

## Train Operation Control on-based of Logical-Linguistic Model

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### Abstract

The article presents a new approach to control of train movement based on a combination of terminal (finite) and fuzzy control methods using a logical-linguistic model whose numerical parameters are determined on the basis of search optimization and simulation modeling. The results of computational experiments are presented and given recommendations to the application and further development of the proposed approach. In particular, the proposed logical-linguistic model can be used in the construction of on-board systems of suburban electric trains.

**Keywords:** on-board control system, suburban electric trains, passenger train, fuzzy logic, logical-linguistic simulation, computing experiment, autodrivers.

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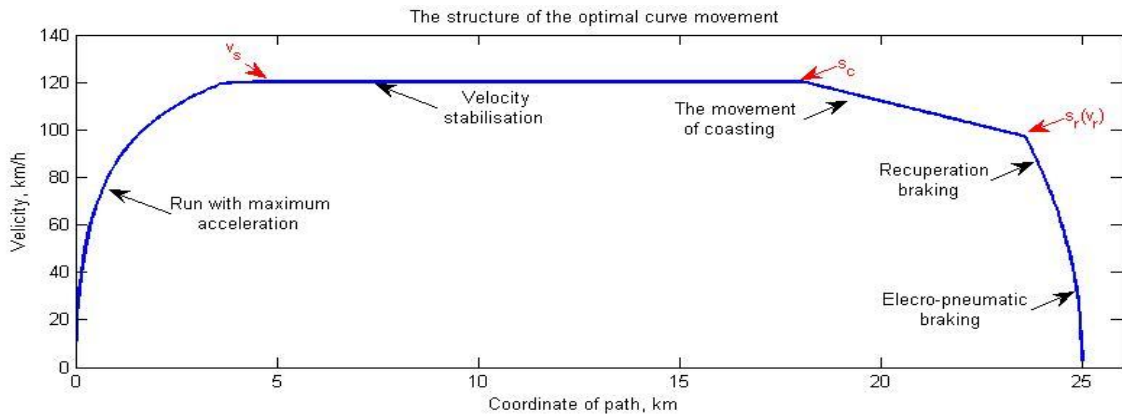
### 1. Introduction

The automation of train traffic control is one of the main ways to improve its safety, save energy resources, improve the working conditions of locomotive crews with strict observance of the traffic schedule [1,2]. The system of train auto-driving must solve the problem of determining and realizing the optimal trajectory of motion in real time mode taking into account the perturbations [3]. This task belongs to the class of terminal (or finite, according Bellman) control.

The results of its solution on the basis of various methods and approaches, as well as the analysis of the experience of driving trains by the drivers, made it possible to determine the general form of the optimal trajectory of the train and the principles of design an automatic train operation system (ATO) [4-12]. In general, such a trajectory

includes acceleration sections with maximum acceleration, speed stabilization, coasting (inertia motion), electrodynamic (recuperative or rheostatic) and mechanical (pneumatic or electro-pneumatic) braking (Fig. 1). In this case, the ATO is most often realized as a two-loop subordinate control system, in which the external circuit is responsible for controlling the travel time, while the internal circuit contains a speed controller [4,5,7].

Further development of systems of this class can be associated with their intellectualization, i.e. application in control loops of methods and models of artificial intelligence. Thus, the possibilities of using the math-based apparatus of fuzzy logic to solve the problem of automating the control of train brakes were considered in [13-16]. This paper presents the author's proposed approach to control the movement of trains on the basis of a combination of methods terminal (finite) and fuzzy control.



**Figure 1.** The structure of the optimal trajectory of the train movement:  $v_s$  - velocity of stabilization;  $s_c$  - coordinate of start coasting;  $s_r(v_r)$  - coordinate or velocity of start recuperation braking

In this case the ATO is constructed as a two-loop feedback system with elements of prediction and approximation of the dependence of the stabilization speed on the motion time. As a regulator of time motion used logical-linguistic model, the numeric parameters being determined on the basis of search optimization and simulation modeling.

The results of simulation modeling allow us to recommend the developed logical and linguistic model of train traffic control for the solution of problems of automation of electric train control, which are characterized by short distances with an explicit structure of the optimal trajectory of motion, presented in Fig. 1.

## 2. Simulation model of train movement

### 2.1. Mathematical model

Dynamics of electric rolling stock taking into account the distributed mass of the train in accordance with the basic provisions of the theory of electric traction [11, 12] can be described by the following system of equations:

$$\frac{dv}{ds} = (\sum S_u + \sum S_{ex}) / ((1 + \gamma)(m_l + \sum_{j=1}^q m_c)); \quad (1)$$

$$\sum S_u = (F - R - B); \quad (2)$$

$$F = F(\mu_F(u_1, v, U_{cw})); \quad (3)$$

$$R = R(\mu_R(u_2, v)); \quad (4)$$

$$B = B(K(P_{bc}(u_3), \varphi(v))); \quad (5)$$

$$\sum S_{ex} = \sum_{j=1}^{p+q} (W_o^j(v) + W_i^j(s_i, l_j) - W_a(\theta)); \quad (6)$$

$$U_m(\mu(u_1, u_2), U_{cw}) = C\Phi(I_B)v + Ir; \quad (7)$$

$$F|R = n_m C\Phi(I_B)I\eta_l; \quad (8)$$

$$B = 1000 \sum K(P_{bc}(u_3)\varphi_k(v)); \quad (9)$$

$$W_o^j(v) = \begin{cases} (a_0 + a_1 v + a_2 v^2)m_l g, j = 1..p \\ (a_3 + \frac{a_4 + a_5 v + a_6 v^2}{m_{ax} g})m_c g, j = 1..q \end{cases}; \quad (10)$$

$$W_i^j(s_j, l_j) = W_r^j(s_j, l_j) + W_k^j(s_j, l_j), \quad (11)$$

where:  $s$  - the coordinate of the path;  $v$  - velocity;  $\sum S_u$  and  $\sum S_{ex}$  the sum of regulated and unregulated external forces:  $F, R, B$  - traction power, electrical and pneumatic automatic braking;  $W_o, W_i, W_a$  - main, additional and the auxiliary resistance to movement;  $p$  and  $q$  respectively the number of locomotives and cars;  $m_l$  and  $m_c$  the weight of the locomotive and wagon;  $m_{ax}$  - weight of wagon on one axis;  $\gamma$  - coefficient of inertia of rotating parts;  $U_{cw}, U_m$  the voltage in the contact system and the engine;  $\mu = (\mu_F, \mu_R)$  - control of traction system;  $C$  - ratio;  $\Phi$  - magnetic flux;  $n_m$  - number of engines;  $\eta_l$  - the efficiency of the locomotive;  $K$  - the force of pressure on the brake pads;  $P_{bc}$  - the pressure in the brake cylinders;  $\varphi_k$  - the friction coefficient;  $a_0, a_1, a_3, a_4, a_5, a_6$  - coefficients depending on the type of rolling stock;  $g$  - acceleration of free fall;  $W_r$  and  $W_k$  - the resistance of slopes and curves the path;  $l_j$  - the length of the  $j$ -th unit of rolling stock;  $\theta$  - a set of determinants  $W_a; u_1, u_2, u_3$  - function control of traction, regenerative and mechanical brake.

### 2.1. Simulation in Matlab/Simulink

To taking into account of the ratios (1) - (11) developed a simulation model for the train movement in Matlab/Simulink, the block-scheme of which is shown in Fig. 2. Here are the basic functional units of the model: simulation traction, recuperation and mechanical braking; forces of the main and additional resistances to motion; blocks of modeling the mechanical motion of a train, input data, restrictions of speed, regulation of speed and time motion and optimal programs; auxiliary units for imaging parameters, management of computing experiment, calculation of power consumption etc..



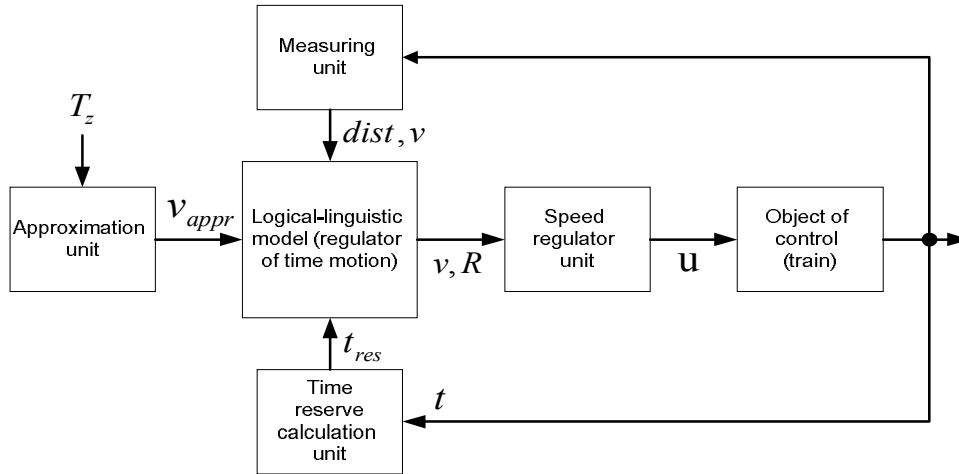


Figure 3. The suggested functional diagram of automatic train operation system

To determine these dependencies use the assumption that the movement is performed in three modes: acceleration with maximum  $a_{tr}$ , value of speed stabilization speed  $v_s$ , movement with the maximum deceleration  $a_{br}$ ,

$$t_{xx} = t_{tr} + t_s + t_{br} = \frac{1}{k_2} \int_{v_0}^{v_s} \frac{dv}{a_{tr}} + \frac{s_k - s_0 - s_{tr} - s_{br}}{v_s} + \frac{v_s - v_k}{k_2 a_{br}};$$

$$s_{tr} = \frac{v_s^2 - v_0^2}{k_1 \cdot a_{tr}}$$

– the length of the acceleration path;

$$s_{br} = \frac{v_s^2 - v_k^2}{k_1 \cdot a_{br}}$$

Using the obtained dependence  $t_{xx}$  can be determined numerically. To obtain the analytical dependence of the integral in the first term can be replaced by the expression:

$$t_{tr} = \frac{(v_s - v_0)m}{0.5k_2(F(v_s) - F(v_0))},$$

where  $F(v_s)$  and  $F(v_0)$  – are the values of traction at the beginning of the movement and the end of acceleration in accordance with the traction characteristics of the locomotive,  $m$  - the train weight,  $v_0$  - the speed at the beginning of the movement.

After calculating  $t_1$  and  $t_2$  be constructing linear approximating function calculation  $v_s$  for arbitrarily specified  $T_x$ :

$$v_s(T_x) = v_{min} + \frac{v_{max} - v_{min}}{T_2(v_{max}) - T_1(v_{min})} (t - T_1(v_{min})).$$

The output of the model is formed of reference for the speed regulator in coordinates: set the speed and mode of movement:

$$R = \begin{cases} 1 \rightarrow \text{traction with } a_{tr} \\ 0.5 \rightarrow \text{stabilisation } v_z \\ 0 \rightarrow \text{coasting} \\ -0.5 \rightarrow \text{recuperation} \\ -1 \rightarrow \text{braking with } -a_{br} \end{cases}.$$

### 3.2. Logical-linguistic model (LLM)

As follows from figure 3, the role of the regulator of time motion (RTM) is performed by the logical-linguistic model LLM, which implements the choice of regime R of train movement based on the data received from other blocks of the system: the distance to the end of the path “Dist”, the current speed “Vel”, the travel time reserve  $t_{res}$  and the stabilization speed  $v_s$ .

As you know, the logical conclusion involves the following four stages: fuzzification, fuzzy implication, fuzzy composition and defuzzification. One of the possible options for implementing the RTM based on fuzzy inference is presented below.

At the stage of fuzzification for clear input values “Dist”, “Vel”,  $t_{res}$  the belonging to separate terms of linguistic variables “Distance”, “Velocity”, “Reserve of time” are calculated. The membership functions shown in Fig. 4-8 are used for this purpose.

The obtained value of the speed of stabilization  $v_s(T_x)$  also inputted in the LLM (unit of regulator of time motion), where it used as a fuzzy number “approximately  $v_s$ ” with membership function Gaussian:

$$\tilde{v}_s(v, \delta, v_s) = e^{-\frac{(v - v_s)^2}{2\delta^2}}.$$

The following steps include: finding the membership functions of the prerequisites of each specific rule for specific input signals; finding the resulting membership functions of each rule and the resulting membership function of the entire set of rules are implemented on the basis of the production rules base presented in table 1. This uses a simplified fuzzy inference scheme in which the right-hand sides of the rules are clearly defined, and the fuzzy inference produces a discrete set of solutions for each element that has a certain degree of confidence. The values of the output variable are selected with maximum confidence.

Thus in fig. 4-7 the following designations are used: ZR - zero, AS – absolute small, VS – very small, SM - small, MD - middle, CN - considerable, BG - big, VB –

very big, and in fig. 8: NBG – negative big, NMD – negative middle, NSM- negative small, ZR - zero, PAS – positive absolute small, PVS - positive very small, PSM -

positive small, PMD – positive middle, PCN - positive considerable, PBG – positive big, PVB - positive very big; ANY - anything.

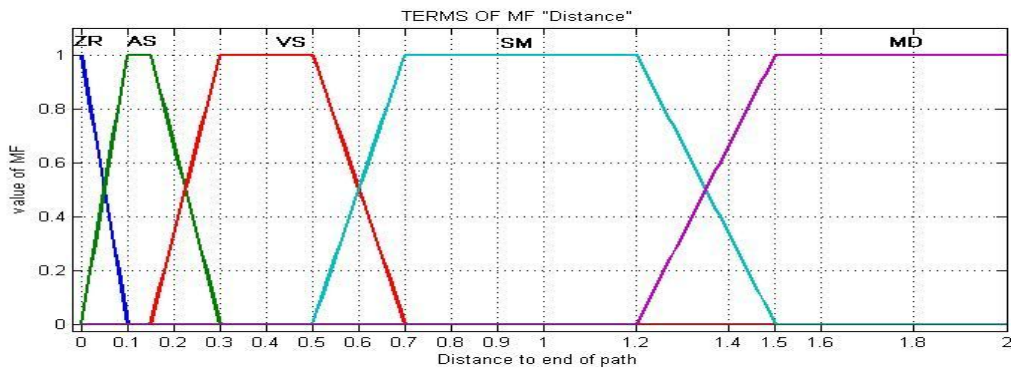


Figure 4. Term-sets ZR, AS, VS, SM, MD of linguistic variable «Distance»

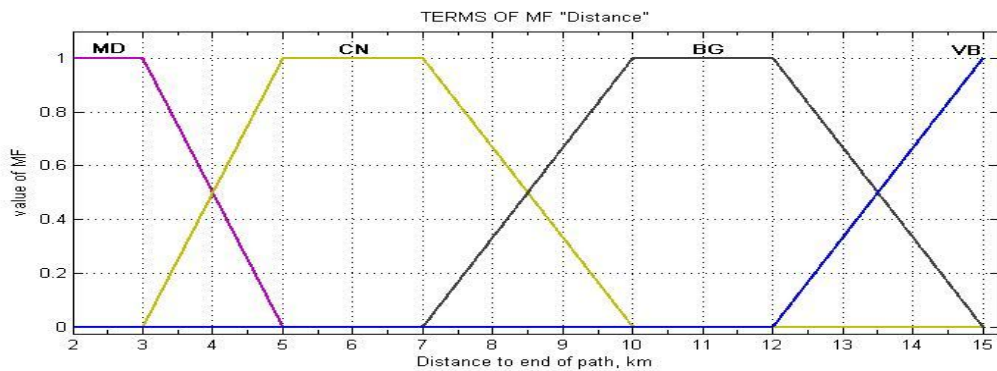


Figure 5. Term-sets MD, CN, BG, VB of linguistic variable “Distance”

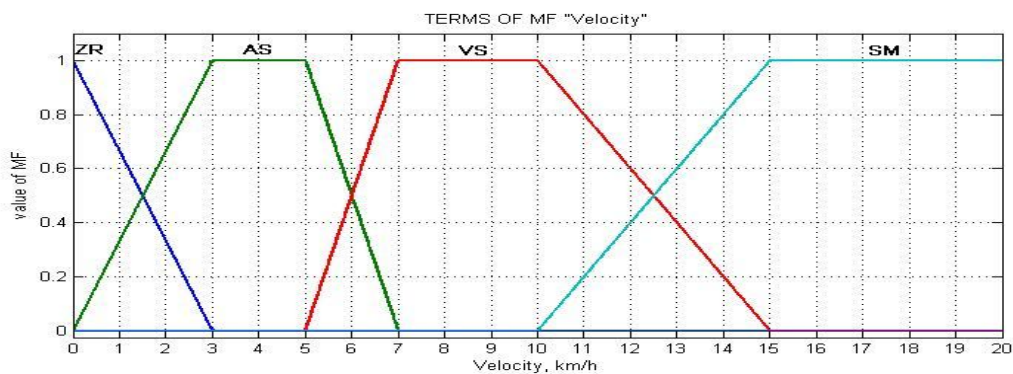


Fig. 6. Term-sets ZR, AS, VS, SM of linguistic variable “Velocity”

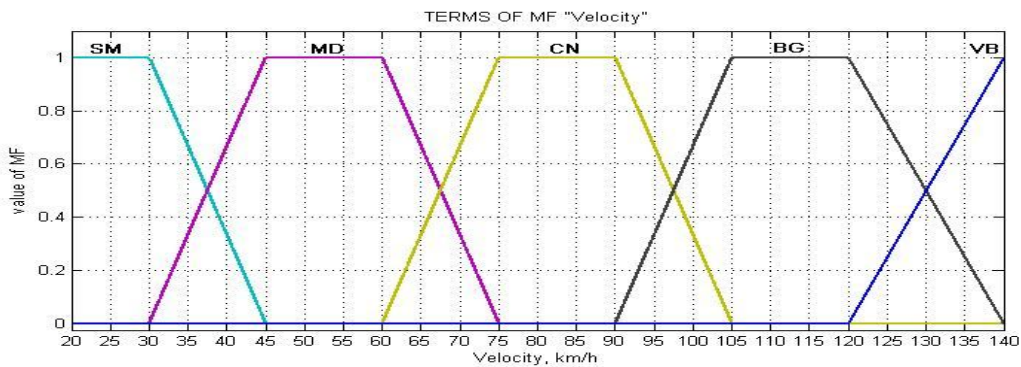


Fig. 7. Term-sets SM, MD, CN, BG, VB of linguistic variable “Velocity”

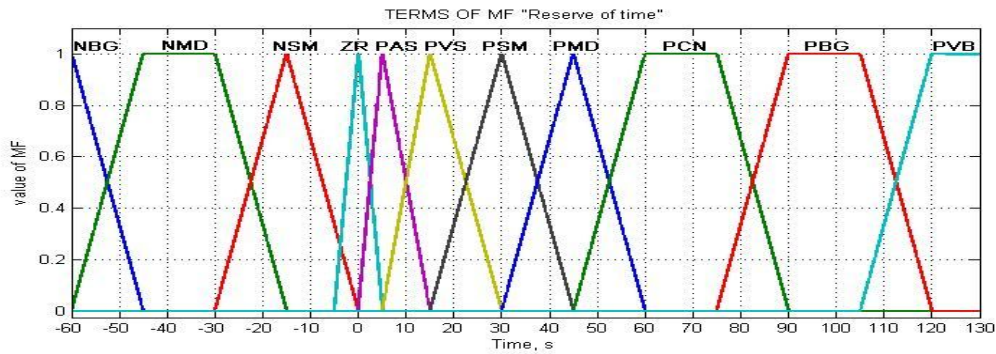


Fig. 8. Term-sets NBG, NMD, NSM, ZR, PAS, PVS, PSM, PMD, PCN, PBG, PVB of linguistic variable “Reserve of time”

Table 1. The base of production rules for fuzzy inference

No of rule	Record of production rule
1	<p><b>IF</b> [(Dist = CN) <b>OR</b> (Dist = BG) <b>OR</b> (Dist = VB)] <b>AND</b>                      [(Vel = ZR) <b>OR</b> (Vel = AS) <b>OR</b> (Vel = VS) <b>OR</b> (Vel = SM) <b>OR</b> (Vel = MD)] <b>AND</b>                      [(Vel = NOT(<math>\tilde{v}_s</math>))] <b>AND</b>                      [(<math>t_{res}</math> = NBG) <b>OR</b> (<math>t_{res}</math> = NMD) <b>OR</b> (<math>t_{res}</math> = NSM)]  <b>THEN</b> R = 1;</p>
2	<p><b>IF</b> [(Dist = BG) <b>OR</b> (Dist = VB)] <b>AND</b>                      [(Vel = CN) <b>OR</b> (Vel = BG) <b>OR</b> (Vel = VB)] <b>AND</b>                      [(Vel = NOT(<math>\tilde{v}_s</math>) <b>OR</b> <math>\tilde{v}_s</math>)] <b>AND</b>                      [(<math>t_{res}</math> = NBG) <b>OR</b> (<math>t_{res}</math> = NMD) <b>OR</b> (<math>t_{res}</math> = NSM) <b>OR</b> (<math>t_{res}</math> = ZR)]  <b>THEN</b> R = 1;</p>
3	<p><b>IF</b> [(Dist = ANY)] <b>AND</b>                      [(Vel = MD) <b>OR</b> (Vel = BG) <b>OR</b> (Vel = VB)] <b>AND</b>                      [(Vel = <math>\tilde{v}_s</math>)] <b>AND</b>                      [(<math>t_{res}</math> = ZR) <b>OR</b> (<math>t_{res}</math> = PAS) <b>OR</b> (<math>t_{res}</math> = PVS) <b>OR</b> (<math>t_{res}</math> = PSM) <b>OR</b> (<math>t_{res}</math> = PMD)]  <b>THEN</b> R = 0.5;</p>
4	<p><b>IF</b> [(Dist = VS) <b>OR</b> (Dist = SM) <b>OR</b> (Dist = MD)] <b>AND</b>                      [(Vel = MD) <b>OR</b> (Vel = BG) <b>OR</b> (Vel = VB)] <b>AND</b>                      [(Vel = ANY)] <b>AND</b>                      [(<math>t_{res}</math> = PSM) <b>OR</b> (<math>t_{res}</math> = PMD) <b>OR</b> (<math>t_{res}</math> = PCN) <b>OR</b> (<math>t_{res}</math> = PBG) <b>OR</b> (<math>t_{res}</math> = PVB)]  <b>THEN</b> R = 0.</p>

These rules define the control in the modes of acceleration, stable speed and coasting. At realization of regenerative and pneumatic braking is carried out the transition to programmed control. In this case the program speed is determined on the basis of the preset deceleration for both modes:  $v_{prog} = \sqrt{25920 \cdot a \cdot dist}$ .

#### 4. Computational experiment

Developed on the basis of ratios (1-11) simulation model of train movement (Fig. 3) allows to explore different ways to control the movement of the train. With its help the developed method of management on the basis of

logical-linguistic model was investigated. The computational experiment included two stages:

1 Search for control as a dependence  $u=u(t)$  (or  $u=u(s)$ ). For this purpose, the authors developed a special algorithm of search optimization using a simulation model based on the optimality criteria set out in section 2.1. This method of control can be assigned to the class of optimal programmed control without feedback. This approach can be used in the laboratory during research, as well as in the development of energy-optimal mode maps of train driving. It requires certain computing resources and special software. The result can be used as a "etalon" to assess the effectiveness of control methods designed to be implemented on Board the train in real time.

2 Simulation modeling of train movement control based on the developed logical-linguistic model. The latter refers to the methods of control with feedback, since the values of the parameters "Dist", "Vel",  $t_{res}$  characterizing the state of the control object are used in the development of the control action (R). This method can be relatively easy to implement on Board the train and does not require such computing resources as method 1.

The developed logical-linguistic model was investigated by means of a computational experiment with a simulation model applied to suburban electric trains as well as passenger trains. The results of control using the LLM was compared with the results of programmed control (control without feedback), calculated on the basis of search optimization. As an example, some simulation results are given in table. 2. The structure of optimal trajectories in both cases corresponds to fig. 1.

Table 2. Result of simulation

No	parameter	value
1	$s_0, km$	0
2	$s_k, km$	25
4	$T_z, sec$	900
5	$m_{train}, ton$	1120
6	$v_{max}, km/h$	120
<i>Result of control with LLM</i>		
8	$v_s, km/h$	113
9	$t_x$	910
10	A, kWt-h	320
<i>Result of programmed control on-based searching optimization</i>		
11	$v_s, km/h$	115
12	$t_x$	898
13	A, kWt-h	326

If using LLM there is a deviation from the schedule within 15 seconds, which can be considered an acceptable result. It compensated a small reduction in energy consumption. It should also be noted that deviations of

actual parameters from those calculated in real operating conditions more influenced for control quality [3] at the programmed control method than control with LLM.

## 5. Conclusions

1 By simulation modeling it is established that the quality of control obtained with the help of LLM is somewhat different from the results of programmed control based on search optimization. The implementation of the latter approach in real time is difficult because it requires considerable computing resources. In addition, the quality of control with the help of LLM is less influenced by the deviation of the actual traffic parameters from the calculated ones and the influence of external disturbances, which can be decisive in operation.

2 The proposed logical-linguistic model can be used in the construction of on-board systems of suburban electric trains.

3 It is advisable to continue research for adaptation of the logical-linguistic model for various types of control objects - passenger and freight trains, as well as traffic conditions, which determined by a complex path profile.

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