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SIMULATION OF TRAIN BREAKING-UP PROCESSES ON SORTING HUMPS WITH CONSIDERATION OF HUMAN FACTORS

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Abstract:

Disbanding of freight trains on sorting humps is a key process in railway transport. At most stations, this process still involves human operators controlling retarders and car speed. The lack of models that account for human participation limits both the reliable evaluation of hump automation measures and the application of computer-based train release planning tools. The purpose of this study is to improve the methods of modelling the disbanding trains on sorting humps to take into account human influence. The method of simulation modelling was used as the main research method. Determining the speed and time of rolling of the hitches is carried out by solving the differential equation of motion where distance is used as a variable. Setting the indicators of the process of disbanding of trains is carried out on the basis of the statistical processing of a series of calculation experiments on the rolling of cuts. In order to take into account the human participation in the process of disbanding the trains in the simulation model, additional restrictions are set on the choice of braking modes of the cuts, which are associated with the need to switch the attention of the operator during the simultaneous control of several braking positions, as well as with the transition of the controller between different tracks. The scientific novelty of the work consists in the improvement of the model of the disbanding of trains on the sorting humps, which, unlike the existing ones, allows to take into account the influence of operators of brake positions and speed regulators of cars on the indicators of the sorting process. The practical significance of the work lies in improving the evaluation of automated train release control systems and supporting the development of decision-support tools for train release planning under uncertainty in cut rolling characteristics and braking execution.

Keywords: *railway transport, freight transport, sorting stations, sorting humps, human factor, simulation*

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1. Introduction

Disbanding and forming of freight trains and shunting gears is one of the most massive processes in both mainline and industrial railway transport. Sorting humps are the main means of disbanding and forming trains on railways. The quality of their work largely determines the cost of the transportation process, as well as its safety, the level of preservation of rolling stock and transported goods. In modern conditions, the main direction of increasing the processing capacity of sorting humps is the automation of the disbanding of trains. However, the high cost of implementation and operation of humps automation systems restrains their implementation. Therefore, the share of humans participation in the performance of hump operations is still significant. The main method of evaluating the functioning of sorting humps in modern conditions is computer simulation of slide processes. In such conditions, the task of taking into account the human factor in simulation models of sorting humps is urgent.

2. Literature review and problem statement

The sorting hump is a man-machine system that is in close interaction with other subsystems of the sorting station and is connected to them by a number of direct and reverse connections. At the same time, track development, train disbanding management, and processed train flow are considered consolidated elements of the sorting hump. There are physical and information connections between system elements. The external environment relative to the sorting hump is the surrounding natural environment and the railway station. The state of the system changes over time and is characterized by the position in space of individual elements of the track development of the hump and the cars on it. The input of the system is the flow of cars arriving for processing and the state of the external environment. The output of the system is formed by trains that are accumulated on the tracks of the sorting park. The behaviour of the system is determined mainly by the influence of physical forces acting on the rolling stock (gravitational force, traction force of the locomotive, movement resistance forces), and the influence of the control system. One of the elements of the control system is a human operator. That is, the sorting hump is an ergatic system. The general characteristics of the sorting hump as a system is given in table. 1.

Table 1. Characteristics of the sorting hump as a system

Classification feature	System class
The nature of the elements	Real
Origin	Artificial
Variability of properties	Dynamic
Predictability of states	Stochastic
Character of behaviour	Controlled
Degree of difficulty	Complex
The degree of communication with the external environment	Open
The degree of human participation in the implementation of control influences	Ergatic

The goals of this system are to ensure the disbanding-forming of the flow of trains at a given pace with minimal operating costs and with unconditional compliance with traffic safety conditions. These goals are contradictory. In particular, an increase in the level of safety can be achieved by reducing the rate of disbanding of trains or by improving the technical support of humps.

The main violations of the safety of the operation of hump devices during the implementation of the process of disbanding and forming trains are the derailments of cars on switches, car retarders and on tracks; damage to cars and cargo due to exceeding the permissible speed of coupling of cars on the sorting tracks or due to the lack of passages on the switches of the descending part of the hump. In addition, a violation of the safety of the sorting process can lead to injuries to workers who ensure the release of trains.

The safety of the operation of sorting humps is a feature of their control system and devices of the hump complex to ensure the disbanding of trains without violating the established requirements. In turn, the violation of operational safety requirements is a consequence of hazardous situations, the sources of which can be both individual factors and various combinations of them, in particular:

- hazardous failures of hump devices and control systems;
- incorrect actions of operators (hump yard master, operators assisting hump yard master, locomotive driver, speed controllers of cars);
- low-quality technical operation and errors of service personnel;
- hazardous failure of the track and rolling stock (breakage of rails, falling of car parts on the rails, etc.);

– natural phenomena, etc.

In these conditions, employees of sorting humps perform various roles related to the direct control of the following routes and the speed of movement of cars, safety control of the process of disbanding and, if necessary, transferring it to safe modes or stops. At the same time, people themselves, as elements of the system, are simultaneously both the source of hazardous destabilizing factors and the objects of damage.

The reason for the emergence of sorting humps in the 19th century was the need to intensify the sorting process (Droege, 1912). The first humps were characterized by the presence of people who ensured the sorting process, directly in the area where the rolling stock was moving. In particular, the control of the rolling speed of the hitches on the humps was carried out by the adjusters with the help of brake shoes. The adjustment of the speed of the humps with shoes (see Fig. 1) remains to this day as the main method for humps with a small amount of processing and additional in case of non-standard and emergency situations on all humps.

The presence of workers directly in the area of movement of cars was a source of constant hazardous situations and industrial injuries. Further development of hump technologies took place in the direction of mechanization, automation and robotization of technological processes, which corresponds to the general trends of industrial production (Sasor & Wydrych, 2004; Yao et al., 2015; Zhukovyts'kyy & Pakhomova, 2018). The technical means that ensured the removal of people from hazardous zones was the invention of car retarders. For the first time, retarders for sorting humps were patented in 1923 in the USA (Signal Section, A.R.A., 1935). The introduction of retarders made it possible to create mechanized sorting humps, the control function of which was retained by a person, but the control influences were carried out remotely (see Fig. 2).

Further intensification of the sorting process was associated with its automation. The first system of automatic control of the rolling speed of the cuts on sorting humps was implemented in 1948 at the North Platt station (USA) ("Builds second large retarder yard to improve operations," 1948). With the improvement of microprocessor technology at the end of the 20th and the beginning of the 21st century, hump systems were developed that allow for the disbanding of trains in automatic mode, such as MSR32 from SIEMENS ("Innovative approaches in railway management," 2024) and PROYARD (Rhodes, 2014) from General Electric.

Fig. 1. Non-mechanized brake position

Fig. 2. Operator of a mechanized sorting hump

They include various systems for collecting information about the parameters of the cuts, the process of their rolling and the conditions of the external environment. On the basis of the received data, the control system determines the need to adjust the speed of the cuts, which is implemented with the help of beam retarders. The main problem of such systems is the complexity, since the effectiveness of their work depends significantly on the completeness and reliability of the information used to make management decisions. Another approach to the automation of slide processes is based on the quasi-continuous adjustment of the rolling speed of the cuts with the help of DOWTY system retarders. An overview of the systems of quasi-continuous control of the speed of rolling of cuts is given in works (Rhodes, 2014; Barwell, 2013; Hill & Petkova, 2000; Nazarov, 2016; Zarecky et al., 2008; Zhang et al., 2000). In contrast to systems with beam retarders, systems of quasi-continuous adjustment of the rolling speed of cuts do not require complex control, as the principle of their operation is based on maintaining the desired speed of movement of cuts due to the insignificant effects of a large number of low-power point retarders. The complexity of implementing these systems is associated with special requirements for the longitudinal profile of the stations, the arrangement of which requires a complete reconstruction of the stations, and sometimes the approaches to them. In general, systems have been created today that are capable of managing the sorting process on humps in automatic mode. However, despite the availability of technical solutions to automate the sorting process, the rate of automation of sorting humps has decreased in the last decade. This is due to the transition of railways to technologies for the transportation of goods by routes such as the unit train and shuttle train in North America and the block train in Western Europe, as well as the high cost of construction and operation of automated sorting humps. Sorting humps are a key element that determines the processing capacity of railway stations (Cenek, 1996; Lin & Cheng, 2011; Trykoz & Bagiyanc, 2017). However, improving the technical support of the humps is not the only possible measure to increase the processing capacity of the stations. The studies carried out in (Monek & Fischer, 2024) show that the introduction of automated control systems for the disbanding of trains on sorting humps is cost-effective under the conditions of a stable flow of cars entering processing. At the same time, short-term peak loads on sorting stations in conditions of unstable car flows should be processed by increasing the number of shunting locomotives, redistributing shunting work between sorting hump and extraction tracks, as well as by increasing the number of employees. Although this approach increases the cost of converting cars, it provides an opportunity to quickly reduce technical support and staff in the event of a drop in the volume of work. Increasing environmental requirements, which is a trend of recent decades, also complicates the mechanization and automation of sorting humps, as brake retarders, especially point ones, are a source of intense noise pollution (Smith, 2013; Zvolenský et al., 2017). Because of these factors, human involvement in ensuring the disbandment and formation of trains on sorting humps will continue to be significant and needs to be studied.

Problems of the influence of the human factor on the functioning of railway transport were studied in works (Golightly et al., 2024; Ohar et al., 2017; Ryan et al., 2021; Staccioli & Virgillito, 2021; Ursarova et al., 2022; Wagner et al., 2021; Banerjee et al., 2017; Kurhan et al., 2024). Despite the existence of a close connection between operational indicators and safety indicators of the functioning of railway transport as a man-machine system, insufficient attention is paid to the problems of researching the relationships between them. Quantitative estimates are determined mainly only at the level of enterprises and the industry as a whole on the basis of statistical methods (Ursarova et al., 2022). Traffic incidents and safety violations on sorting s humps are subject to investigation (Zhang & Li, 2010a; Zhao et al., 2022). Their result, as a rule, is the development of additional instructions for personnel, which are actually additional restrictions for the execution of the technological process. At the same time, the processing capacity of the stations is not reassessed after their implementation.

Implementation of modern systems of mechanization and automation on sorting humps requires technical and economic substantiation of projects. At the same time, the possibility of making calculations is complicated by the lack of methods of quantitative assessment of the risks of hazardous situations associated with the participation of people in the process of disbanding trains. It should be noted that the coupling of cars at high speeds, as a rule, does not lead to derailment or visible damage to cars and cargoes directly during the sorting process. The main undesirable consequence of such couplings is the accumulation of residual deformations in the structure of the cars and their accelerated failure. Moving of cuts on the tracks inappropriately during the operation of the humps takes place systematically. Elimination of the consequences of such events requires the organization of breaks in the disbanding of trains and the performance of additional shunting work. However, such cases are analyzed only when their consequences led to train delays. Despite the large number of violations, traffic incidents on humps are recorded relatively rarely and are mostly explained by the influence of the human factor. In particular, on the railways of Ukraine, in 2015, at the Korosten station, an incident of derailment of one tank car with diesel fuel took place. In 2018, an accident occurred at the Znamyanka station, which consisted in the derailment of a tank with diesel fuel. Given that in both cases the transport incidents occurred with cars transporting hazardous goods, they could potentially lead to serious consequences in the event of an unfavorable combination of circumstances. An example of such an event is the explosion of a propane tank during the sorting of cars at the Syzran-1 station (USSR) in 1980, which killed 41 people and destroyed 44 houses.

The process of rolling down the cuts from the hump is one of the main elements of the disbanding and formation of freight trains at stations. In modern conditions, research into the process of cars rolling down a hump is performed using the method of mathematical modelling. The first models of rolling down the cuts appeared at the beginning of the 20th century and used classical methods of traction calculations, the same as for researching the movement of trains. However, despite the common principles, the nature and duration of the forces acting on the rolling stock on the humps and on the trains are different. The peculiarity of hump processes is the movement of cars mainly under the influence of gravity, control of the rolling speed of cars with the help of external influence on them by retarders or brake shoes, a rapid change in the state of the system within fractions of a second. To account for these features, a significant number of studies were conducted to evaluate the running properties of car cuts and to develop models of their rolling dynamics. In particular, in the early 1970s, the USSR All-Union Scientific Research Institute of Railway Transport conducted an extensive series of observations, field tests, and scale model experiments to assess the statistical patterns of freight car rolling resistance. These findings were published in Issue 545 (1975) of the institute's proceedings, titled «Resistance to Movement of Freight Cars when Rolling down Humps». Similar studies were conducted in the United States during the same period (Wong et al., 1981). The availability of data on car rolling resistance enabled the development of high-quality mathematical models for their descent from sorting humps. Currently, mathematical modeling is the primary method for investigating humping processes. During modelling, the calculation of the speed and time of rolling of the cuts is, as a rule, carried out on the basis of the solution of the differential equation of motion, where the variable is the distance:

$$dx = \frac{v\mathrm{d}v}{g'\left(i(x) - w_{rr} - w_{pr}(x,v) - w_{cr}(x,v) - w_{ew}(v) - w_r(x)\right)} \quad (1)$$

or time

$$dt = \frac{\mathrm{d}v}{g'\left(i(x) - w_{rr} - w_{pr}(x,v) - w_{cr}(x,v) - w_{ew}(v) - w_r(x)\right)} \quad (2)$$

where g' – acceleration of gravity with wheels rotational inertia effect, m/s^2;
x – distance from top of the hump to the first axle of the rolling cut (m);
v – cut velocity (m/s);
$i(x)$ – gradient under the cut of cars (‰);
w_{rr} – rolling resistance coefficient (N/kN);
$w_{pr}(x, v)$ – point resistance coefficient (N/kN);

$w_{cr}(x, v)$ – curve resistance coefficient (N/kN);
$w_{ew}(v)$ – environment and wind resistance coefficient (N/kN);
$w_r(x)$ – retarders or rail skates resistance coefficient (N/kN).

Simulation models, constructed on the basis of the aforementioned expressions, form the foundation of the software widely used for designing the layout and longitudinal profile of hump yards. Such models are presented, for example, in the works (Nazarov, 2016; Botirovich et al., 2022; Guo et al., 2016; Kampczyk, 2023; Khadjimuhametova et al., 2022; Khadjimuhametova, 2020; Maxkamov et al., 2021; Meng & Zhang, 2014; Mezitis et al., 2019; Ohar et al., 2020; Panchenko et al., 2018; Saidivaliev, 2023; Zhang & Li, 2010b; Zhang et al., 2017).

The disadvantage of the models traditionally used in the design of sorting humps is that they do not fully take into account the stochastic and controllable nature of their operation. The disbanding of the trains is a sequential rolling of the cuts. At the same time, it is necessary to maintain time intervals between them sufficient for the operation of shift changes and brake retarders, and the speed of the approach of the cuts to the cars on the sorting tracks should not exceed the permissible one. When solving design problems, it is accepted that the calculated parameters of cuts and the operating conditions of the sorting humps are the most unfavorable. However, the models used in the design are deterministic and all their parameters are known before the start of calculation experiments. The complexity of solving problems of operation of sorting humps is connected with the fact that the parameters of the cuts differ among themselves. Moreover, the exact values of the parameters of the cuts and the characteristics of their rolling conditions are unknown (Sasor & Wydrych, 2004; Wong et al., 1981; Moczarski, 2020; Kozachenko et al., 2024; Novytskyi et al., 2019; Bobrovskiy et al., 2016; Zhang et al., 2015).

Solving this problem on automated sorting humps is ensured by implementing various systems for collecting information about rolling conditions and the application of adaptive control algorithms that adjust retarder operations based on refined data (Novytskyi et al., 2019; Zhu et al., 2009; Savage et al., 1981). However, this approach complicates humps systems, increases the cost of their construction and operation. Moreover, even with the availability of accurate data on the running properties of the cuts, operators of sorting humps and regulators are not able to accurately implement the necessary modes of their braking. Therefore, an important direction of scientific research in the field of railway transport operation is the development of algorithms for the automatic control of the process of rolling down the cuts in the absence of accurate information about their running characteristics and the conditions of rolling down the cuts (Kozachenko et al., 2018).

Since simulation modeling of car cuts allows for high accuracy in reproducing the dynamics of wagon movement on sorting humps, this method was chosen as the primary approach in our study. To account for the influence of random factors on the humping process, the Monte Carlo method and mathematical statistics are applied to estimate the distribution parameters of such random variables as cut velocity and travel time. It should be noted that the existing models of cuts disbanding are focused on automated humps, and little attention is paid to the processes taking place on mechanized and non-mechanized sorting humps. At present, automatic control systems for sorting humps are characteristic of only a small number of the most powerful sorting stations. At the same time, management of the process of disbanding trains at the majority of stations is carried out manually. The lack of train disbanding models, which take into account the participation of people in the control of the rolling speed of the cuts, on the one hand makes it difficult to obtain reliable estimates of the effectiveness of measures for the automation of sorting humps, and on the other hand, limits the possibility of using computer technology for planning the disbanding. In this regard, the improvement of simulation models in order to take into account the human influence on the process of disbanding of trains is an urgent scientific and applied task.

3. Methods

3.1. Object of research

A sorting hump with three brake positions was chosen as the object of research in this work. The first and second brake positions are located on the descending part of the hump and are mechanized by beam retarders. The third brake position is located on the sorting tracks and is served by the speed controllers of the cars. The scheme of track development of the sorting hump is presented in fig. 3. For comparison, the same hump is considered under conditions of mechanization of the braking position on sorting tracks and automation.

In the process of disbanding, before passing the top of the hump, the train is divided into groups of cars, which are called cuts. After crossing the top of the hump, the cuts roll down under the influence of gravity. By reducing the speed of individual cuts at braking positions, it is necessary to ensure the separation of cuts on shift changes when following the routes to different sorting tracks, as well as the permissible speed of movement of cuts on the hump and their approach to cars standing on the sorting tracks.

In order to assess the working conditions of the personnel at the braking positions, the operation of the speed regulators of the cars was observed. In the process of work, regulators are exposed to a large number of hazardous and harmful destabilizing factors, namely:

– rolling stock, vehicles, devices and mechanisms;
– increased noise level;
– increased level of vibration;
– increased dustiness and gassiness of the air in the working area;
– increased or decreased air temperature of the working area;
– increased humidity and air mobility;
– insufficient lighting of the working area in the dark;
– physical overloads.

Before disbanding the train, the senior control officer distributes the sorting tracks among the control officers. As a rule, from 3 to 6 sorting tracks are fixed behind the control officer, depending on the intensity of the arrival of cars on them. In the majority of cases, the control officer is located on the track in advance of passing through the branch of the border post. During the movement of the cut in the area of the shoe brake position, a visual assessment of its speed and driving characteristics is carried out. As a rule, the control officer accompanies the cars until they cross the shoe-dropper. As a result of the survey of control officers, it was established that in the absence of accurate information about the driving characteristics of the cuts and the braking effect of the shoes, the use of late braking of the cuts allows to more efficiently implement the requirements of aimed regulation of their speed. Used shoes accumulate after the shoe dropper. Before release and if there are breaks between the arrival of cuts, the control officer moves the shoes to the initial position. The control officer cannot switch to another track if it is crossed by a rolling cut.

Potentially hazardous situations were recorded during the observation:

– - lack of sufficient time to move the control officer between tracks and switch to running;
– maintenance of tracks that were not fixed in the initial plan of disbanding, as assistance to other control officers;
– stopping of cuts in the area of the shoe brake position and blocking the passages between the tracks for the control officers;
– passing cars on separate tracks without escort.

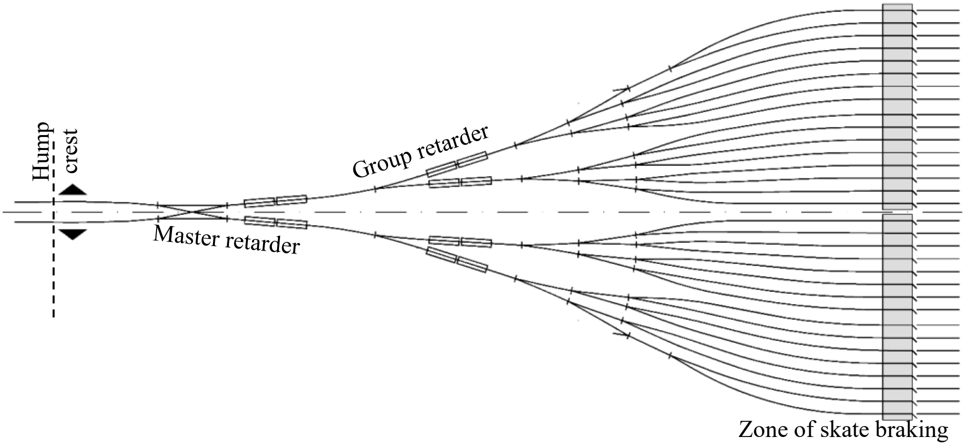

Fig. 3. Plan of track development of the sorting hump

The main reason for the occurrence of potentially hazardous situations is the small time intervals between the arrival of cuts on different tracks.

Observation results highlight a substantial divergence of the real-world shunting process from the idealized models of automated hump yards typically found in modern research and standards (Savage et al., 1981). This gap is primarily driven by the human factor in hump yard operations. While automated systems can perform instantaneous, parallel management of numerous objects, human participation necessitates a sequential control logic during the train disbanding process. In particular, operations such as separating cuts at switches and regulating their speed at retarders are processes constrained by the operator's cognitive switching and reaction time. According to research (Naweed & Rainbird, 2015; Reinach & Viale, 2006), limited reaction time is a primary factor contributing to transport safety breaches. Therefore, under conditions of high-intensity disbanding, human physical and psychophysiological capabilities become a limiting factor, reducing the efficiency and safety of the humping process compared to idealized automated systems. To account for this fact, our model treats the human operator as a specific control link within the system. In alignment with the systems-thinking principles formulated by Leveson (Leveson, 2011), this study does not treat human error as the root cause of hazardous transport incidents. Instead, operator errors are viewed as symptoms of underlying systemic deficiencies—specifically, when a control system is inadequately designed and fails to provide the human operator with the necessary operational conditions and temporal buffers required for safe performance. This approach allows for the continued use of existing verified mathematical models of humping processes, while augmenting them with parameters of human activity. Given that human psychophysiological parameters and the standards for performing technological operations, such as reaction time and movement speed, are well-established, the reliability of the results is ensured by the synthesis of a proven physical core for the car-rolling model and the application of standardized parameters of human activity. Therefore, the objective of improving the simulation modeling method is to establish train humping control modes that, with a high degree of probability, provide the human operator with a time interval for performing technological operations that is no less than the established standard.

The implementation of such control directly depends on the spatial characteristics of the track sections where the interaction between the human and the cars occurs. In the future, we will refer to the area of 25 m long from the shoe dropper in the direction of the hump as the speed control zone. The control officer must be located in the regulation zone before the cut enters it. The total length of the speed control zone ensures a safe passage between the tracks and an initial assessment of the running characteristics and speed of the cut. We will call the braking zone a part of the speed control zone with a length of 20 m from the shoe dropper towards the top of the hump in which shoes are placed under the cars. At the same time, the length of the cut does not lead to the formation of sliders on the wheels.

Control of mechanized brake positions on the descent part is carried out by operators. Each operator remotely controls four retarders. The evaluation of running characteristics and speed of rolling of cuts is carried out on the basis of the data of type sheets and visually.

The analysis of the functioning of the sorting hump and the results of field observations show that the human factor is an inseparable element of the sorting humps, where the management of the disbanding process is carried out manually. For such humps, taking into account the influence of the human operator in simulation models is critically necessary to obtain reliable estimates of carrying capacity, cost and, most importantly, the safety of their operation.

3.2. Model of the rolling process of cuts

Simulation modelling is used as the main research method in this work. Modelling of the movement of the cuts is carried out on the basis of the numerical solution of the differential equation of motion in which the variable is the distance (1). The advantage of this method is a higher speed of obtaining a solution in comparison with methods based on equation (2). This is important as obtaining statistical characteristics of the rolling process requires a series of experiments. The disadvantage of the models based on equation (1) in comparison with the models based on equation (2) is that the rolling of each cut is carried out separately and to simulate the disbanding of the train, it is necessary to carry out additional operations to synchronize the results of the rolling of individual cuts.

The model of the cut rolling process contains a model of the plan and longitudinal profile of the sorting hump, as well as a model of the cut.

The input model of the sorting hump is intended for human preparation of the output data for modelling. In this model, the sorting hump is given by a weighted directed graph in which arcs are sections of track, and vertices are characteristic points in plan and profile connecting arcs with different characteristics. As arcs, straight sections, sections of circular curves, shift changes and brake positions are distinguished. The direction of the arcs is chosen from the top of the hump to the sorting tracks. The input model is automatically converted into an internal model, which is directly used in the simulation of rolling. In the internal model, the hump is considered as a set of rolling routes. In this study, a rolling route is defined as the track section extending from the beginning of the approach track before the hump crest to the end of the destination classification track, which allows for simulating the movement of the cut from the moment of its separation from the train until it comes to a complete stop. The rolling route plan is considered as a set of $m_{ik} \in \mathbf{M}$, $i = \overline{1..n}$, $k = \overline{1..K_i}$ (here **M** is the set of rolling routes;; i is cut number; n is cuts amount; k is number of the element of the rolling route; K_i is the amount of elements on the rolling route of the i-th cut). Each element of the rolling route is represented by a structure

$$m_{ik} = \{l_{ik}, u_{ik}, R_{ik}, w_{sc,ik}, w_{r,ik}\}, \tag{3}$$

where l_{ik} stands for section length, m;
u_{ik} stands for element type (u_{ik} =0 is straight section; u_{ik} =1 is curve; u_{ik} =2 is switch change; u_{ik} =3 stands for brake position);
R_{ik} stands for radius of the curve on the section, m;
$w_{sc,ik}$ stands for average weighted coefficient of resistance of switches and curves on the site;
$w_{r,ik}$ stands for specific braking resistance on the track section N/kN.

The longitudinal track profile along the rolling route S_i is described by a modified cubic spline, each node of which is represented by a structure

$$s_{ij} = \{x_{s,ij}, b_{0,ij}, b_{1,ij}, b_{2,ij}, b_{3,ij}\}, \tag{4}$$

where $x_{s,ij}$ is abscissa of the j-th node of the spline on the rolling route of the i-th cut, m;
$b_{0,ij}, b_{1,ij}, b_{2,ij}, b_{3,ij}$ are spline coefficients;
j is spline node vertex number, $j = 1..J_i + 1$;
J_i is the number of profile elements on the rolling route of the i-th cut.

The slope at some point x on the rolling route is determined by the formula

$$\begin{aligned} i(x) = b_{0,ij} + b_{1,ij}(x - x_{s,ij}) + \\ + b_{2,ij}(x - x_{s,ij})^2 + b_{3,ij}(x - x_{s,ij})^3. \end{aligned} \tag{5}$$

In the input model, the cut represents a set of cars, where each car is matched with its type and mass. For simulation, the input model is automatically converted to the internal model. In the internal model, the cut is modelled as an inextensible flexible rod. At the same time, the cut is set by the structure

$$c_i = \{q_i, w_{rr,i}, K_{ew,i}, \mathbf{A}_i\}, \tag{6}$$

where q_i is mass of the i-th cut, t;
$w_{rr,i}$ is the main specific resistance of the movement of the i-th cut, t;
$K_{ew,i}$ is coefficient for calculating the resistance of the external environment and wind;
$\mathbf{A}_i$ is vector of interaxial distances of the cut.

The given model is supplemented with data on initial launch speed, distance to the aiming point, ambient temperature, wind speed and direction.

The calculation of the resistance to the movement of the cut on the basis of the model is carried out by traditional methods (Hill & Petkova, 2000; Kampczyk, 2023; Zhang et al., 2017; Kozachenko et al., 2024), which have passed the adequacy test. Equation (1) is solved by the Runge-Kutta IV method. To ensure the accuracy of the numerical solution of the differential equation of motion, the rolling route of the cuts is discretized with a baseline step of Δs = 1.0 m. In cases where a change in the character of the forces acting on the cut occurs within the step Δs, such elements are subjected to additional sub-segmentation. This approach, together with the use of the Runge-Kutta IV method, ensures high accuracy and computational efficiency in simulating the controlled rolling of the cut. The result of the solution is the dependence of speed and time of rolling on the coordinate, respectively v=f(x) and t=f(x). To take into account the stochastic nature of the rolling process, a series of its simulations is carried out with random deviations of the values of the mass of the cut and movement resistance.

The brake positions realize the set speeds of the release of the cuts from them with an error. It is assumed that the error value has a normal distribution law. At the same time, the average squared deviation of the actual speed of the cut exit from the specified one with automatic retarder control is 0.06 m/s, with operator control of the retarders 0.2 m/ s, and at non-mechanized braking positions 0.3 m/ s. Unlike traditional models, which, as a result of a calculation experiment, allow you to set v and t values for each characteristic point of the route with the x coordinate, the proposed model allows you to obtain samples of random values $\{v_1, v_2, \ldots, v_e\}$ and $\{t_1, t_2, \ldots, t_e\}$ (here e is the number of calculation experiments). Based on the data of these samples, the dependences of the mathematical expectation and the mean square deviation of the speed and the rolling time from the coordinate are determined, respectively $M[v]=f(x)$, $s[v]=f(x)$ and $M[t]=f(x)$, $s[t]=f(x)$. For example, fig. 4 and 5 present the results of 300 simulation experiments on the rolling of the cut from the sorting slide with automatic control of braking positions and with control of the decelerators of the descent part by operators and non-mechanized braking positions on the sorting tracks.

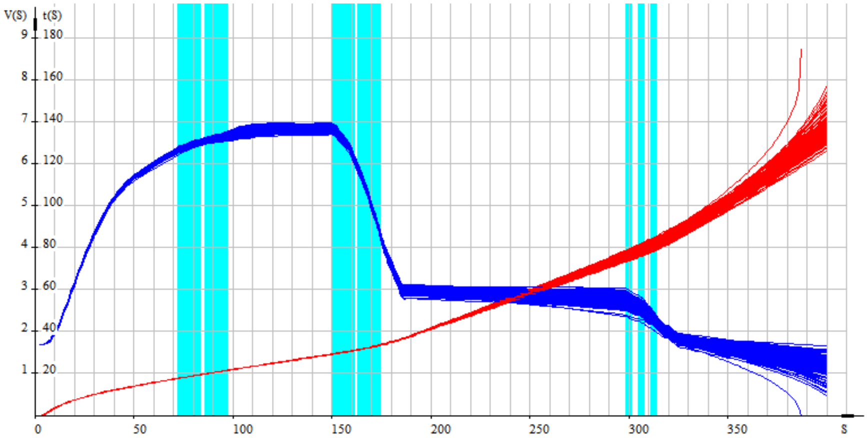

Fig. 4. Curves of the speed and time of rolling of the cut during automatic control of brake positions

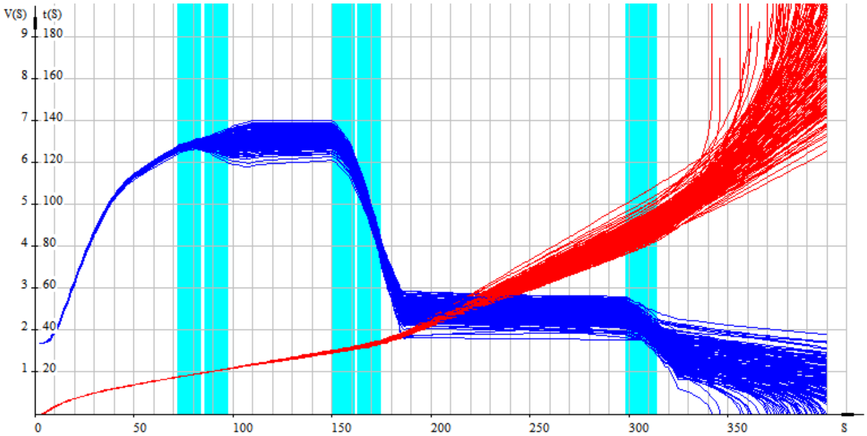

Fig. 5. Curves of the speed and time of the rolling of the cut when controlling the retarders of the descent part by operators and non-mechanized braking positions on the sorting tracks

3.3. Management of the disbanding process

Management of the train disbanding process includes dividing the train into groups of cuts whose disbanding is carried out continuously, selection of the speed of disbanding for each such group, selection of exit speeds from braking positions for each cut. The total time spent was chosen as an integral indicator by which the control of disbanding of the train is evaluated T_b.

We will call the vector $\mathbf{v}_i=\{v_{1,i}, v_{2,i}\}$ (here $v_{1,i}$, $v_{2,i}$ are the exit speed of the cut from the first and second braking positions) the tap cut mode. The output speed of the cut from the third braking position is dependent on $v_{1,i}$, $v_{2,i}$. The cut braking mode is determined by the speed of the cut entering the braking position, the running characteristics of the cut and the power of the braking position. These modes are limited by aimed and interval speed control requirements. In accordance with the requirements of the aimed adjustment the exit speed of the cuts from the braking positions should be chosen so that the cuts do not stop at the switch zone and approach the cars standing on the sorting tracks at permissible speeds. The stop of the cut on the boom neck causes the need for additional maneuvering work and a break in the disbanding. There is also a risk of damage to cars and cargo due to exceeding the permissible coupling speed between the standing cars on the track and the tolling cuts. Economic losses are the consequence of stoppages of trains at boom neck. It is assumed that the admissible probability of trains stopping at boom necks is 0.005. Exceeding the permissible coupling speed of rolling cars with cars on sorting tracks leads to the risk of damage to cars and cargo. Such unwanted events are frequent and result in economic losses. It is assumed that the permissible probability of exceeding the permissible coupling speed of rolling cars with cars on the sorting tracks is 0.1.

Permissible braking modes under the conditions of targeted adjustment of the rolling speed of cuts can be presented in the form of closed areas of permissible braking modes Ω_i (Bobrovskiy et al., 2016; Savage et al., 1981).

The requirements for the interval adjustment of the speed of the cuts provide for the creation of intervals at shift changes and braking positions sufficient to separate the cuts along different rolling routes. The probability of non-separation of cuts on the separation element is determined by the expression $p(\delta t_i < t_{de,i})$ (here δt_i stands for the time interval between the moment the separation element is released by the i-th cut and the moment it is occupied by the i+1-th cut; $t_{de,i}$ is the minimum permissible separation interval between the i-th and i+1-th cuts) and can be established based on the results of a series of experiments using the formula (Bobrovskiy et al., 2016)

$$p(\delta t_i < t_{de,i}) = \\ = \Phi\left(\frac{\theta_i - t_{de,i} - M[\tau_i] + M[t_{i+1}]}{\sqrt{D[\tau_i] + D[t_{i+1}]}}\right) \tag{7}$$

where $\Phi(x)$ is the Laplace function;
θ_i is the initial interval between the i-th and i+1-th tap at the cut of the hump, s;
τ_i and t_{i+1} are respectively, the rolling time of the i- th cut from the moment of detachment to the moment of release of the separating element and the next cut to the moment of occupation of the separating element, s;
$M[\tau_i]$, $M[t_{i+1}]$ are respectively the mathematical expectation of quantities τ_i and t_{i+1}, s;
$D[\tau_i], D[t_{i+1}]$ are respectively, the variance of values τ_i and t_{i+1}, c^2.

The consequence of not separating the cuts at shift changes and brake retarders, as well as in the case of stopping the cuts at the shift zone, is economic loss. It is accepted that the permissible probability of such an event is 0.005.

The operator's participation in the process of releasing the cuts imposes additional restrictions on the interval adjustment of the sliding speed, which are not taken into account in the existing models. In contrast to automatic systems that control the movement of cuts on different tracks in parallel, during simultaneous control of retarders, the operator must divide attention between them (see Fig. 6). Such activities are undesirable and can lead to economic losses.

It is assumed that the interval between the release and arrival of cuts on retarders controlled by one operator should be sufficient for cognitive switching and be at least t_r=3 seconds. Failure to comply with this requirement may result in economic losses. It is assumed that the permissible probability of such an undesirable event is 0.1.

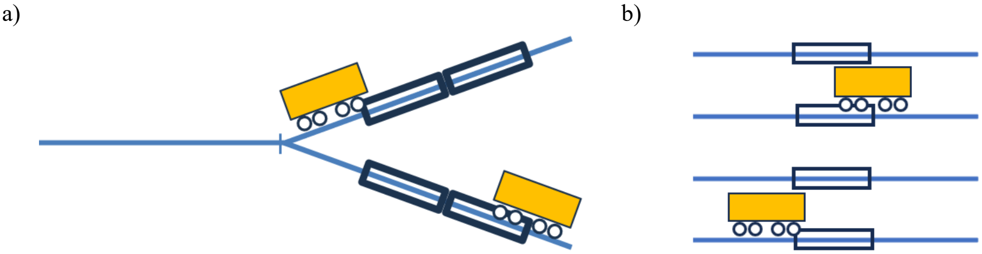

Fig. 6. Undesirable options for the location of cuts on decelerators controlled by one operator: *a* – at the brake position of the descent part of the slide; *b* – on the parking brake position

In the case of operation on a hump of non-mechanized braking positions, the time interval between the release of the speed control zone by the previous cut and the entry of the next cut into the control zone must be sufficient for cognitive switching of the controller, its passage between tracks and taking the initial position in the braking zone

$$t_{ch} = \frac{l_m}{v_m} + t_r + t_s, \tag{8}$$

where l_m, v_m are the distance and speed of the speed controller passage between the brake positions, respectively m and m/s;
t_s are time spent on taking the brake shoe and taking the initial position, s.
The route of travel of the railway traffic controller between the tracks may or may not require crossing the route of the cut. In the first case, the limitation in the transition time between brake positions leads to the risk of injury or death of the railway traffic controller. It is accepted that such events should be unlikely, and the probability of their occurrence should not exceed 10^{-6}. In the second case, violation of the requirement may cause economic losses. It is accepted that the probability of occurrence of such undesirable events should not exceed 0.005.
The value of the initial interval between the cuts at the top of the hump can be determined by the expression

$$\theta_i = (l_i - x_{u,i} + x_{u,i+1})/v_h \tag{9}$$

where l_i is length of the i-th cut, m;
$x_{u,i}, x_{u,i+1}$ are respectively, the coordinates of the separation points of i and i+1 cuts, m;
v_h is disbanding speed, m/s.
The speed of disbanding of the train is limited by the technical characteristics of the hump in the interval

$$v_h \in [v_{\min}, v_{\max}], \tag{10}$$

where $v_{\min}, v_{\max}$ are respectively, the minimum and maximum permissible disbanding speed, m/s.
The process of disbanding the train can be divided into parts by stopping it and organizing breaks. Let **z** be a vector of Boolean values that determines the place of formation of breaks in the dissolution of the composition. Each element of this vector z_i (here i=1,…,n−1) indicates the presence of a break between the i-th and i+1-th cut:
- z_i =0 means that i-th and i+1-th cuts belong to one group and their disbanding occurs continuously;
- z_i =1 means that the disbanding of the train stops after the i cut, and starting from the i+1 cut, the disbanding of another group begins.
Let us denote the speed at which the i-th cut is disbanded by $v_{h,i}$. It is assumed that the speed of disbanding of all cuts included in the same group is the same. Then the duration of disbanding of the train can be set by the expression

$$T_b = \sum_{i=1}^{n} \frac{l_i}{v_{h,i}} + t_{ps} \sum_{i=1}^{n-1} z_i, \tag{11}$$

where t_{ps} is the duration of the break between disbandings.
The method of finding acceptable parameters of disbanding of the train consists in solving the problem of minimizing the duration of its disbanding (5) under the restrictions imposed by the requirements of aimed and interval adjustment of the rolling speed of cuts. To find a solution to this problem, an iterative algorithm is used, at each step of which one cut is added to the previous train.

Consider a composition consisting of one cut. The permissible rolling modes of a single cut are determined by its area Ω_i. The existence of such an area for all possible cuts is ensured at the stage of designing the sorting hump.

Let's consider the elementary task of disbanding a train of two cuts. We will call the mode in which the braking of the cuts is delayed at the positions that are further from the top of the hump, the fast rolling mode of the $\mathbf{v}_{f.i}$ cuts. This mode ensures the earliest moments of release of the separating elements $\square_i$. We will call the mode in which cut braking is performed at positions located as close as possible to the top of the hump as the slow rolling $\mathbf{v}_{s.i}$ mode of the cut. This mode provides the latest moments of occupation of dividing elements t_i. The absolutely optimal rolling mode of the first cut is the fast mode, as its use ensures the maximization of the intervals between it and the following of the train, and therefore minimizes the probability of non-separation with them.

The search for an permissible mode of disbanding of the train of two cuts is performed on the basis of the following algorithm.

1. Set $v_{h,i}=v_{\max}$ ($i=[1, 2]$), $z_1=0$, $v_1=v_{f,1}$.
2. If during the rolling of the second cut in the fast mode $v_2=v_{f,2}$ the probability of its non-separation with the first cut (3) assumes an acceptable value, then accept $v_2=v_{f,2}$. End of solution.
3. If, when rolling the second cut in the slow mode $v_2=v_{s,2}$, the probability of its non-separation with the first cut (3) takes an unacceptable value, then it is impossible to disband the composition with the given speed $v_{h,i}$. As a mode of disbanding of the train, it is necessary to adopt a regime that involves reducing the rate of disbanding or dividing the train into groups so that $z_1=1$. As the mode of disbanding, the one that provides less time consumption is chosen (5).
4. Permissible conditions for the disbanding of the train are provided by the intermediate mode ($v_{f,2}$, $v_{s,2}$). The establishment of such a mode can be performed by direct search methods, for example, the golden section. End of the solution.

The search for the permissible speed of cut disbanding is performed according to the following algorithm

1. Set vpr=vh,i, vh,i = vmin, v1=vf,1.
2. If at v2=vs,2 the probability of non-separation of cuts (3) takes an unacceptable value, then it is impossible to disband the train by one group. End of solution.
3. To know within the interval [vmin, vpr] such disbanding speed vh,I, at which the probability of non-separation of cuts (3) is equal to the permissible value. Solving this problem can be performed by direct search methods.

Consider a train of n_2 cuts for which the condition holds

$$\frac{\sum_{i=1}^{n_1} l_i}{v_{hp1}} + t_{ps} + \frac{\sum_{i=n_1+1}^{n_2} l_i}{v_{hp2}} < \frac{\sum_{i=1}^{n_2} l_i}{v_{hu}}, \tag{12}$$

where v_{hp1}, v_{hp2} are speed of disbanding of the first and second groups of cuts of the train, m/s;
$v_{hu}$is speed of disbanding of combined train, m/s;
n_1 is the number of cuts in the first group.

Adding a new n_2+1 cut causes the need to check the conditions of its separation with the previous cuts. At the same time, adding a new cut only imposes additional restrictions on the rolling modes of previous cuts and does not allow improving the conditions for their separation.

So, $v_{hp1} \geq v_{hp1}^*$, $v_{hp2} \geq v_{hp2}^*$, $v_{up} \geq v_{up}^*$ (here $v_{hp1}^*, v_{hp2}^*, v_{up}^*$ are optimal speeds of disbanding of the first and second groups of cuts, as well as the combined train after adding a new cut).

The selection of the train disbanding mode after adding n_2+1 cut is performed as follows.

1. If the condition is met

$$\frac{\sum_{i=n_1+1}^{n_2} l_i}{v_{hp2}} + t_{ps} + \frac{l_{n_2+1}}{v_{\max}} \leq \frac{\sum_{i=n_1+1}^{n_2+1} l_i}{v_{hp2}} \tag{13}$$

   then it is advisable to allocate n_2+1 cut to the third group of cars without checking the separation conditions with previous cuts. Take $z_{n_2} = 1$, $v_{h,n_2+1} = v_{\max}$, $\mathbf{v}_{n_2+1} = \mathbf{v}_{f,n_2+1}$. End of solution.
2. If at the speed v_{hp2} and the braking mode $\mathbf{v}_{n_2+1} = \mathbf{v}_{f,n_2+1}$ the requirements for the interval adjustment of the n2+1 cut with all the cuts of the second group are met, then connect the n2+1 cut to the second group. Take $z_{n_2} = 0$,

$v_{h,n_2+1} = v_{hp2}$, $\mathbf{v}_{n_2+1} = \mathbf{v}_{f,n_2+1}$. End of solution.

3. If at the speed v_{hp2} and the braking mode $\mathbf{v}_{n_2+1} = \mathbf{v}_{s,n_2+1}$ the requirements of the interval adjustment of the n_2+1 cut with all the cuts of the second group are met, then connect the n_2+1 cut to the second group and find the maximum permissible speed $\mathbf{v}_{n_2+1} \in (\mathbf{v}_{f,n_2+1}, \mathbf{v}_{s,n_2+1}]$. Take $z_{n_2} = 0$, $v_{h,n_2+1} = v_{hp2}$. End of solution.
4. Take

$$v^*_{hp2} = \sum_{i=n_1+1}^{n_2+1} l_i \bigg/ \left(\frac{\sum_{i=1}^{n_2+1} l_i}{v_{hu}} - \frac{\sum_{i=1}^{n_1} l_i}{v_{hp1}} - t_{ps} \right), \qquad (14)$$

If there is a mode of disbanding the group from n_1+1 to n_2+1 cut, in which the requirements of interval speed regulation at the speed v^*_{hp2} are met, then keep the break in disbanding after cut n_1. It is optimal to disband the group from n_1+1 to n_2+1 cut at the speed $[v^*_{hp2}, v_{hp2})$, or its division into two parts. End of solution.

It is optimal to disband the train from 1 to n_2+1 cut at the speed $[v_{\min}, v^*_{hp2})$, or to divide it into two parts. End of solution.

It should be noted that the given algorithm determines the permissible mode of formation of the train, which ensures minimal time consumption. The search for braking modes that provide minimal risks of separation of cuts during their rolling and minimal "windows" on sorting tracks is the subject of specific studies and is not considered in this work.

3.4. Simulation results

Graphically, the restrictions imposed by the requirements of the aimed adjustment of the speed of the rolling cut can be represented in the form of the area of permissible modes of its braking Ω_i. Fig. 7 shows the areas of permissible braking modes of the cut in the conditions of automatic control of retarders $\Omega_{a,i}$, when retarders are controlled by operators $\Omega_{m,i}$ and in conditions of non-mechanized braking position on sorting tracks $\Omega_{n,i}$. The decrease in the area of permissible braking modes of cuts when the braking positions are controlled by operators in comparison with automatic control is explained by a worse assessment of the running characteristics and speed of movement of the cuts. Unlike automatic systems, which are capable of obtaining quantitative evaluations, operators evaluate these values only qualitatively: "good runner", "bad runner", "very fast", "fast", "slow", etc. The decrease in the area of permissible braking modes at a non-mechanized braking position compared to a mechanized one is explained by the limitation of the speed of the cuts entering the shoe, the lower power of the braking position and the need for systematic use of the decelerators of the descent part of the hump not only for interval, but also for aimed adjustment of the speed of the cuts. The perimeter of area $\Omega_{a,i}$ is 26.8 m/s, area $\Omega_{m,i}$ is 24.8 m/s, area $\Omega_{n,i}$ is 19.6 m/s. According to the research results given in (Kozachenko et al., 2024), the optimal regimes of interval adjustment of the speed of cuts are reached at the boundary of the area Ω_i. Therefore, human participation in the processes of adjusting the speed of rolling cuts leads to the exacerbation of contradictions between the goals of aimed and interval adjustment of the speed of cuts.

For permissible modes within the Ω_i area, the indicator of the quality of the system of aimed adjustment of the rolling speed of cuts is the average value of the "window" – the distance between the actual stopping point of the cut and the aiming point on the sorting track. For the example shown in fig. 6, in the conditions of automatic control of retarders, the average value of the "window" is l_{wa}=0.06 m, in the conditions of mechanized braking positions l_{wm}=0.98 m, in the conditions of non-mechanized braking positions on the sorting tracks l_{wn}=4.11 m. The increase in the mathematical expectation of the "window" value is associated with a worse human assessment of the running characteristics of the cuts and its implementation of braking modes. This causes the need to perform additional shunting work to eliminate gaps between cars on sorting tracks. Thus, the proposed model makes it possible to obtain a quantitative assessment of human influence on the quality of filling the sorting fleet with cars from the time of disbanding of trains.

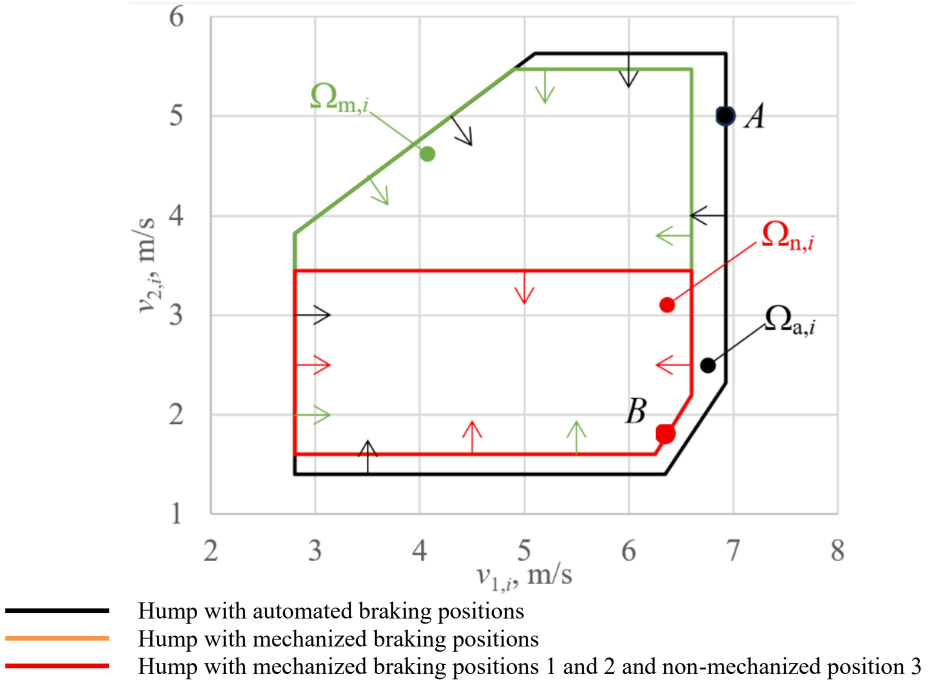

Fig. 7. Areas of permissible braking modes of cuts

The graphic interpretation of condition (3) is presented in Fig. 7 and 8. In both cases, the rolling of the same pair of cuts onto adjacent sorting tracks is considered. The second cut of the pair has better running characteristics and to ensure its separation from the first cut, it must brake. Fig. 8 corresponds to a hump with automatic retarder control. On such a hump, it is necessary to observe an interval between cuts lasting 1 s from the moment of release of the turnout, which divides the following routes into sorting tracks by the first cut, to the moment of its occupation by the second cut. The non-separation of cuts corresponds to the simultaneous occurrence of a random value of the rolling time of the first and second cuts in the zone of non-separation (see Fig. 7). In order for the probability of occurrence of such events not to exceed 0.005, the average interval between cuts on the dividing shift change should be at least 2.3 s. Such conditions are achieved when the first cut is rolling in fast mode and the output speeds of the second cut are set $v_{1,2}$=6.9 m/s and $v_{2,2}$=5.0 m/s (point A in Fig. 6).

Fig. 9 corresponds to a hump with mechanized braking positions on the descent part and non-mechanized braking positions on the sorting tracks. The speed control mode in this case requires a further decrease in the speed of the second cut to ensure a time interval sufficient for the transition of the speed controller of the cars between the tracks. Due to the poor predictability of the cut sliding time at low speeds, the mathematical expectation of the interval between cuts should be at least 24.2 s. An increase in the time interval between cuts is achieved by reducing the speed of movement of the second cut and setting the exit speeds of its exit from the braking positions $v_{1,2}$=6.4 m/c and $v_{2,2}$=1.8 m/c (point B in Fig. 7). As a result, this leads to a worsening of the conditions for aimed adjustment of the speed of its movement and the conditions for the separation of the second cut with subsequent cuts.

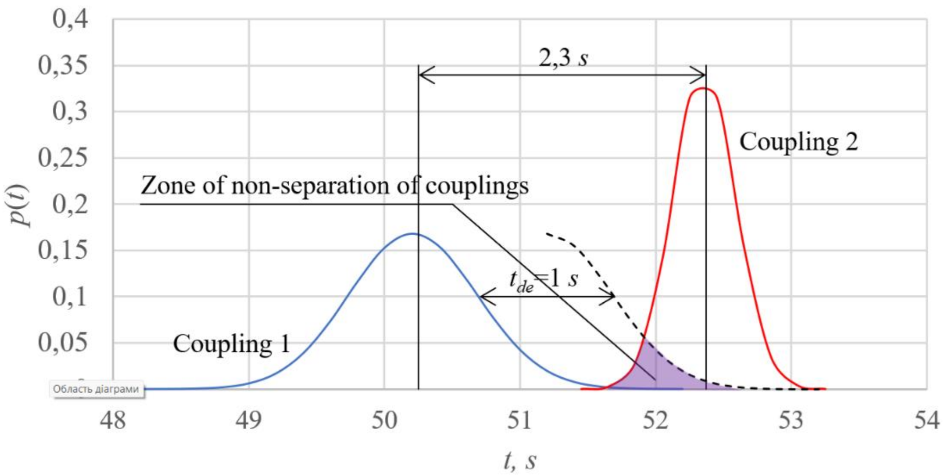

Fig. 8. Separation of cut on the shift change of the sorting hump with automated brake positions

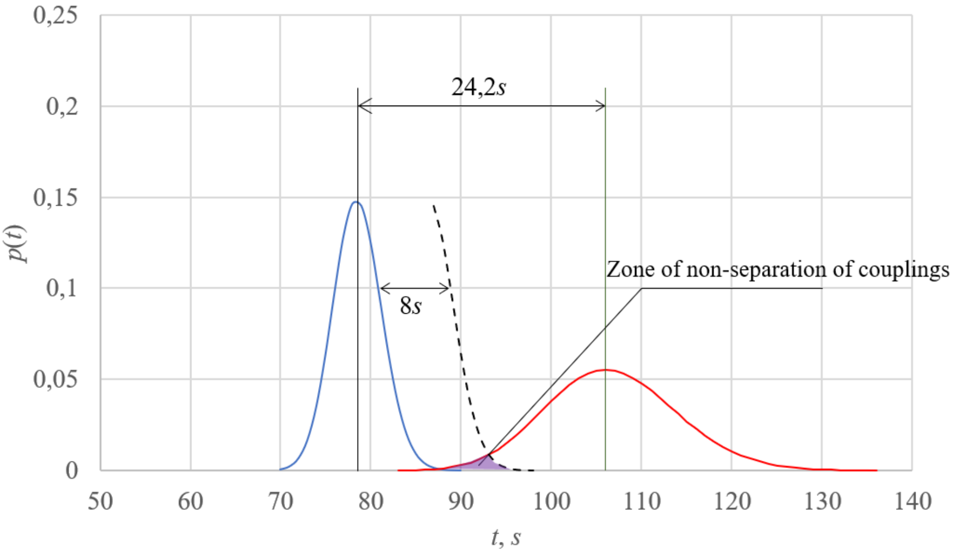

Fig. 9. Separation of cuts on the shift change of the sorting hump with mechanized braking positions on the descent part and non-mechanized braking positions on the sorting tracks

For a comprehensive assessment of the human influence on the conditions of interval regulation of the speed of rolling of cuts, the disbanding of a train of 15 cuts on a sorting slide was considered, a fragment of which is shown in fig. 3. The parameters of the composition are indicated in the table. 2. The table indicates l_{tg} – the distance from the top of the hump to the cars on the sorting tracks; PL – platform car; PV – semi-car; KR – covered car; CS – tank car.

The optimal time-consuming mode of disbanding the train on the hump with mechanized braking positions on the descent part and non-mechanized braking positions on the sorting tracks is given in the table 3.

Table 2. Parameters of the disbanding trains

Cut №	Car №	Type	Train mass	l_{tg}, m	Destination track	Cut №	Car №.	Type	Train mass	l_{tg}, m	Destination track
1	1	PL	42	412	14	7	12	CS	77	422	13
2	2	PV	71	467	11	8	13	PV	85	437	14
	3	PV	71			9	14	PL	79	504	16
	4	PV	71				15	PL	79		
3	5	CS	22	486	17	10	16	PV	30	474	17
	6	CS	22			11	17	CS	80	787	14
4	7	KR	54	504	11	12	18	PV	58	1085	12
	8	KR	54				19	PV	58		
5	9	CS	80	787	13	13	20	PL	80	669	15
6	10	KR	65	492	18	14	21	PV	70	462	17
	11	KR	65			15	22	PV	78	1070	12

Table 3. Time-optimized train disbanding mode on the hump with mechanized braking positions on the descent part and non-mechanized braking positions on the sorting tracks

Cut	*1*	*2*	*3*	*4*	*break*	*5*	*6*	*7*	*8*
v_p, m/s	*1.7*					**1.7**			
Mode	*FM*	*FM*	*FM*	*FM*		*FM*	*FM*	*FM*	*FM*

Cut	*break*	*9*	*10*	*break*	*11*	*12*	*13*	*14*	*15*
v_p, m/s		*1.7*			*1.7*				
Mode		*FM*	*FM*		*FM*	*Separation with cut 11 on arrow 4*	*FM*	*Separation with cut 13 on arrow 4*	*FM P*

Rolling of all cuts can be carried out in fast mode (FM), with the exception of cuts 12 and 14, the braking modes of which are selected from the conditions of ensuring their separation, respectively, with cuts 11 and 13 on the arrows of the descending part of the hump. In order to ensure sufficient time intervals for the transition of the speed controller between the sorting tracks, breaks should be provided between 4 and 5, 8 and 9, 10 and 11 cuts. The total time for disbanding the train under manual control is 4.0 minutes. In contrast, on an automated hump, the same train can be processed at a constant speed of 1.7 m/s without interruptions, resulting in a total time of 3.0 minutes. The obtained results demonstrate that ensuring operational safety when humans are involved in controlling the rolling speed of car cuts necessitates a reduction in the humping rate to accommodate the conflicting requirements of interval and target speed regulation. Thus, the proposed model enables a quantitative assessment of human influence on the duration of the disbanding process. Furthermore, these results can be integrated into comprehensive sorting yard simulation models (Bobrovskiy et al., 2014; Dick, 2021) to evaluate the potential impact of automation on overall station performance.

4. Scientific novelty and practical significance

The scientific novelty of the work consists in the improvement of the model of the formation of trains on the sorting humps, which, unlike the existing ones, allows to take into account the influence of operators of brake positions and speed regulators of cars on the indicators of the sorting process.

The practical significance of the work lies in the fact that its results make it possible to improve the methods of evaluating the effectiveness of the implementation of automated train disbanding control systems, as well as to develop information and advisory systems for speed planning and breaks in the disbanding of trains, taking into account the inaccurate assessment of the running characteristics of cuts and the implementation of their braking modes by brake position operators and car speed controllers.

5. Conclusion

Disbanding and forming of freight trains and shunting gears on sorting humps is one of the main processes in railway transport. To date, technical systems have been created that are capable of managing the sorting process on humps in automatic mode. However, due to the high cost of construction and operation of such systems, they are typical for only a small number of the most powerful sorting stations. At the same time, management of the process of disbanding trains at the majority of stations is carried out with the participation of people as operators of mechanized brake positions or speed regulators of cars. The lack of models of disbanding of trains, which take into account the participation of people in the control of the rolling speed of cuts, on the one hand, makes it difficult to obtain reliable estimates of the effectiveness of measures for the automation of sorting humps, and on the other hand, limits the possibility of using computer technology for planning disbanding.

As a result of the performed research, the simulation model of the process of disbanding of trains was improved, which takes into account the ergatic and stochastic nature of the functioning of the sorting hump as a system. In order to take into account the human participation in the process of disbanding the trains in the simulation model, additional restrictions are set on the choice of braking modes of cuts, which are associated with the need to switch the attention of the operator during the simultaneous control of several braking positions, as well as with the transition of the regulator between different tracks. In order to take into account the lack of accurate information about the characteristics of cuts and the conditions of their rolling, the evaluation of indicators of the sorting process is carried out on the basis of a series of calculation experiments on rolling of cuts under the influence of random factors.

The use of modelling makes it possible to evaluate the impact of human participation in the process of controlling the rolling speed of cuts on humps in comparison with sorting humps where automatic control of retarders is implemented. For the performed experiments, the average distance from the cut stop point to the cars standing on the sorting track on a hump with a non-mechanized brake position is 68.5 times greater than the same indicator for a hump with automated brake positions, the duration of train disbandment on a hump with a non-mechanized brake position is 1.33 times higher than the same indicator for a hill with automated brake positions. The reasons for this are the lower accuracy of a person's assessment of the driving characteristics of cuts and environmental conditions, the lower braking power of the shoe braking position compared to brake retarders, and the presence of additional restrictions on the braking modes of cuts.

The consequence of human participation in the process of controlling the speed of rolling of the cuts is a decrease in the rate of disbanding of the trains, and accordingly, the processing capacity of the sorting humps. At the same time, the developed model allows to establish safe modes of disbanding of compositions taking into account the uncertainty that a person brings to the sorting process. On sorting humps that have reserves of processing capacity, the use of this approach allows for the creation of cheap information and reference systems that are able to establish safe disbanding modes depending on the quality of input information about the sorting process and the accuracy of control of the speed of cuts.

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