The influence of random factors on the estimation of the speed and time of rolling cuts from sorting humps

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Abstract. The main direction of increasing efficiency and safety of the work of sorting humps is the management automation of breaking-up of trains. The difficulty of solving this problem is due to the fact that it is solved in the absence of accurate information about the running characteristics of the cars, the parameters of their routes of rolling and environmental conditions. In addition to this, car retarders implement given modes with errors. The purpose of this study is to assess the influence of various random factors on the indicators of cars rolling from the sorting humps. The research was carried out using methods of simulation modeling, planning of factorial experiments and statistical analysis. As a result, it was established that the main factors affecting the mean square deviation of the time of the cars rolling are the distance of unregulated rolling and the specified speed of the cut leaving the car retarders. The research results make it possible to improve algorithms for determining braking modes for retarders in the absence of accurate information to solve the problem.

1 Introduction

1.1 Relevance of the paper

The breaking- and making-up of freight trains and cars' groups is one of the most massive processes both on the main line and on industrial railway transport. Sorting humps are the main means of breaking up and making up of the freight 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. The most complex process that takes place during breaking-up of trains is the process of controlled rolling of the cars down the hump. Scientific studies of this process began at the beginning of the 20th century, and this problem has not lost its relevance to the present time.

Considering the high cost and risk of dangerous events occurring during physical experiments on real-life sorting humps, scientific observation and mathematical modeling are the main methods of scientific research in the process of cuts rolling down the humps. Therefore, the topic of this work, aimed at improving the models of cars rolling down humps, is an urgent task for railway transport.

1.2 Literature review

The controlled objects at the humps are rolling single cars and groups of coupled cars that are called cuts. The mathematical model's development of the process of rolling cuts from sorting humps began at the beginning of the 20th century. Initially, the need for such models was associated with the tasks of determining the height and designing the longitudinal profile of sorting humps. In the future, the rolling cuts models were developed and today they are the main tool for solving various problems of evaluating design options and technical facilities of sorting humps. Articles [1-6] are devoted to the problems solving of improving the design of sorting humps and yards. It should be noted that at the design stage, calculated cuts with known parameters and their various unfavorable combinations are mainly considered. This approach allows you to assess the performance of the sorting hump, but does not allow you to assess its technical and operational indicators.

The next stage of the mathematical models development of the process of rolling cuts down from the sorting humps was connected with the automation of the process of breaking up the trains. The first station in the world equipped with such a system was the North Platt station (USA) built in 1948. The development of computer technology has made it possible to create complex systems for managing the breaking-up of trains, which will continue to develop [7, 8]. At the same time, both the results of observations [9, 10] and the results of theoretical studies [11, 12] show that the process of breaking-up of trains is influenced by a large number of random factors. The lack of accurate information about the running characteristics of the cuts and their rolling conditions significantly complicates decision-making on

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the choice of modes of interval and targeted regulation of the rolling speed of the cuts. One of the approaches to the solution of the problem of automatic control of the breaking-up of trains is its solution in a deterministic setting [13] by replacing the values of random variables with their mathematical expectations and improving the quality of the evaluation of the running characteristics of the cuts and the accuracy of the implementation of the specified braking modes by the retarders. Such approach requires the complication of the technical means of sorting humps, and therefore is associated with an increase in the cost of their construction and operation. On the other hand, the majority of sorting humps are still operating under the conditions of retarders' control by operators. At the same time, despite the absence of accurate information about the running characteristics of the cuts and their rolling conditions, the operators are able to provide acceptable indicators of the sorting process. The research results, presented in [14], indicate the existence of significant areas of admissible modes of cuts, which ensure the fulfillment of the conditions of interval and targeted speed regulation of cuts. The rolling cuts on the sorting humps has a mass character. Therefore, their parameters are subject to statistical processing both for network conditions and for a separate sorting hump. This creates the conditions for solving the problem of automatic management of the breaking-up of train in a stochastic setting. With this approach, either control modes are defined that provide the necessary indicators of interval and aiming adjustment with the speed of rolling cuts with a given probability, or, if this is not possible, interruptions in the breaking-up are provided. In order to solve such problems, it is necessary to improve the mathematical models of the rolling cuts in order to obtain statistical estimates of the speed and time of movement of the cuts on their rolling routes.

1.3 Problem statement

In this study, the solution to the problem of modeling the rolling cuts before the start of the breaking-up of trains is considered. The purpose of this study is to assess the influence of various random factors on the indicators of movement of cars from the sorting humps. The research was carried out using methods of simulation modeling, planning of factorial experiments and statistical analysis.

2 Methodology

The results of observations of the operation of the sorting humps show that the movement supports of the cars are not only random in nature, but also change during their rolling due to the change in environmental conditions, as well as due to the interaction of the cars with the rail track and retarders. Considering the fact that this study is focused on solving the problem of choosing the modes of braking cuts before the start of the breaking-up, a simplified model was used for the simulation experiments, when the running resistances are constant during the rolling of cuts, but are unknown to the experimenter.

2.1. Modeling rolling of cars from a hump.

The research was carried out for a sorting hump equipped with two positions of clasp retarders at sloping part (master retarder and group retarder). In this study, the cut is considered as an inextensible flexible rod. The cut's position on the rolling route is given by one coordinate *s*, which corresponds to the distance between the position of its first axis and the top of the hump in meters. A differential equation of motion is used to describe the process of a cut rolling down a hump, in which the independent variable is the displacement

$$ds = \frac{10^3\left(1+\dfrac{0,42n}{Q}\right)vdv}{g\left[i(s)-w_0-w_sc(s,v)-w_ew(v)-b(s,r)\right]},$$

where v is the speed of the cut at point s, m/s; g - acceleration of free fall, m/c2; $i(s)$ is the reduced slope of the track under the cut, ‰; w_0 – the main specific resistance of the cut movement, N/kN; $w_{sc}(s,v)$ – specific resistance to the cut movement from curvilinear sections and turnouts depending on its coordinate and speed of movement, N/kN; $w_{ew}(v)$ – the specific resistance of the cut to the environment and the wind depending on the speed of its movement, N/kN; $b(s, r)$ - the specific resistance to the movement of the cut from the retarders depending on its coordinate and the selected braking mode r, N/kN; n – the number of axles in the branch line; Q is the mass of the cut, i.e. The solution of this equation leads to the well-known recurrent expression, which is widely used until now for modeling the free rolling cuts

$$v_j^2 = v_{j-1}^2 + \frac{\left(s_j - s_{j-1}\right)}{10^3\left(1+\dfrac{0,42n}{Q}\right)}\times$$
$$\times g\left[i(s)-w_0-w_sc(s,v)-w_ew(v)-b(s,r)\right], \qquad (1)$$
$$j=\overline{1\ldots k},\ s_0 = s_{dr},\ v_0 = v_{thr}.$$

where k is the number of sections into which the rolling route is divided; s_{dr} – coordinate of separation of the branch from the train or locomotive, *m*; v_{thr} is the speed of the rolling stock moving up the hump, m/s.

The rolling time of the cut from the moment of separation to the point s_j is determined by the expression

$$t_j = t_{j-1} + \frac{2\left(s_j - s_{j-1}\right)}{v_{j-1}+v_j},\ t_0 = 0\,. \qquad (2)$$

It should be noted that the solution to the equation of motion of the cut on the basis of expression (1) is approximate, and its accuracy depends on the selected distance step (s_j-s_{j-1}). Modern computers allow you to take rather small steps of the distance and practically eliminate the calculation error for this reason.

Controlled variables in expression (1) are the initial speed of the cut v_0 and the braking mode r. On the basis of calculations according to formula (1), checks of the admissibility of the rolling speed of cuts are carried out at certain control points (cut entry into and out of retarders, release of the switch zone, approach to cars on the sorting tracks), which have the form

$$v_{min,j} \le v_j \le v_{max,j} \,. \quad (3)$$

where $v_{\min,j}$, $v_{\max,j}$ are respectively the minimum and maximum allowable cut speeds at point s_j, m/s.

On the basis of calculations according to formula (2), check the conditions of separation of cuts on separation elements (turnouts and retarders). At the same time, the value of the interval between cuts on the dividing element is determined by the expression

$$\delta t_p = d_p + t_{p+1} - \tau_p ,\ p = \overline{1, c-1}, \quad (4)$$

where d_p is the initial interval at the top of the hump in the p pair between the p and p+1 cuts, c; t_{p+1} is the time required for rolling the p+1 cut from the moment of detachment from the train to the moment of occupation of the isolated section of the separating element with the p cut, c; τ_p is the time required for rolling the p cut from the moment of detachment from the train to the moment of release of the isolated section of the separation element with the p+1 cut. The possibility of separation of cuts on the separation element is determined by a condition

$$\delta t_p \ge t_{sep,\,p} \,, \quad (5)$$

where $t_{sep,\,p}$ is the minimum time required to change the state of the separating element between the cuts of the p pair, c.

The difficulty of estimating the conditions of rolling cuts (3) and (5) is due to the fact that the exact values of expression (1) are unknown. Therefore, the obtained estimates are probabilistic in nature.

2.2. Parameters of cuts and characteristics of their humping conditions.

2.2.1 The mass of the cut.

The mass of the cut Q is defined as the total gross mass of the cars included in its composition. Parameter Q is included in expression (1). In addition, on the basis of data on the mass of cars, their weight category is determined and the magnitude of the reduced slope and movement resistance for multi-car cuts are calculated. Before the breaking-up of the train, the mass of its individual cars is determined according to the data of the transport documents. The tare weight of the car can be determined by its number, the weight of the cargo in the car is determined during loading by various methods (weighing on scales, by stencil, by standard, by measurement, conventionally and by calculations). During movement, the mass of the car may change both due to the loss of cargo for various reasons, and due to the entry of atmospheric moisture and snow into the wagon. A comparison of the mass of cars determined by transport documents and by weighing data shows that the deviation of the real mass of the car from the mass determined by transport documents ΔQ is a random variable subject to the normal distribution law. The estimation of the parameters of the distribution law was carried out based on the results of the observation of the incoming flow of cars on the private siding of Transinvestservice LLC. It showed that the mathematical expectation of the value ΔQ is close to 0, and the mean square deviation is 1.5 tons. For sorting humps, where weights are installed on the push track, the parameters of the law of deviation of the value ΔQ can be determined individually.

2.2.2 Resistance of the cars motion.

The main resistance to the car motion is the result of the action of a number of random factors, such as the friction of the wheel pairs axles in the bogies, the rolling friction between the wheels of the car and the rails, the impact of the wheels on the joints, uneven tire wear, misalignment of the axles, etc.

The main specific resistance to a single car motion is a random variable that obeys the gamma distribution and in a separate experiment during simulation modeling can be determined as

$$w_0 = -\frac{1}{b}\ln\left(\prod_{j=1}^{a} R_j\right),$$

where a, b are parameters of the gamma distribution depending on the weight category of the tap; R_j are random numbers uniformly distributed in the interval [0, 1].

The resistance value to the car motion from curved sections and from turnouts is proportional to the square of the speed of the turnout. The value of the specific resistance of the cut movement from curved sections and from turnouts in a separate experiment can be determined by the expression

$$w_{sc} = -\frac{\left(0{,}56m_s + 0{,}23\sum \alpha_c\right)1}{8000 l_{sc}}\ln\left(\prod_{j=1}^{a} R_j\right),$$

where m_s – number of turnouts; $\Sigma\alpha_c$ – sum of swerve angles, deg; l_{sc} – length of turnouts and curves, m.

The resistance value to the car motion from the environment and wind is proportional to the square of the relative speed of the branch and air masses v_{rl}.. At the same time, the wind in the surface layer is usually characterized by irregular pulsations of speed and changes in direction. For example, Fig. 1 shows the results of wind speed measurement during the dissolution of one train. The blowing area of cars depends on their design features, and for open rolling stock, on the cargo loaded into it. In a separate experiment, the amount of wind load can be determined by the expression

$$w_{ew} = c_{ew} v_{rl}^2 \left(1 + k_{ew} Z\right),$$

c_{ew} – the air resistance coefficient, which depends on the parameters of the car cuts and the ambient temperature; k_{ew} – coefficient characterizing the variability of wind pressure, k_{ew}=0,12-0,16; Z – a random number from a standard normal distribution.

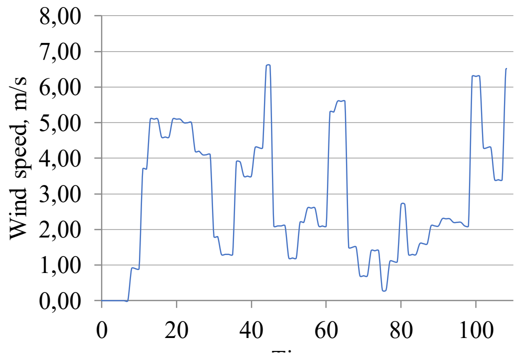

Fig. 1. Wind speed change graph during breaking-up.

2.2.3 Braking force of car retarders.

The main controllable parameter of the rolling process of the cuts is the speed of the cut leaving the car retarders. The braking force of the beam-type retarders is created due to the friction of its tires against the wheels of the cars. The magnitude of the braking force is determined by the expression
where P_{tw} - the pressure force of the retarder tire on the wheel, H; μ - friction coefficient of the wheel against the tire of the retarder; h_b - height of the retarder tire above the rail head, m; R_w - external radius of the wheel rim, m.

It should be noted that the values of parameters μ and R_w are random. The P_{tw} value for pneumatic retarders is also random. In this regard, the amount of kinetic energy of the cut (braking power), which can be extinguished by the retarder, is a random value. In the case when it is necessary to extinguish the kinetic energy less than the braking force of the retarder allows, the hump operator or the automated control system varies the degree of braking and the distance traveled by the cut in the braked retarder. Braking stops when the predicted cut exit speed corresponds to the set value. Due to errors in estimating the running characteristics of the cuts and the braking force of the retarders, the actual speed of their exit from the retarders $v_{ex,p}$ differs from the specified $v_{d,p}$. According to the results of the observations, the braking force of the retarders and the error of realization of the specified speed of the cuts from the retarder position are random variables with a normal distribution law. When simulating the rolling process of cuts through the retarder position, the speed of cut exit from it is set according to the normal distribution law as

$$w_{ex,\,p} = v_{d,\,p} + \sigma\left[v\right]_p Z,$$

where $\sigma\left[v\right]_p$ – mean square deviation of the actual speed of the cut exit from the retarder position from the set point.

Also, according to the normal distribution law, the braking force of the retarder and the braking specific resistance $b_{\max,p}$, which corresponds to it, are set. According to the simulation results, the maximum possible cut speed leaving the retarder position $v_{\max,p}$ is set, provided it passes without braking at b_p=0, and the minimum possible cut speed leaving the retarder position $v_{\min,p}$ provided its full braking force is used at b_p=$b_{\max,p}$. If $v_{ex,p}$>$v_{\max,p}$, it is accepted b_p=0, $v_{ex,p}$=$v_{\max,p}$; else if $v_{ex,p}$<$v_{\min,p}$, it is accepted b_p=$b_{\max,p}$, $v_{ex,p}$=$v_{\min,p}$; otherwise the value of the specific braking resistance in expression (1) is set on the basis of ensuring the speed of exit from the braking position.

2.2.4 Other random parameters for rolling conditions

The train is pushed up the hump by a shunting locomotive. The specified speed of breaking-up is implemented with an error, the value of which has a normal distribution law.

Determining the position of car on sorting tracks is carried out by a system for controlling their filling. The law and parameters of the distribution of the random value of the distance to the aiming point depend on the type of track filling control system. For systems implemented on the principle of shunting, the distance to the aiming point is a random value distributed uniformly in the interval [$s_{c,d}$, $s_{c,d}$+$l_{c,d}$] (here $s_{c,d}$, $l_{c,d}$ – accordingly, the start coordinate and the length of the first occupied isolated section of the plot). For systems implemented on the principle of pulse sensing, the distance to the aiming point is a random value distributed according to the normal distribution law.

2.3. Software implementation of the model of rolling cuts.

The described model is implemented in the C++ language in the form of a software complex for simulating the rolling cuts. Determining the parameters of the process of controlled rolling is a series of simulation experiments in each of which a set of random parameters of the rolling and its rolling conditions is formed, and for them the curves of speed $v(s)$ and rolling time $t(s)$ are constructed. An example of such curves is presented in Fig. 2.

Also, the results are presented in the form of text protocols for statistical processing.

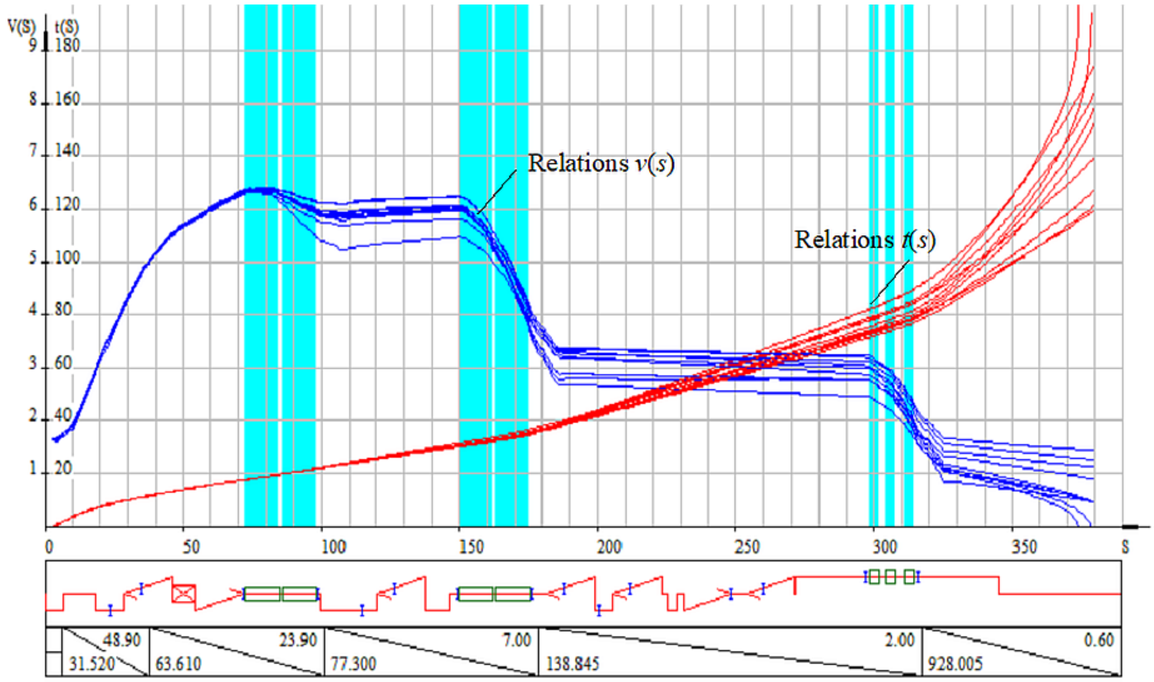

Fig. 2. Speed curves $v(s)$ and time curves $t(s)$ of the rolling cut obtained on the basis of a series of computational experiments.

3 Results

The processing of the rolling results for a certain coordinate s allows determining the parameters of the distribution of random values of the time of entry and exit of the cuts to the separating elements, the speed of entry of the cuts into the retarder and their coupling speed with the cars on the classification tracks, etc. An example of a histogram of the distribution of a random value of the time of rolling from the moment of separation to the occupation of the isolated section of the fifth turnout in Fig. 3.

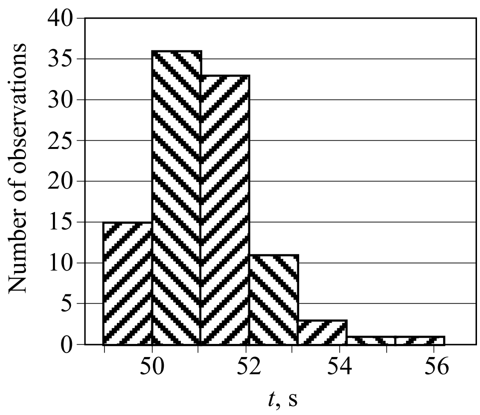

Fig. 3. Histogram of the distribution of the random value of the rolling time from the moment of separation to the occupation of the isolated section of the fifth dividing turnout.

One of the main factors that affect the mean square deviation of the random value of the rolling time of the cut to some turnout on the route is the distance of unregulated rolling and the speed of the cut leaving the retarders. Fig. 4 shows the dependence of the mean square deviation of the rolling cut time σ[t] on the exit speed from the group retarders v_{gr} for different rolling distances after this position s_{gr}. Analysis of these dependencies shows that they are significantly non-linear.

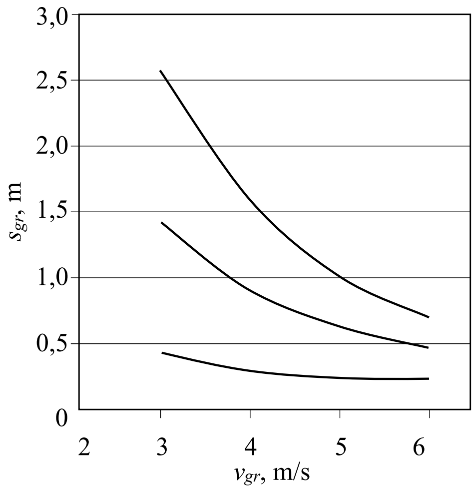

Fig. 4. Dependences of the mean square deviation of the time of cut's rolling on the exit speed from the group retarders

At a close to constant speed of cut's rolling along the turn zone v in a separate experiment, the error in determining the time required to overcome the distance l can be calculated by the formula

$$\Delta t = \frac{l}{v} - \frac{l}{v+\eta} = \frac{l\eta}{v^2 - v\eta},$$

where η - error in estimating the cut speed, m/s.

In cases where the cut speed significantly exceeds the error of its estimation, it can be assumed that the error in the estimation of the cut time will be inversely proportional to the square of the cut speed.

To assess the influence of various factors on the mean square deviation of the cut motion time σ[t], a full factorial experiment was performed according to plan 2^5 to identify the model

$$\sigma[t] = f\left(n, q, \sigma\left[v_{gr}\right], l, 1/v_{gr}^2\right),$$

where q – the average weight of the car at the cut, t; v_{gr} – specified cut exit speed from the group retarder, m/s; σ[v_{gr}] – mean square deviation of the cut exit speed from the group retarders, m/s.

Factors and levels of their variation in model identification experiments σ[t] presented in the table. 1.

Table 1. Factors and levels of their variation in model identification experiments σ[t]

Factor	Parameter	Levels	
		Lower x=-1	Upper x=-1
x_1	n	4 axles	12 axles
x_2	q	25 t	83 t
x_3	σ[v_{gr}]	0,1 m/s	0,3 m/s
x_4	l	50 m	150 m
x_5	$1/v_{gr}^2$	1/36 (s/m)^2	1/9 (s/m)^2

After processing the results of the experiments, a polynomial of the first degree was obtained, which characterizes the dependence between the mean square deviation of the cut motion time and the factors that affect it

$$\sigma[t]=1{,}1-0{,}21x_1-0{,}22x_2+0{,}44x_3+0{,}79x_4+0{,}64x_5+ \\ +0{,}33x_3x_4+0{,}27x_3x_5+0{,}55x_4x_5+0{,}22x_3x_4x_5.$$

The analysis of the coefficients of the given polynomial shows that the main factors affecting the average square deviation of the rolling cut time are the distance of unregulated rolling and the specified cut speed leaving the retarder. As a result, the separation elements located further from the retarder positions will be characterized by larger mean square deviations of the tripping time of the cuts and the separation intervals between them in comparison with the separation elements located closer. For example, in Fig. 5. the density functions of the distribution of intervals between cuts on the fifth and third points along the rolling route are given. It should be noted that both samples have the same mathematical expectation of the size of the separation interval, however, due to the difference in the mean square deviation of the size of the intervals, the conditions of their separation will be significantly different.

The specified speed leaving cuts from the retarders affects not only the mathematical expectation of time consumption $t(s_p)$ to overcome the distance by the cut s_p, but also on the mean square deviation of this time σt. Larger average squared time deviations are characteristic for lower speeds of the leaving cuts from retarders $t(s_p)$, and, accordingly, larger time reserves are needed to ensure reliable separation of cuts according to condition (5).

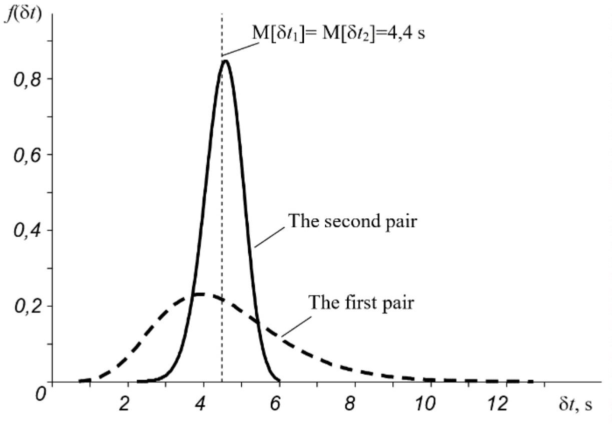

Fig. 5. Density functions of the distribution of random values of the intervals between cuts in the first pair on the fifth turnout and in the second pair on the third turnout.

4 Scientific novelty and practical significance of work

The scientific novelty of the work lies in the fact that it presents an improved model of the cuts' rolling from sorting humps, which allows taking into account the influence of random parameters of cuts and their rolling conditions. The research results make it possible to improve algorithms for determining braking modes for work in the absence of accurate information to solve the problem.

5 Conclusions

The investigations performed make it possible to draw the following conclusions:

1. The process of cuts' rolling takes place under the influence of a large number of random factors that significantly affect the speed and time motion of the cut along the routes. The cuts' rolling on the sorting humps has a mass character. Therefore, their parameters are subject to statistical processing both for network conditions and for a separate sorting hump. This creates conditions for solving the problem of automatic control of the train breaking-up in a stochastic setting.
2. In the work, the simulation model of cuts' rolling has been improved, which allows taking into account the inaccuracies of estimates of the main motion resistance, motion resistance from the environment and wind, turnouts and curves, as well as the inaccuracy of the implementation of specified braking modes by retarders. The software implementation of the specified model allows you to obtain statistical estimates of the speed and time motion of the cuts along the routes.
3. The main factors affecting the mean square deviation of the time motion of cut along the route are the distance of unregulated rolling and the specified exit speed of the cut from the retarders. Larger average

squared deviations of the rolling cut time will be characteristic for the dividing elements located further from the retarders and for the lower speeds of the cuts leaving the retarders. These properties must be taken into account in order to determine the time reserves on the separating elements, sufficient to ensure the requirements of the interval adjustment of the rolling cuts speed with a given probability.

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