179},\quad R = 0.708.$$

The following parameter values are proposed for determining the E_{50} secant modulus

$$n = 0.7045D^{-0.1633},\quad R = 0.532;$$
$$\lg K = 3.2719D^{0.0611},\quad R = 0.655.$$

These parameter values are close to those proposed in [18], where n = 0.5 and lg$K$ = 3.61 are valid for almost all ballast particle sizes.

Basalt ballast

The values of elastic moduli of basalt ballast obtained experimentally in [19] are given in *Table 2*. The dimensions are the same as for limestone at the same value of volumetric compression pressure.

Dependence of the initial tangential modulus parameter E_i of dry ballast on particle size

$$n = 0.381D^{0.0435},\quad R = 0.403;$$
$$\lg K = 0.0057D + 4.0099,\quad R = 0.771.$$

Similar parameters for the secant module E_{50}

$$n = 0.9647D^{-0.473},\quad R = 0.835;$$
$$\lg K = 0.4505D + 3.0307,\quad R = 0.857.$$

Parameters of module E_{ur} of the dry ballast

$$n = 0.1794D^{0.2869},\quad R = 0.964;$$
$$\lg K = 4.763D^{-0.0241},\quad R = 0.924.$$

Table 2

Elastic modulus values of basalt ballast

Dimension type	Pressure σ_3, kPa	Initial modulus E_i, kPa	Secant modulus E_{50}, kPa	Unloading-loading module E_{ur}, kPa
B-2,36	35	4.58×10^4	2.71×10^4	1.04×10^5
	70	5.76×10^4	4.24×10^4	1.20×10^5
	105	7.32×10^4	4.57×10^4	1.39×10^5
B-4,75	35	4.72×10^4	2.44×10^4	1.06×10^5
	70	5.49×10^4	3.71×10^4	1.28×10^5
	105	7.33×10^4	4.25×10^4	1.45×10^5
B-9,5	35	5.76×10^4	5.11×10^4	1.10×10^5
	70	7.59×10^4	5.92×10^4	1.62×10^5
	105	9.42×10^4	6.81×10^4	1.64×10^5

Data for basalt in [19] and [21] differ from each other with the number of load cycles 102 but the difference is insignificant. Possible divergences are explained by different origin of the material and different types of its processing as well as by the fact that particle sizes in [21] ranged from 16 to 53 mm. Therefore, a mixture of pre-compacted particles with different sizes was tested. The data of [21] are based on a higher number of loading cycles than in [19] and therefore have a significance of their own. Before the values of elastic moduli can be used in practical calculations, ballast test pieces must be tested in facilities which allow for the triaxial stress state.

The tests [19] of the pieces exposed to water at pressures of 35, 70 and 105 kPa showed that the values of elastic moduli of dry test pieces are 25 % less than the corresponding values of wet test pieces.

CONCLUSION

The values of elastic initial modulus and secant modulus of ballast of basalt are larger for ballast particle sizes of 4.75–60 mm than for ballast of limestone. The difference can be regarded as insignificant. The modulus values increase with ballast particle enlargement in the above size range.

The loading-unloading modulus of limestone is slightly higher than that of basalt. Both materials have similar moduli values when the same particle size is used. This conclusion is based on tests up to $5 \cdot 10^4$ load cycles. Additional research with $5 \cdot 10^5$ loading cycles is necessary for final conclusions.

Increase of ballast particles size in above range of values results in corresponding increase of elastic moduli.

The above expressions for initial and loading-unloading modulus values depending on ballast particle size are valid within 50 % confidence limits and for the estimation of final modulus within 100 % confidence limits.

The values of elastic moduli of dry ballast are on average 25 % lower than those of wet ballast.

Double ballast of different particle sizes has higher shear resistances and load-displacement modulus values than single-layer ballast of the same particle size.

There are limited databases available in the public domain on research into the elastic moduli of ballast of different materials in relation to particle size. There are differences between domestic test rules and GOSTs and foreign ones. Therefore, the above moduli values require experimental confirmation by testing the type of ballast which is to be used in practice for track construction.

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Method for detecting the source of radio interference affecting train radio communication in the band of 2.13 and 2.15 MHz

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ABSTRACT There are many factors that influence the process of organising train movements, quality radio communication being one of the most important.

The intelligibility of the dispatcher's commands to the driver is important in deciding what action to take, and in informing the dispatcher of the train situation on a particular section of the track.

Sources of radio interference that have an interfering effect on the quality of the train radio signal are natural and artificial interference. The sources are mainly low-frequency interference. One of the constant sources of high-frequency emissions that affect stable operation of train radio communications refers to discharges generated in the high-voltage insulation of power lines, including discharges generated in the insulation of overhead wires.

Spark discharges, the source of radio interference, occur both on the surface of the insulator (usually called surface partial discharges (SPD)) and inside the insulation (such discharges are called partial discharges (PD)). In the operation of high voltage insulation, those insulators that contain PD and PPD are called defective insulators. PD and PD diagnostics are carried out twice a year by means of a laboratory car. Discharge registration is performed in the visible and ultraviolet range. There are acoustic methods for registering PD and SPD. It is proposed to register discharges in the electromagnetic frequency range.

For prompt detection radio interference, it is recommended to place antennas on the laboratory car, and combine measurements with current diagnostics of high-voltage insulation, that will allow increasing reliability of the results received in the course of diagnostics. To increase the accuracy of radio interference source detection, two antennas are considered to be placed on the laboratory car.

KEYWORDS: radio interference; high voltage diagnostics of overhead line insulation; train radio communication; partial discharges; and surface partial discharges

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Научная статья

Способ обнаружения источника радиопомех, влияющих на работу поездной радиосвязи в диапазоне 2,13 и 2,15 МГц

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АННОТАЦИЯ На процесс организации движения поездов влияет множество факторов, качественная радиосвязь является одним из важнейших.

Разборчивость команд диспетчера, направленных машинисту, важна для принятия решения о каких-либо его действиях, а также при информировании диспетчера о поездной ситуации на конкретном участке железной дороги.

Источниками радиопомех, оказывающих мешающее воздействие на качество полезного сигнала поездной радиосвязи, служат естественные и искусственные помехи. В основном источники вырабатывают низкочастотные помехи. Одним из постоянно действующих источников высокочастотного излучения, оказывающих влияние на устойчивую работу поездной радиосвязи, являются разряды, возникающие в высоковольтной изоляции линий электропередачи, в том числе разряды, образующиеся в изоляции контактной сети.

Искровые разряды — источник радиопомех — образуются как на поверхности изолятора (как правило, их называют поверхностными частичными разрядами (ПЧР), так и внутренней толще изоляции (такие разряды называются частичными разрядами (ЧР)). При эксплуатации высоковольтной изоляции те изоляторы, которые содержат ЧР и ПЧР, называют дефектными. Диагностику ЧР и ПЧР проводят два раза в год посредством вагон-лаборатории. Регистрацию разрядов выполняют в видимом и ультрафиолетовом диапазоне. Существуют акустические методы регистрации ЧР и ПЧР. Предлагается регистрировать разряды в электромагнитном частотном диапазоне.

Для оперативности выявления радиопомех антенны рекомендуется разместить на вагоне-лаборатории, а измерения совместить с действующей диагностикой высоковольтной изоляции, что позволит повысить достоверность полученных во время диагностики результатов. Для увеличения точности определения источника радиопомехи на вагоне-лаборатории рассматривается размещение двух антенн.

КЛЮЧЕВЫЕ СЛОВА: радиопомехи; высоковольтная диагностика изоляции контактной сети; поездная радиосвязь; частичные разряды; поверхностные частичные разряды

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INTRODUCTION

The intelligibility of speech in train radio operation is essential, so it is important to ensure that this critical form of dispatch communication remains up and running at all times. However, there are a number of factors that interfere with the smooth operation of the train radio communication. Such analysis is given, for example, in work [1].

One of the main causes of radio interference source are partial discharges (PD) and surface partial discharges (SPD) [2–4]. Attempts have already been made to localise the source of interference. Such a possibility has been considered in [5]. Earlier studies [6–10] have determined that diagnostics should be performed in the frequency range of 1 to 80 MHz. It is expedient to make the antenna with the necessary radiation pattern and necessary geometrical parameters at frequencies from 20 MHz, as the antenna receiving signals at frequency of 2 MHz, will have the sizes, considerably exceeding the dimensions of the car roof.

Although several methods have been developed to detect defective insulation [6–9], there is a problem of missing defective high-voltage insulators when performed by the existing diagnostic methods. The paper proposes to combine the most common optical method of diagnostics by means of an ultraviolet camera installed in a specialized laboratory car with PD and SPD registration by means of antennas, because PD and SPD are the primary electrophysical process determining technical condition of high-voltage insulation. Using two diagnostic techniques (optical and electromagnetic) will increase the reliability of faulty insulation detection, ultimately increasing the probability of detecting sources of interference.

A different solution to this problem is to use GSM-R (GSM Railway) standard, which has been specially developed for railways, in conjunction with equipment included in the European Train Control System, as in European countries, for example. DMR radio standard, which operates at 160 MHz, is also being intensively implemented. DMR, like GSM-R, is less susceptible to interference from electrical equipment than the 2 MHz RRS standard existing in most sections. Mass application of DMR, GSM-R, as well as LTE standards on the networks of “Russian Railways”, OJSC would significantly improve the quality of radio communication, reduce level of interference, but implementation is cost and time effective. At organisation of radio communication on standards GSM-R and DMR there are

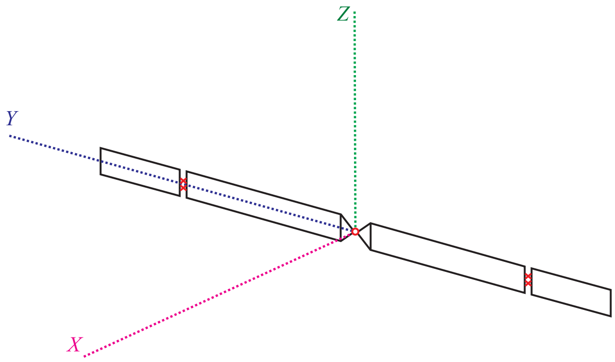


Fig. 1. Appearance of the traveling wave dipole

equipment failures [11, 12], for example, related to interference of waves, demanding equipment reloading.

At indisputable advantages of digital radio communication before analogue radio communication at the present time in operation on a network of "Russian Railways", OJSC there is a RRS working at frequencies of 2.13 and 2.15 MHz. In the following the issues of interference detection in this frequency range will be considered.

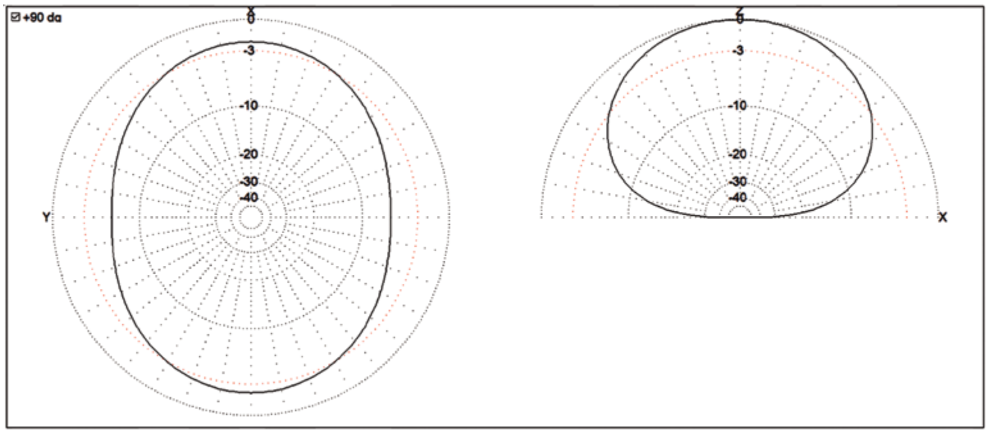
ANTENNA MODELLING

In order to automate and jointly conduct measurements in order to reduce operating costs for diagnostics, it is proposed to locate the recording equipment in the contact network, automation and communication control car. Radio interference caused by insulators and various fittings of the contact network is supposed to be recorded by a digital oscilloscope by means of antennas [5].

It is known that radio interference has an interfering effect on the operation of radio communications in a wide frequency range. Under the influence of such interference fall radio stations operating at frequencies 2.13 and 2.15 MHz. One of the main sources of radio interference are discharges (PD and SPD) arising in the high-voltage insulation of railway contact lines. Generally, PD and SPD are recorded between 1 and 100 MHz, so the antenna has to operate in this frequency range. Previously, a method [13] was proposed to carry out diagnostics by means of electromagnetic registration of signals that occur in the high-voltage line insulation of an AC contact network. This patent defines a method for recording such signals up to 80 MHz. This frequency range is the basis for the further choice of antenna.

As a prototype antenna, a traveling wave dipole designed with MMANA-GAL basic software [14, 15], which operates in the frequency range from 2 to 33 MHz, the appearance is shown in *Fig. 1*. In order to make calculations in MMANA-GAL basic easy, a typical variant was chosen from those proposed in this software product.

The radiation pattern and parameters of the selected travelling wave dipole are shown in *Fig. 2*. All data are shown for a frequency of 3.55 MHz. The choice of frequency is due to the proximity to the operating frequency of RRS — 2.13 and 2.15 MHz.



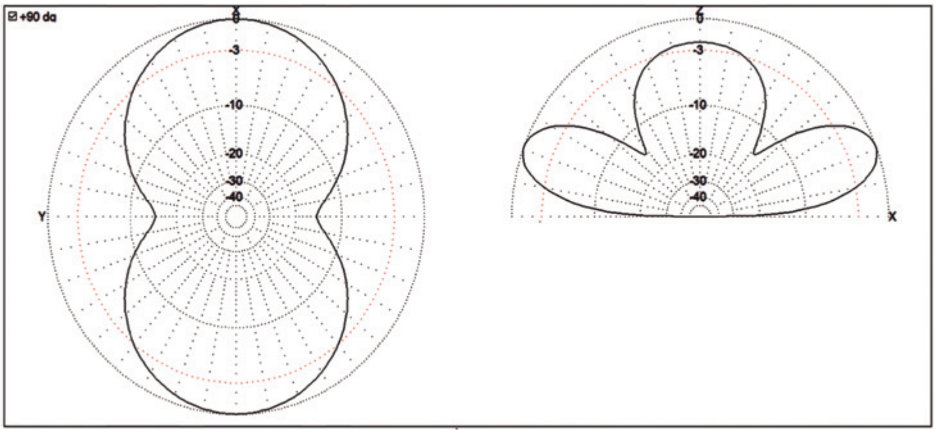
H-polarisation V-polarisation

Ga: 0.18 dBi = 0 dB (H-polarisation); F/B: −1.28 dB; rear azimuth 120 degrees, elevation 60 degrees;

F: 3.550 MHz; Z: 302.171+j161.581 Ohm; SWR: 1.7 (300 Ohm);

Elevation degree: 90.0 degrees (real ground height = 10.00 m); for zenith angle 45.0 degrees, gain = −1.9 dBi

Fig. 2. Radiation pattern and parameters of the traveling wave dipole



H-polarisation V-polarisation

Ga: 1.94 dBi = 0 dB (H-polarisation); F/B: 0.00 dB; rear azimuth 120 degrees, elevation 60 degrees;
F: 20.000 MHz; Z: 219.807-j64.736 Ohm; SWR: 1.5 (300 Ohm);
Elevation degree: 20.9 degrees (real ground height = 10.00 m)

Fig. 3. Antenna radiation pattern after scaling

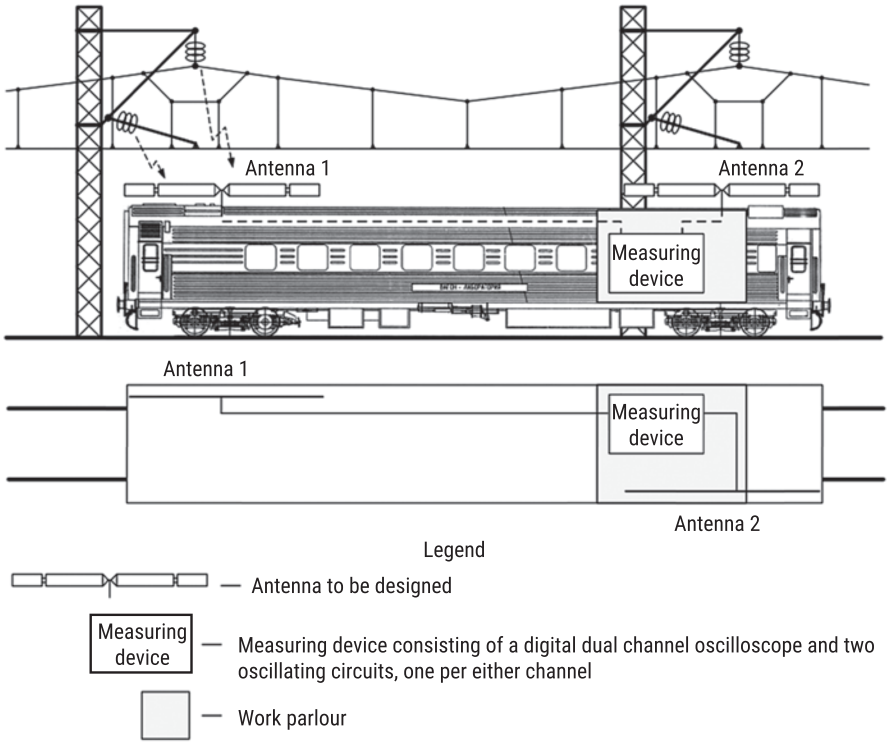


Fig. 4. The layout of the antennas on the roof of the laboratory car

The geometrical dimensions of the antenna (length 700 mm, width 320 mm) in the range from 3 to 33 MHz do not allow placing it on the roof of the laboratory car. It was noted earlier that PD and SPD are recorded in a wide frequency range, so we use the scaling function in the MMANA-GAL basic program, e.g. at 20 MHz. In this case it is necessary to enter a value of 20 MHz in the software, which results in a change in the radiation pattern and a reduction in the size of the antenna, maintaining the correct proportion between the an-

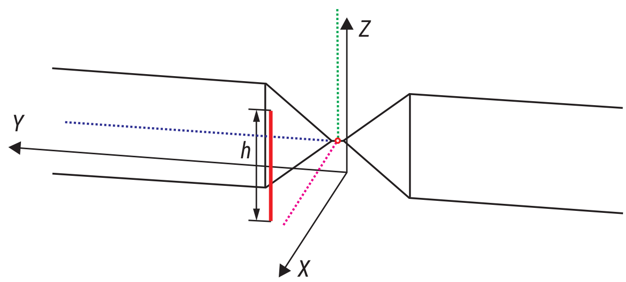
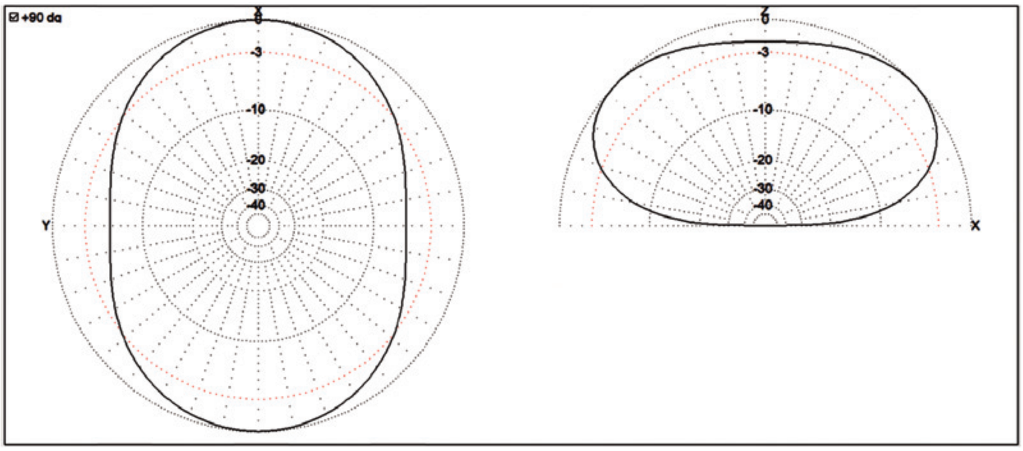


Fig. 5. Determining the antenna width



H-polarisation V-polarisation

Ga: 0.67 dBi = 0 dB (H-polarisation); F/B: 0.00 dB; rear azimuth 120 degrees, elevation 60 degrees;

F: 20.000 MHz; Z: 238.480-j88.112 Ohm; SWR: 1.5 (300 Ohm);

Elevation degree: 43.0 degrees (real ground height = 5 m)

Fig. 6. Antenna radiation pattern at a height of 5 m

tenna elements. *Fig. 3* shows the radiation pattern and parameters of the antenna at 20 MHz.

Next, the height of the antenna to be installed on the roof of the laboratory car must be determined (*Fig. 4*). To do this, set the height of the antenna location in the software.

The mounting height of the antenna should be taken from its width, which is determined by the *Z* coordinate, as shown in *Fig. 5*. The vibrator is located at the origin of the coordinates. The width h of the element highlighted in red is 320 mm.

The height of the antenna is the sum of the following values: height of the laboratory car — 4350 mm; half of the antenna width — 160 mm; height of the antenna installation — 500 mm, provided that the antenna elements do not touch the roof of the car. Total height of antenna location will be 5010 mm. For the calculations in MMANA-GAL basic a height of 5000 mm is assumed. The parameters and the radiation pattern of the antenna at a height of 5000 m are shown in *Fig. 6*.

ANALYSIS OF THE FINDINGS AND CONCLUSIONS

In order to finally determine the working frequency range of the antenna, a study of the standing wave ratio (SWR) in the frequency range from 20 to 70 MHz is required. Using MMANA-GAL basic software product, a plot of SWR versus operating frequency can be plotted (*Fig. 7*).

According to the graph, the SWR varies from 1.25 to 1.5 in the frequency range 20 to 32.5 MHz; from 1.5 to 2 in the frequency range 35 to 67 MHz. Above 67 MHz there is an increase in SWR above 2. From the above parameters, it follows that this antenna satisfies the optimum range of SWR, which is 1.05 to 2 only in the frequency range 20 to 67 MHz.

For further analysis of the antenna pattern variation in the investigated frequency range, it is necessary to study the shape of the radiation pattern in the frequency range from 20 to 70 MHz.

Since, according to the calculated data (*Fig. 8*), there is an increase in the antenna gain relative to the isotropic radiator Ga with increasing frequency, it can

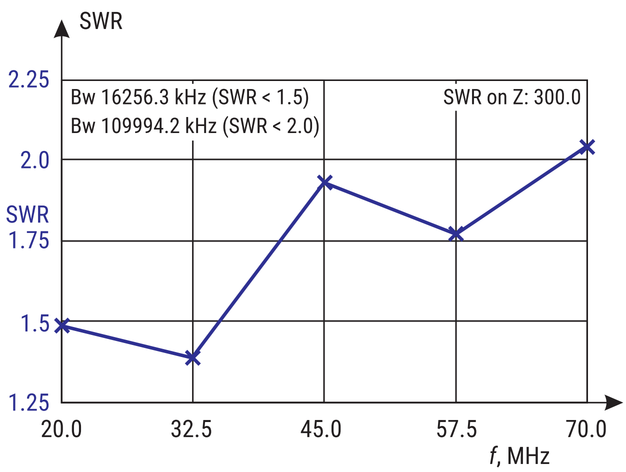


Fig. 7. Graph of the SWR dependence on the operating frequency

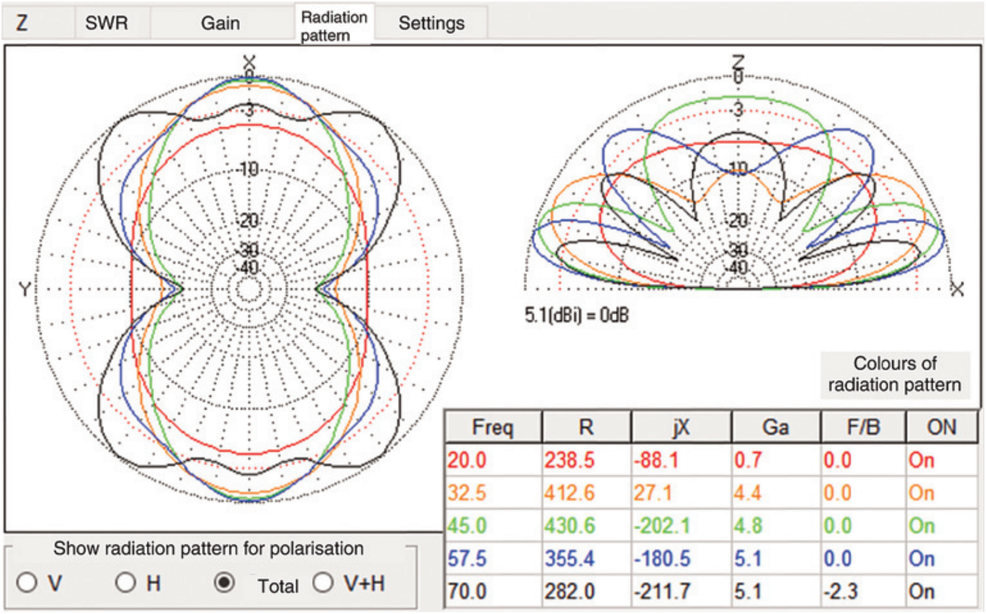


Fig. 8. Antenna radiation pattern in the frequency range from 20 to 70 MHz at a height of 5 m

be concluded that the antenna gain improves with increasing frequency.

CONCLUSION

The analysis of the plot of dependence of SWR on operating frequency (*Fig. 7*) and change of antenna gain Ga (*Fig. 8*) allow finally establishing the operating frequency range of the selected antenna — from 20 to 67 MHz.

In order to ensure precise location of the radio interference source it is necessary to place two antennas on the roof of the laboratory car (*Fig. 4*).

Having analysed the radiation patterns of the antennas in *Fig. 6* and *8*, it can be concluded that it is necessary to take it into account when installing the antenna directly on the roof of the laboratory car.

Increased accuracy of measurements is planned to be achieved after conducting additional studies of real sources of radio interference emission. Based on the results of the study, it is assumed that there is a need for additional modelling of antenna parameters, not excluded the correction of its type variant.

Practical application of the antenna will require consideration of the rigidity of the antenna mount and measurement scheme to protect personnel and equipment against induced voltages. In addition, consideration should be given to the referencing of the measurement results to the path coordinate for the location of the radiation source.

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Application of different types of motor-axle bearings of locomotive wheel-motor units in the Far North

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ABSTRACT Improvements in locomotive wheel-motor unit (WMU) design over the last decade have been made in terms of the transition to rolling motor-axle bearings (MAB) instead of plain bearings, which was the basis for the proposed study. The study is aimed to provide a theoretical estimation of power losses in different types of locomotive WMU MAB and its validation depending on heating temperature and bearing specifications. The study is aimed to determine power losses in MABs using new approaches to their determination.

New methods of determining the power losses in the plain and rolling MABs of locomotive WMUs are suggested.

These methods allow calculating the values of power losses depending on the specifications of MAB and its heating temperature. Depending on the bearing heating temperature, recommendations are provided with regard to operating conditions of a particular type of locomotive WMU bearing. It is recommended to operate motor-axle plain bearings in the temperature range of 10 to 20 °C, and rolling bearings from 20 °C and above.

The suggested methodologies for calculating power losses of locomotive WMU MABs can be used to determine the energy efficiency of a given drive type, taking into account the type of the grease, its temperature, design features and operating conditions. The obtained results can serve as recommendations for the selection of the type of MAB.

KEYWORDS: motor-axle bearing; axial oil; dynamic viscosity; friction coefficient; traction rolling stock; plain bearing; rolling bearing; power loss; and wheel-motor unit

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Научная статья

Применение различных типов моторно-осевых подшипников колесо-моторных блоков локомотивов в районах Крайнего Севера

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АННОТАЦИЯ Совершенствование конструкции колесо-моторного блока (КМБ) локомотива в последние десять лет осуществлялось в части перехода на моторно-осевые подшипники (МОП) качения вместо подшипников скольжения, что стало основанием для предлагаемого исследования. Цель исследования — теоретическая оценка уровня потерь мощности в различных типах МОП КМБ локомотивов и ее апробация в зависимости от температуры нагрева и технических характеристик подшипников. Задачи исследования — определение потерь мощности в МОП с использованием новых подходов к их установлению.

Предлагаются новые методики определения потерь мощности в МОП скольжения и качения КМБ локомотивов.

Данные методики позволяют рассчитывать величины потерь мощности в зависимости от технических характеристик МОП и его температуры нагрева. В зависимости от температуры нагрева подшипника приводятся рекомендации по условиям эксплуатации конкретного типа подшипника КМБ локомотива. Моторно-осевые подшипники скольжения рекомендуется эксплуатировать в диапазоне температур от 10 до 20 °C, подшипники качения от 20 °C и выше.

Предложенные методики расчета потерь мощности МОП КМБ локомотивов могут быть использованы для установления энергетической эффективности данного типа привода, принимая во внимание тип смазочного материала, его температуру, конструктивные особенности и условия его эксплуатации. Полученные результаты могут послужить рекомендациями по выбору типа МОП.

КЛЮЧЕВЫЕ СЛОВА: моторно-осевой подшипник; осевое масло; динамическая вязкость; коэффициент трения; тяговый подвижной состав; подшипник скольжения; подшипник качения; потери мощности; колесо-моторный блок

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INTRODUCTION

Improvements in wheel-motor unit (WMU) design in terms of motor-axle bearings (MAB) in the last ten years have been associated with a transition to rolling bearings [1]. Differences in design and operating principle between plain and rolling bearings place different demands on the lubricant used and the performance of the bearings[1].

Operation of locomotives in the Far North in winter in terms of high negative temperatures affects physical and chemical properties of the grease [2–5]. In this regard, the question of energy efficiency of different types of locomotive WMU MABs in the Far North regions of Russia is relevant.

The purpose of this paper is to provide a theoretical evaluation of power loss level in plain and rolling MABs of locomotive WMU and its validation depending on heating temperature and bearing specifications.

MATERIALS AND METHODS

Calculation methodology for power losses in plain MABs

The methodology for calculating power losses in plain MABs of locomotive WMU with axle-suspension was presented earlier [6]. The friction coefficient *f* in plain bearings changes with increasing speed according to a rather complex characteristic described by the Hersey-Stribeck diagram[2], shown in *Fig. 1* [7, 8].

The angular rates of transition from dry friction ω_{WS1} to semi-liquid friction and from semi-liquid friction to liquid friction ω_{WS2} can be determined from the following ratios [6, 9]

$$\omega_{WS1} = \frac{4}{3 \cdot 10^8} \frac{F_{r\,MAB}}{c \cdot \mu \cdot d_{MAB}^2 \cdot l_{MAB}}; \quad (1)$$

$$\omega_{WS2} = \frac{F_{r\,MAB}}{l_{MAB} \cdot d_{MAB}^3} \frac{\Delta^2}{\mu \cdot [S_0]}, \quad (2)$$

where $F_{r\,MAB}$ is radial load on the MAB, N; l_{MAB} is MAB insert length, m; d_{MAB} is diameter of MAB shaft journals, m; $[S_0]$ is dimensionless Sommerfeld number.

According to the works [6–8] in the dry friction range the coefficient of friction f_{0-1} may be taken as equal to 0.12.

In the area of liquid friction (section 2–3 in *Fig. 1*), in accordance with the works[3] [6] the friction coefficient f_L in plain MAB is

$$f_L = 3.7339 \frac{d_{MAB}^{0.731}\, l_{MAB}^{0.577}\, \mu^{0.577}}{\Delta^{0.154} F_{r\,MAB}^{0.577}}\, \omega_{WS}^{0.577}, \quad (3)$$

where Δ is diametrical clearance in the bearing.

[1] Anisimov I.G., Badyshtova K.M., Bnatov S.A. et al. Fuels, lubricants, technical liquids. Product range and application: Handbook. Moscow, Tekhinform, 1999;596. (In Russ.).

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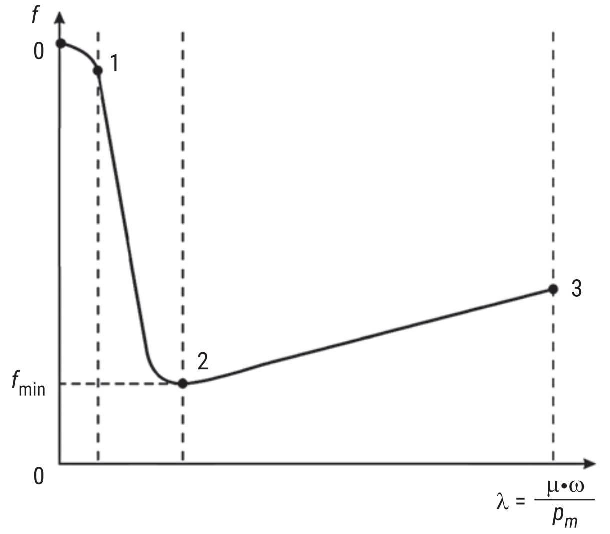

Fig. 1. Guersey – Striebeck diagram:
μ — dynamic viscosity of the grease (Pa · s); ω — angular speed of rotation of the shaft (in our case, the wheelset ω_{WS}, rad/s); p_m — average specific bearing load, Pa

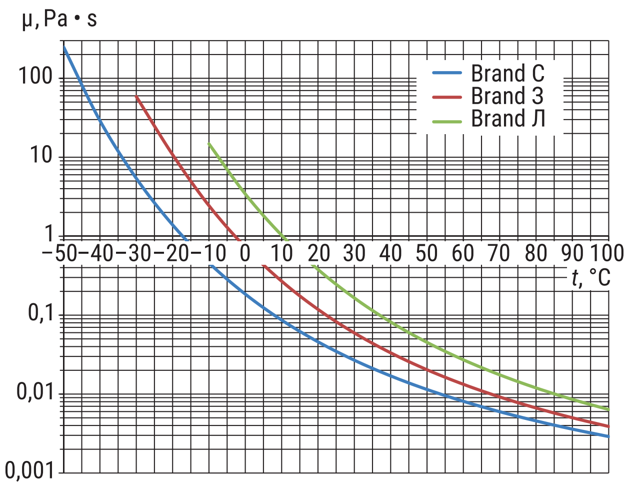

Fig. 2. The results of determining the dynamic viscosity of different brands of axial oils depending on temperature

In the area of semi-liquid friction, the friction coefficient f_{SL} is determined by

$$f_{SL} = \frac{f_1(\omega_{WS2} - \omega_{WS}) + f_2(\omega_{WS} - \omega_{WS1})}{\omega_{WS2} - \omega_{WS1}}. \quad (4)$$

The power loss capacity of the plain MAB is calculated according to the following relationship

$$\Delta P_{MAB} = F_{r\,MAB} d_{MAB} f \omega_{WS}. \quad (5)$$

As can be seen from the above dependencies, the friction coefficient and power loss capacity of the MAB is influenced by the dynamic oil viscosity μ and the diameter gap Δ.

The dynamic oil viscosity μ depends mainly on the type of oil used and its temperature. The main requirements for physical and chemical characteristics of the oil in plain MABs of locomotives are defined according to GOST 610-2017.

The dependence of the dynamic viscosity of these oils on the ambient temperature was determined analytically have been determined in the work[3], as shown in *Fig. 2*.

Calculation methodology for power losses in rolling MABs

Friction loss capacity of the rolling MABs is determined by

$$\Delta P_{MAB} = \sum_{i=1}^{2} \Delta M_{MAB\,i}\, \omega_{WS}, \quad (6)$$

where $\Delta M_{MAB\,i}$ is friction loss moment in one of the rolling bearings.

According to the publication[2], friction torque in the rolling bearing can be calculated according to the following relationship

$$\Delta M_{MAB} = \Delta M_{MAB0} + \Delta M_{MAB1}, \quad (7)$$

where ΔM_{MAB0} is friction loss torque depending on bearing type; ΔM_{MAB1} is friction loss torque depending on bearing load.

Considering the lubrication conditions, one of the dependencies is used at $\nu\omega_{WS} \geq 209$

$$\Delta M_{MAB0} = 10^{-7} f_0 \left(\nu \frac{30}{\pi}\right)^{2/3} D_{0MAB}^3 (\omega_{WS})^{2/3}; \quad (8)$$

at $\nu\omega_{WS} < 209$

$$\Delta M_{MAB0} = 160 \cdot 10^{-7} f_0 D_0^3, \quad (9)$$

where f_0 is coefficient depending on bearing type and lubrication conditions; ν is kinematic viscosity of the grease, mm²/s; D_0 is average bearing diameter.

In equations (8) and (9) the torque value is obtained in Nmm.

Spherical roller double row bearing 23048/W33 and radial single row bearing 20-7032148 are used as rolling MABs on locomotives[4] [2, 9, 10].

We will find the average diameter of the rolling MAB according to the equation

$$D_{0MAB} = \frac{1}{2}(d_{MAB} + D_{MAB}), \quad (10)$$

where d_{MAB} is bearing inner diameter; D_{MAB} is bearing outer diameter.

[4] 2TE25KM mainline freight double section diesel locomotive. Operation manual. Part 1. Technical description. MC BMBP, CJSC, 2015;153. (In Russ.).

Substituting the bearing dimensions into equation (10), we will obtain:

$$D_{0MAB} = 0{,}5 \cdot (240 + 360) = 300 \text{ mm}.$$

According to the paper[3], for a spherical roller double row angular contact bearing the coefficient f_0 is 4 to 6 and for a single row radial roller bearing the coefficient f_0 is 6 to 12.

Friction loss torque depending on bearing load ΔM_{MAB1}, is determined on the basis of the ratio[3]

$$\Delta M_{MAB1} = f_1(g_1 P) D_0, \qquad (11)$$

where f_1 is coefficient depending on bearing type and degree of loading; g_1 is coefficient depending on the ratio between the radial and axial loads borne by the bearing.

Coefficient f_1, included in the equation (11), according to the data[3] can be taken as equal to $f_1 = 0.0005$ for the rolling MABs used.

The coefficient depending on the ratio of the radial load to the axial load taken by the bearing is determined by the ratio

$$g_1 = P_1 F_r, \qquad (12)$$

where F_r is radial load on the bearing.

The radial load on the rolling MAB is taken as equal to the radial load on the plain MAB.

Consequently, the values of the torque components ΔM_{MAB1} on both supports will be equal and calculated according to the following relationship

$$\Delta M_{MAB1} = f_1 F_{r\,MAB} D_{0MAB}. \qquad (13)$$

Substituting these results into the equation (6), we will obtain the following relationship for determining power loss in a rolling MAB: at $\nu\omega_{WS} \geq 209$

$$\Delta P_{MAB} = = \left[\begin{matrix} 0.1 \left(f_0' + f_0'' \right) \left(\nu \dfrac{30}{\pi} \right) D_{0MAB}^3 \left(\omega_{WS} \right)^{2/3} + \\ + 2 f_1 F_{rMAB} D_{0MAB} \end{matrix} \right] \omega_{WS}, \qquad (14)$$

at $\nu\omega_{WS} < 209$

$$\Delta P_{MAB} = \left[\begin{matrix} 16 \left(f_0' + f_0'' \right) D_{0MAB}^3 + \\ + 2 f_1 F_{rMAB} D_{0MAB} \end{matrix} \right] \omega_{WS}. \qquad (15)$$

Given the design features of WMU with rolling bearings [10], the coefficients f_0' and f_0'' mean that their values are different for the bearing supports.

The characteristics presented (14), (15) show that the change in power loss capacity in a particular rolling MAB depends on the angular rotation speed of the wheelset ω_{WS} and kinematic viscosity of the mineral oil.

As an example, let's take LOCOLIT rolling bearing grease by "TITAN-SM", LLC. This type of grease is used in the range of operating temperatures from –50 to +150 °C.

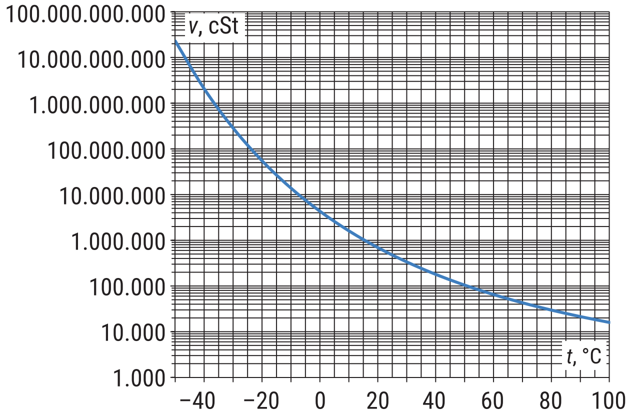

Fig. 3. Kinematic viscosity of LOCOLIT grease for rolling bearings as a function of temperature

The values of the kinematic viscosity at different temperatures are determined according to Walter's empirical formula [9]

$$\lg(\lg(\nu_t + c)) = a + b \lg(T); \qquad (16)$$

where ν_t is kinematic viscosity of the liquid at a given temperature, cSt; a, b, c are coefficients which are constant for a given liquid type; T is liquid temperature, °K.

Using dependence (16), kinematic viscosity values in the range of operating temperatures from –50 to +100 °C were determined (*Fig. 3*).

RESULTS OF THE STUDY

Calculation of power losses in different types of locomotive WMU MABs

WMU plain MABs used on diesel locomotives 2TE116, 2TE116U and 2TE25KM (with motor-axle plain bearings) have the following main dimensions:

- l_{MAB} — MAB insert working length — 0.262 m;
- d_{MAB} — shaft journal diameter — 0.215 m.

Given the unladen weight of the WMU of 5.8 t [11], the radial load per bearing can be taken as equal

$$F_{r\,MAB} = \frac{1}{2} \cdot 5.8 \cdot 10^3 \cdot 9.81 = 28\,450 \text{ H}.$$

Using dependencies (1)–(5) and the values of the dynamic viscosity μ of the axial oils according to GOST 610-2017, the results of the calculation of the power loss in plain MAB using C grade oil at –10; 0; 10; 20 °C and various values of the diameter clearance are proposed Δ.

Specifications of rolling bearings of locally produced WMUs used in TEM18DM, 2TE116U, 2TE25KM locomotives are presented above. Using dependencies (14) and (15), let's determine power losses in rolling MABs at different heating temperatures. Calculation results are given in *Fig. 8*.

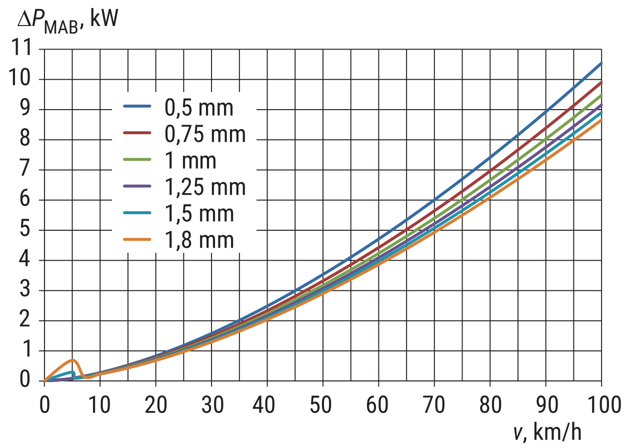

Fig. 4. Change in power loss in plain MAB at different values of diameter clearance and temperature −10 °C

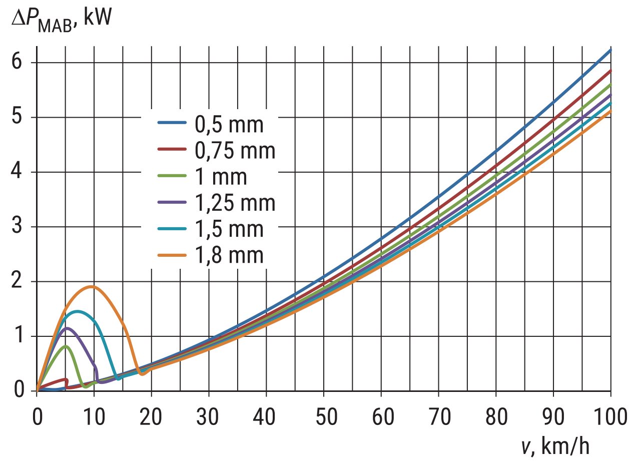

Fig. 5. Change in power loss in plain MAB at different values of diameter clearance and temperature of 0 °C

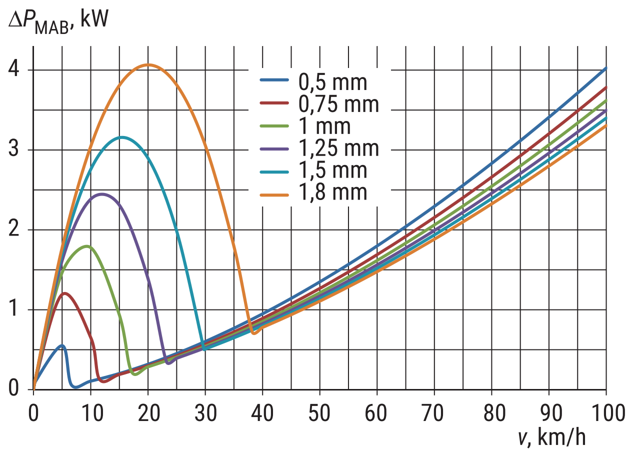

Fig. 6. Change in power loss in plain MAB at different values of diameter clearance and temperature of 10 °C

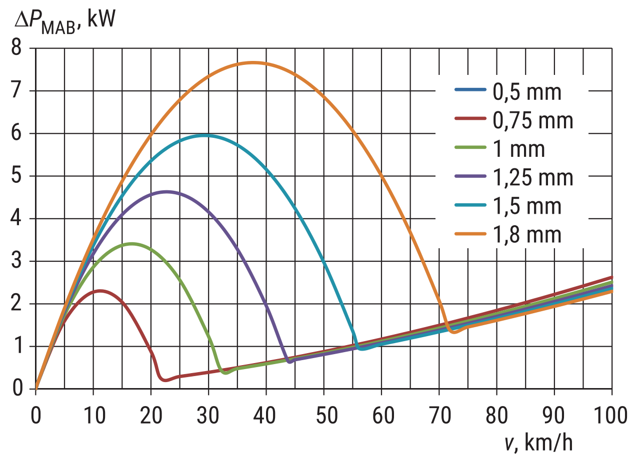

Fig. 7. Change in power loss in plain MAB at different values of diameter clearance and temperature of 20 °C

Power loss analysis of motor-axle bearings

Calculation results for plain MABs show that power losses vary widely, are increased at increase of sub-zero temperature and can reach 10–17 kW in the speed range of 75–90 km/h (*Fig. 4*). *Fig. 6*, *7* show power losses at heating temperatures 10; 20 °C, where stepwise increase of power losses in a range of speeds 0–70 km/h it is observed, thus the higher temperature of heating the wider range of speeds is. The calculation of the energy efficiency of plain bearings (*Fig. 4–7*) confirms the influence of the diameter clearance Δ and heating temperature on the power loss [12].

A determination of the power loss of a rolling MAB as a function of the heating temperature is shown in *Fig. 8*. In the speed range of 20 to 40 km/h, the losses are up to 20 kW at different temperatures. At a heating temperature of –10 °C after 40 km/h, the power loss is increased significantly.

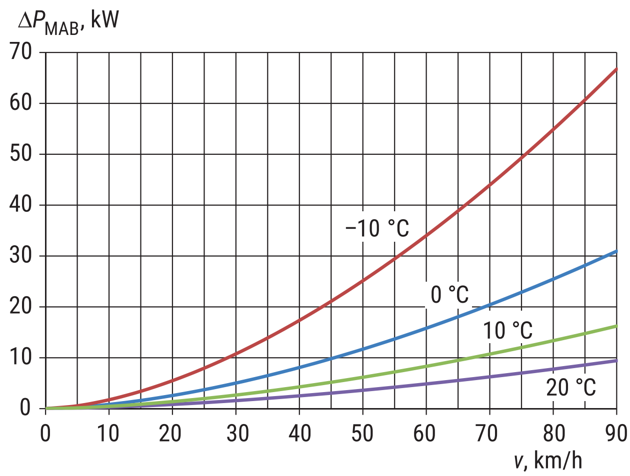

Fig. 8. Change in power loss in rolling MABs at different heating temperatures

CONCLUSION AND DISCUSSION

The following conclusions can be drawn from the above:

- The dependencies shown in *Fig. 4–7* allow concluding that the most effective operation of plain bearings must be carried out with the minimum diameter clearance permitted by the standard technical documentation and heating temperature range from 10 to 20 °C;
- An increase in the heating temperature of the plain bearing leads to a reduction of power loss in a wide speed range, as shown in *Fig. 4–7*;
- Calculation results for rolling MABs showed, that increasing heating temperature reduces power losses, thus operation of these bearings is most favourable at low speeds and positive heating temperature from 10 to 20 °C;
- The use of plain MABs improves the energy efficiency of WMU compared to rolling bearings when operating in the temperature range from 0 to 10 °C.

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This article is a prerequisite for further research into different types of WMU MABs in terms of their thermal balance issues.

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Particularities of the formation of the air masses structure in the tunnel during the train movement

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ABSTRACT The effect of aerodynamic factors on the rolling stock and railway infrastructure has been analysed. The formation of air mass structure in tunnel structures during the movement of high-speed rolling stock has been investigated. The processes of aeroelastic interaction of rolling stock with tunnel portal structures are analysed by means of numerical simulation. The description of mathematical models and the ways of their three-dimensional realization in the Solid Works Flow Simulation software complex are presented. Methods of finite elements and volumes for the solution of the set tasks are used. The results of the numerical research of velocity fields near the tunnel portal area obtained with the help of the developed mathematical models for the cases of entry and exit of the rolling-stock into the tunnel are given. The complex structure of air masses formation in the gap between the train body and tunnel lining which leads to increased resistance to the train movement in the tunnel is revealed. The patterns in the changes of pressure dynamics on the surface of the head fairing when the train enters the tunnel are found. The fact of negative effect of high and low pressure zones, as well as their abrupt difference, on the locomotive crew and passengers has been established.

KEYWORDS: aeroelastic interaction; rolling stock; boundary layer; turbulent regime; pressure; air mass velocity; and structure of disturbed air medium

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Научная статья

Особенности формирования структуры воздушных масс в тоннеле при движении поезда

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АННОТАЦИЯ Выполнен анализ влияния аэродинамических факторов на подвижной состав (ПС) и железнодорожную инфраструктуру. Проведено исследование формирования структуры воздушных масс в тоннельных сооружениях при движении высокоскоростного ПС. Проанализированы процессы аэроупругого взаимодействия ПС с портальными сооружениями тоннелей с помощью численного моделирования. Представлено описание математических моделей и способы их реализации в трехмерной постановке в программном комплексе SolidWorks Flow Simulation. Использованы методы конечных элементов и объемов для решения поставленных задач. Приведены результаты численных исследований полей скоростей вблизи портальной зоны тоннеля, полученные с помощью разработанных математических моделей для случаев входа ПС в тоннель и выхода из него. Выявлена сложная структура образования воздушных масс в зазоре между корпусом поезда и обделкой тоннеля, которая приводит к повышенному сопротивлению движения поезда в тоннеле. Обнаружены закономерности в изменении динамики давления на поверхности головного обтекателя при въезде поезда в тоннель. Установлен факт негативного влияния зон повышенного и пониженного давления, а также их резкий перепад на локомотивную бригаду и пассажиров.

КЛЮЧЕВЫЕ СЛОВА: аэроупругое взаимодействие; подвижной состав; пограничный слой; турбулентный режим; давление; скорость воздушных масс; структура возмущенной воздушной среды

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INTRODUCTION

The trend in rail transport is to increase the speed of the rolling stock. The speed of freight and passenger delivery plays the most important role in today's dynamic world. Increasing train speeds lead to a number of problems.

One such problem that engineers have to address is analysing the impact of aerodynamic processes on rolling stock and railway infrastructure. Complex aerodynamic processes and the movement of large volumes of air masses can have a major impact on the safety and efficiency of transport. This problem is particularly significant when high-speed rolling stock passes through tunnels.

The formation of air masses during the movement of a train in a tunnel is very complex. There are local zones of increased and decreased pressure in the front and tail parts of the train, accelerated air flows directed towards the train, and also local zones of compression and dilation in the portal part of the tunnel at the train's entrance [1, 2].

The physical processes accompanying aeroelastic interaction of moving rolling stock and tunnel structures can be considered in detail by numerical simulation.

MATERIALS AND METHODS

When trains move through a tunnel there is a significant air pressure drop in the front and tail section of the train. The pressure drop in the tunnel depends on many factors such as train speed, air viscosity kinematics, cross-sectional area, the shape of the front of the train and the shape features of the tail section [3, 4].

Numerical simulation of the train movement process in a tunnel confirms the wave nature of air mass movement [5]. On road sections where tunnels are encountered on the track, the moving train causes accelerated compression of the air medium, which leads to the formation of a compression zone in front of the train's fairing. Due to the viscosity of the air, there is a rarefaction zone immediately outside this compression zone around the train. This rarefaction zone is formed in the space between the train and the tunnel. Such phenomena have an impact on train safety and therefore must be taken into account in the design and operation of railway lines, tunnel design, and in the design of ventilation and air conditioning systems inside tunnels. The results are presented as calculation diagrams made in SolidWorks Flow Simulation software package using finite element and volume methods [6].

RESULTS OF THE STUDIES

Stable high-density vortex formations create the main mechanical resistance to train movement. The structure of the air medium in the train-tunnel gap is a system of multidirectional, interacting air medium flows with layer-by-layer distribution. The thickness of air medium layers depends on the surface profile of the train body, flow velocity, viscosity of the fluid medium. At high density sections the trajectories of air masses moved by the train take spiral shape [7].

Air flow distributions when a train moves in a tunnel at a speed of 200 km/h are shown in the *Fig. 1*.

The cross-sectional diagram in red shows the velocity flows of differently directed air masses, with them in the immediate vicinity of the train, and in the upper part and troughs in the opposite direction (see *Fig. 2*, *3*).

Particular attention must be paid to the boundary layer. In the boundary layer there is a transition from laminar to turbulent air masses. The transition point is at some distance from the surface edge, with the higher the velocity, the closer to the leading edge this point is [8].

The frictional force of the flow on the hull surface in turbulent mode is several times greater than in laminar mode and is proportional to the velocity gradient of the viscous medium [9].

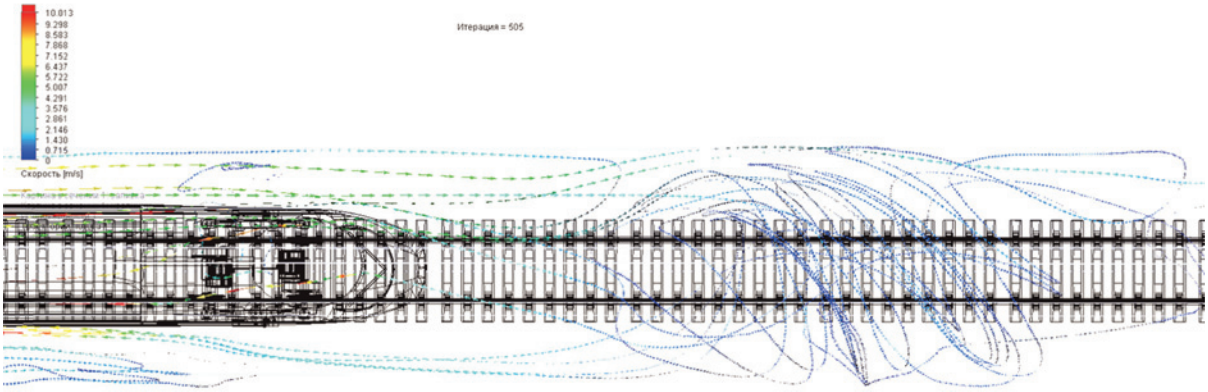

Fig. 1. The trajectory of the movement of air masses in the process of formation of the piston effect (the tunnel is not shown for clarity)

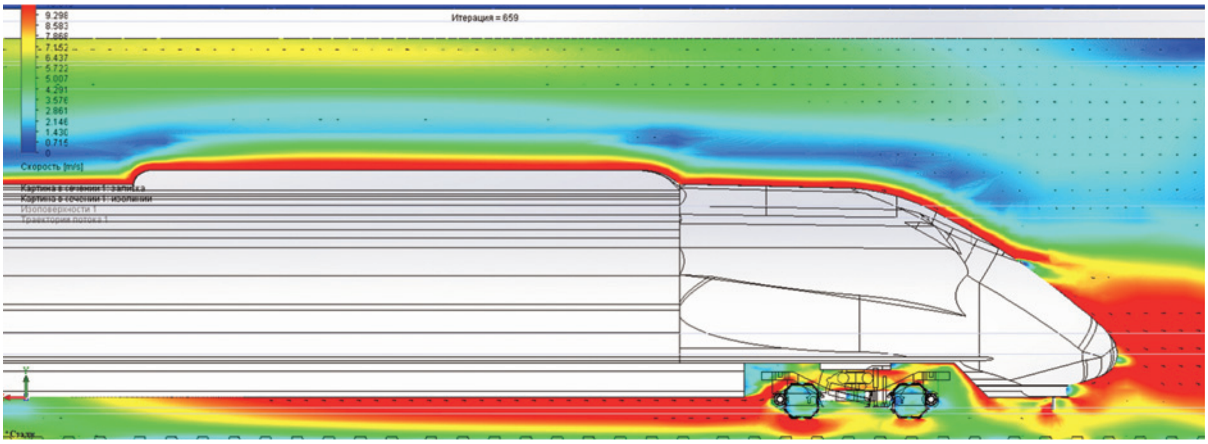

Fig. 2. Diagram of the distribution of air flow velocities near the mobile station moving in the tunnel

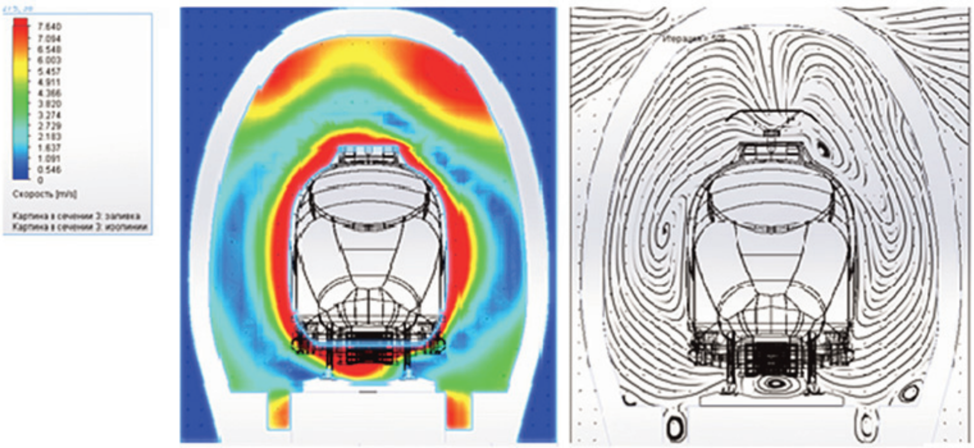

Fig. 3. Formation of the rotational movement of air masses located in the "train-tunnel" gap and the scheme for the formation of a vortex structure

The complex surface configuration of the rolling stock hull slows the airflow at certain points. This contributes to the detachment of the boundary layer and disruption of the flow, which contributes to the formation of a rotating vortex.

Disruptive vortices form periodically, with their centroids tending to gradually shift towards the tail of the train, followed by their collapse (see *Fig. 4*).

For the same reason, a stall vortex is formed at the tail end of the train, which creates destabilising

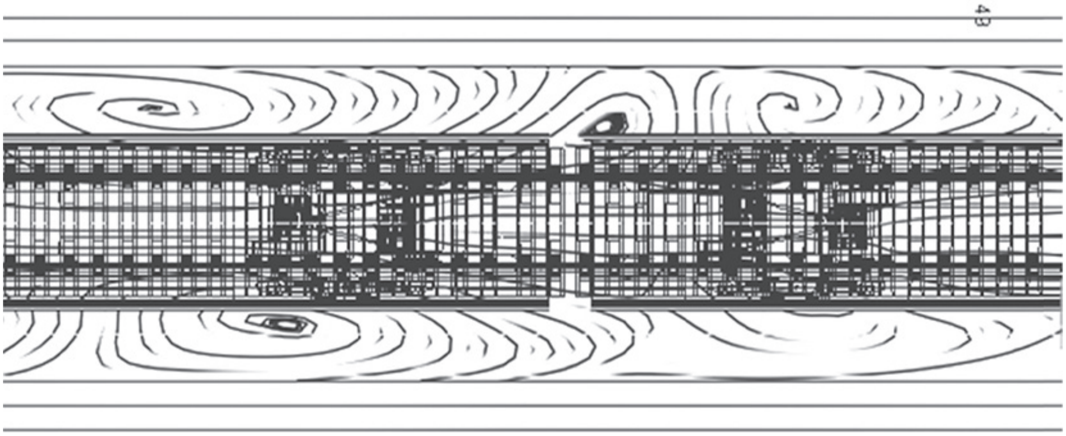

Fig. 4. Periodic formation of stall vortices on the side surfaces of the rolling stock

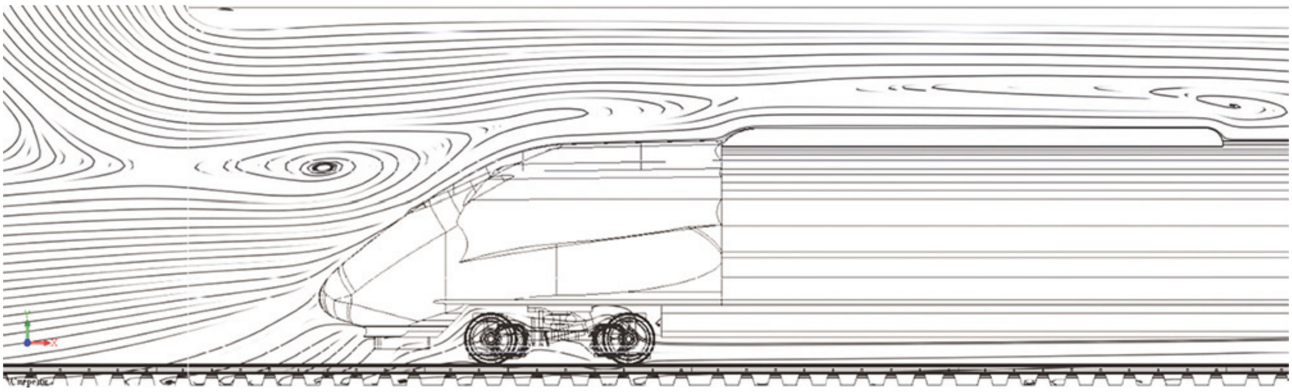

Fig. 5. Formation of a stall vortex in the tail section of the train

conditions for the train's movement (jolting, unstable behaviour). For rail transport, this problem only became relevant once certain speed regimes were reached, especially in tunnel traffic conditions (see *Fig. 5*) [10, 11].

It should also be noted that during the movement of a train in a tunnel, the nature of the structure of the disturbed air medium varies periodically depending on the position of the contours of the rolling stock surfaces and the tunnel lining. The most characteristic are combinations of decreasing cross section in the direction of movement (confusor), and increasing (diffusor).

In such sections, turbulent flow conditions are formed in the clearance between the train and the tunnel. Rotating eddies block the free flow of air masses in this gap and provide additional resistance to train movement, and therefore lead to an increase in traction energy costs for the train. This is particularly evident when the train exits the tunnel due to the interaction of air masses coming from the environment into the rarefaction zone behind the tail end of the rolling stock. This results in a powerful vortex flow towards the train, increasing the aerodynamic drag [12, 13].

CONCLUSION

Thus, the formation of both compacted and rarefied regions of air masses in the vicinity of train fairings creates conditions of increased resistance to train movement. The elastic interaction of the vortex structures discussed above increases the equivalent aerodynamic resistance to train movement in cramped tunnel conditions.

The phenomena described above have a negative impact on the traction energy consumption of the train as they significantly increase the drag and in addition cause significant discomfort to passengers.

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Multimodal transport system challenges & prospects in Ethiopia

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ABSTRACT The article examines the importance of transport for the Federal Democratic Republic of Ethiopia, and also characterizes the existing state of the main types of land transport: road and rail. The article defines the territorial location of the industrial parks of Ethiopia, on the basis of which possible directions of multimodal transport corridors, existing, under construction and promising railway and road transport facilities are assigned. The external and internal factors influencing the formation of variants of the multimodal transport network scheme based on the methodology of designing the integrated development of a multimodal transport network are determined. This will be used to develop the scheme of the multimodal transport network of Ethiopia. The scheme will become the basis for the formation of a variety of possible strategies for gradually changing the appearance and capacity of multimodal transport network facilities and calculating options for the required freight and passenger flows along multimodal transport corridors.

KEYWORDS: Federal Democratic Republic of Ethiopia; transport network; multimodal transport corridors; scheme of the multimodal transport network of Ethiopia

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Научная статья

Проблемы и перспективы мультимодальной транспортной системы в Эфиопии

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АННОТАЦИЯ Рассматривается значение транспорта для Федеративной Демократической Республики Эфиопия, характеризуется существующее состояние основных видов наземного транспорта: автомобильного и железнодорожного. Определено территориальное расположение индустриальных парков Эфиопии, на основании которого назначаются возможные направления мультимодальных транспортных коридоров, имеющиеся, строящиеся и перспективные объекты железнодорожного и автомобильного транспорта. Приведены внешние и внутренние факторы, влияющие на формирование вариантов схемы мультимодальной транспортной сети на основе методологии проектирования комплексного развития транспортной сети. Данные исследования могут быть использованы для разработки схемы мультимодальной транспортной сети Эфиопии. Схема станет базой для формирования множества возможных стратегий постепенного изменения внешнего вида и пропускной способности объектов мультимодальной транспортной сети и расчета вариантов требуемых грузовых и пассажирских потоков по мультимодальным транспортным коридорам Эфиопии.

КЛЮЧЕВЫЕ СЛОВА: Федеративная Демократическая Республика Эфиопия; транспортная сеть; мультимодальные транспортные коридоры; схема мультимодальной транспортной сети Эфиопии

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INTRODUCTION

Transportation is a system comprising infrastructure, administration, motorized and non-motorized vehicles, trains, ships, aircraft and users. Analysis of the transportation system can take its engineering, economics or societal issues.

In Ethiopia, transportation is one of the most essential sectors with its extended impact in the habitants' day to day life as well as trade activities and tourism. More than 100 million people resides in Ethiopia, and they have the need for mobility in their day-to-day life such as commuting to and from work, school and other social interactions.

The country is among the fast-growing developing countries in Africa having defined targets to achieve in the coming 10 years. To date, 13 Industrial parks have been constructed and are operational in different regions of the country [1, 2]. These industrial parks give priority for the production of textile and apparel, leather &leather products, pharmaceuticals, Agro-processing, tourism, ICT and Mining & Energy. These industrial parks are substantial source of foreign currency for the government; furthermore, their contribution in job creation for the youth both in their construction stage and operation stage is significant. Therefore, the timely transportation of raw materials to these industrial parks and timely delivery of final products plays major role to the companies' profits.

Similarly, Ethiopia's economy is predominantly dependent on agriculture. Competent mode of transportation is mandatory for transporting these agricultural products both locally and internationally, particularly for agricultural products that are intended for exporting.

Being rich with historical assets that goes back more than 3000 years, Ethiopia is a major tourism destination. It is home to archaeological findings, historical monuments and natural resources to mention but a few. Hence, having efficient public and private means of transport will be a satisfaction to the tourists and this will increase the number of tourists coming to visit these destinations. In addition to the evident economic advantages, this is a guaranteed way of promoting the good picture of the country globally.

Ethiopia is a multi-cultured country with 11 regions and 2 chartered cities having more than 80 nations and nationalities. One of the main considerations for having strong social and economic integration between these regions is the existence of multi-modal transportation. Furthermore, Addis Ababa is not only the capital of Ethiopia, but also the capital of Africa. Different offices of the African Union, including its headquarter, is located in Addis Ababa.

The main land modes of transport in Ethiopia are road and rail [3–5].

Currently, toll roads on expressways are being adopted and construction of BRT (Bus Rapid Transit) is planned in the capital city, Addis Ababa.

MATERIALS AND METHODS

Ethiopia's road network has been improving each year. As of the end of fiscalyear 2017/18, Ethiopia had 120.171 kilometres (74.670 miles) of all-weather roads — about 32 % of the required road network in the country. In fiscal year 2017/18, the Government of Ethiopia (GOE) invested 33.9 billion Birr ($1.24 billion) in road construction. The Ethiopian Roads Authority plans to build an additional 10,000 kilometres of road at a cost of 41 billion Birr ($1.5 Billion) during the coming year. In the past fifteen years, the Government of Ethiopia has been vigorously engaged in new road construction as well as expansion of the existing road network through Ethiopia's Road Sector Development Programs (RSDP) (*Fig. 1*).

During the Growth Transformation plan (GTP) II period covering 2015/16 to 2019/20, the Government of Ethiopia anticipates a further expansion of the country's road network to 220.000 kilometres (136.701 miles). In the past, U.S. firms have bid on tenders for road design, construction and supervision services. However, most of them have not been price competitive. Ethiopia will continue to need construction vehicles (bulldozers, cranes, trucks, and forklifts), vehicle attachments, and mechanized and non-mechanized equipment to level and pour construction materials. Most projects open for international competitive bidding are funded either by the Government of Ethiopia (GOE) or major international financial institutions, such as the World Bank's International Development Association (IDA) and the African Development Bank (AFDB). In the coming years, international and domestic private investors can engage in the Ethiopian road construction projects (*Table*).

Ethiopia is aggressively working on building an extensive rail network. As a landlocked country, Ethiopia primarily uses the port of Djibouti as a gateway for the vast majority of its internationally traded goods (90 to 95 %), with most of the goods essentially transported to and from the port by trucks. This situation has made Ethiopia's trade logistics very expensive and uncompetitive. Ethiopia's reopening of diplomatic relations with Eritrea creates the potential for expanded logistics operations via the Eritrean ports of Assab and Massaewa. The government has plan to connect Assab (Massaew) (by the railway line Metema – Wereta – Weldia – Assab) to Sudan via Weldia (Which is connected by the railway line from Awash – Kombolcha – Mekele railway line). In addition, the project visibility has been studied to Kenay by connecting with

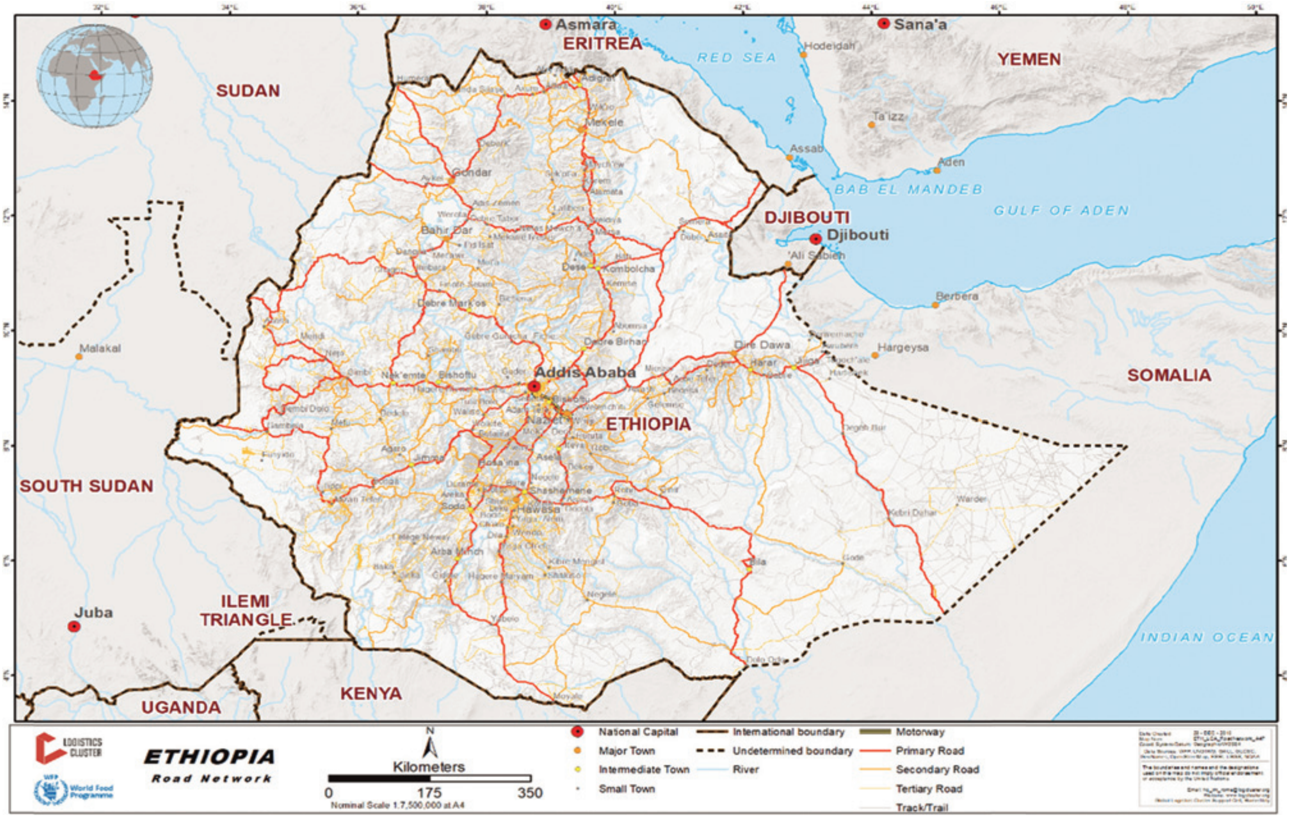

Fig. 1. Map showing Ethiopia road network

one of the most important railway line Mojo – Moyale (about 900 km) (*Fig. 2*).

The Government of Ethiopia (GOE) established the Ethiopian Railways Corporation (ERC) under the Ministry of Transport with a mandate to create a modern nationwide railway network, replacing the Franco-Ethiopian railway that is no longer in service. ERC recently completed a 656 kilometres railway network construction project that links the capital city Addis Ababa to the port of Djibouti. This railway expansion project was carried out by two Chinese companies, State-owned China Railway Group and the China Civil Engineering Construction Corporation. The new rail system started commercial operation in mid-2018. The two Chinese companies will operate and manage the $3.4 billion railway line for the next six years as local employees are trained to takeover in due course.

The other new completed railway line is Awash-Kombolcha-Hara Gebeya Railway Project, which has a length of 392 km, initiating from north east of the city of Awash and arrive to Hara Gebeya (Weldia) through the city of Kombolcha.

Table

Length of New Highways in Ethiopia by Type of Construction Financing

Road Network	Unit: Kilometers			
	2016	2017	2018 (Estimated)	2019 (Estimated)
Total Market Size	113.066	120.171	138.000	150.000
Total Local Production*	60.000	65.000	70.000	75.000
Total Exports		–		
Total Imports**	53.066	55.171	68.000	65.000
Imports from the U.S.***			2.000	4.000

Source: National Bank of Ethiopia
* indicates length of road projects carried out by local contractors.
** indicates length of road projects carried out by foreign companies.
*** indicates estimated length of road projects that can be constructed by U.S. companies Source: National Bank of Ethiopia

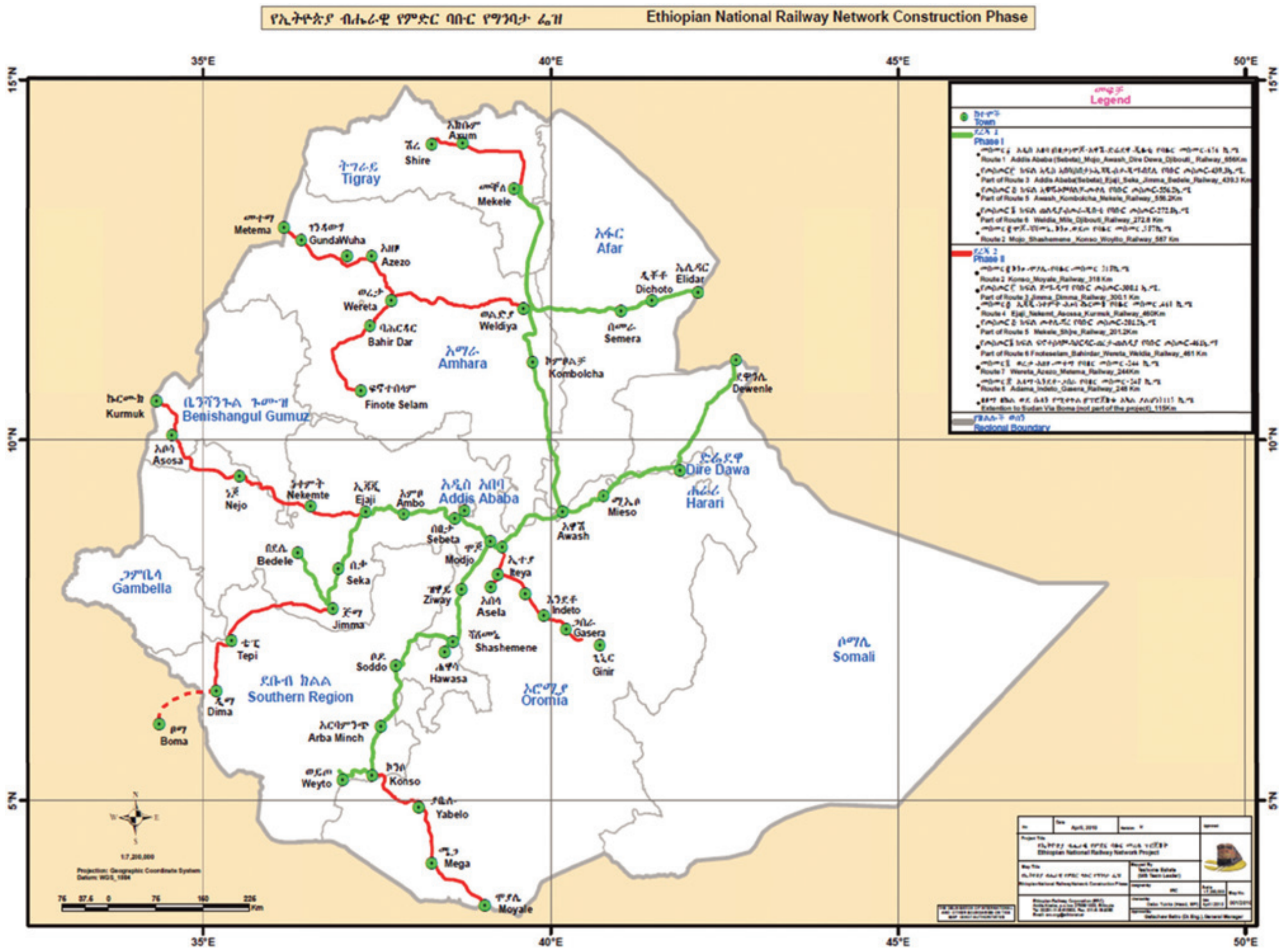

Fig. 2. Map showing Ethiopia railway network

The Awash-Kombolcha-Hara Gebaya (AKH) Railway Project has a significant importance as it connects the northern and eastern economic and traffic corridor of Ethiopia. The railway that has been building will connect the railway lines from Mekele to Hara Gebeya and then Addis to Djibouti, which is the main transport corridor for both passenger and freight traffic, and for transport of imported and exported goods via Djibouti Port. Furthermore, the construction of this railway will play an active and significant role in connecting the northern region of the country with the central part.

The Awash-Kombolcha-Hara Gebaya Railway Project which has a 1,7 Billion USD (is being funded by the Turkish EX-IM bank and the Swiss Credit Consortium in addition to direct government spending).

This infrastructure project will significantly improve Ethiopia's international trade by reducing traders' logistical costs and time of delivery. The new electric railway cuts transport time from Djibouti to Modjo (a dry port city 70 kilo meters away from Addis Ababa) from the current 84 hours to just 10 hours. Cargo capacity on the rail network is 3500 to 4000 tons of freight per train, with ERC anticipating 6 to 7 million tons of cargo per year in its first year of operation. Cargo volume will increase to 10 million tons in the mid-term.

It is internationally recognized that the Ethiopian economy is among the fastest growing economy of the globe. Transport sector is therefore one of the sub service Contributor of this Economic growth.

RESULTS AND DISCUSSION

There are problems for the formation of the multimodal transport system. They include:

- lack of physical facilities (IT infrastructure especially in the private sector);
- poor coordination among the sectoral agencies;
- reliance on paper documents, fax, and emails in the exchange of official information between government agencies and the private sector;
- lack fully fledged cargo tracking along the logistics supply chain;
- less capable of operators;

- there are close to 7.000 trucks operating on the corridor to Djibouti. Ownership of the trucking fleet is in the hands of operators of individual trucks, road transport companies, and associations of individual truck owners.

There are potential prospects for the development of the logistics industry. They include: government policy, Modjo logistics Hub (MLH) Project, the customs management system, electronic single window and other initiatives [6–8].

By the government of Ethiopia, it is well perceived that, the logistics industry is a critical element for the Ethiopian economy. Accordingly, the major strategic directions of the government are mainly building the capacity of the dry ports and enhancing Multimodal Transport system there by improving the logistics service.

The investments in infrastructure at Modjo Dry port support the facility to achieve three key objectives (as it is indicated in the WB document):

- to improve the efficiency of processing of current traffic flows;
- to increase the capacity of Modjo to process the projected increasing volumes of trade, including the interconnectivity between rail and road transportation;
- to facilitate the transformation of Modjo to become a logistics hub offering a wide range of logistics services to exports as well as imports and to support diversification into a wider range of higher value-added exported products.

Ethiopian Revenue and Customs Authority is now engaged its self to migrate from Assycuda++ system to the new and the state of the art Customs Atomization that can Manage:

- air Cargo E-freight including Advance Passengers Information (API);
- electronic submission of documents;
- e-payment and other paperless operations.

This Customs Atomization is emplacing based on the Kyoto Convention General Annex Guide lines.

In order to interface all stakeholders in single platform an ESW project is undertaking. Accordingly, a business process analysis and re-engineering to streamline stakeholders' processes and integrate into a common electronic Single Window platform is already Accomplished.

The other projects that enhance the logistics bottlenecks in general and the multimodal includes, among other things

- cargo tracking System;
- cargo scanning Machine at every entry point;
- OSBP with neighboring countries to avoid a duplication of efforts at borders and to harmonize and simplifying the customs practices.

CONCLUSION

The article considers the importance of transport for the Federal Democratic Republic of Ethiopia, and also identifies factors influencing the formation of variants of the multimodal transport network scheme based on the methodology of designing the integrated development of a multimodal transport network. This will be used to develop the scheme of the multimodal transport network of Ethiopia [9–11]. The scheme will become the basis for the formation of a variety of possible strategies for gradually changing the appearance and capacity of multimodal transport network facilities and calculating options for the required freight and passenger flows along the multimodal transport corridors of Ethiopia.

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