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## ЕКСПЛУАТАЦІЯ ТА РЕМОТ ЗАСОБІВ ТРАНСПОРТУ

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### COMPLEX SIMULATION MODEL OF TRAIN BREAKING-UP PROCESS AT THE HUMPS

**Purpose.** One of the priorities of station sorting complex functioning improvement is the breaking-up process energy consumptions reduction, namely: fuel consumption for train pushing and electric energy consumption for cut braking. In this regard, an effective solution of the problem of energy consumption reduction at breaking-up subsystem requires a comprehensive handling of train pushing and cut rolling down processes. At the same time, the analysis showed that the current task of pushing process improvement and cut rolling down effectiveness increase are solved separately. To solve this problem it is necessary to develop the complex simulation model of train breaking-up process at humps. **Methodology.** Pushing process simulation was done based on adapted under the shunting conditions traction calculations. In addition, the features of shunting locomotives work at the humps were taken into account. In order to realize the current pushing mode the special algorithm of hump locomotive controlling, which along with the safety shunting operation requirements takes into account behavioral factors associated with engineer control actions was applied. This algorithm provides train smooth acceleration and further movement with speed, which is close to the set speed. Hump locomotive fuel consumptions were determined based on the amount of mechanical work performed by locomotive traction. **Findings.** The simulation model of train pushing process was developed and combined with existing cut rolling down model. Cut initial velocity is determined during simulation process. The obtained initial velocity is used for further cut rolling process modeling. In addition, the modeling resulted in sufficiently accurate determination of the fuel rates consumed for train breaking-up. **Originality.** The simulation model of train breaking-up process at the humps, which in contrast to the existing models allows reproducing complexly all the elements of this process in detail and evaluate accurately its quality, was improved by the author. **Practical value.** The developed model can help to determine a rational processing mode of sorting complex. For this purpose, it is appropriate to include the model into the decision support system of dispatching station staff.

*Keywords:* train pushing and breaking-up process; hump; hump locomotive; fuel consumption

#### Introduction

In modern conditions one of the priorities of station sorting complex functioning improvement is the breaking-up process energy consumptions reduction.

Energy costs, which take place during the train breaking-up at humps, consist of fuel consumption for train pushing and electric energy consumption for cut braking. In this regard, an effective solution

of the problem of energy consumption reduction at breaking-up subsystem requires a comprehensive handling of train pushing and cut rolling down processes. At the same time, the analysis [6] showed that the current task of pushing process improvement and cut rolling down effectiveness increase are solved separately.

Thus, the existing pushing models [13, 17] only simulate the process of shunting train movement; while the movement of some cuts is modelled be-

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fore their uncoupling at the hump apex (HA) without their further rolling. As a result, these models do not allow assessing the impact of the selected breaking-up mode of a train on the conditions of interval and target braking of its cuts. In addition, the existing pushing models are based on traction calculations for train operation [16], which do not include features of shunting at the humps and do not allow with sufficient accuracy to determine the pushing and breaking-up process fuel consumption.

At the same time, both when optimizing the cut braking modes with the help of the method [4, 14, 19], and when imitating their rolling down with the help of the models [9, 21, 22] we take the constant breaking-up velocity  $v_0$ , the value of which is the same for each cut. This approach does not correspond to the real conditions of train humping and does not allow determining with sufficient accuracy the rational cut braking mode and calculating the sorting process quality coefficients.

### Purpose

The purpose of this work is to develop a complex simulation model of train breaking-up process at humps that will allow elaboration of the method for resource saving controlling of train pushing and breaking-up, aimed at high quality of sorting process with minimum energy consumption for its implementation

### Methodology

To achieve the set purpose, the train humping model was developed and combined with the existing cut rolling model [4], resulting in the complex simulation model of train breaking-up process.

In the developed model the train pushed to the hump is assumed as a set of cuts with certain parameters (number of cars, their type, length, mass and basic specific movement resistance) and as non-extendible flexible rod with uniform longwise weight. This train model allows the best consideration of its movement conditions when transferring from one profile element to another and after further cut breaking-up.

To solve the problem of pushing and breaking-up modelling it is sufficient to consider the controlled forward movement of a shunting train, so during its simulation process it is necessary to take

into account only external forces that coincide with the movement direction or are opposite to it. Accordingly, the following forces were taken into account:  $F_t$  – tangent locomotive power;  $W_r$  – train motion resistance force;  $B_b$  – locomotive braking force. In the shunting train motion equation the relevant specific forces are considered  $f_t$ ,  $w_r$ ,  $b_b$ ; the total force  $f_{tl}$  depends on the hump locomotive operation mode and equals  $f_{tl} = f_t \pm w_r$  in traction mode,  $f_{tl} = \pm w_r$  – in rundown mode and  $f_{tl} = \pm w_r - b_b$  – in idling mode.

The work [3] developed the method of calculating the forces acting on the shunting train during pushing and breaking-up. Thus, the tangent locomotive power  $f_t$  in the model is determined by partial (intermediate) traction characteristics that can be realized in terms of grip, and then by the following intermediate characteristics until reaching the automatic (external) characteristics [12].

Specific movement resistance force  $w_r$  is determined as

$$w_r = w'_0 + w''_0 + w_{ew} + w_{sc} + w_g + w_{st}, \quad (1)$$

where  $w'_0$  – locomotive basic specific motion resistance;  $w''_0$  – car basic specific motion resistance;  $w_{ew}$  – additional specific resistance due to environment and wind;  $w_{sc}$  – additional specific resistance due to switches and curves;  $w_g$  – additional specific resistance due to track gradient;  $w_{st}$  – additional specific resistance due to starting.

The locomotive basic specific motion resistance  $w'_0$  and additional specific resistance due to starting  $w_{st}$  are determined by method [16]. The car basic specific motion resistance  $w''_0$  is calculated as a weighted average of the cut basic specific motion resistance and is adjusted after further cut breaking-up; herewith the value  $w''_{ri}$  for each car is included in the train model structure. Additional motion resistance values due to environment and wind  $w_{ew}$ , points and curves  $w_{pc}$  are calculated by the method [15].

Additional specific resistance due to track gradient  $w_g$  is taken numerically equal to the average gradient  $i$ , where the shunting train is located;

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while for pushing simulation in the longitudinal profile model the gradient value  $i$  on the rise is positive ( $i > 0$ ) and on the descent – negative ( $i < 0$ ). Average gradient  $i$ , where there is a train, when its first axis is at the point  $S_j$ , is determined by the difference in marks of the first  $h(S_j)$  and the last  $h(S_j - l_t)$  train axles:

$$i(S_j) = \frac{h(S_j) - h(S_j - l_t)}{l_t}, \quad (2)$$

where  $l_t$  – shunting train length, m.

Due to the fact that in the breaking-up process at hump the train automatic brakes do not as a rule actuate its velocity is reduced only by shunting locomotive braking force, the specific value of which  $b_b$  is calculated by the following formula [16]:

$$b_b = 1000 \theta_d \varphi_{df}, \quad (3)$$

where  $\theta_d$  – design braking factor;  $\varphi_{df}$  – brake pad friction design factor.

The values  $\theta_d$  and  $\varphi_{df}$  are determined by the method [7] based on the number of locomotive axles and in case of brake actuation in the train – on the number of car axles, where the automatic brakes are actuated, as well. It should be noted that the braking force  $b_b$  from the brake position valve switch moment gradually increases to its maximum value. In addition, the shunting train braking modelling should take into account the time required for the driver's reaction. In this regard, the design braking factor  $\theta_d$  in (3) is considered as the braking duration function  $t_{br}$ , the value of which is accepted in accordance with [7].

The peculiarity of the train breaking-up process modelling is the change of its settings at cut uncoupling. In this regard, during the train movement simulation one must control the possible next cut uncoupling at every step  $\Delta t$ . After recording the cut uncoupling the model performs the appropriate train length and weight reduction; herewith it changes the coordinate of its first axis  $S_j$  and re-calculates the basic specific resistance  $w''$ . This, in turn, causes corresponding changes in the hump locomotive operation mode aimed at maintaining the set breaking-up velocity  $v_0$ .

Train motion in the model is described by second order differential equation  $S'' = f(t, S, S')$  in which the independent variable is the time  $t$ :

$$S'' = \frac{d^2 S}{dt^2} = \frac{g}{1 + \gamma} f_{it} 10^{-3}, \quad (4)$$

where  $g/1 + \gamma$  – accelerated gravity force with consideration of rotating mass inertia.

The motion equation (4) allows performing joint modelling of train breaking-up and cut rolling down processes.

It is known that equation (4) has a unique solution if his right part  $f(S, V)$  is continuous and differentiated. However, the nature of force change  $f_{it}$  in this equation does not always meet the specified condition. Thus, in moments of controller position switching the tangent power  $f_t$  can change stepwise. The braking power  $b_b$  during train deceleration also changes unevenly. The motion resistance in curves is a step function, the discontinuities of which occur at curved track section enter and exit points by shunting train. In addition, at the time of the next cut uncoupling at HA the train parameters are changed. Therefore, the model assumed that within the integration step  $\Delta t$  the shunting train motion mode remains constant; to this end there is chosen sufficiently small step  $\Delta t$  ( $\Delta t = 1$  sec). Controller position is not changed within the traction mode  $\Delta t$ ; while at the end of the step the train velocity is analysed and if necessary the locomotive operation mode is adjusted and the simulation is repeated.

Similarly, the braking force  $b_b$  at each step  $\Delta t$  is taken constant and if the train velocity at the end of the step became below the mark, then, depending on motion conditions, the transition to traction or idling mode is performed.

Besides, within the integration step  $\Delta t$  both ends of shunting train must not go beyond the beginning or the end of the curve. If at some step this condition is not met, then this step is divided into separate parts with a certain length  $\Delta S_1, \Delta S_2, \dots, \Delta S_n$ . Herewith, at the modelling steps  $1 \dots (n-1)$  the train is moved using the first-order differential equation  $V' = f(S, V)$  with independent variable  $S$ :

$$V' = \frac{dV}{dS} = \frac{g}{1 + \gamma} \cdot \frac{f_{it}}{V}, \quad V > 0 \quad (5)$$

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At the last step  $n$  the train motion is simulated with the help of equation (4) by the time  $\Delta t' = \Delta t - \Delta t^*$  that remained till the end of the initial step. The same algorithm is used for train motion simulation when the next cut is broken-up from it at HA.

To ensure the continuity of functions  $i(S)$  and  $f_{il}(V)$  the model uses the method of spline approximation of track longitudinal profile [5] and locomotive traction characteristics. Integration of differential motion equations (4) and (5) are performed by the Runge-Kutta fourth-order method [1].

When modelling, the train to undergo breaking-up is considered as controlled system that operates in terms of internal and external factors, as well as control impacts [2]. Controlled movement of the train is determined by the hump locomotive operation mode. Herewith the major controllable parameters are tangent power  $F_t$  and braking force  $B_b$  of the shunting locomotive, depending on the actuated controller position  $n_c$  and the auxiliary brake valve position.

The simulation must provide such a hump locomotive control that allow the train velocity at the pushing completion time  $t_{pc}$  to be equal to the specified breaking-up velocity  $v_0$ , and the subsequent phase trajectory  $V(t)$  to meet for all  $t_{pc} \leq t \leq t_e$  corresponded to the set breaking-up mode, where  $t_e$  is the traction motion end point. The initial time  $t_0$  is assumed to be 0; the final time  $t_f$  is assumed as the last cut off-locomotive uncoupling time.

The work [3] developed the algorithm of hump locomotive controlling, which along with the safety shunting operation requirements takes into account behavioural factors associated with engineer control actions. This algorithm provides train smooth acceleration and further movement with speed, which is close to the set breaking-up velocity  $v_0$ . Herewith the actual velocity  $v_a$  at every step  $\Delta t$  may deviate from the specified velocity  $v_0$  by the realization error value  $\delta \square v_a = [v_0 - \delta; v_0 + \delta]$ .

The shunting train simulation results in determination of fuel consumption  $G$  by shunting lo-

comotive during pushing and breaking-up processes. According to the research [8] the fuel consumption  $G$  for train breaking-up at humps should be determined based on the amount of mechanical work performed by locomotive traction  $R_{mj}$ :

$$G = \sum_{j=1}^n k_j R_{mj}, \quad (6)$$

where  $k_j$  – transition coefficient.

Mechanical traction work  $R_{mj}$ , t·km is determined as [11]:

$$R_{mj} = F_{ij} \Delta S_j, \quad (7)$$

where  $\Delta S_j$  – train motion in step, km.

The transition coefficient  $k_j$  is a co-relation, expressed in kilograms of fuel consumed to perform 1 t·km of mechanical work by locomotive, and is determined as [10]:

$$k_j = \begin{cases} -0,00002v_j^2 - 0,0021v_j + 0,969 & \text{– for TEM2,} \\ 0,00002v_j^2 - 0,0030v_j + 0,920 & \text{– for ChME3.} \end{cases} \quad (8)$$

Thus, at each simulation step  $j$  the tangent power  $F_{ij}$  and average velocity  $v_j$  are determined. Then, using these values and the expressions (7) and (8) there are calculated, respectively, the performed mechanical work  $R_{mj}$  and transition coefficient  $k_j$ , based on which the fuel consumption  $G$  is determined by formula (6).

### Findings

The developed train breaking-up model based on the shunting-adapted traction calculations allows the detailed simulation of hump locomotive operation mode and train motion process. This makes it possible to determine the initial velocity of each cut at its off-train uncoupling time at HA. The obtained initial velocity is used for further cut rolling process modeling. In addition, the modeling resulted in sufficiently accurate determination of the hump locomotive fuel consumption rates  $G$ , the value of which is necessary to determine the rational train breaking-up mode.

The developed model allows simulating various train breaking-up modes. For example, Fig. 1 shows the results of simulation of 3869 ton train breaking-up and pushing by TEM2 hump loco-

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itive. Herewith the mode implied the train acceleration up to the set breaking-up velocity  $v_0 = 1.7$  m/s, with the following breaking-up at a constant speed. As shown in Fig. 1, *a*, the locomotive control algorithm [3] provides smooth acceleration of the train and its further movement with the velocity  $v_a$ , close to set breaking-up velocity  $v_0$  ( $v_a \in [1.52; 1.74]$ ). It should be noted that at the final stage of breaking-up (Fig. 1, *a*, section *B-C*) when the train length does not exceed 10 cars, its motion mode changes abruptly. These changes are caused by train weight reduction at the end of the breaking-up process, resulting in inflated intensity of acceleration even at the first controller positions.

In order to verify the model adequacy the experimental studies of sorting process at the Nizhnedneprovsk station even system were performed. Herewith for each breaking-up train the following items were recorded: cut parameters; the duration of pushing and breaking-up operations and the dynamics of engineer controller switch during their performance; cut uncoupling time at the HA; hump locomotive fuel consumption (using «BIS-R» system). In addition, the data were obtained on the design of plan and longitudinal profile of receiving yard tracks and the hump of the station even system.

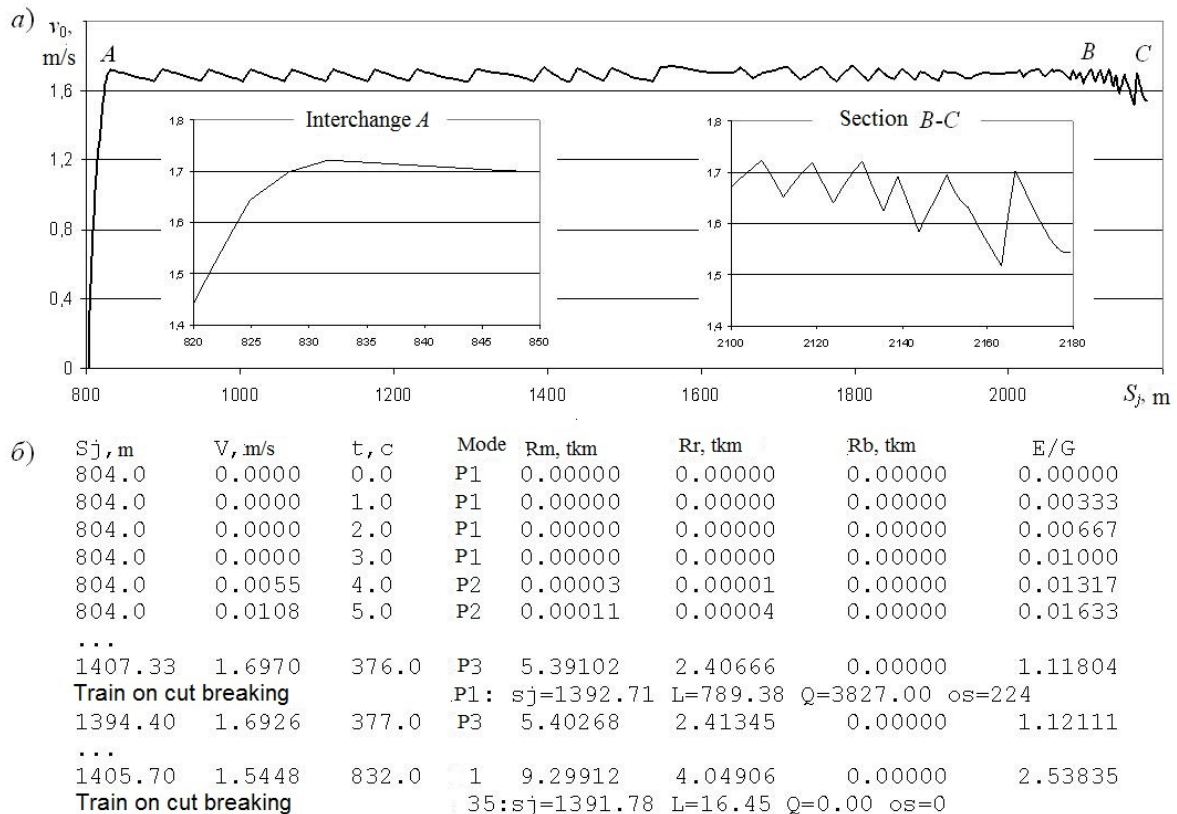


Fig. 1. The breaking-up and pushing process simulation results:  
*a* – train speed diagram; *b* – simulation report

The above data combined with the developed model allowed simulation of 17 real train breaking-up processes.

In accordance with the existing methods of statistical analysis [18], the adequacy of the developed train breaking-up model is proved by homogeneity of sampled data derived from experimental studies and simulation.

The experimental research and simulation resulted in two fuel consumption random variable samples; wherein the above samples are dependent. To test the hypothesis of homogeneity of these samples Wilcoxon *T*-criterion [20] was used.

Checking by the specified criterion is performed as follows. It is assumed that  $R(Z_i)$  is the

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rank  $|Z_i|$  in the range from the smallest to the largest values of differences  $|Z_1|, |Z_2|, \dots, |Z_n|$ , where the value  $|Z_i|$  is the difference of experimental research data  $x_i$  and simulation  $y_i$  ( $Z_i = x_i - y_i$ ).

We define the counter variables  $Q(Z_i)$  as:

$$Q(Z_i) = \begin{cases} 1, & \text{where } Z_i > 0, \\ 0, & \text{where } Z_i < 0. \end{cases} \quad (9)$$

Statistics of  $T$ -criterion is as follows:

$$T^+ = \sum_{i=1}^n R(Z_j)Q(Z_j). \quad (10)$$

When fulfilling the null hypothesis the statistics of  $n$  observations

$$T^{++} = \frac{T^+ - \frac{n(n+1)}{4}}{\sqrt{\frac{n(n+1)(2n+1)}{24}}} \quad (11)$$

has asymptotic standard normal distribution with expectation 0 and variance 1. Thus, the decision rule at the 5% significance level is as follows: if  $|T^{++}| \leq 1,96$ , then the dependent samples homogeneity hypothesis by Wilcoxon criterion is accepted, otherwise – is rejected.

According to the check the  $T$ -criterion statistics made:  $T^+ = 67$ ;  $T^{++} = -0,46$ . Thus, the conducted statistical analysis of experimental results and simulation demonstrates the adequacy of the designed model train breaking-up process at hump.

### Originality and practical value

The simulation model of train breaking-up process at the humps, which in contrast to the existing models allows reproducing complexly all the elements of this process in detail and evaluate accurately its quality, was improved.

The developed simulation model can be used as a decision support system to identify effective operation modes of sorting complexes.

### Conclusions

1. The fact was established that the initial velocity of each cut at its off-train uncoupling time at the hump apex is a random variable whose value is

different from the set breaking-up velocity  $v_0$ . At the same time the cut initial velocity value significantly affects the regulating conditions of their velocity during rolling down from the hump. Therefore, the breaking-up modelling should consider the train pushing and cut rolling operations as interrelated processes that need joint simulation.

2. Detailed modelling of the shunting train movement and the hump locomotive operation mode is possible by performing traction calculations; while the existing method of traction calculations needs adapting to the shunting work conditions.

3. Hump locomotive fuel consumptions for train breaking-up should be determined based on the amount of mechanical work performed by locomotive traction. This approach in contrast to existing methods allows determination of impact of breaking-up velocity, as well as of hump and train design parameters, on the amount of fuel consumption.

4. To ensure the specified humping mode the model uses the hump locomotive control algorithm that provides smooth train acceleration and its further motion at the velocity close to the set one. At the final breaking-up stage when the train length does not exceed 10 cars, the train motion velocity fluctuations are increasing sufficiently. These fluctuations are caused by train weight reduction at the end of the breaking-up process, resulting in inflated intensity of acceleration even at the first controller positions

5. The statistical analysis of experimental studies and simulation results, using Wilcoxon  $T$ -criterion, proved adequacy of the developed model of train breaking-up at the hump.

6. The developed train breaking-up model allows a comprehensive assessment of the sorting process quality that is needed to determine a rational processing mode of sorting complex. For this purpose, it is appropriate to include the model into the decision support system of dispatching station staff.

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## КОМПЛЕКСНА ІМІТАЦІЙНА МОДЕЛЬ ПРОЦЕСУ РОЗФОРМУВАННЯ СОСТАВІВ НА СОРТУВАЛЬНИХ ГІРКАХ

**Мета.** Одним із пріоритетних напрямків підвищення ефективності функціонування сортувальних комплексів станцій є скорочення енергетичних витрат на розформування составів, а саме: витрат палива на їх насув та електроенергії на гальмування відчепів. У зв'язку з цим ефективне вирішення проблеми зниження енерговитрат у підсистемі розформування вимагає комплексного розгляду процесів насуву та розпуску составів. Проте, як показав аналіз, у теперішній час задачі удосконалення процесу насуву та підвищення ефективності процесу розпуску вирішуються окремо. Для вирішення вказаної проблеми в роботі необхідно розробити комплексну імітаційну модель розформування составів. **Методика.** Моделювання процесу насуву та розпуску составів виконувалось на основі адаптованих до умов маневрової роботи тягових розрахунків; при цьому були враховані особливості роботи маневрових тепловозів на сортувальній гірці. Для реалізації заданого режиму насуву було застосовано спеціальний алгоритм управління гірковим тепловозом, який, окрім вимог із безпечного виконання маневрової роботи та експлуатації локомотивів, враховує й біхевіоральні фактори, що пов'язані з керуючими діями машиніста. Даний алгоритм забезпечує плавний розгін та подальший рух составу з близькою до встановленої швидкістю. Витрати палива гірковим тепловозом визначались на основі величини виконаної механічної роботи сили тяги локомотива. **Результати.** Розроблено модель насуву составів, яку було об'єднано з існуючою моделлю скочування відчепів. У процесі моделювання визначається початкова швидкість відчепів у момент їх відриву від составу. Отримана початкова швидкість відчепів використовується для подальшого моделювання процесу їх скочування. У результаті моделювання з достатньою точністю визначаються витрати палива гірковим локомотивом на розформування составів. **Наукова новизна.** Автором удосконалена імітаційна модель процесу розформування составів на сортувальних гірках, що, на відміну від існуючих, дозволяє комплексно відтворювати всі елементи цього процесу та детально й достовірно оцінювати його якість. **Практична значимість.** За допомогою розробленої моделі можливо визначати раціональний режим функціонування сортувального комплексу. З цією метою вказана модель доцільно включити до складу системи підтримки прийняття рішень диспетчерського персоналу станції.

*Ключові слова:* насув та розпуск составів; сортувальна гірка; гірковий тепловоз; витрати палива

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## КОМПЛЕКСНАЯ ИМИТАЦИОННАЯ МОДЕЛЬ ПРОЦЕССА РАСФОРМИРОВАНИЯ СОСТАВОВ НА СОРТИРОВОЧНЫХ ГОРКАХ

**Цель.** Одним из приоритетных направлений повышения эффективности функционирования сортировочных комплексов станций является сокращение энергетических затрат на расформирование составов, а именно: расхода топлива на их надвиг и электроэнергии на торможение отцепов. В связи с этим эффективное решение проблемы снижения энергозатрат в подсистеме расформирования требует комплексного рассмотрения процессов надвига и роспуска составов. Однако, как показал анализ, в настоящее время задачи совершенствования процесса надвига и повышения эффективности процесса роспуска решаются раздельно. Для решения указанной проблемы в работе необходимо разработать комплексную имитационную модель расформирования составов. **Методика.** Моделирование процесса надвига и роспуска составов выполнялось на основе адаптированных к условиям маневровой работы тяговых расчетов; при этом были учтены особенности работы маневровых тепловозов на сортировочной



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горке. Для реализации заданного режима надвига был применен специальный алгоритм управления горочным тепловозом, который наряду с требованиями безопасности выполнения маневровой работы и эксплуатации локомотивов учитывает и бихевиоральные факторы, связанные с управляющими действиями машиниста. Данный алгоритм обеспечивает плавный разгон и дальнейшее движение состава с близкой к установленной скоростью. Расходы топлива горочным тепловозом определялись на основе величины выполненной механической работы силы тяги локомотива. **Результаты.** Разработана имитационная модель надвига составов, которая была объединена с существующей моделью скатывания отцепов. В процессе моделирования определяется начальная скорость отцепов в момент их отрыва от состава. Полученная начальная скорость отцепов используется для дальнейшего моделирования процесса их скатывания. В результате моделирования с достаточной точностью определяются расходы топлива горочным локомотивом на расформирование составов. **Научная новизна.** Автором усовершенствована имитационная модель процесса расформирования составов на сортировочных горках, которая в отличие от существующих, позволяет комплексно воспроизводить все элементы этого процесса и подробно и достоверно оценивать его качество. **Практическая значимость.** С помощью разработанной модели возможно определять рациональный режим функционирования сортировочного комплекса. С этой целью указанную модель целесообразно включить в состав системы поддержки принятия решений диспетчерского персонала станции.

*Ключевые слова:* надвиг и роспуск составов; сортировочная горка; горочный тепловоз; расход топлива

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