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MODELING OF VEHICLE MOVEMENT IN COMPUTER INFORMATION-CONTROL SYSTEMS

The subject of the article is the processes of synthesis of a mathematical model of control objects functioning in computer information-control systems of critical purpose for the needs of high-speed railway transport. The main emphasis is on modeling the movement of a passenger train in the high-speed system of Ukrzaliznytsia. The aim is to study the process of regulating the speed of railway vehicles under conditions of uncertainty in the primary information of microprocessor information-control systems of railway transport. Tasks: determination of the criterion of the safety of railway vehicle auto control; obtain a mathematical model of train movement under conditions of uncertainty; check the adequacy of the model. The method used is the mathematical apparatus of discrete models. The following results have been obtained. The mathematical model of train movement developed in this work includes not only information on train position, reference point, direction, and speed of the vehicle but also a variable control indicator to reflect the process of railway traffic adequately. The study shows that, based on the synthesized model, it is possible to use the so-called fuzzy distance between adjacent trains. This approach improves the accuracy of determining the critical distance between trains, the time required to eliminate the risk of collision, the start time of braking, and braking time considering the angle of inclination of the track, as well as the distance of the braking distance. The necessity to determine the control indicator, its value for many points of time, while there is a reduction in speed for the safe movement of trains. Based on the proposed mathematical model, a computer simulation of the process was performed to determine the required time reserve for the train driver to respond to changes in the speed of the previous train, as well as speed ranges that require immediate emergency action. Conclusions. The scientific novelty of the obtained results is the development of a mathematical model of the behavior of mobile units in computer systems for critical use for the needs of railway transport in the presence of failures in the primary information from sensors that record motion parameters. The behavior of the control system at different values of train speed and changes in the value of the interval of the accompanying journey is studied. The theory of traction calculations in computer control systems for mobile units has been further developed. The obtained scientific results will be used in the development of an application program for many critical computer systems for railway.

Keywords: *microprocessor train traffic control systems; selfregulation; interval of accompanying following; train traffic; traffic control under conditions of uncertainty; traffic safety.*

1. Introduction

1.1. Motivation

The regulation of the movement of railway vehicles has been based on the discrete length of sections with some fixed length for many years. Accordingly, as the main technical means of autoregulation and traffic safety, traffic lights were used, which by their nature are also a device of discrete action. This approach provides a fairly simple technical implementation and a clear and understandable algorithm for the operation of the traffic control system. While the speed of trains was not significant enough, this approach met the requirements of railways and society, but the emergence of high-speed express trains has significantly changed the situation. Traditional

autoregulation using the discrete method did not allow to effectively realize the benefits of high-speed traffic effectively, which led to the formation of a fundamentally new approach based on inter-train sections of variable length. At the same time, the methodology of calculating the interval of the accompanying sequence has not changed dramatically, although the process of speed control takes place under conditions of increased number of factors, the consequences of which are often very difficult to predict. These factors primarily include primary data from primary sensors on vehicle motion parameters. Since the existence of railway information and control systems, there is a problem of reliability of these primary data. There are two main components to this problem. First, the primary information from the sensors can take many values in a very wide range. Second,

researchers do not have enough statistics, so even the introduction of modern computer technology does not solve the problem. In fact, management takes place under conditions of some uncertainty with the need for a guaranteed result, which in turn requires a thorough scientific study of this process.

1.2. State of the Art

The regulation of the movement of railway vehicles is based on the principle of dividing the interstation race into block sections of fixed length. The main purpose of the calculations was to ensure traffic safety and determine the length of sections for a guaranteed train stop in the worst conditions. The calculations took into account the value of the plan and profile of the track, the characteristics of the rolling stock, etc. [1].

Classical approaches to the theory of locomotive traction are carefully considered in [2]. Separately, studies of the impact of the train speed on the performance of the railway are presented in [3]. Based on this, the conditions for improving the control technology [4] and the introduction of train schedule through the solution of the destination problem were formed [5]. A further development of the theoretical foundations of autoregulation was the introduction of a system of automatic regulation of train speed in the subway. In contrast to the previous method, additionally, the developers took into account the mass of the train, the dynamics of possible changes in speed (acceleration or deceleration) [6].

Mathematical model, according to which the locomotive control system determines the speed of the train, has the ordinates of trains as logical variables, the distance to the train following in front, data on the section of track on which the train moves, its characteristics and other indicators [1].

Methods for estimating throughput by classical methods are considered in [7], but more and more researchers consider it appropriate to use Internet of Things technologies in new railway management systems [8].

For example, the cybernetic approach to security management systems based on Industry 4.0, described in [9].

At the same time, the emphasis is on the need for integrated automation in solving existing problems of the main branches of railway transport, such as automation of train schedules [10].

It should be noted that all the above works are based on the use of the concept of fixed block sections for the branching of adjacent trains and, accordingly, to ensure traffic safety. This concerns the issues of optimizing the trajectory of several trains [11], the

problems of planning the movement of railway transport [12] and improving the methodology for determining locomotive circulation schemes [13].

European countries mainly use traffic control systems based on the concept of so-called mobile block sections, an example is the TGV alarm system, which is described in [14]. However, some European railways use fixed block systems - ERTMS (European Rail Traffic Management System) [15]. They are common in most developed countries of the European Union.

Recently, among the specialists dealing with the problems of improving rail transport, much attention is paid to improving the technology of freight rolling stock management and the introduction of a new timetable system. Fuzzy control models are becoming increasingly used in train control processes and operational work in general. Of particular note is the work [16], which addresses the problems of ensuring the stability of rail transport using fuzzy models, but it should be noted that the ideas of the authors are still based mainly on the concept of fixed block sections.

Problems of optimization of real-time traffic control for new general-purpose railway networks are considered in [17]. Paper [18] considers a general model of a track with arbitrary geometry, including irregularities in the centerline of the rails. Instead, in [19] the issues of improving the management system of industrial railway transport based on ZigBee are considered. Although the research [20] provides a model for determining the state of railway automation equipment with restrictive statistics, but it considered the example of only two complex modern systems that use the previous concept of tools application. At the same time, the article [20], devoted to the measurement of the parameters of the movement of the couplings on the sorting slides, only partially solves the existing problems of measurement accuracy in information and measuring systems, which are carefully considered in [21]. The influence of uncertainty under real operating conditions on the safety of a rail vehicle resulting from possible changes in rail inclination and rail surface deviations from nominal dimensions is shown in [22]. The authors of the work only partially solve the existing problems of measurement accuracy in information-measuring systems, which are thoroughly considered in [23]. This means that on the basis of objectively obtained parameters of the motion process it becomes possible to synthesize a modernized control system in conditions of uncertainty with the involvement of the results obtained in [24].

Due to the existing limitations of traditional research tools, more and more scientists are beginning to deal with management issues under conditions of uncertainty. An attempt to solve this problem with the help of classical information theory is shown in [25],

and in [26] the normative documents regulating the work of railway transport are presented. All the above-mentioned scientific works can serve as a basis for the synthesis of new models and approaches to the implementation of the process of interval regulation in conditions of uncertainty in the primary information.

An additional obstacle is the limited number of statistics on possible manifestations of destabilizing factors, the occurrence of which may be the cause of a traffic accident. In this sense, the scientific approach formed in [2] is quite interesting, which provides a guaranteed result of the management process under conditions of uncertainty. The structure of the input data can be represented using the approach outlined in [27]. However, the mechanical, formal transfer of this mathematical apparatus to solve the problems of train traffic control is not possible due to the specificity of the technology of railway transport and the priority of transport safety.

Therefore, the *purpose* of this article is to determine the necessary reaction time of the train driver to a change in the speed of the previous train, as well as the speed ranges that require immediate action as part of the study of the process of speed control of rail transport under conditions of uncertainty of primary information. To achieve this goal, the authors proposed to allocate in the whole set of primary data a range that can guarantee the achievement of a useful result and most adequately describes the behavior of the control system. The formation of the specified range or area is carried out by heuristic methods.

2. Diagram of a computer control system for train traffic

Modern computer systems for railways are multifunctional and extensive complexes.

They provide automatic regulation of train movement with minimal human involvement. In Ukraine, systems with discrete tracking intervals and the use of traffic lights are still used.

The diagram of such systems consists of three separate functional subsystems (Fig. 1).

This is a stationary, mobile and information exchange subsystem (train communication). The main task of the mobile subsystem is to ensure safe driving with respect to the appropriate speed mode. The stationary subsystem provides control of train movement within the control area. Its work is based on the model of the train situation, which is updated by receiving data on the location of a single train.

These data are determined by the locomotive model of train movement, which receives information from the unit for determining the location and the unit of parameters of the locomotive. The position of the locomotive on the site is determined by information from track sensors, usually balises, and the GPS navigator signal. The locomotive model determines all the necessary parameters of train movement, which are implemented automatically. The driver monitors the operation system and, if necessary, takes control.

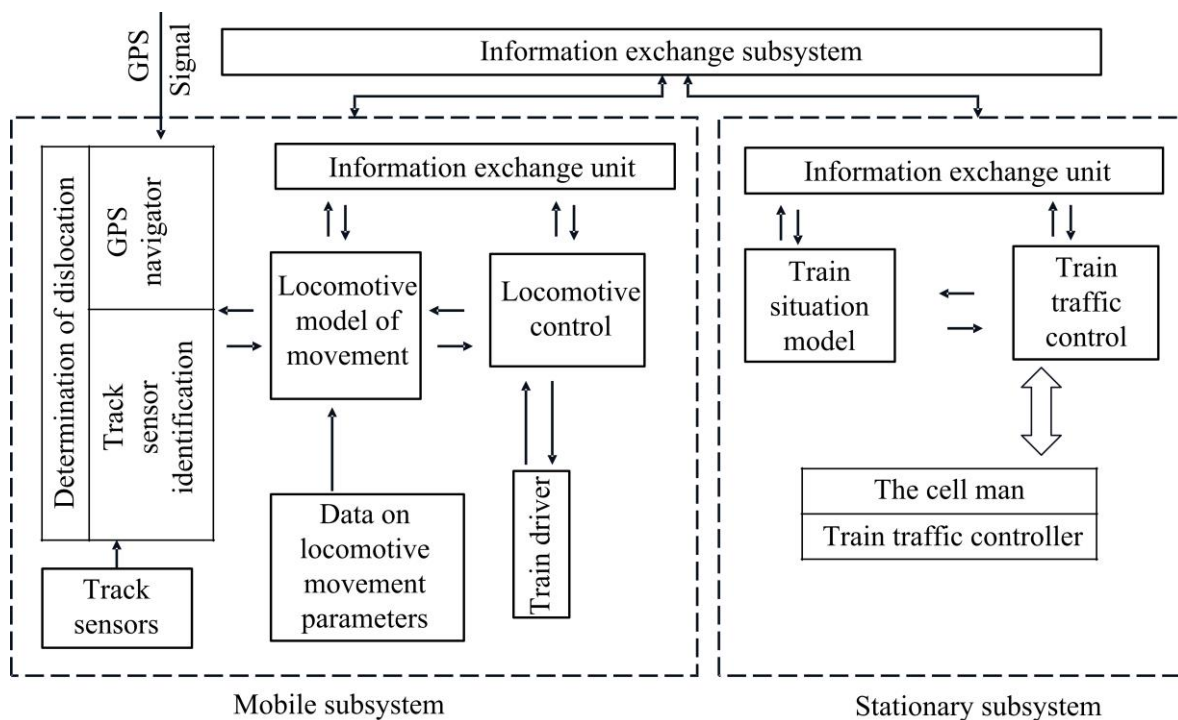


Fig. 1. Diagram of a computer control system for train traffic

Information exchange subsystems provide continuous information interaction of mobile and stationary subsystems, including locomotive driver and train traffic controller.

In Ukraine, this system is used with somewhat narrowed functions due to the use of block sections of fixed length, but the models of movement are quite similar. The Southern, Donetsk and Dnieper railways have full-featured computer control centres with real-time train simulation. One of the main problems of control centres is to ensure stable operation of the train model under conditions of limited stochastic data on traffic parameters.

The main message for modeling the movement of railway vehicles is to exclude the possibility of their collision. This requirement means the establishment of some critical value of the distance between vehicles L_{kp} , which guarantees the safety of the transport process at the established level. In this sense, the most difficult situation is with the use of air transport moving in three-dimensional space (X, Y, Z) . Therefore, it is obvious that the control system must implement some function with parameters $F(X_{kp}, Y_{kp}, Z_{kp})$.

3. A mathematical model of train movement

3.1. Development of the model

The variable Y_i indicates the existence of a route, or rather its changes, which is typical for the station.

In the race, the situation looks much simpler: in fact, we have only one variable that characterizes the interval of the accompanying sequence.

The task of traffic safety is to maintain inequality

$$X_i \geq X_{kp} \quad (1)$$

throughout the transportation process.

From the point of view of maximizing the capacity $X_i \rightarrow X_{kp}$, i.e. if the ordinate of the i^{th} train is equal to X_i , for $i + 1$ – it will look like:

$$X_i + X_{kp}. \quad (2)$$

The automatic control system must ensure the fulfillment of equation (1), but it should be borne in mind that the value of X_{kp} is in some way proportional to the speed of vehicles, which complicates the implementation (1). This is especially true when two vehicles are moving at different speed.

For $V_1 < V_2$ (where V_1, V_2 is the speed of train 1 and train 2, respectively), the distance L between trains 1 and 2 obviously increases, for $V_1 = V_2$ it is constant, so we consider the last situation when $V_1 > V_2$, i.e. object (vehicle) 1 "catches up" object (vehicle) 2 moving in front of V .

As can be seen from the above, information about the position of trains (coordinates X_1 and X_2) is not enough to reflect the process adequately. You need to know the direction of movement and speed. Therefore, to reflect the process of train movement, we introduce a system of phase coordinates, which will include the position (X coordinate) and the speed (V coordinate) of the train.

We also have to set a starting point. The process takes place in time. It is impossible to determine the above values continuously in practice, so we consider that the vector of parameters is measured at discrete moments of time

$$t_n = n \cdot \tau, \quad (3)$$

where τ – the quantization period.

We have the following task.

Given: two moving units which are moving in the same direction in the race from point A to point B.

The position of trains is determined at times:

$$t_n = n \cdot \tau + t_0, \quad (4)$$

where t_0 – the starting point of time.

Set and accurately measured phase coordinates at the initial time t_0 :

$$\begin{pmatrix} X_0 \\ VX_0 \end{pmatrix} \text{ and } \begin{pmatrix} Y_0 \\ VY_0 \end{pmatrix}, \quad (5)$$

where X_0 and Y_0 – the distance from point A to the first and second trains;

VX_0 and VY_0 – the speed of movement of the first and second trains, respectively.

The first train follows the second. We use the theoretical approach outlined in [24] to build a mathematical model of train motion.

At time t_n , the position of the trains is described by the following phase coordinates:

$$\begin{pmatrix} X_n \\ VX_n \end{pmatrix} \text{ and } \begin{pmatrix} Y_n \\ VY_n \end{pmatrix}, \quad (6)$$

where X_n and Y_n – the distance from point A to the first and second trains;

VX_n and VY_n – the speed of movement of the first and second trains, respectively.

The positions of trains in the n th and $(n + 1)$ moments of time are related by the following relations:

$$\begin{cases} X_{n+1} = X_n + \tau \cdot VX_n; \\ Y_{n+1} = Y_n + \tau \cdot VY_n. \end{cases} \quad (7)$$

The distance between them at the n th time:

$$D_n = Y_n - X_n, \quad (8)$$

and at $(n + 1)$ th time:

$$\begin{aligned} D_{n+1} &= Y_{n+1} - X_{n+1} = \\ &= (Y_n + \tau \cdot VY_n) - (X_n + \tau \cdot VX_n) = \\ &= D_n + \tau(VY_n - VX_n). \end{aligned} \quad (9)$$

The system is also controlled, which consists of changing the speed of trains to the values of UX_{n+1} and UY_{n+1} in $(n + 1)$ th time, as follows:

$$\begin{cases} VX_{n+1} = VX_n + UX_{n+1}; \\ VY_{n+1} = VY_n + UY_{n+1}. \end{cases} \quad (10)$$

The values of control variables can be both positive (acceleration) and negative (braking), and they are limited to a certain interval:

$$\begin{cases} U_{\min} < UX_n; \\ UY_n \leq U_{\max}. \end{cases} \quad (11)$$

The values of U_{\min} and U_{\max} differ from the speed of a particular train at the moment, its technical characteristics and the value of τ . The nature of this dependence will be considered below.

We assume that the velocity remains constant in the measurement intervals, so we can say that the distance changes over the period τ by the value of $\tau(VY_n - VX_n)$.

Accordingly, if $VY_n \geq VX_n$, i.e. the distance increases or remains unchanged, this case can be excluded from consideration.

It is important when $VY_n < VX_n$, i.e. the distance decreases.

We consider that at discrete moments of time $t_n = n \cdot \tau$ we obtain the exact values of X_n , Y_n , and VX_n , and in addition we know the value of control

UX_n . We also know the values of position and speed of both trains at previous times. By direct measurement we obtain X_n , Y_n , and the value of VX_n is determined from relation (10).

If to speak about the velocity of the second train VY_n , in the $(n + 1)$ th moment of time we can determine it from the relation accurately:

$$VY_n = \frac{Y_{n+1} - Y_n}{\tau}. \quad (12)$$

At the n th moment of time, we can define the limits for the value of VY_n , in which it can be changed from the value of VY_{n-1} , which can already be determined.

The task is to choose the control value UX_{n+1} to prevent the distance between trains below the critical level, which poses a threat to the safe movement of trains.

To do this, first, you have to determine the critical distance. Obviously, it depends on the value of $(VY_n - VX_n)$, as well as the distance to point B. It is also necessary to determine the amount of control for the first train, which makes it possible to prevent the threat.

An important condition is to minimize the critical distance. For this purpose, consider the situation within the allowable velocity values for relations (9). Obviously, the fastest distance D_{n+1} decreases with $(VY_n = 0; VX_n = V_{\max})$. We have:

$$D_{n+1} = D_n - \tau \cdot V_{\max}. \quad (13)$$

Obviously, if you do not reduce the speed of the train, the collision will occur after a time equal to T_z (collision time), where

$$T_z = \frac{D_n}{V_{\max}}. \quad (14)$$

Time T_z can be represented as a certain number of k_z moments τ :

$$T_z = k_z \cdot \tau. \quad (15)$$

Obviously, $D_n + k_z = 0$ at constant speed.

The distance between the trains at time $t_{n+1} = \tau(n + 1)$ is:

$$D_n = T_z \cdot V_{\max} = k_z \cdot \tau \cdot V_{\max}. \quad (16)$$

Determine the time required to eliminate the risk of collision in this case.

The speed of the train is V_{max} , and braking can occur with maximum acceleration U (since this braking is $U < 0$). The distance that the train will travel during period $[t_n, t_{n+1}]$ is determined as follows:

$$VX_{n+1} \cdot \tau = VX_n \cdot \tau + U \cdot \tau^2 = \tau(VX_n + U \cdot \tau). \quad (17)$$

Then from relation (10) we obtain:

$$\begin{aligned} VX_{n+2} \cdot \tau &= VX_{n+1} \cdot \tau + U \cdot \tau^2 = \\ &= VX_n \cdot \tau + U \cdot \tau^2 + U \cdot \tau^2 = X_n \cdot \tau + 2U \cdot \tau^2 \\ &\dots\dots\dots \\ VX_{n+i} \cdot \tau &= VX_{n+i-1} \cdot \tau + U \cdot \tau^2 = \\ &= VX_n \cdot \tau + i \cdot U \cdot \tau^2 \\ &\dots\dots\dots \end{aligned} \quad (18)$$

Also from relation (10) we obtain the value of $UX_{n+1} = U \cdot \tau$ – brake control (accident prevention).

Obviously, this control must be applied until $(n + s)$ while the conditions are met:

$$\begin{cases} VX_{n+s-1} > U \cdot \tau; \\ VX_{n+s} \leq U \cdot \tau. \end{cases} \quad (19)$$

Then the braking will decrease to $UX_{n+1} = VX_{n+s}$. In the next time interval $[t_{n+s}, t_{n+s+1}]$, when the train speed becomes zero, the catching train will stop.

Thus, the distance travelled during the time $[t_n, t_{n+s+1}]$ in which the braking occurred is equal to:

$$\begin{aligned} D_n &= VX_n \cdot \tau + VX_{n+1} \cdot \tau + \dots + VX_{n+s} \cdot \tau = \\ &= \sum_{k=0}^s VX_{n+k} \cdot \tau = \sum_{k=0}^{s-1} (VX_n \cdot \tau + k \cdot U \cdot \tau^2) + \\ &+ VX_{n+s} \cdot \tau. \end{aligned} \quad (20)$$

Simplifying expression (20) we obtain:

$$\begin{aligned} D_n &= s \cdot VX_n \cdot \tau + U \cdot \tau^2 \cdot \sum_{k=0}^{s-1} k + VX_{n+s} \cdot \tau = \\ &= s \cdot VX_n \cdot \tau + s \cdot U \cdot \tau^2 \cdot \frac{s-1}{2} + VX_{n+s} \cdot \tau. \end{aligned} \quad (21)$$

From conditions (8) and the value of velocity we have two inequalities:

$$\begin{cases} VX_n \cdot \tau + (s-1) \cdot U \cdot \tau^2 + U \cdot \tau^2 < 0; \\ VX_n \cdot \tau + (s-1) \cdot U \cdot \tau^2 > 0. \end{cases} \quad (22)$$

We obtain restrictions on the value of s :

$$-\frac{VX_n}{U \cdot \tau} \leq s < -\frac{VX_n}{U \cdot \tau} + 1. \quad (23)$$

Since $VX_n = V_{max}$, we have:

$$-\frac{V_{max}}{U \cdot \tau} \leq s < -\frac{V_{max}}{U \cdot \tau} + 1. \quad (24)$$

Thus, we determined the moment of the beginning of braking use with the maximum accuracy, both in the general case of speed VX_n , and at $VX_n = V_{max}$.

Define the braking distance in terms of V_{max}, U, τ , because these values are defined. As the value of s we take its lower limit from (24), and the corresponding VX_n , instead of VX_{n+s} we take its upper limit $X(U \cdot \tau)$ (19).

$$\begin{aligned} D_n &= \left(-\frac{1}{U} + \frac{1}{2 \cdot U \cdot \tau}\right) \cdot V_{max}^2 + \\ &+ V_{max} \cdot \frac{1}{2} - U \cdot \tau^2. \end{aligned} \quad (25)$$

It is true that the number of k_z moments τ (time to collision) is less than the value of s .

Now suppose the standard situation, at time t_n , when the train in front moves at speed $VY_n > 0$ (the second train), and the first moves behind at speed VX_n .

From the calculations (22) and (23) above it follows that the braking distance of the second train, if it starts braking at time t_n will be:

$$\begin{aligned} \text{Dist}(VY_n) &= sY \cdot VY_n \cdot \tau + \\ &+ sY \cdot U \cdot \tau^2 \cdot \frac{sY-1}{2} + VY_{n+sY} \cdot \tau. \end{aligned} \quad (26)$$

We obtain restrictions on the value of sY :

$$-\frac{VY_n}{U \cdot \tau} \leq sY < -\frac{VY_n}{U \cdot \tau} + 1. \quad (27)$$

Braking time is $T(VY_n) = sY \cdot \tau$. The distance between the trains at time t_n will be $D_n = Y_n - X_n$.

The braking distance of the first train $Dist(VX_n)$ is determined by the previously obtained relation (21).

Taking the restrictions into account (23), the braking time is $T(VX_n) = s \cdot \tau$. Since $VX_n > VY_n$, then $s > sY$, and, accordingly, the braking distance of the first train is bigger.

At real movement of a train a brake way

S_r is divided into two parts: S_n – preparatory braking distance; S_d is the actual braking distance. The distance S_n train passes for the time spent preparing the brakes for action. Assume that the train passes this way at a constant speed, then its value is:

$$S_n = 1000 \cdot V_0 \cdot \frac{t_n}{3600} \approx 0,278V_0 \cdot t_n, \quad (28)$$

where t_n – the time of preparation of the brakes for action;

V_0 – the speed of the train at the beginning of braking.

The time of preparation of the brakes for action t_n depending on the length of the train and the type of brakes is given in [22]. Appropriate ratios are also provided to adjust the time due to the slope of the track.

It also takes time to determine that the second train has started braking. Obviously, this takes at least 2τ time.

After that, a decision must be made to reduce the speed of the first train (the one that catches up), taking into account the preparatory braking distance. That is to determine the control, its value for a number of points of time, while there will be a decrease in speed.

Obviously, on the basis of the mathematical model above, it is advisable to conduct computer simulations of the process, in order to determine the required time for the train driver to respond to changes in speed of the previous train, as well as ranges of speed that require immediate action.

3.2. Research results

To perform computer simulation of the process, it is necessary to determine the input data for the time interval τ of the deceleration value U . Carry out the transformation of equation (25) and obtain:

$$-U^2 \cdot \tau^2 + \left(\frac{V_{max}}{2} - D_n \right) U + \left(\frac{1}{2\tau} - 1 \right) V_{max}^2 = 0.$$

To do this, assume that the braking distance D_n varies from 1200 to 1800 m, with an initial train speed $V_{max} = 80, 100, 120, 140, 160$ km/h.

We obtain the control values U , which are given in Table 1.

Determine the braking time $s \cdot \tau$ for each control case. The results of the calculations are shown in Table 2.

Table 1

Numerical control values U

$V_{max}, \text{ km/h}$	$D_n, \text{ m}$			
	1800	1600	1400	1200
80	-0,14	-0,16	-0,18	-0,21
100	-0,22	-0,24	-0,28	-0,33
120	-0,31	-0,35	-0,4	-0,47
140	-0,43	-0,48	-0,55	-0,64
160	-0,55	-0,62	-0,72	-0,84

Table 2

Numerical values of braking time

$V_{max}, \text{ km/h}$	$D_n, \text{ m}$			
	1800	1600	1400	1200
80	161,15	143,14	125,12	107,1
100	128,45	114,1	99,71	85,31
120	107,1	95,08	83,05	71,04
140	91,52	81,24	70,95	60,66
160	80,05	71,05	62,03	53,02

Now we have to expand the calculation by determining the braking time at fixed speed and different control values (Table 3 and Fig. 2).

As we can see the braking time varies quite widely. The maximum value is 322,31, which is more than 5 minutes. This is too important for braking the train, because at this speed the whole way between the departure point and the destination may take less time.

Therefore, we will analyze the obtained control values for the adequacy of the braking distance. We can see from the table that the bigger braking time is, the bigger the initial speed is. This can lead to too much braking distance at low control values. We have to calculate the braking distance and build Table 4.

In Table 4 we highlight in yellow the values of the path in excess of 1801 m. Now based on table 4 it is possible to determine the permissible values of the controls for each initial speed. For example, consider the speed of 120 km/h (the third column of the table). The braking distances from 4041,61 to 2005,55 at the top are too large, so control values from -0,14 to -0,28 can also be discarded. The first allowable path value is 1800,24, which corresponds to control -0,31. Starting with this control and down the table, the controls are permissible for speed of 120 km/h.

Table 3

Values of braking time at fixed speed and different values of the control indicator

U	V_{max} , km / h				
	80	100	120	140	160
-0,14	161,15	201,81	241,73	282,38	322,31
-0,16	143,14	179,25	214,71	250,82	286,28
-0,18	125,12	156,68	187,68	219,24	250,24
-0,21	107,1	134,12	160,66	187,67	214,21
-0,22	102,57	128,45	153,86	179,73	205,15
-0,24	91,11	114,1	136,67	159,65	182,23
-0,28	79,62	99,71	119,44	139,52	159,25
-0,33	68,13	85,31	102,19	119,37	136,25
-0,31	71,4	89,41	107,1	125,12	142,81
-0,35	63,39	79,38	95,08	111,07	126,78
-0,40	55,37	69,34	83,05	97,02	110,74
-0,47	47,36	59,31	71,04	82,99	94,72
-0,43	52,23	65,4	78,34	91,52	104,46
-0,48	46,36	58,06	69,55	81,24	92,73
-0,55	40,49	50,7	60,74	70,95	80,98
-0,64	34,62	43,35	51,93	60,66	69,24
-0,55	40,03	50,12	60,04	70,14	80,05
-0,62	35,52	44,48	53,29	62,25	71,05
-0,72	31,02	38,84	46,52	54,35	62,03
-0,84	26,51	33,2	39,76	46,45	53,02

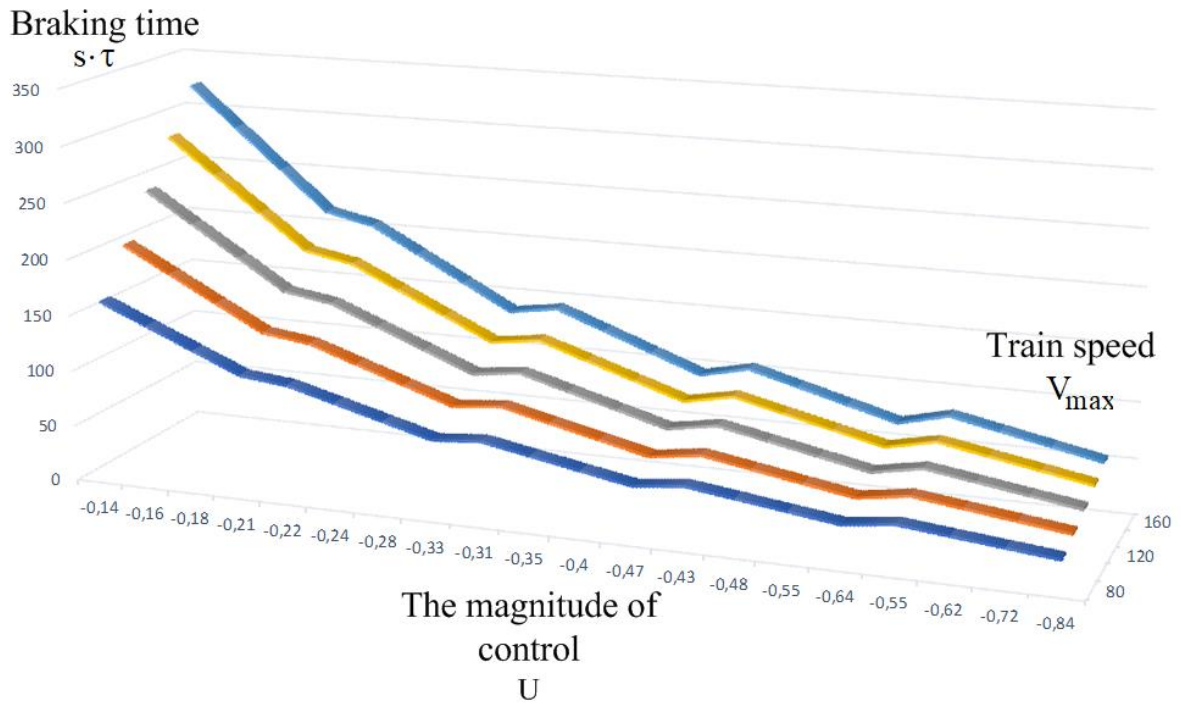


Fig. 2. Changing the braking time at fixed speed and different values of the control indicator

Table 4

Braking path time values at fixed speed and different control values

U	V _{max} , km / h				
	80	100	120	140	160
-0,14	1800,05	2819,14	4041,61	5511,93	7177,58
-0,16	1600,14	2505,64	3591,79	4898,09	6377,88
-0,18	1400,11	2191,96	3141,71	4283,89	5577,72
-0,21	1200,16	1878,39	2691,78	3669,90	4777,82
-0,22	1149,88	1799,54	2578,63	3515,50	4576,67
-0,24	1022,70	1600,09	2292,45	3124,96	4067,88
-0,28	895,21	1400,15	2005,55	2733,44	3557,81
-0,31	803,98	1257,07	1800,24	2453,25	3192,79
-0,33	767,62	1200,05	1718,42	2341,60	3047,32
-0,35	715,07	1117,61	1600,13	2180,17	2837,01
-0,40	626,11	978,09	1399,91	1906,93	2481,02
-0,47	537,26	838,73	1199,93	1634,01	2125,45
-0,43	591,27	923,44	1321,50	1799,92	2341,61
-0,48	526,22	821,40	1175,07	1600,07	2081,24
-0,55	461,09	719,24	1028,44	1399,96	1820,52
-0,64	396,03	617,16	881,94	1200,01	1560,00
-0,55	455,95	711,18	1016,88	1384,18	1799,95
-0,62	406,04	632,86	904,47	1230,76	1600,07
-0,72	356,09	554,49	791,99	1077,23	1400,03
-0,84	306,18	476,15	679,54	923,74	1200,02

Analysis of the results shows that the most difficult situation is a sharp change in the control parameter, but it is encouraging that even at maximum speed we have a fairly confident result. This is very important in real operation, when a separate part of the input information of the microprocessor train control system has a greater or lesser degree of uncertainty of the primary information due to malfunctions of the primary sensors.

4. Conclusions

4.1. Discussion

The safety criterion for automatic control of rail transport vehicles is the exclusion of the possibility of various vehicle collisions. This criterion implies establishment of some critical value of distance between vehicles, at which safety of transportation process is guaranteed. The mathematical model of train movement developed in the work includes not only information about the position of the train, the landmark, the direction of movement and speed of the vehicle, but also a variable benchmark to fully reflect the process of trains. The model makes it possible to determine with

maximum accuracy the critical distance between trains, the time required to eliminate the threat of collision, the moment when braking begins, the braking time considering the inclination of the train, the angle of the route and the braking distance. The simulation results can be used in the Automated Transportation Planning System in the development of the train schedule. This will optimize the planning process by analyzing the change in the guiding parameter, i.e. the braking distance, depending on the traffic conditions on a particular section. This makes it possible to create a new ideology of building a railway transport management system on the basis of a comprehensive automated data processing system. This approach will ensure a gradual transition from automated information and control systems of quasi-real time to the implementation of transport technology control in real time in the future.

Therefore, the results obtained in this work allow to ensure more stable operation of the automatic train control subsystem under the existing restrictions, failures and distortions of primary information in the train control systems for the main railway transport and subway. In order to simplify the mathematical apparatus in the article, the authors artificially introduced a range of changes of the control operator. In the future, it is

advisable to study its changes depending on the temperature, plan and profile of the train and its weight, paying special attention to the factors that create uncertainty of the primary information.

4.2. Future research

A further development of these studies should be the integration of the obtained computer model with the automated traction calculation system, which is currently used in Ukrzaliznytsia. The use of the results obtained in this work in the automatic traffic control systems of railroad vehicles can reduce the number of failures of the guidance system in cases of distortion or temporary loss of information coming from the primary sensors.

Contributions of authors: review and analysis of references, formulation of the purpose and tasks of research, formulation of conclusions – **K. Trubchaninova**; development of conceptual provisions and methodology of research – **V. Moiseenko**; development of mathematical models and analysis of research results – **O. Golovko**; selection and application of software and hardware tools for modeling and presentation of results – **V. Butenko**. All authors have read and agreed to the published version of the manuscript.

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МОДЕЛЮВАННЯ РУХУ ТРАНСПОРТНИХ ЗАСОБІВ У КОМП'ЮТЕРНИХ ІНФОРМАЦІЙНО-КЕРУЮЧИХ СИСТЕМАХ

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Предметом вивчення в статті є процеси синтезу математичної моделі функціонування об'єктів керування в комп'ютерних інформаційно – керуючих системах критичного призначення для потреб магістрального залізничного транспорту. Основний наголос зроблено на моделюванні руху пасажирського поїзда в системі швидкісного руху Укрзалізниці. Метою є дослідження процесу регулювання швидкості руху залізничних транспортних засобів за умов невизначеності у первинній інформації мікропроцесорних інформаційно – керуючих систем залізничного транспорту. Завдання: визначення критерію безпечності автокерування засобами залізничного транспорту; отримання математичної моделі руху поїзда за умов невизначеності; перевірка адекватності моделі. Використаним методом є математичний апарат дискретних моделей. Отримані наступні результати. Розроблена в роботі математична модель руху потягів включає в себе не тільки інформацію про положення потягів, точку відліку, напрям руху і швидкість транспортного засобу, але і змінний показник керування для адекватного відображення процесу руху залізничного транспорту. В роботі показано, що на основі синтезованої моделі є можливість застосування так званої нечіткої відстані між суміжними поїздами. Такий підхід дозволяє підвищити точність визначення критичної відстані між потягами, час, що потрібний для усунення загрози зіткнення, момент початку використання гальмування та час гальмування з урахуванням кута нахилу ділянки слідування, а також дистанцію гальмівного шляху. Доказана необхідність визначення показника керування, його величину на протязі деякої кількості моментів часу, поки буде відбуватись зменшення швидкості для безпечного руху потягів. На базі запропонованої математичної моделі проведено комп'ютерне моделювання процесу з ціллю визначення необхідного запасу часу на реагування машиністом потяга на зміни швидкості попереднього потяга, а також діапазони зміни швидкості, які вимагають негайних екстрених дій. Висновки. Наукова новизна отриманих результатів полягає у розробленні математичної моделі поведінки рухомих одиниць в комп'ютерних системах критичного призначення для потреб залізничного транспорту при наявності збоїв у первинній інформації від датчиків, які фіксують параметри руху. Досліджено поведінку системи керування при різних значеннях швидкості поїзда та змінах величини інтервалу попутного слідування. Отримала подальшого розвитку теорія тягових розрахунків в комп'ютерних системах керування рухомими одиницями. Отримані наукові результати будуть використовуватися при розробленні прикладного програмного забезпечення залізничних комп'ютерних систем критичного призначення.

Ключові слова: мікропроцесорні системи керування рухом поїздів; авторегулювання; інтервал попутного слідування; рух поїздів; керування рухом за умов невизначеності; безпечність руху.

МОДЕЛИРОВАНИЕ ДВИЖЕНИЯ ТРАНСПОРТНЫХ СРЕДСТВ В КОМПЬЮТЕРНЫХ ИНФОРМАЦИОННО-УПРАВЛЯЮЩИХ СИСТЕМАХ

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Предметом изучения статьи являются процессы синтеза математической модели функционирования объектов управления в компьютерных информационно – управляющих системах критического назначения для нужд магистрального железнодорожного транспорта. Основной упор сделан на моделировании движения пассажирского поезда в системе скоростного движения Укрзалізниці. Целью является исследование процесса регулирования скорости движения железнодорожных транспортных средств в условиях неопределенности в первичной информации микропроцессорных информационно – управляющих систем железнодорожного транспорта. Задачи: определение критерия безопасности автоуправления средствами железнодорожного транспорта; разработка математической модели движения поезда в условиях неопределенности; проверка адекватности модели. Использованным методом является математический аппарат дискретных моделей. Получены следующие результаты. Разработанная в работе математическая модель движения поездов включает в себя не только информацию о положении поездов, точке отсчета, направлении движения и скорости транспортного средства, но и переменный показатель управления для адекватного отображения процесса движения железнодорожного транспорта. В работе показано, что на основе синтезированной модели есть возможность применения так называемого нечеткого расстояния между смежными поездами. Такой подход позволяет повысить точность определения критического расстояния между поездами, время, необходимое для устранения угрозы столкновения, момент начала использования торможения и время торможения с учетом угла наклона участка следования, а также дистанцию тормозного пути. Доказана необходимость определения показателя управления, его величину в течение некоторого количества моментов времени, пока будет происходить уменьшение скорости для безопасного движения поездов. На базе предложенной математической модели проведено компьютерное моделирование процесса с целью определения необходимого запаса времени на реагирование машинистом

поезда на изменения скорости предыдущего поезда, а также диапазоны изменения скорости, требующие немедленных экстренных действий. Выводы. Научная новизна полученных результатов заключается в разработке математической модели поведения движущихся единиц в компьютерных системах критического назначения для нужд железнодорожного транспорта при наличии сбоя первичной информации от датчиков, фиксирующих параметры движения. Исследовано поведение системы управления при разных значениях скорости поезда и изменении величины интервала попутного следования. Получила дальнейшее развитие теория тяговых расчетов в компьютерных системах управления движущимися единицами. Полученные научные результаты используются при разработке прикладного программного обеспечения железнодорожных компьютерных систем критического назначения.

Ключевые слова: микропроцессорные системы управления движением поездов; авторегулирование; интервал попутного следования; движение поездов; управление движением в условиях неопределенности; безопасность движения.

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