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PROBABILISTIC APPROACH FOR THE DETERMINATION OF CUTS PERMISSIBLE BRAKING MODES ON THE GRAVITY HUMPS

Summary. The paper presents the research results of cuts braking modes on the gravity humps. The objective of this paper is developing the methods for assessment of braking modes of cuts under conditions of fuzziness of their rolling properties, as well as selecting the permissible starting speed range of cuts from retardant positions. As a criterion for assessing the modes of target control of cut rolling speed, it was proposed to use an average gap size on a classification track at the established norms of probable exceeding of permissible speed of cars collision and their stop in retarders. As a criterion for evaluating the modes of interval control of cuts rolling speed, using the risk of their non-separation on the switches was proposed. Using the simulation modeling and mathematical statistics, the configuration of the range of permissible speed of cuts coming out from retardant positions has been set. The conducted researches allow simplifying the choice of cut braking modes in systems of automatic control of cut rolling speed.

ВЕРОЯТНОСТНЫЙ ПОДХОД К ОПРЕДЕЛЕНИЮ ДОПУСТИМЫХ РЕЖИМОВ ТОРМОЖЕНИЯ ОТЦЕПОВ НА СОРТИРОВОЧНЫХ ГОРКАХ

Аннотация. В статье представлены результаты исследований режимов торможения отцепов на сортировочных горках. Целью статьи является разработка методов оценки режимов торможения отцепов в условиях неопределенности их ходовых характеристик, а также поиск области допустимых скоростей выхода отцепов из тормозных позиций. В качестве критерия для оценки режимов прицельного регулирования скорости скатывания отцепов предложено использовать среднюю величину окна на сортировочном пути при установленных нормах вероятности превышения допустимых скоростей соударения вагонов и остановки их в замедлителях. В качестве критерия для оценки режимов интервального регулирования скорости скатывания отцепов предложено использовать риск их неразделения на стрелках. С помощью методов имитационного моделирования и математической статистики установлена конфигурация области допустимых спcolumnростей выхода отцепов из тормозных позиций. Выполненные исследования позволяют упростить решение задачи выбора режимов торможения отцепов в системах автоматического управления скоростью их скатывания.

1. INTRODUCTION

Gravity humps are basic technical facility, which provides breaking-up and making-up of freight trains. Automation of sorting process is the main direction of improvement of safety in trains breaking-up, improvement of working conditions and reduction of operational costs for processing car traffic volume on hump yards. Nowadays different automation systems of hump operations are developed [1-5]. It should be pointed out that such systems PROYARD III, Star II, MSR-32 are expensive complexes, equipped with plenty of various sensors and complex systems for control of stop blocks. At the same time hump conductors successfully deal with sorting process proceeding from their own experience. In this respect solution of tasks for sorting process automation to a large extent depends on improvement of algorithms for automation of trains splitting-up control. It allows to rise sorting process quality due to software upgrading, but not due to complication of technical facilities and, thus, to reduce cost of splitting-up control systems.

2. LITERATURE REVIEW AND DEFINING THE PROBLEM

On large Ukrainian hump yards three-position gravity humps equipped with beam stop blocks are used. Control of speed of cuts rolling over a hump is one of basic tasks to be solved while breaking-up trains. Purposes being achieved due to this are related to ensuring of cuts separation on point switches and stop blocks on their rolling routes, ensuring of permissible speeds of cuts running on stop blocks, permissible speeds of cuts reaching cars standing on marshaling tracks, achievement of maximum filling of marshaling tracks without gaps.

Automated control of rolling speed of cuts is based on a mathematical model of its motion along the hump.

In the process of rolling the gravity force effects on the cut, as well as motion resistance forces: main resistance (friction of car parts with each other, wheels friction over rail track, wheel impact over rail track in joints etc.), environmental and wind resistance, resistance due to points and curves, resistance of car stop blocks [6-7]. At that the rolling process of the cut can be described with a differential motion equation, which independent variable is a route

$$ds = \frac{vdv}{g'\left(i(s) - w_r - w_{sc}(s,v) - w_{ew}(v) - b_r(s)\right)} \tag{1}$$

where: g' – is gravity acceleration, considering inertia of rotating masses, m/s$^{2;}$ s – is distance from top of the hump to the first axle of the cut being rolled down, m; v – is motion speed of the cut, m/s; $i(s)$ – is reduced slope under the cut, ‰; w_r – is main specific motion resistance, N/kN; w_{sc} – is specific resistance due to points and curves, N/kN; w_{ew} – is specific environmental and wind resistance, N/kN; b_r – is specific resistance being created by car stop blocks, N/kN.

The abovementioned equation is solved through numerical computations [8].

Rolling speed of cuts is controlled due to action of stop blocks on cars and their creation of additional resistance force. Herewith controllable parameters are speeds of cuts coming out of retarder positions specified by control system. These speeds form braking mode of the cut

$$\mathbf{v} = \{v', v'', v'''\}. \tag{2}$$

Braking modes selection is limited with a set of conditions.

In particular, braking modes must ensure permissible speeds of cuts running into the second braking position $v_{bp2}^{\max}$, as well as cuts approaching to cars standing on marshaling tracks $v_t^{\max}$

$$\begin{cases} v_{bp2}(v') \le v_{bp2}^{\max}; \\ v_t(v', v'', v''') \le v_t^{\max}. \end{cases} \tag{3}$$

With successive rolling of cuts additional time intervals between them should be provided in order to throw over points and to forward cuts according to their rolling routes. Otherwise the cut will be forwarded to an incorrect track of the break-up yard and an additional shunting work will be necessary to move it to the appropriate track. Also an additional time interval should be ensured for switching over stop blocks between stages while braking of different cuts, otherwise braking mode of the cut will not conform to the calculated one.

The interval value on a point or a stop block between successively rolling cuts is determined from the expression

$$\delta t_i = \theta_i + t_{i+1}(v'_{i+1}, v''_{i+1}) - \tau_i(v'_i, v''_i), \;\; 0 < i < n, \tag{4}$$

where: θ_i – is an initial interval between cuts in *i*-th pair on top of the hump, s; τ_i, t_{i+1} – is time of *i*-th cut rolling from breakaway torque until unlocking a separating element and of the next cut until reserving the separating element, s; n – is number of cuts in a train.

Cuts are separated en route, if:

$$\delta t_i \geq t_{de}, \tag{5}$$

where: t_{de} - is time necessary for functioning of hump automation systems when throwing over a point or switching over a stop block, s.

Intervals between cuts in a train are related to each other. At that increase of interval with the preceding cut, as a rule, results in decrease of interval with the next one. Due to this a group of three cuts is regarded as a design group when solving the task of selection of braking modes of cuts; in this group braking modes of extreme cuts are fixed and braking mode of the middle cut varies.

Solution of task of selecting braking modes of the controllable cut in the design group is given in [8]. Disadvantage of the solution represented in [8] is that it is obtained with known values of motion resistances and exact realization of specified speeds of cuts coming out by retarder positions. In fact, processes taking place on gravity humps are stochastic and all indicated values are random [9-11]. Besides, the fact that conditions of regulation of rolling speed of cuts are inequalities is evidence of existence of a great number of permissible braking modes of cuts. The purpose of this investigation is to select the range of permissible braking modes of the middle cut in the design triplet of cuts under conditions, when motion resistances of cuts and their speeds of coming out of retarder positions are random values.

3. METHODOLOGY

Investigation of rolling of cuts is made by means of software package, which simulates the process of their rolling over a gravity hump [11]. The main window of the software package, simulating cuts rolling with representation of time curves *t=f(S)* of three cuts successively rolling is shown in Fig.1. A plan and a longitudinal profile of rolling routes, parameters of cuts, parameters of distribution of random values of resistances to motion of cut and speeds of its coming out of retarder positions are specified as initial data for simulation. In this investigation rolling down were performed for conditions of the gravity hump with 32 tracks in the break-up yard and 5 separating points along routes of cuts motion. The gravity hump is equipped with two retarder positions on its sloping part after the first and second separating points, as well as the yard retarder position on marshaling tracks. Reference designation of the rolling route is shown in Fig.1 below. When simulating rolling of the cut, a set of parallel experiments with various initial values of the random-number generator is being made. According to the results of rolling the parameters of random values of motion speeds of cuts in characteristic points are determined, as well as time of cuts rolling to these points.

In formalization of task of selection of braking modes of cuts the variables are specified speeds of cuts coming out of retardant positions of the gravity hump.

$$\mathbf{v} = \{v'_d, v''_d, v'''_d\}. \tag{6}$$

It should be pointed out that not all specified speeds can be realized by retardant positions due to their limited capacity.

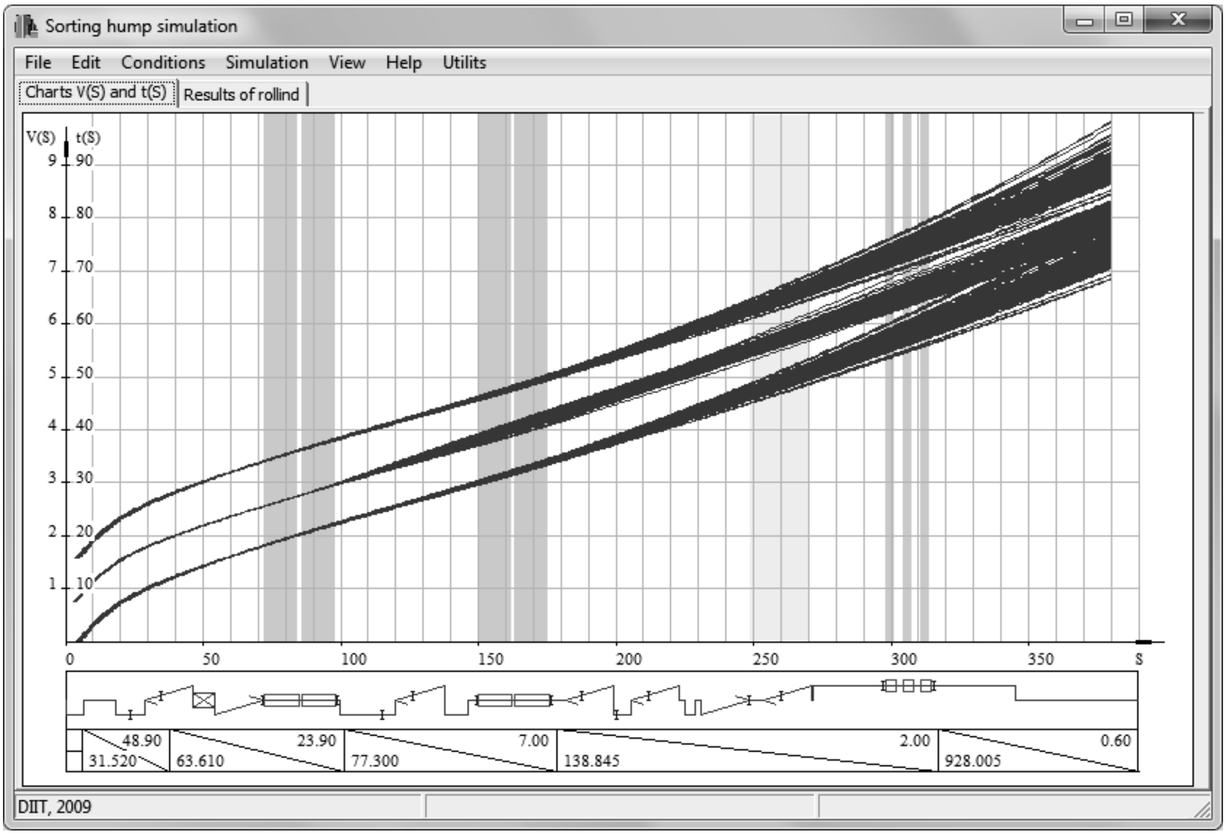

Fig. 1. Main window of the software, simulating cuts rolling from the gravity hump
Рис. 1. Главное окно программы, моделирующей скатывание отцепов с сортировочной горки

In order to decrease scale of the task let us consider the process of target braking of the cut by the third retardant position. An ideal solution of this task is to determine such speed of the cut coming out of the third retardant position v_d''', at which it connects to cars standing on the marshaling track with permissible speed. However owing to lack of exact information about rolling conditions such solution of this task is not applicable to all cases. At that rise of value v_d''' results in improvement of marshaling track filling and decrease of probable size of "gap" between cars $l_g\left(v_d'''\right)$, but simultaneously probability of exceeding the specified speed of cars collision $p_t\left(v_d'''\right)$; reduction of value v_d''' respectively results in the opposite change of indices. With low values v_d''' probability of stopping the cut in the yard retardant position $p_r\left(v_d'''\right)$ rises. Considering that values $p_t\left(v_d'''\right)$ and $p_r\left(v_d'''\right)$ characterize safety of trains breaking-up, they are suggestion to be normalized. As a result, the task of selection of specified speed of cuts coming out of the third retardant position will be as follows:

$$l_g\left(v_d'''\right) \to \min;$$
$$\begin{cases} p_t\left(v_d'''\right) \le p_{t,\max}; \\ p_r\left(v_d'''\right) \le p_{r,\max}, \end{cases} \tag{7}$$

where: $p_{t,\max}, p_{r,\max}$ - are respectively permissible probabilities of exceeding the specified speed of cars collision and stopping the cut in the stop block.

It's worth noting that value v_d''' does not influence conditions of interval regulation of rolling speed of cuts, because the third retardant position is located after the last separating point.

Speed of cuts coming out of the second retardant position v''_d is the factor, which connects conditions of target and interval regulation of rolling speed of cuts. As a result of investigations it is concluded that in solution of the task (7) for every value v''_d the single value $v'''_d\left(v''_d\right)$ can be specified, which corresponds to the best indices of target regulation of rolling speed of cuts, which can be reached under these conditions. According to the results of set of simulation experiments for different values v''_d a dependence of probable size of "gap" on speed of the cut coming out of the second retardant position can be established. General view of such dependence is represented in Fig. 2.

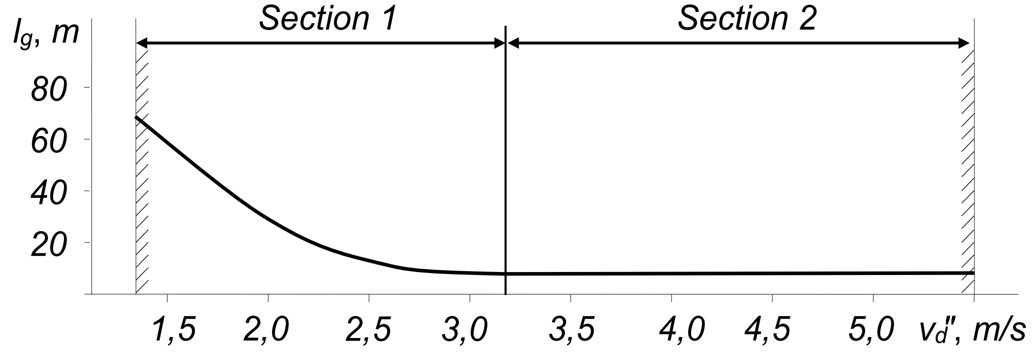

Fig. 2. Dependence of probable size of the gap on speed of the cut coming out of the second retardant position
Рис. 2. Зависимость вероятной величины окна от скорости выхода отцепа со второй тормозной позиции

Speed of cut coming out of the second retardant position is restricted within the limits of $v''_{d,\min} \le v''_d \le v''_{d,\max}$. In cases if $v''_d < v''_{d,\min}$, probability of stopping cuts in the third retardant position or before it exceeds the permissible value even with absence of braking at the latter. In cases if $v''_d > v''_{d,\max}$, probability of exceeding the specified speed of cars collision in the break-up yard exceeds the permissible value even with full-rated braking of cuts at the third retardant position. Within the limits of permissible values of speeds of cuts coming out of the second retardant position two sections can be selected. On the first section $v''_{d,\min} \le v''_d < v''_{dt}$ probable size of the gap in the marshaling track decreases with increase of value v''_d, so if $v''_{d1} > v''_{d2}$, $l_g\left(v''_{d1}\right) > l_g\left(v''_{d2}\right)$. On the second section $v''_{dt} \le v''_d \le v''_{d,\max}$, probable size of the gap is a constant value in spite of v''_d. Thus, a conclusion can be made that conditions of target regulation of rolling speed of cuts restrict permissible speeds of cuts coming out of the second retardant position. Herewith the speed of cuts coming out of the third retardant position depends on cuts coming out of the second retardant position. For this reason representation of braking mode of the cut (6) can be simplified and represented as follows

$$\mathbf{v} = \left\{v'_d, v''_d\right\}. \tag{8}$$

For graphical representation of braking modes of cuts for all of them an appropriate point in the plane can be put. At that permissible rolling modes for a single cut are represented as a closed range Ω_t. Rolling speeds of cuts physically are nonnegative values. Due to this all possible speeds of cuts coming out of retardant positions are in the first quadrant. The marginal or maximum permissible speeds of cuts coming out of retardant positions conform to boundary of range Ω_t. Description of these restrictions is given in Table 1.

An important peculiarity of range Ω_t is that it consists of two sub-ranges Ω_{t1} and Ω_{t2}, separated by line $v''_d = v''_{dt}$. Braking modes of section 1 conform to braking modes in sub-range Ω_{t1} (see Fig.3). Within the limits of this sub-range a change in speed of cuts coming out of the second retardant position results in a change of indices of target regulation of cuts rolling speed. Braking modes of section 2 conform to braking modes in sub-range Ω_{t2} (see Fig.3). Within the limits of this sub-range indices of target regulation of cuts rolling speed do not depend on braking modes at retardant positions on the sloping part of the hump and have constant values.

Table 1

Restrictions of permissible rolling modes of a single cut

No.	Description
1	Modes with maximum permissible speeds of cuts coming out of the first retardant position. They are realized while rolling the cut at the first retardant position without braking. Restriction is linear.
2	Modes with maximum permissible speeds of cuts coming out of the second retardant position. They are realized while rolling the cut at the second retardant position without braking. Restriction is nonlinear.
3	Restriction on permissible probability of stopping the cut in stop blocks of the yard retardant position. Restriction is linear.
4	Restriction on permissible speed of cars collision in the break-up yard. Restriction is linear.
5	Restriction on permissible speed of the cut coming into the second retardant position. Restriction is linear.
6	Restriction on capacity of the first retardant position. They are realized while rolling the cut with full-rated braking at the first retardant position. Restriction is linear.
7	Restriction on capacity of the second retardant position. They are realized while rolling the cut with full-rated braking at the second retardant position. Restriction is nonlinear.

Additional restrictions of braking modes appear during successive rolling of cuts from the hump. In this case restrictions on conditions of the cut separation from the preceding and next one on points and stop blocks appear [12]. Considering the fact that the process of rolling cuts is stochastic, these conditions can be represented as follows:

$$p\left(\delta t_i < t_{de,i}\right) < p_d, \tag{9}$$

where: p_d – is permissible probability of non-separation of cuts.

According to [13] the value $p\left(\delta t_i < t_{de,i}\right)$ can be determined on the basis of statistical analysis of simulation results of cuts rolling from the following expression

$$p\left(\delta t_i < t_{de,i}\right) = \Phi\left(\frac{\theta_i - t_{de,i} - M[\tau_i] + M[t_{i+1}]}{\sqrt{D[\tau_i] + D[t_{i+1}]}}\right), \tag{10}$$

where: $\Phi(x)$ – is Laplace's function; $M[\tau_i], M[t_{i+1}]$ – are mathematical expected values τ_i and t_{i+1}, s, respectively; $D[\tau_i], D[t_{i+1}]$ – are dispersions of values τ_i and t_{i+1}, s^2, respectively;

Requirements of interval regulation of rolling speed of cuts is represented in the form of restrictions 8-10, conforming to braking modes with limit values of probability of cuts separation. Description of these restrictions is given in Table 2.

Table 2

Restrictions of permissible modes of the cut rolling under conditions of separation from adjacent cuts

No.	Description
8	Restriction on permissible probability of separation from the preceding cut on a separating point. Restriction is nonlinear.
9	Restriction on permissible probability of separation from the next cut on a separating point. Restriction is nonlinear.
10	Restriction on permissible probability of separation from the preceding cut on a stop block of the second retarder position. Restriction is linear.
11	Restriction on permissible probability of separation from the next cut on a stop block of the second retarder position. Restriction is nonlinear.

Restrictions 1, 2 and 8-10 select the range of permissible braking modes of the cut provided that it is separated from adjacent cuts Ω_d. Configuration of this range depends on rolling characteristics and conditions of the controllable cut as well as cuts adjacent to it.

When breaking-up real trains consisting of more than three cuts the number of restrictions implied by conditions of interval regulation of rolling speed may increase owing to separation of non-adjacent cuts [14].

4. INVESTIGATION RESULTS

An example of selection of the range of permissible braking modes is shown in Fig. 3. In this figure range Ω_t. is shown with a thick line. Shaded areas conform to range Ω_d.

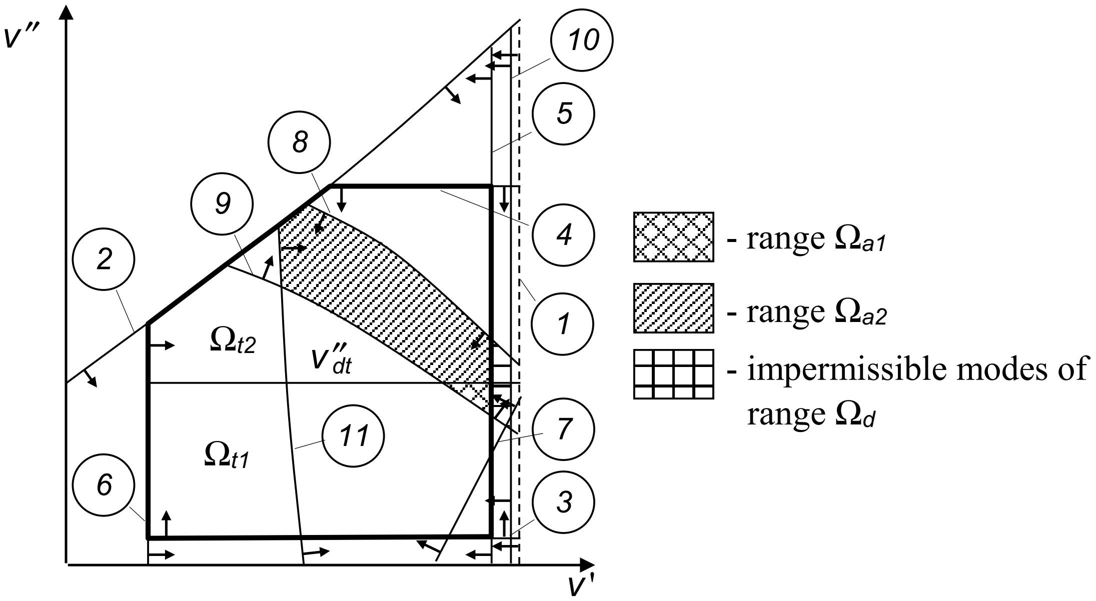

Fig. 3. Selection of range of permissible braking modes
Рис. 3. Выделение области допустимых режимов торможения

Range of permissible braking modes is an intersection of ranges $\Omega_a = \Omega_t \cup \Omega_d$. An essential peculiarity of range Ω_d is that it can be separated into two sub-ranges $\Omega_{a1} = \Omega_{t1} \cup \Omega_d$ and $\Omega_{a2} = \Omega_{t2} \cup \Omega_d$. In the range Ω_{a1} when braking modes **v** are changed, indices of both target and interval regulation of rolling speed of cuts are changed. In the range Ω_{a2} when braking modes **v** are changed, only indices of interval regulation of rolling speed of cuts are changed, but indices of target regulation remain constant.

Availability of many permissible braking modes allows solving the task of regulation of rolling speed of cuts even in the absence of exact information about rolling characteristics of cuts and conditions of their rolling. Area S_Ω is an important characteristic of permissible braking modes. The largest areas of ranges Ω_a are typical for cases, when the group includes multi-car cuts or separation occurs on points 1 and 2 en route of rolling. In these cases area of range Ω_a can be equal to area of range Ω_t. The smallest areas of range Ω_t are typical for cases, when separation of single-car cuts on the last separating point in the first and second pairs. Zero area of range Ω_a is indicative of the necessity to change braking modes of adjacent cuts or to reduce breaking-up speed.

5. CONCLUSION

Investigations made allow to make the following conclusions. Braking modes of cuts can be characterized with speeds of the cut coming out of retardant positions located on the sloping part of the hump. At that the speed of cuts coming out of the third retardant position depends on the speed of cuts coming out of the second one and is selected proceeding from conditions of reaching the best indices of target braking. Range of permissible braking modes is an enclosed area, in which indices of target and interval regulation of rolling speed of cuts take permissible values. Basic restrictions of braking modes of cuts are established. Investigations made, allow simplifying solution of task of controlling rolling speed of cuts, when there is exact information about both rolling performance and rolling conditions.

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