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Prospects of autonomous railway transport development

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ABSTRACT The implementation of unmanned train control systems offers a number of advantages, such as increasing the capacity of railway lines and traffic volumes, reducing the 'human factor', as well as reducing operating costs. The paper considers the challenges arising from the use of automatic train control systems, and presents the prospects for the implementation of automatic technologies in railway transport for various railway systems. The social and economic aspects of changing professional activities in railway transport are described. Grades of automation applicable to surface urban railway transport are presented. The issues of proving the functional safety of machine vision systems as part of the train traffic control system and determining their level of safety completeness are discussed. Examples of railway transport automation in Russia and other countries are given. Basic scenarios of automatic control system operation describing normal and abnormal situations are formulated. In conclusion, the levels of technological readiness of the reviewed solutions in the field of train traffic automation are defined. The tasks faced by railway companies in implementing these technologies are outlined, and possible ways of overcoming obstacles to the introduction of automatic systems are proposed, taking into account the current political situation.

KEYWORDS: autonomous transport; grades of automation; automatic train control system; machine vision; artificial intelligence (AI); machine learning; datasets; functional safety; safety integrity level (SIL)

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Научная статья

Перспективы развития беспилотного железнодорожного транспорта

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АННОТАЦИЯ Внедрение систем беспилотного управления поездами предоставляет ряд преимуществ, таких как повышение пропускной способности железнодорожных линий и объемов перевозок, снижение «человеческого фактора», а также сокращение эксплуатационных затрат. В статье рассмотрены вызовы, возникающие при использовании систем автоматического упраавления движением поездов, представлены перспективы реализации автоматических технологий на железнодорожном транспорте для различных железнодорожных систем. Описаны социоэкономические аспекты изменения профессиональной деятельности в сфере железнодорожного транспорта. Представлены уровни автоматизации, применимые к наземному городскому железнодорожному транспорту. Рассмотрены вопросы доказательства функциональной безопасности системы технического зрения в составе системы управления движением поездов и определения их уровня полноты безопасности. Приведены примеры автоматизации железнодорожного транспорта в России и странах мира. Сформулированы базовые сценарии работы системы автоматического управления, описывающие штатные и нештатные ситуации. В заключении определены уровни технологической готовности рассмотренных решений в области автоматизации движения поездов. Указаны задачи, стоящие перед железнодорожными компаниями при реализации таких технологий, а также предложены возможные способы преодоления препятствий на пути внедрения автоматических систем с учетом текущей политической обстановки.

КЛЮЧЕВЫЕ СЛОВА: беспилотный транспорт; уровни автоматизации; система управления движением поездов; система технического зрения; искусственный интеллект (ИИ); машинное обучение; датасеты; функциональная безопасность; уровень полноты безопасности (SIL)

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INTRODUCTION

The rapid development of digital technologies, such as artificial intelligence, computer vision, and broadband radio communications, is contributing to the active introduction of elements of unmanned control systems in railway transport. The interest in these systems is motivated not only by the general trend towards digitalisation, but also by social and economic factors related to the growth of urban agglomerations and the changing structure of the professional orientation of society, resulting in a reduction in the number of qualified personnel available on the market in a number of basic railway industry occupations, including train driver.

In many countries of the world, including the BRICS countries, railway companies are already feeling the effects of labour market changes in the form of a shortage of qualified basic engineering staff, and this trend is likely to increase. The transfer of most of the monotonous routine vehicle driving tasks to automatic control systems may be a part of the solution to this problem. The advantage of an automatic control system is not only a reduction in the number of personnel, but also an increase in throughput — a reduction in the interval between trains. In addition, there is a trend of increasing remuneration costs and reducing the cost and labour intensity of developing train automation systems. A good example of such a situation is the cost of a lidar (a laser scanner): over the last five or six years, its price has fallen more than ten times, while the technical characteristics have increased by two to three times.

GRADES OF AUTOMATION OF TRAIN MOVEMENT CONTROL

The IEC 26690:2014 standard describes general requirements for an automatic control system for surface urban railway transport. In 2022, the Research Institute of Informatisation, Automation and Communications in Railway Transport (NIIAS JSC) developed a Russian analogue — the national standard GOST 70059[1], which describes the following grades of automation (GoAs) (*Fig. 1*):

GoA0: Fully manual control of the rolling stock. At this grade of automation, the driver performs all train control activities without the need for additional systems to control the train. Permissions to proceed, slow orders, and route determinations can be given by means of wayside signals, permanent railway traffic rules, or by personal or radioed verbal instructions.

GoA1: Manual control of the rolling stock. At this grade of automation, the driver in the locomotive cab monitors track vacancy and wayside signal aspects, controls the traction and braking systems, as well as the opening and closure of the doors. His actions are monitored by an on-board safety device installed on the train, which prevents him from exceeding the speed limit and passing a stop signal aspect.

GoA2: Semi-automatic train control, where the driver is responsible for activating the system, switching it to an ATO (automatic train operation) mode, checking for obstructions on the track, opening/closing doors and taking action in the event of abnormal situations. Traction and braking control, as well as supervision of compliance with speed limits, are done automatically.

GoA3: Train control without a driver. At this grade of automation, the driver is not in the train cab. All functions related to train control are performed by the automatic system. Since the driver is unable to monitor the vacancy of track sections, the occurrence of obstacles in the course of the train movement must either be unlikely enough to eliminate the need for a person in the cab, or be detected by additional technical means for monitoring the track. Automatic control of rolling stock without a driver requires the presence of a conductor on board. His or her duties may include ensuring the safe departure of the train from the platform, closing the doors, assisting passengers, and taking necessary actions in emergency situations.

[1] GOST R 70059-2022.

Grade of automation	Train operation	Setting train in motion	Driving and stopping the train	Door closure	Operation in event of disruption
GoA1	ATP with Driver	Driver	Driver	Driver	Driver
GoA2	ATP and ATO with Driver	Driver/ Automatic	Automatic	Driver	Driver
GoA3	Driverless	Automatic	Automatic	Attendant/ Automatic	Attendant
GoA4	Unattended	Automatic	Automatic	Automatic	Automatic

Fig. 1. Grades of automation of operating modes in railway transport

GoA4: Fully automatic rolling stock control. Fully automatic operation corresponds to the highest grade of automation 4. The train is controlled in a fully automatic mode without any personnel on board, so additional safety measures are required. Personnel are usually only involved during maintenance or in the event of abnormal events, e.g. a fire on the train. In this scenario, actions to neutralise abnormal situations are carried out with the participation of a driver-operator, dispatchers, and a rapid response team.

In terms of passenger safety, even at the fourth grade of automation, an automatic control system does not pose any additional threats to people inside an electric train. Automatic blocking systems and on-board safety devices, which have the maximum safety level and have been in use for many years, protect against collisions with other rolling stock.

Numerous comparative tests of obstacle detection systems using human dummies show that the developed machine vision system (ODS — an obstacle detection system) outperforms human drivers in terms of detection range and reaction time. This will reduce the likelihood of non-work related injuries in the future.

At the same time, the issue of selecting a methodology for proving the functional safety of the ODS as part of an on-board train control system (OTCS), including the determination of the safety integrity level (SIL) for such a system, is still open and requires additional research. It is obvious that the use of an artificial neural network (ANN), whose behaviour cannot be fully described or predicted, does not allow us to categorise an ODS as a system with a high level of functional safety SIL4.

Many experts propose to divide the OTCS into a safety part (safety kernel) represented by a locomotive safety device operating in a protected control loop, and a machine vision system that operates in a separate control loop (see *Fig. 2*) [1].

Functional safety refers to the ability of a safety related system to fulfil all of its designed safety functions under all specified conditions for a specified period of time while maintaining the residual risk of hazardous events at an acceptable level. Safety completeness is the level of satisfactory fulfilment by a safety-related system of the required safety functions under all specified conditions for a specified period of time. The higher the level of safety completeness of systems, the lower the probability of failure of these systems when they fulfil the required safety functions. In determining safety completeness, all causes of failures leading to an unsafe condition should be considered, e.g. hardware failures, failures caused by software, hardware failures, or operator errors.

Safety integrity level 1 (SIL1) is the lowest, but it requires the use of good development expertise. It can be achieved relatively easily if the requirements of quality standards are applied throughout the system development and production phases. IEC 61508-12 and other documents categorise SIL1 as 'non-safety related'.

The second level (SIL2) is not much more difficult to achieve than the previous one, but it requires a greater number of inspections and tests. This level requires that there is a good design and application practices correspond to the level required by ISO 9001. As a result, the cost of the system increases.

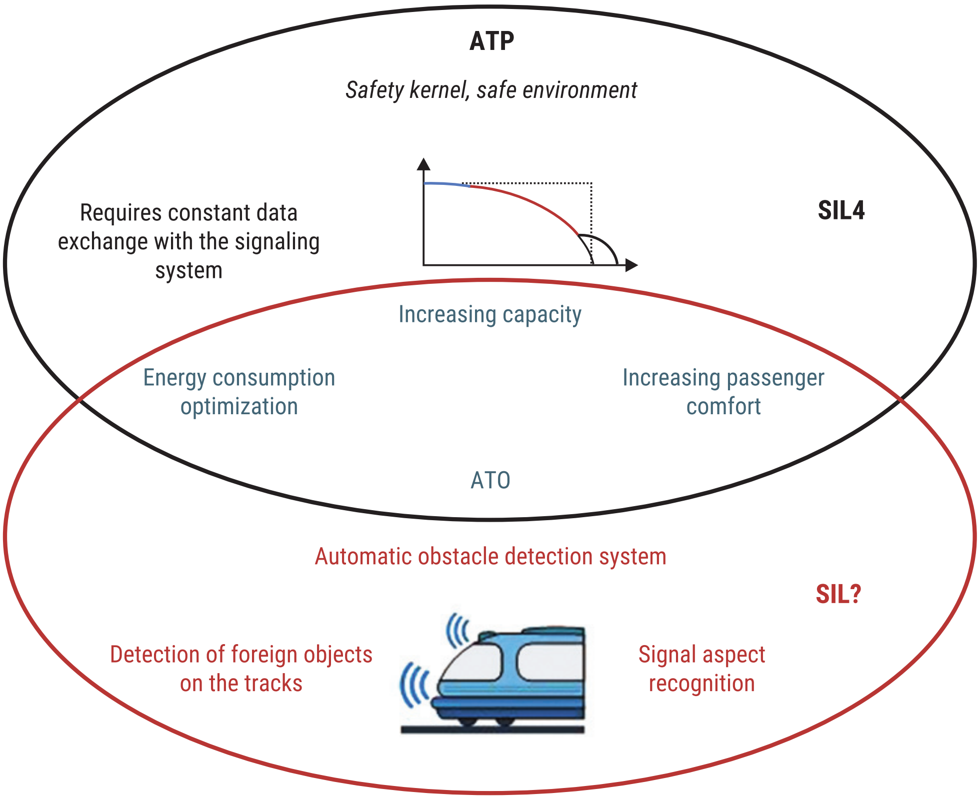

Fig. 2. Schematic diagram of a modern OTCS with intelligent control

Achieving Safety Integrity Level 3 (SIL3) requires greater effort and higher developer competence than for SIL1 and SIL2, along with the use of multi-channel hardware and multi-version software. The system cost and development time are important factors. In this case, the choice of implementers becomes limited, as few of them are able to provide this level.

Level 4 (SIL4) requires the most rigorous development, including the application of formal methods. The cost of the project will be extremely high and the system will require an extremely high level of expertise. In some cases, it is possible to avoid the use of SIL4 by adding more protection levels.

A dangerous failure is a rare event, and determining its probabilistic parameters by experimental methods will take much longer than the lifetime of the device under study. Mathematical modelling of the processes of occurrence of dangerous failures allows for accelerating the investigation of devices and control systems for compliance with safety requirements. To implement the modelling requires an appropriate mathematical description of the object of study — the process of occurrence of dangerous failures, which cannot be fully implemented in relation to a system that includes an ANN. When creating complex multilevel OTCS, it is necessary to develop a comprehensive approach to the rational use of analytical and experimental ways and methods of safety proof by combining heterogeneous information to obtain reliable estimations of proof of functional safety of such systems. For this purpose, it is advisable to combine the results of mathematical modelling with accelerated in-situ tests, results of expert examination of technical and design documentation, tests of simulation models of software and hardware, bench tests, and safety assessments based on statistical data on failures in use [2].

Functional safety requirements are preliminarily checked by developers for their realisability taking into account the available resources of a particular project and, if necessary, adjusted in terms of composition and values taking into account the risks. At the same time, an additional element performing the function of control and limitation can be introduced into the OTCS with the use of automatic obstacle detection. A remote driver-operator is most often considered as such an element for making decisions in case of data inconsistency in control loops, but other fully automatic variants are also being studied.

As an example, let us take the scheme of the OTCS implemented on the Moscow Central Circle (MCC). The MCC OTCS is implemented as a multi-loop control system with two control modes: ‘autonomous’ and remote (remote-controlled operation). In *Fig. 3*, the red dotted line highlights the subsystems that make up the safety loop of the GoA3/4 mode [3].

In addition to the traditional system of automatic train signalling based on coded track circuits, the MCC OTCS features radio-channel interaction between sta-

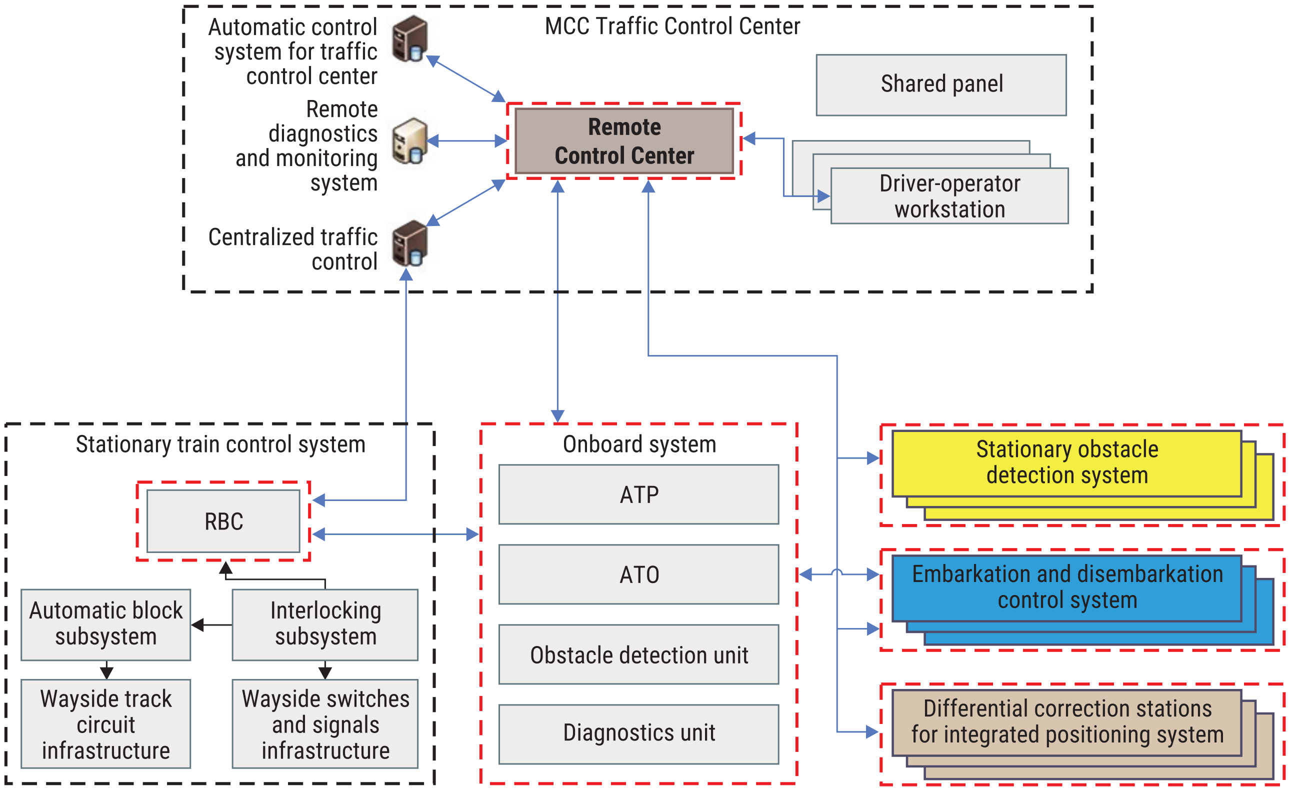

Fig. 3. General design of the MCC OTCS

tionary and on-board train traffic control systems, while a separate circuit solves the tasks of automatic obstacle detection by on-board and stationary visual inspection devices using artificial neural networks and transmitting relevant information to the Remote Monitoring and Control Centre.

REMOTE DRIVER'S ROLE

Automatic train control systems are designed so that if there is an obstacle on the railway track, such as a fallen tree, the train will automatically stop. Further actions after the train has stopped are already the responsibility of a human driver, who will decide whether it is necessary to dispatch a rapid response team or whether it is possible to proceed in remote control mode if the obstacle does not endanger the movement of the rolling stock.

The profession of a driver-operator is relatively new, but the development of digital technology and the increase in traffic volumes are opening wide prospects for it. Among the tasks of such a specialist are remote control of electric trains and remote control of a train in the event of an abnormal situation. The driver-operator must be able to process a large amount of information and take prompt action to resolve the situation. His workstation reflects data on the condition of trains and infrastructure, passenger boarding and disembarkation processes, and the occurrence of irregularities and deviations in the operation of systems of an electric train[2].

It is natural to consider the question of designing a workplace for such a specialist. The Locomotive Engineering Design Bureau of Russian Railways JSC, in cooperation with NIIAS JSC, is developing a driver-operator workplace included in the integrated technology of unmanned electric train traffic on the Moscow Central Circle [4]. It is assumed that in the future driver-operators will remotely control several trains on the railway network. And if now the tested technology and algorithm capabilities provide for one driver-operator for four trains, in the future, the number of trains under the control of a single driver-operator can be significantly increased. The task of monitoring a large amount of information involves a larger field of view, so the images from cameras of electric trains are displayed on a 49" widescreen monitor. The controls must be within arms' reach and be positioned identically to those in the cab of an operating electric train. Some controls, such as for changing the lighting or heating in the cab, will no longer be necessary, so the functionality of the driver's workstation should also be reviewed. It is also necessary to provide for the

[2] Driver-operator / RZD Digital. URL: https://rzddigital.ru/career/professions/mashinist-operator-/

possibility of quick switching between controlled electric trains. When developing the remote control and control panel for unmanned electric trains, the functional duties of the driver-operator and the experience of current driver-instructors who take part in the testing and generation of ergonomic requirements for the workplace are taken as a basis.

UNMANNED TRAIN OPERATING SCENARIOS

Analysing the actions of employees and the functioning of systems in regular and abnormal situations also provides the basis for defining scenarios for the operation of the automatic control system. Since the organisation of unmanned train traffic requires that its operation algorithms include a response to any possible situations, the specialists of NIIAS JSC and Russian Railways JSC developed and approved 39 scenarios [5]. All possible variants were thought out, actions of all systems and participants of the transportation process were prescribed and coordinated. Six scenarios describe normal operation of systems and include the departure and arrival of electric trains from/to coach yards and depots, following the route, passenger embarkation and disembarkation. The largest group of scenarios describes the operation of systems in abnormal situations (derailment of rolling stock, heating or destruction of axle units, an obstacle on the electric train's route, running over a person, etc.). 16 scenarios take into account the occurrence of various train or infrastructure faults (see *Fig. 4*).

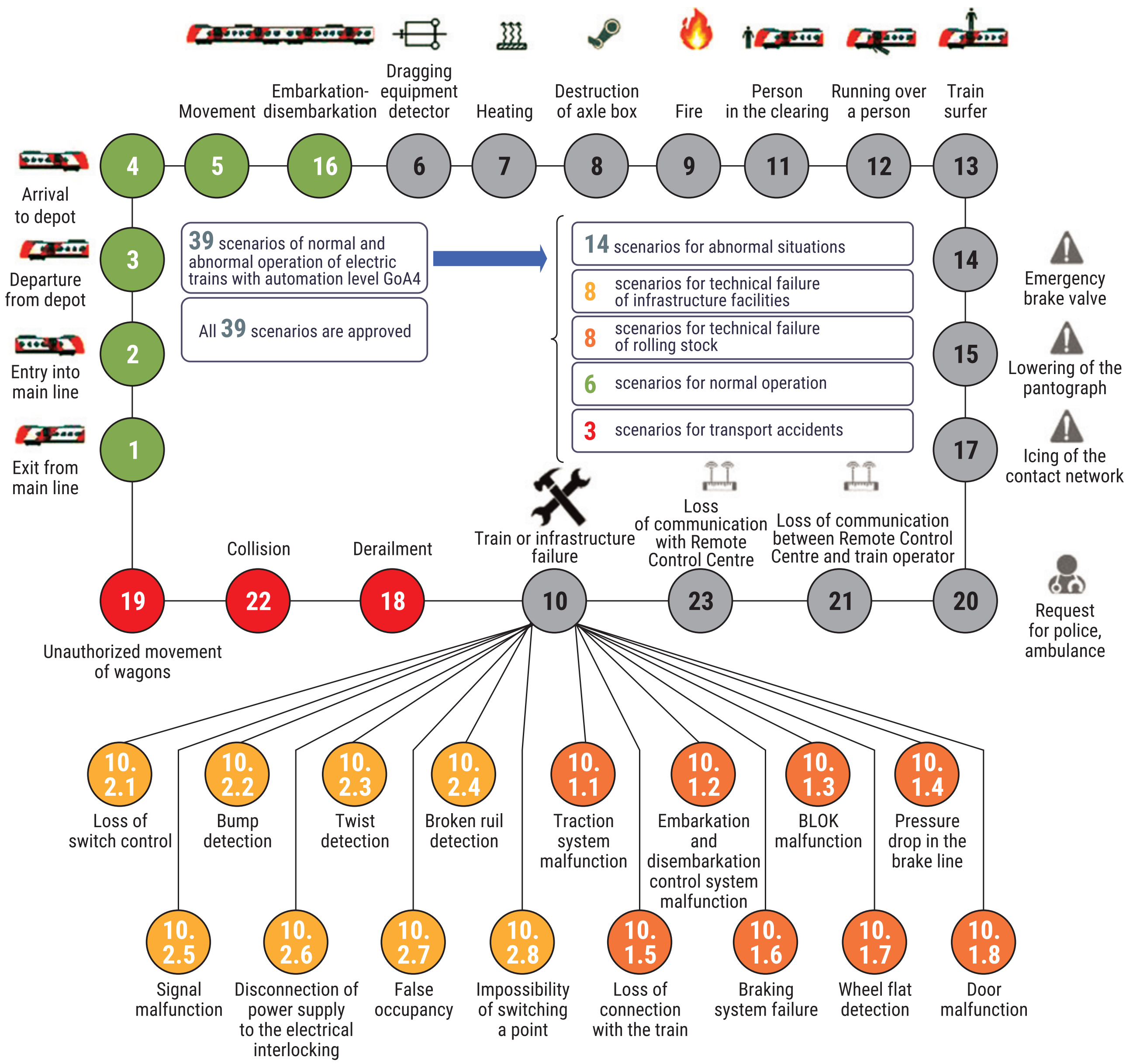

Fig. 4. Baseline operational scenarios on the MCC

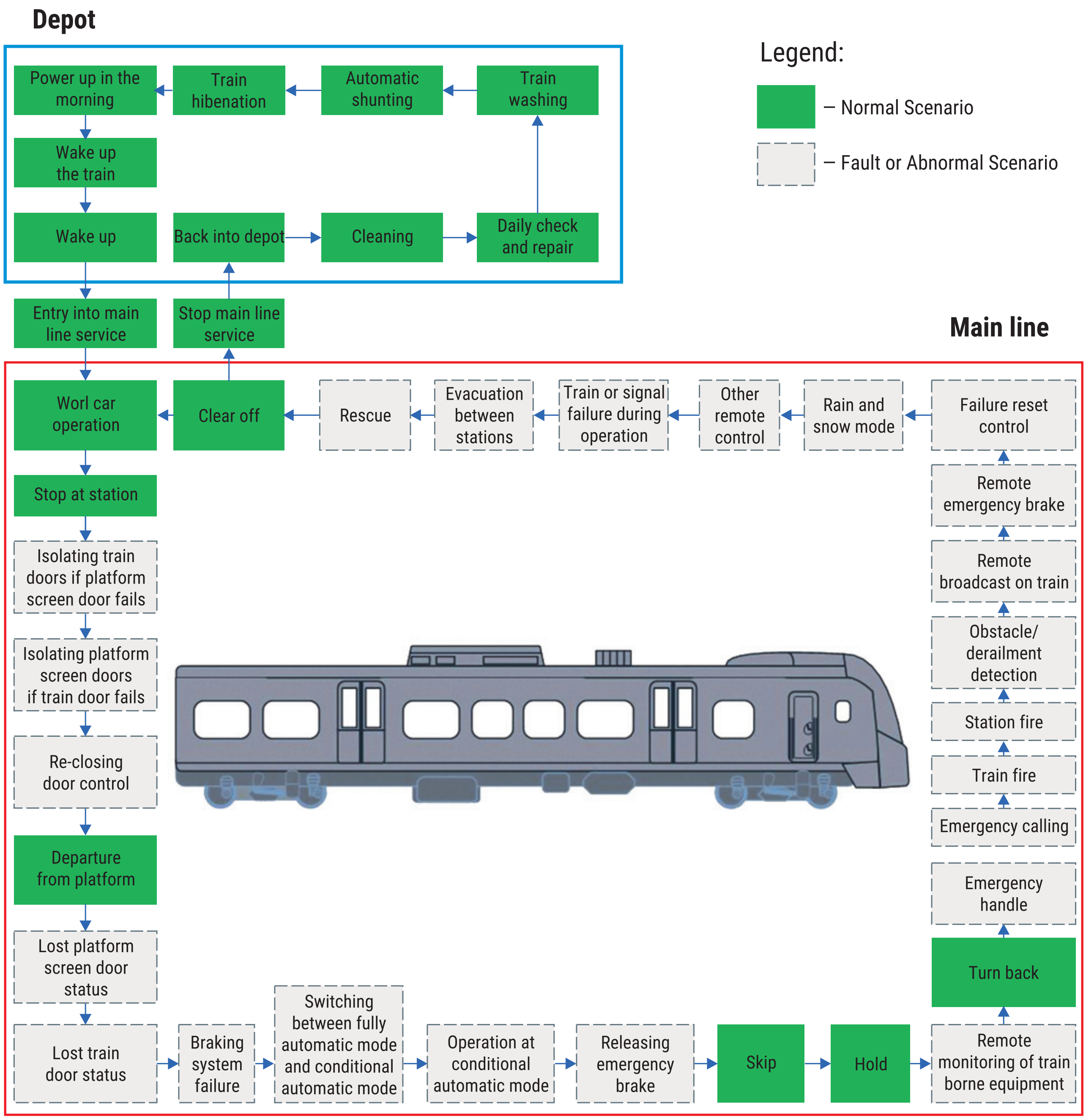

Fig. 5. Basic scenarios of unmanned transport operation

The developed scenarios are tested in a simulator and also drilled at the actual site of system implementation. The time and nature of the systems' response are specified and the personnel's actions are verified. In the course of pilot operation of electric trains in automatic mode, scenarios can be modified and their number can be increased.

In general, the development and refinement of scenarios should take into account a wide range of factors, including the specifics of train traffic management and regulatory requirements of each individual country, local features of the infrastructure, dispatch control systems, signalling, radio communication, diagnostics and monitoring devices, as well as transport safety equipment used on a particular urban railway. *Figure 5* shows a set of basic universal scenarios that can be taken into account and adapted to the operational requirements of a particular railway in BRICS countries.

AUTOMATIC OBSTACLE DETECTION SYSTEM

From a technical point of view, an automatic control system should be built on the basis of modern digital sensors and digital methods of processing information about the train situation using computer vision methods and artificial intelligence technologies that allow for timely detection and classification of foreign objects on the tracks to make a decision on the appropriate response of the unmanned train [6]. Radars, lidars, video cameras, thermal imaging cameras, and ultrasonic sensors are used as these sensors. They function in different ranges of the electromagnetic spectrum and have their own advantages and disadvantages which can be manifested under different conditions of light, humidity, dust, etc. Settings are selected based on the ambient conditions and operational tasks for the rolling stock.

Data from the sensors are processed using artificial intelligence technologies that allow for detecting a railway track, detecting obstacles and infrastructure objects, classifying the objects found, estimating the depth from the camera data, detecting anomalies, and so on. It is important to note that the system is able to detect and recognise only those objects that it has been trained to detect, so a significant issue remains the availability and accessibility of datasets from sensors on which the necessary objects are labelled [7]. For railway transport, a set of public datasets is extremely limited compared to, for example, the road transport sector. Access to railway infrastructure is limited, and the creation of a high quality labelled dataset has a high cost, so if a company is involved in its preparation, most often the dataset is not made freely available. Among the open datasets in the field of railway transport, we can mention several [8]:

- RailSem19 — 8,500 images of railway and tram scenes from 38 countries;
- FRSign — 105,352 images of French railway signals labelled with frames;
- GERALD — 5,000 images of German signals;
- RAWPED — 26,000 images of pedestrians labelled with frames;
- OSDaR23 — 1,534 labelled images and 204,091 objects to be labelled.

A limitation of most available datasets is that they only represent certain scenarios, environments and components. Track elements, rolling stock and climate may vary from country to country, so datasets created in one environment are not always suitable for training systems operating in other environments. There are several open datasets available in Russia, created by the St. Petersburg branch of NIIAS JSC. Four datasets are available for download at datasets.vniias.ru, and all interested users are invited to solve real problems on detection and segmentation of railway transport and infrastructure facilities.

RADIO COMMUNICATION INFRASTRUCTURE

The transition to unmanned traffic is virtually impossible without the introduction of broadband radio communications with a significantly higher bandwidth, which will enable the implementation of such functions as video streaming. Given that the existing GSM-R radio communication system is narrowband and cannot be adapted to the increasing information flow, in 2014, the International Union of Railways (UIC) initiated the FRMCS project aimed at preparing for the implementation of a new digital radio communication system for railways. The 5G standard was chosen as the communication standard on the basis of which the FRMCS system is being developed. This standard provides for a high bandwidth and is optimised for the creation of highly reliable data networks with ultra-low signal delay.

It should be noted that the implementation of communication systems based on the 5G technology on trunk lines is limited by the high cost of their construction. A possible and promising alternative may be the use of satellite communication systems that are currently being actively implemented in Russia. Thus, within the framework of the Sfera project, Roscosmos State Corporation launched the Skif-D demonstration communications satellite to test technologies for creating an orbital constellation for a broadband Internet system. It is planned that the Skif satellite constellation will consist of 12 spacecraft [9]. By the end of 2024, the Marathon–IoT spacecraft is expected to be launched, which will provide communication with ground-based sensors and control systems, including trains. The full-scale orbital constellation 'Marathon–IoT' will include 264 spacecraft [10]. Interesting is the solution of Bureau 1440, which launched three spacecraft 'Rassvet' in 2023. The satellite supports a data transfer rate of 12 megabits per second with a delay of only 41 milliseconds. This speed is enough to implement remote control of trains. According to the company's plans, 250 satellites will be launched at the first stage to provide basic coverage, and by 2030 their number will increase to 700 satellites, which will provide global coverage [11]. The development of such technologies will significantly facilitate the development and implementation of unmanned railway technologies in remote areas.

CHALLENGES AND PROSPECTS FOR THE INTRODUCTION OF UNMANNED TECHNOLOGIES

In terms of the prospects for the introduction of unmanned technologies, the most accessible is the deployment of such systems at marshalling yards where LTE broadband has already been deployed. Low traffic speeds, short braking distances and the absence of other types of traffic make it easier to create an automatic train control system. In Russia, an unmanned shunting locomotive has already started operating at the Luzhskaya marshalling station in 2017. At the moment, three fully unmanned locomotives equipped with an obstacle detection unit, which includes radars, lidar and cameras, are operating at the station. Movement along the set route, approach to wagons, coupling with wagons and pushing wagons onto the marshalling yard are performed in a fully automatic mode. The locomotives are monitored by driver-operators at the control centre, who make decisions in emergency situations and can remotely control the locomotive via the remote control panel.

Another promising application of automation technologies is the introduction of unmanned goods trains. An Australian mining company, Rio Tinto Limited, has become a pioneer in this area by introducing unmanned long-distance heavy-haul trains with GoA4 grade of automation on its railway network. The company worked with Hitachi Rail STS S.p.A. to implement the AutoHaul project, which has increased the network capacity and reduced the time it takes to deliver iron ore from mines in the Pilbara region to port terminals in Dampier and Cape Lambert. The full transition to automatic train control took place in June 2019 [12]. All activities that were previously performed manually by the driver are now taken over by ATO systems and, if necessary, by driver-operators from the control centre located in Perth, 1,500 km from the mine [13].

Rio Tinto locomotives were equipped with new systems, including a collision avoidance system, a safety system that monitors the train speed, and on-board cameras that allow for continuous monitoring from a control centre [14]. To identify potential threats on the train track, the locomotives were equipped with an advanced artificial intelligence-based obstacle detection system created by Rail Vision Ltd., Israel. The system detects obstacles in a given area at a distance of up to two kilometres in virtually all weather and light conditions, after which it classifies the obstacles and generates visual and audible warnings for the driver-operator and dispatcher in real time [15, 16].

Special attention was paid to the existing level crossings on the network, which were identified as the highest risk locations during the AutoHaul project development. The crossings were equipped with lighting, video surveillance and laser obstacle detection systems, which are connected to an ALS (automatic locomotive signalling) system. High-resolution (4K) video cameras were used, allowing for a good overview of the situation at a crossing from the control centre.

However, it should be noted that Rio Tinto has an isolated railway network with only company-owned homogeneous rolling stock, so replicating the technical solutions implemented in the Pilbara region on railways with different conditions may not be sufficient to ensure safety.

The main issues to be solved during the implementation process are as follows: ensuring reliable broadband communication between trains and the control centre, improving the reliability of rolling stock, and solving problems associated with the occurrence of abnormal situations. And, of course, the transition to such technology should be carried out sequentially. At first, it is necessary to implement the one-person operation (OPO) technology (where a train is operated by the driver alone, without an assistant driver) on goods trains. Then it is possible to implement partial automation, for example, to create unmanned pusher locomotives. It is possible to launch a package of goods trains where the crew is present on only one train. The task of railway scientists is to work out the technological aspects of various implementation options and determine the further development path of automation in freight transport. In general, in the near future, unmanned goods trains may be in demand in almost all BRICS countries.

When automating passenger railway traffic, additional challenges arise. It is necessary to create a system for controlling the embarkation and disembarkation of passengers and ensuring their safety, to provide for the possibility of communication between a passenger and a railway employee, etc. Different countries around the world are implementing some kind of train automation projects. In Germany, as part of the Sensor4Rail research project, an electric train was equipped with a machine vision system and field tests were conducted [17]. In 2021, France's national railway operator SNCF launched a prototype passenger train which ran on a commercial mainline railway in a test mode and recorded data to improve signal recognition algorithms [18]. Interest in automatic train control has also been observed in BRICS countries. For example, in China, TCT has developed an obstacle detection system using artificial intelligence technologies and received a SIL4 safety certificate for it [19]. Indian Railways has held several tenders for the supply and testing of machine vision systems to assist drivers with driving in heavy fog.

Russia is among the leading countries in the development of unmanned trains. At the moment, Russian railways are implementing several projects to automate the movement of locomotives and electric trains. At marshalling yards, the operation of shunting locomotives of various types is being automated. As for electric trains, a large amount of work has been done to achieve the third grade of automation for the ES2G Lastochka train manufactured by Ural Locomotives LLC. Further work is planned to achieve Level 4 for all types of new Russian-made electric trains, including high-speed trains.

Two trains of different versions equipped for GoA3+ automated operation are currently being tested on the

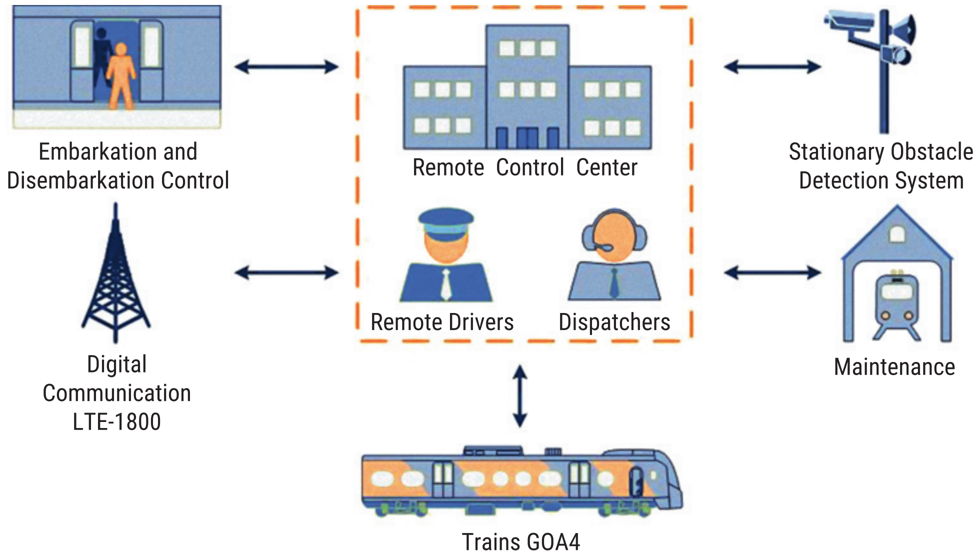

Fig. 6. Unmanned railway transport infrastructure of the MCC

MCC. The trains are equipped with systems for ATO, obstacle detection and positioning on the infrastructure, as well as a communication unit for communicating with the remote control centre. The prototypes can independently follow an energy-optimal schedule, as well as automatically activate braking and stopping algorithms if an obstacle is detected. However, during the tests, there is a driver in the cab of the prototype, who is always ready to take control. Engineers are also watching the train movement and monitoring all the systems of the unmanned train in real time. The infrastructure of unmanned railway transport has been created and tested at the MCC, which is generally universal and can be further standardised for further replication on urban railway transport (*Fig. 6*).

At the same time, the cost of switching to fully unmanned traffic is significant, as it requires investment in both rolling stock and infrastructure. It is necessary to design electric trains and locomotives that are equipped with machine vision, a remote control system, and a new braking system with the possibility of remote control. In fact, all rolling stock units that are now controlled only manually by the driver must be redesigned. In terms of infrastructure, it is necessary to build a digital broadband communication network, build a system for controlling passenger embarkation/disembarkation on platforms, introduce a radio-based collision avoidance system, adapt dispatching personnel's workstations, and build a remote control and management centre for the work of driver-operators. In addition, it is required to train the relevant personnel and make the necessary changes to industry regulations and documents.

A lot of tasks will need to be solved in terms of import substitution. The first machine vision devices were assembled entirely using imported sensors and computing facilities. Currently, the situation is changing, but not radically. At the initial stages, it is probably more correct to speak not so much of import substitution as of technological independence from Western-made components and of achieving sovereignty in this respect. Obviously, it is unlikely that in the coming years it will be possible to organise full production of machine vision devices using domestic components only. But it is possible to organise such production using certain components from friendly countries. In this regard, it is necessary to develop product requirements for domestic manufacturers on the basis of the experience of using imported devices and to carry out gradual replacement of sensors taking into account the requirements of independence from imports.

TECHNOLOGY READINESS OF AUTOMATION SOLUTIONS

If we consider solutions for ensuring the GoA3/4 automation levels of train control from the point of view of their technological readiness level (TRL), currently it varies from country to country. However, in the countries that lead the way, TRLs can be in the range from TRL6 to TRL9.

In assessing the TRL, we rely on the principles laid down in the international standard for defining Technology Readiness Levels and evaluation criteria (see *Table*)[3].

[3] ISO 16290:2013 Space systems — Definition of the Technology Readiness Levels (TRLs) and their criteria of assessment

Table

Technology readiness levels

Technology readiness levels	Description
TRL1	Exploration of basic concepts
TRL2	Formulation of the technology/solution concept
TRL3	Analytical testing of the concept
TRL4	Validation of the prototype in laboratory conditions
TRL5	Validation of the technology/solution components in close-to-real conditions
TRL6	Demonstration of the prototype in close-to-real conditions
TRL7	Demonstration of the prototype in operational conditions
TRL8	Verification of the technology/solution
TRL9	Operationalization of the technology/solution
TRL9.1	Start of implementation/operation
TRL9.2	Implementation/operation in a limited (pilot) area
TRL9.3	Large-scale implementation (replication)/operation

Taking into account the analyses of GoA3/4 projects in different countries of the world, it can be concluded that at the moment, the efforts are mainly focused on the following:

- Demonstration of the prototype in close-to-real conditions;
- Demonstration of the prototype in operational conditions;
- Verification of the technology/solution).

A separate issue is operationalization of the technology/solution, which primarily concerns rolling stock manufacturers and their willingness to promptly solve the problems of adapting existing designs for the installation of new sensors and equipment, as well as to promptly create new locomotives without a driver's cab.

Of course, for a full-fledged comprehensive assessment of the readiness of a given innovation solution, a number of unified parameters — supporting systems that characterise the development and balance of an innovation project — should be taken into account, namely:

- technology readiness;
- production readiness;
- engineering readiness;
- organisational readiness;
- market readiness.

The criterion that allows for the most correct analysis of the information on unmanned railway systems projects presented above is the technology readiness level (TRL). However, this criterion depends on the influence of a set of factors that are closely interrelated with each other and have different levels of maturity: on-board and wayside equipment, hardware and software, safety and capacity of unmanned transport, quality and efficiency of the 'machine vision' solution under different weather conditions and at different times of the day, relevance of the regulatory framework, etc. In order to objectively assess the TRL, it is necessary to base on the lowest value of the maturity level of the factor that is most significant among those listed above, considering it as a limiting factor. For all unmanned railway systems, the most significant factor is traffic safety, which has a direct impact on the TRL assessment.

A comparison of current trends in the development of railway infrastructure around the world suggests that the level of technology readiness (TRL) should be assessed taking into account the isolation of the system. With regard to the level of automation GoA4, it is currently possible to talk about TRL 9.1 or 9.2 when it comes to projects implemented in depots and marshalling yards or on railway lines operating in a manner that is little different from that of the underground (a closed system with homogeneous rolling stock running at specified intervals). As for mainline and regional railway lines, the level of automation GoA4 is still quite difficult to achieve in terms of practical implementation. Consequently, in this case we can only talk about the level of automation GoA3, which has reached a technology readiness level no higher than TRL 7 or 8.

At the same time, it is necessary to recognise a high intensity of research and testing efforts in the field of unmanned railway transport that are currently taking place in Germany, France, Great Britain, the Netherlands, Russia, China, and a number of other countries. The number of publications on the subject of unmanned transport is increasing, as is the number of patents in this area. Among the BRICS member countries, China is the leader in terms of the number of patents related to automatic vehicle control. NIIAS JSC also actively carries out intellectual activity in the field of unmanned train control. The specialists of the Institute have prepared and registered more than 40 patents and computer programmes, and have written at least 65 scientific publications on this subject.

The active interest in transport automation in the world allows us to assert with a high degree of confidence that as early as by 2026 passenger and/or goods trains with automation level GoA4 may appear in several countries that will operate on limited sections of main and regional railway lines, i.e. corresponding to the technology readiness level (TRL) 9.1.

Thus, 2026 may be the beginning of a new stage in the development of unmanned railway transport. Regulatory and technical documentation developed for obtaining permits to allow fully automatic rolling stock operation and the introduction of relevant amendments to legislation will become a powerful driver for the development of the market for on-board and wayside equipment, as well as hardware and software required for the organisation of safe, energy-efficient and high-performance unmanned railway transportation. The possibility for a large number of equipment manufacturers to participate in tenders for the supply of components for railway systems with the grades of automation GoA3/4 will not only allow for significant price reductions, but will also contribute to the emergence of innovative solutions in the market, which will make it possible to raise the technical characteristics of lidars, radars, ultrasonic sensors, video cameras and other critical components for unmanned trains, as well as the corresponding software to a fundamentally new level. This may also have a significant impact on increasing the investment attractiveness of unmanned railway transport in general.

As for the technology readiness level (TRL) 9.3 of fully unmanned technologies that can be used on mainline and regional railway lines, given the current state of the industry, it is still premature to make any conclusions. This issue is directly related to the timing of verification, validation and standardisation of unmanned train solutions around the world. The speed of development and implementation of FRMCS, a new radio communications standard, may also be a critical factor.

In addition, for a number of reasons, a significant part of railway lines around the world does not allow, in principle, for increasing the level of automation of transportation operations on them to the level of GoA3 without first undertaking large-scale works on their comprehensive reconstruction and modernisation. Consequently, one of the most critical factors for the further development of unmanned transport on mainline and regional lines is the amount of investment allocated for the modernisation and development of railway infrastructure by various countries around the world.

Nevertheless, the use of machine vision as part of modern train control systems is becoming one of the key and long-term trends in the development of modern control systems, which poses a wide range of challenges that require a comprehensive approach. The effective solution of these problems will determine the prospects of a mass transition to fully automatic (driverless) train traffic control, the main condition for which is a guaranteed safety level at least as good as the existing one.

CONCLUSION

Unmanned technologies in the railway industry have broad prospects and are already being implemented, especially in marshalling yards and in isolated, metro-like railway systems. Russia and other countries are actively developing the automation of train control using modern obstacle detection and remote control systems.

Further development of these technologies and the introduction of fully unmanned control on main lines requires significant investment in the modernisation of rolling stock and infrastructure, and also leads to changes in the professional structure. For example, the new profession of driver-operator, who will be responsible for remote control and control of automatic trains in abnormal situations, requires the creation of a workstation that can process a large volume of information and respond promptly to emerging problems. It is also necessary to develop scenarios for the operation of an automatic control system including analysing the actions of all systems and participants in the transportation process in all kinds of situations.

From a technical point of view, automatic train control systems require the use of advanced obstacle detection systems based on digital sensors and information processing methods using computer vision and artificial intelligence to detect and classify objects on the tracks. The main issue to be addressed is the methodology for proving the functional safety of such systems, since the behaviour of an artificial neural network cannot be fully described and predicted. In addition, it is difficult to train artificial intelligence systems. The availability and quality of the datasets required for this represent a limited and costly aspect, especially in the railway industry.

Another crucial challenge is setting up information transmission systems. The transition to unmanned traffic in the railway industry requires broadband radio communications with a high capacity, which requires the introduction of new communication systems, such as 5G. However, the implementation of 5G on trunk lines is costly, which makes the alternative satellite communication systems attractive.

It is advisable to introduce unmanned technologies in stages, starting with partial solutions and gradually moving to full automation. It is also necessary to take into account the issues of import substitution and technological independence when developing and implementing new systems.

These tasks on the BRICS railways can be achieved by combining the efforts and resources of railway administrations and sectoral institutions, including through the creation of the Railway Research Network. This coordination mechanism could become a platform for promoting railway initiatives, exchanging innovations, as well as helping to resolve issues related to the development and manufacture of components and parts for ATO systems. It seems reasonable to undertake a joint benchmarking study to be followed by the elaboration of a common strategy for the development of autonomous railway transport. The research network can become a common knowledge base and serve as an expert body for the creation and implementation of various innovative solutions on the BRICS railway network in areas such as collision avoidance, train traffic control and safety systems, process simulation, digital communications, intelligent diagnostics of rolling stock and infrastructure, satellite and geoinformation systems, etc. The network will also be able to develop and implement various innovative solutions on the BRICS railway network. The exchange of competencies, best practices, technological solutions and approaches to railway development will contribute to improving the quality and attractiveness of railway transport services in the BRICS countries.

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