Пропонується побудова математичної моделі формування керуючих дій водія при виборі швидкості руху на суміжних ділянках дороги, для чого використовуються методи теорії автоматичного регулювання із застосуванням передатних функцій водія. Запропонована модель враховує реакцію водія на зміну дорожньої обстановки за узагальнюючою характеристикою – максимальною ентропією середовища руху

Ключові слова: поводження водія, сприйняття інформації, ентропія середовища, швидкість руху, передатна функція

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Предлагается построение математической модели формирования управляющих действий водителя при выборе скорости движения на смежных участках дороги, для чего используются методы теории автоматического регулирования с применением передаточных функций водителя. Предлагаемая модель учитывает реакцию водителя на изменение дорожной обстановки по обобщающей характеристике – максимальной энтропии среды движения

Ключевые слова: поведение водителя, восприятие информации, энтропия среды, скорость движения, передаточная функция

DEVELOPMENT OF A MODEL OF A DRIVER'S CHOICE OF SPEED CONSIDERING THE ROAD CONDITIONS

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1. Introduction

The basic purpose of the driver's activity optimization is the creation of comfortable working conditions, when a change in the mental and psychological state of a driver when driving along the road goes smoothly, i. e., the transient process gets as simple as possible. Undesirable transient processes of drivers are the consequence of an abrupt change in the traffic situation while a driver moves from one road section to another. Regulating the parameters of a road situation, it is possible to influence the conditions of a driver's work when s/he passes different road sections.

The subject of scientific studies in the area of arranging a driver's working place is regarding him/her as an element of the "supervising" control system. The behavior of a driver in this system results in the change in speed and in a motion trajectory in accordance with the changing traffic environment. A driver of a motor vehicle visually evaluates a road section in front and selects the speed of the safe motion. The connection between the information and the actions of a driver bears a nonlinear character. The actions of a driver and the character of an automobile motion depend both on the information s/he obtains and the characteristics of a vehicle. An abrupt change in traffic conditions can lead to the emergency and, as a result, to a road accident. For designing and constructing the roads, it is necessary to consider all complex interactions, to distinguish the role of a driver in the system "driver – automobile – road environment" (DARE). Therefore, the development of a model of a driver's choice of the motion speed considering the traffic situation is a relevant task in forming the environment of a driver's working activity.

2. Analysis of scientific literature and the problem statement

The contemporary studies of the scientists, engaged in the assessment of the driver's behavior and the DARE system, are based on the theory of control incorporating the achievements of cybernetics, the theory of automatic regulation, ergonomics and the theory of information.

The analysis of the mathematical models of the activity of a human operator, carried out in the work [1], showed that the models were developed given the fact that a driver was experienced and they did not show the way the model changed with an increase in the professionalism of a driver. In the studies [2], a step-by-step formation of a driver's images and actions when driving on the road, the mathematical model of the speed motion calculation in the zone of the influence of the traffic environment elements in front, has been developed. But in the presented models, the stochasticity of the driving actions due to the instability of a driver's psycho-physiological state has not been taken into account.

The need of taking into consideration the individual specific features of a driver when s/he estimates the motion speed, is shown in the paper [3]. However, the proposed models are directed toward the research, connected with the prevention of running into another vehicle due to not keeping the safe distance.

The application of the transmission functions is a relevant direction of mathematical analysis in the estimation of the behavior of a driver. In the work [4], the model of the system of controlling an automobile which unites the transmission functions of a driver and those of a vehicle has been developed. However, this model cannot be used for the solution of the

set task, since the output parameter is the rotation angle of the controlled wheels or the lateral displacement, which complicates the use of this model for assessing the motion speed on the roads sections. For the same reason, the model in the work [5], in which the transmission function of an automobile considers the steering wheel rotation angle cannot be used either.

In the work [6], the model of a driver's behavior is used for designing the intellectual controllers of a vehicle. The method of designing the controller of driving is based on the analysis of the human behavior in the form of a linear continued inverse connection, and the functions of control are presented in the form of transmission function. In the work [7], driving a vehicle in the system "Driver – automobile – road" is researched from the positions of the theory of information considering a driver's dynamic qualities as a nonlinear system. The data of the study are directed toward the solution of the problem of guaranteeing the controllability of an automobile with the turning of a steering wheel in the mode of " tracking" and do not make it possible to estimate the motion speed.

The models of driving a motor vehicle by the motion speed channels are the closest to the solution of the set problem [8]. Meanwhile, the gradation of the models according to three degrees of a driver's motivational perception of a road situation hampers their practical use for the measures of the roads construction.

The approach of the scientists to the content of the information received by a driver is not single–valued. In the paper [9], the behavior of a driver is determined, first of all, on the basis of the signals, which emanate from a vehicle, but not from the environment. In other studies, the perception of a road situation by a driver is evaluated by the influence of the separate elements of a road. Thus, in the work [10], the study of a driver with the help of the transmission function showed that his/her selection of a speed depends on the quality of processing the information about the various traffic conditions, relating to the separate road elements. In the studies [11], the selection of the safe motion speed by a driver is evaluated by the influence of the horizontal curves of a road, which excludes the use of a complex index of the road environment estimation.

Thus, among the available scientific research into the models, practically none gives the opportunity to simulate the actions of a driver as for the selection of the motion speed according to the information on the environment, the influence of which would be evaluated by an integrated index.

3. The purpose and objectives of the study

The purpose of this work is the construction of the model of forming a driver's controlling actions and selecting the motion speed considering the changing traffic situation in the adjacent road sections.

For achieving the set goal, it is necessary to solve the following tasks:

– to estimate the complexity of the road conditions by tmaximum entropy on the basis of the experimental data;

– to develop a mathematical model of a driver's controlling actions on the selection of the motion speed, in which the special features of driver's perception of the information about the traffic environment and the characteristics of a vehicle are considered;

– to compare the results of this model with the experimental data.

4. Experimental research into road conditions complexity

In accordance with his/her experience and technical special features of a vehicle, the driver makes changes in the position of a vehicle and its speed during the motion. In each specific case, s/he estimates the transformation of the traffic environment according to the generalizing characteristic, which contains both the quantitative and qualitative components of this transformation. On the basis of obtained information, the images of the external environment are formed in the consciousness of a driver, the totality of which constitutes the information model of the object, the generalizing characteristic of which may serve as the maximum entropy [12], determined by the formula [13]:

$$H_m = n^2, \tag{1}$$

where H_m is the maximum entropy, bit; n is the number of the objects of the perception field.

Conducting experimental studies lay in the fixation of the constant (stationary) and the variable factors of the traffic environment and the motion speed during the motion.

As shown in the paer [12], the coordination of the sections by the maximum entropy of a driver's perception area is the initial stage of guaranteeing the motion conditions on the adjacent sections of roads. In this case, the complexity of traffic environment can be determined on the basis of the stationary road elements, when upcoming and overtaking motor vehicles or pedestrians do not get into the perception area of a driver. Therefore, after excluding from the data of the experiment the sections, in which other traffic participants were fixed, the dependence of the actual motion speed on the maximum entropy of a driver's perception area was built up (Fig. 1). In Fig. 1, the variation of the values of speed (they are marked by the points) under the influence of the constant value of maximum entropy on a driver, is clearly expressed. This testifies to the stochasticity of a driver's actions at one and the same signal. The obtained connection shows that with an increase in entropy, the speed also increases. This is explained by the fact that with a high motion speed, the perception area of a driver is not dispersed and, narrowing, lengthens along the road.

The analysis of dependence $V = f\left(H_m^{const}\right)$ showed the curvilinear connection (Fig. 1), which is determined by the expression:
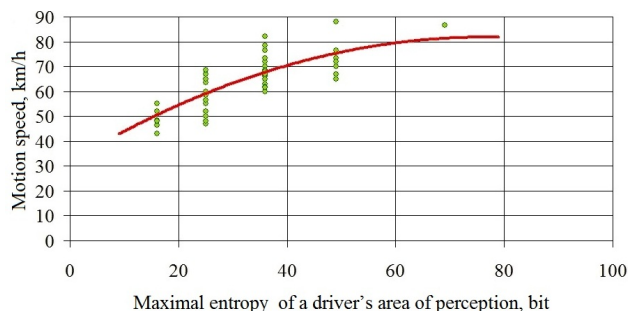
$$V = -0{,}0093H_m^2 + 1{,}358H_m + 31{,}12. \tag{2}$$

Fig. 1. Dependence of actual motion speed on maximum entropy under the influence of constant factors of traffic environment

The correlation ratio r=0,630 testifies to the average influence of the maximum entropy on the motion speed on the

road sections within which the driver is under the influence of only the elements of engineering maintenance.

5. Building up a system of automatic regulation, forming driver's controlling actions by the choice of a motion speed

From the position of cybernetics and the theory of automatic control, the regulation is the process of the goal-directed influence on the driver and a motor vehicle automobile for providing the required change in the state of the system DARE.

The mathematical model of a motor vehicle driver's actions must consider the psycho-physiological characteristics of a human as well as the influence of different kind of external factors on his/her activity and the results of this activity. The result of researching into the activity of a driver as a human operator is the creation of the adequate description in the form of the mathematical model of the dynamics of his/her behavior. In the system of automatic control, the character of the regulation is determined by the transient process, which can be assigned with the help of the transmission functions of a motor vehicle and a driver.

As an example of the dynamic system, let us examine the mathematical model of the automatic control system of the driver's motion on the road sections, realized in the interactive medium for making the scientific and engineering calculations MATLAB with the extension package of Simulink.

Three models of the simulation of a vehicle driving effectiveness on the motion speed channel, which are different by the degrees of the motivational perception of a road situation [8] have been examined. Out of them, the model with a low degree of motivation is chosen. It is substantiated by the fact that such a model corresponds to a road situation "without hindrances", when there is no need for overtaking, i. e., the motion is in row and is controlled by the signs and road marking [8].

The main stages of the information perception by a driver include: the reception of information, the evaluation of information, decision making (a decrease or an increase in speed, making the maneuver of a specific intensity), a decision realization (movement reaction), the control of the realized actions (speed, motion trajectory, a deviation from the chosen route). This control is achieved with the help of the feedback, which is the information about the results of a driver's controlling actions.

It is offered to supplement the suggested model taking into account all the constituents of a driver's reaction. A driver in the model [8] is represented as the integral-differentiating component, i. e., the component, which consists of two links. The first one is an integral link, which considers the inertness of a driver, and characterizes a delay in making controlling actions, connected with the muscular activity. The transmission of the "command" of the brain to increase the muscular effort lasts for $0,1 \div 0,2$ second – within this limit, the value of time constant T_1 can be accepted. The second is the differentiation link, which character-

izes the prognostic ability of a driver, i. e., it depends on the skill, learning ability, a degree of tiredness, and evaluates the ability to react to a change in the input signal. In fact, this is the time necessary for decision making and its value must be less than 1 ($T_2 \leq 1$) [1].

The transmission function of a motor vehicle includes the time of reaction to snapping into action of the actuating mechanisms of a motor vehicle. In this model it is proposed to present it by the inertia link.

$$W_A(s) = \frac{K_V}{T_3 s + 1}, \tag{3}$$

where $W_A(s)$ is the transmission function of a vehicle; K_V is the amplification factor of transformation (for example, for the automobile GAZ-21 «Volga» depending on the motion speed $K_V = 0,2 \div 2,3$ [14]); T_3 is the time constant, which depends on the motion speed, the type of a motor vehicle, the type of a drive, and is determined by the time of snapping into action of the actuating mechanisms of a vehicle.

On the basis of the fact that the average time of the brake system switching on/off is $0,05 \div 0,4$ seconds [14], the value of the constant T_3 must be within these limits.

It is expedient to supplement the accepted model by another additional inertia link. This link characterizes a driver's reaction to the road situation, which is estimated by the generalizing characteristic – the entropy of the traffic environment and is determined by the transmission function:

$$W_H(s) = \frac{1}{T_4 s + 1}, \tag{4}$$

where $W_H(s)$ is the transmission function of the inertia link characterizing a driver's reaction to the estimation of the traffic environment.

T_4 is the time of a driver's reaction to the entropy of the traffic environment, s.

The time of a driver's perception of a road situation consists of the duration of transferring the sensation from the sensory organ to the brain, which takes $0,15 \div 0,30$ second and the time of the reaction for converting the sensation, which is spent on information processing and makes $0,15 \div 0,20$ second [14]. Thus, it is possible to consider that the reaction of a driver to a change in the entropy of the traffic environment T_4 lies within the limit of $0,30 \div 0,60$ seconds and is considered as a delay.

Within the package of MATLAB Simulink, the model of the system of the automatic regulation was built up (Fig. 2).
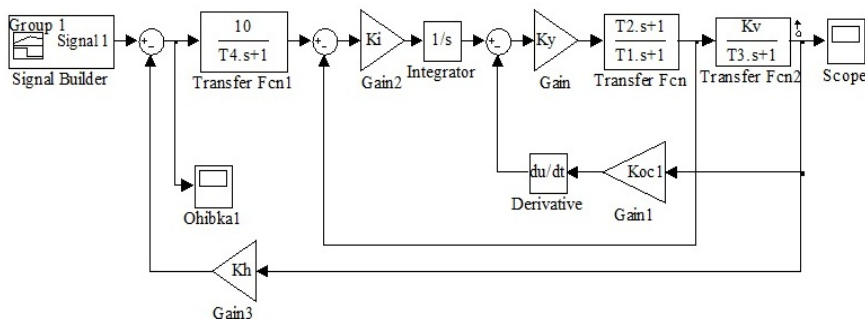

Fig. 2. Model of the system of the automatic regulation forming a driver's conrolling actions on the choice of motion speed

In the model (Fig. 2) the following designations are accepted:

– K_i is the conversion ratio of the misalignment meter;

– K_y is the conversion ratio of forming link ("intellectual" control device), the value of which can be considered in the limits of $K_y = 0,5 \div 10$ [1];

– $\dfrac{1}{s}$ is the integrating link of the first order, the delay link, connected with a change in the behavioral misalignment and decision making;

– T_1, T_2, T_4 are the time constants characterizing the behavioral functions of a driver;

– K_{oc1} is the ratio of a negative feedback "by the speed", which is considered as a strengthener of the differentiating link, which makes it possible "to regulate" an error in the control loop;

– K_h is the ratio of a negative feedback of the general regulation system. An increase in the value of this ratio leads to a decrease of an error in the regulation system and an increase of the oscillating process.

At first, the studies of the system as for its reaction to a single impulse were carried out. The transmission functions of the presented model have constant parameters: $T_1=0,2$; $T_2=0,5$; $T_3=0,6$; $T_4=0,6$; $K_y=2$; $K_i=1$; $K_V=0,5$; $K_h=0,8$; $K_{oc1}=0,1$. The transmission process of the system "DARE" to a single signal is represented in Fig. 3. According to Fig. 3, the changes in the output value bear an oscillatory character with damping and the tendency of process toward the certain steady value in the course of time.
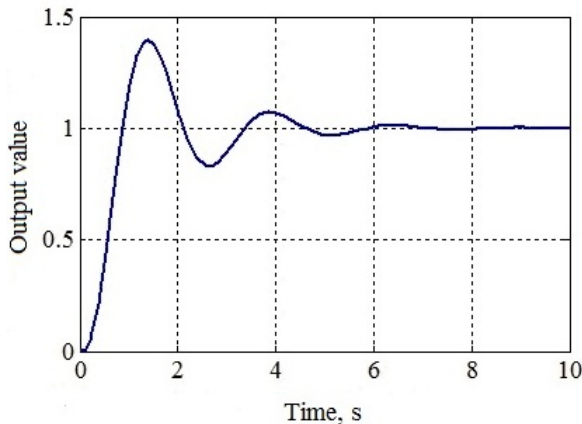

Fig. 3. Transmission process of the system "DARE" to a single signal

For mapping the periodically changing maximum entropy of a driver's perception area, presented in the form to the sequence of square impulses, the block Signal Builder is introduced at the input of the model. With the help of this block, the signal with the definite parameters is assigned, which gives the opportunity to estimate how the system will work in the actual conditions. This approach gives the opportunity to simulate the motion speed according the change in the value of maximum entropy at the system input.

On the basis of the suggested model of the automatic regulation of forming a driver's controlling actions, the transmission function of the considered system is obtained. For the simplification of the transmission function, the linearization of model is used and the poles and zeros of the linearized model are defined. The arrangement of poles and zeros of the linearized model is represented in Fig. 4.

As it can be seen from the diagram (Fig. 4), the transmission function of the linearized model has four poles and zero. The coordinates of the poles are: $P_1=-2$; $P_2=-0,845+2,55j$; $P_3=-0,845-2,55j$; $P_4=-9,65$. The coordinates of zero are $O_1=-2$. According to this, the transmission function of the linearized model is equal

$$W(s) = \frac{(s+2)}{(s+2) \cdot (s+0,845+2,55j) \cdot (s+0,845-2,55j) \cdot (s+9,65)} =$$
$$= \frac{1}{((s+0,845)^2 + 2,55^2) \cdot (s+9,65)}. \qquad (5)$$

In (5) it is taken into account that the pole with the coordinate $P_1=-2$ and zero $P_1=-2$ compensate each other. The total amplification coefficient equals 71,42.

Thus, on the basis of the system of the automatic regulation of forming a driver's controlling actions, the transmission function of the "DARE" system is obtained, which is determined by the expression

$$W(s) = \frac{71,42}{(s^2 + 1,69s + 7,217) \cdot (s+9,65)}. \qquad (6)$$

The transmission function takes the form of

$$W(s) = \frac{V(s)}{H_m(s)}, \qquad (7)$$

where $W(s)$ is the transmission function of the system "DARE"; $V(s)$ is the the motion speed in the operative form as the value of the output signal; $H_m(s)$ is the maximum entropy in the operative form as the value of the input signal.

Hence, the motion speed at the output of the system will be defined as

$$V(s) = W(s) \cdot H_m(s). \qquad (8)$$

Then formula (8) is converted to the form

$$V(s) = \frac{71,42}{(s^2 + 1,69s + 7,217) \cdot (s+9,65)} H_m(s). \qquad (9)$$

As it is shown in the work [15], the development of driver's reactions with the periodic change in maximum entropy of a driver's perception area is possible to be presented in the form of the sequence of square impulses. This sequence is described as the total of the single impulses $h_i(t)$ [15]:

$$H_m(t) = \sum_{i=1}^{N} h_i(t), \qquad (10)$$

where $h_i(t)$ is a single pulse, defined as

$$h_i(t) = \begin{cases} H_{m_O} & \text{to } (i-1)t_2 < t < (i-1)t_2 + t_1, \\ 0 & \text{to } (i-1)t_2 + t_1 < t < i\,t_2, \end{cases} \qquad (11)$$

where H_{m_O} is the amplitude of action (impulse); i is the number of am impulse action, $i = 1, 2, 3 \ldots N$; t_2 is the alternation of the action (the duration of a period); t_1 is the duration of the action (part of the period).
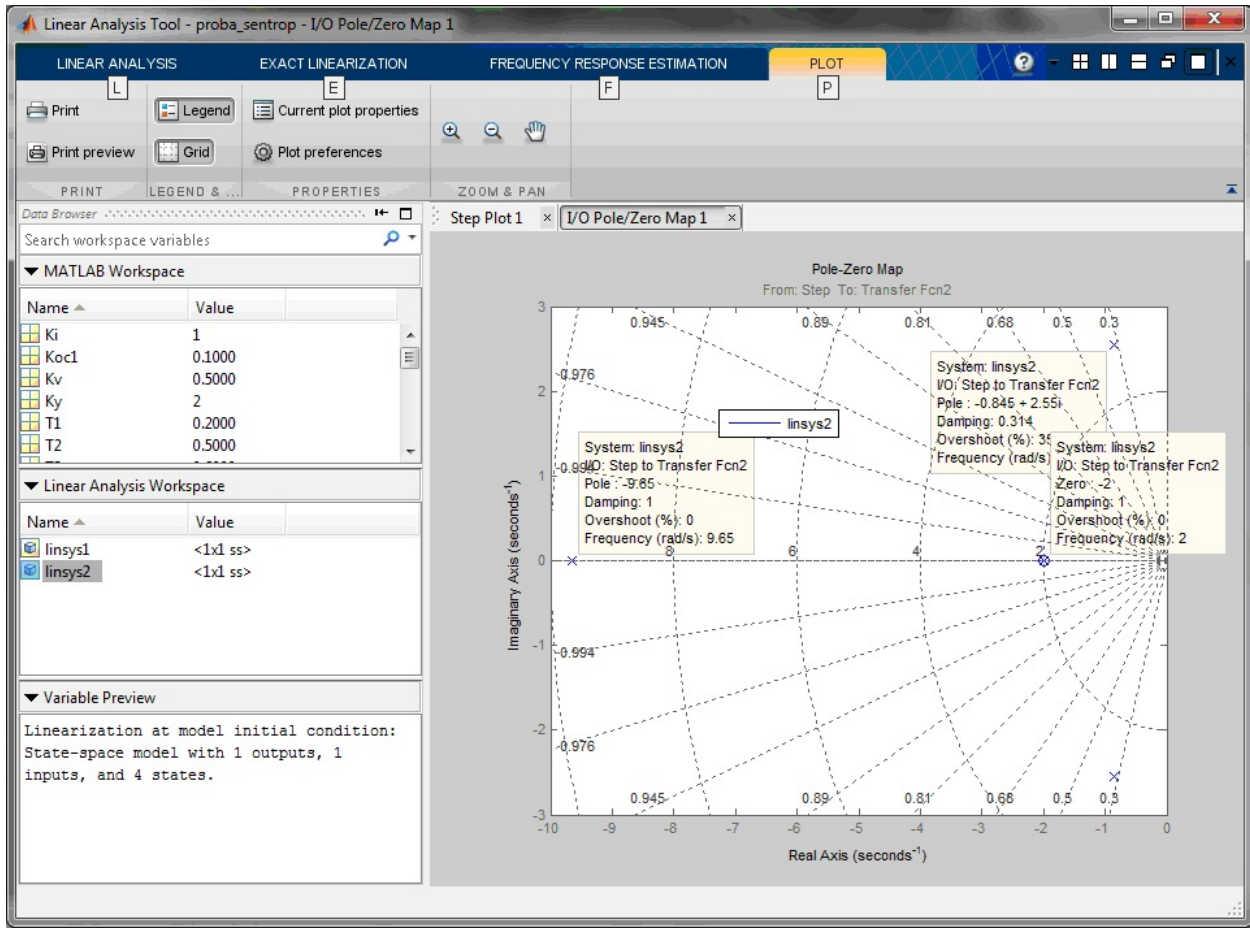
Fig. 4. Results of the analysis of the linearized model in the package MATLAB

Let's transfer $h_i(t)$ into the image space $h_i(t) \longleftrightarrow h_i(s)$. Then the expression (9) taking into account (10) is written down as

$$V(s) = \frac{71,42}{(s^2 + 1,69s + 7,217) \cdot (s + 9,65)} \sum_{i=1}^{N} h_i(s). \qquad (12)$$

Let us present $h_i(t)$ as the total of two step functions [15], using Heaviside function $\eta(t - t_0)$, where

$$\eta(t - t_0) = \begin{cases} 0 & \text{to } t < t_0, \\ 1 & \text{to } t > t_0, \end{cases}$$

$$h_i(t) = H_{m_O} \left[\eta(t - (i-1)t_2) - \eta((i-1)t_2 + t_1) \right]. \qquad (13)$$

The Laplace conversion for this function will take the form of

$$h_i(s) = \frac{H_{m_O}}{s} \left[e^{-(i-1)t_2 \cdot s} - e^{(i-1)t_2 s - t_1 s} \right]. \qquad (14)$$

For the total of impulses we have

$$H_{in}(s) = \sum_{i=1}^{N} h(s) = \sum_{i=1}^{N} \frac{H_{m_O}}{s} \left[e^{-(i-1)t_2 \cdot s} - e^{-(i-1)t_2 s - t_1 s} \right]. \qquad (15)$$

Therefore, taking into account the formula (9) we obtain the expression

$$V(s) = \frac{71,42}{(s^2 + 1,69s + 7,217) \cdot (s + 9,65)} \times$$
$$\times \sum_{i=1}^{N} \frac{H_{m_O}}{s} \left[e^{-(i-1)t_2 \cdot s} - e^{-(i-1)t_2 s - t_1 s} \right]. \qquad (16)$$

Let us conduct the conversion

$$V(s) = \frac{71,42}{(s^3 + 11,34s^2 + 23,5s + 69,64)} \times$$
$$\times \sum_{i=1}^{N} \frac{H_{m_O}}{s} \left[e^{-(i-1)t_2 \cdot s} - e^{-(i-1)t_2 s - t_1 s} \right]. \qquad (17)$$

On the basis of the expression (17), the input signals are formed with the help of the step functions, for which a change in the maximum entropy corresponds to the data in the graph (Fig. 1), and the value of the increase in the impulse are equal to the difference in the sequential values of the motion speed (Fig. 5).

As a result, the function of a change in the values of the motion speed in the form of the impulse signals is obtained at the output (Fig. 6).

The analysis of the comparison of the results of the simulation and those of the experiment proves the adequacy of the developed model. The data obtained with the help of the model, given in Fig. 6, show that the change in the section entropy to the value within the limits of $7 \div 17$ bit leads to a driver's reaction which results into a change in a vehicle mo-

tion speed. There appears the transient process, which has an oscillatory character with insignificant, within the limits of 5 km/h, motion changes and with the duration of about $5 \div 6$ seconds. These changes correspond to the experimental data obtained earlier and given in Fig. 1.
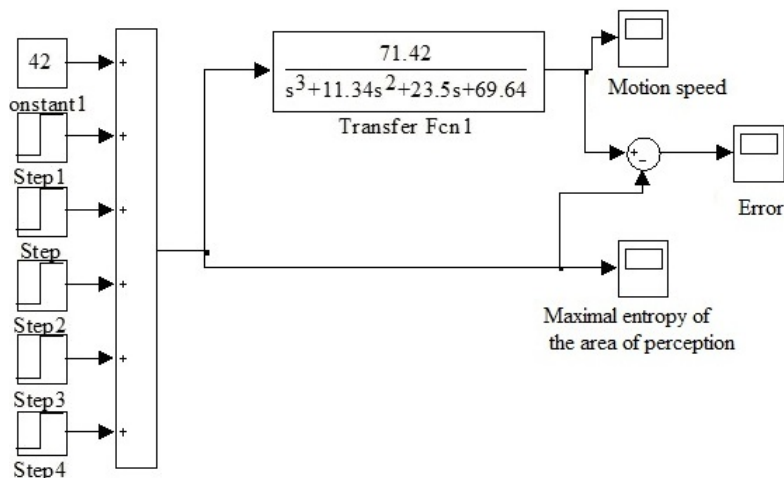

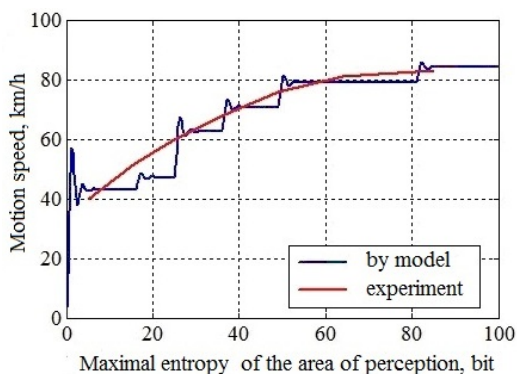Fig. 5. Model for determining the value of the motion speed at the output of the system

Fig. 6. Results of the simulation of suggested model

6. Discussion of the results of the research of the influence of the maximum entropy of a driver's perception area on the motion speed

The model of the driver's choice of the motion speed taking into account the road situation, the characteristic of which is the maximum entropy of a section located within the perception area, has been developed. The model includes the earlier developed models of the motor vehicle dynamics and a driver's actions and the additional inertia link describing a driver's perception of information about the road section.

A driver's actions of controlling a vehicle motion significantly depend on the information he obtains. The information load on the driver depends on the arrangement and the information coordination of the road sections located one by one. The misalignment of the information load of the adja-

cent sections must be reduced to a minimum. Reaching this is possible by coordinating the road sections by the entropy value. The experimental studies were conducted in the road sections free from other traffic participants.

For putting the results of the study into practice, the model of a driver's behavior and the calculation of a transient process according to the value of the maximum entropy difference of the adjacent road sections was developed. If a transient process leads to the steady value and, the value of the motion speed change appearing in this case is not higher than 5 km/h, this testifies to the coordination of the adjacent road sections. Thus, on the basis of the model research data, it is possible to evaluate the influence of the information content of the traffic environment on the results of a driver's activity, which finally makes it possible to develop measures on regulating the parameters of a traffic situation and to influence a driver's working conditions.

Taking into account quite complex dependences, which describe the dynamics of a vehicle and the dependence of the motion character on a driver's actions, the motion speed change, connected with the maneuvering due to the interaction with other traffic participants should be investigated in the process of further development of the model.

8. Conclusions

1. On the basis of the experimental data, the dependence of the actual motion speed on the maximum entropy with the influence of the constant factors of traffic environment was obtained. It was shown that with a change in the maximum entropy of the perception field within the limits from 9 to 81 bits, the speed grows from 42 to 82 km/h.

2. The updated model of forming a driver's controlling actions on the choice of the motion speed on the adjacent road sections, taking into account the changing situation has been developed. The value of the maximum entropy was suggested as a generalizing characteristic of forming the traffic environment image. The inertia link which determines a driver's reaction to the entropy value of the road section located within the perception is included in the model. The motion speed of a vehicle is obtained as the output value.

3. The simulation of a driver's reaction to a road situation change was made. It was established that in case of changing the section entropy, the transient process, which has an oscillatory character with the insignificant, within the limits of 5 km/h, motion speed changes and the duration of nearly $5 \div 6$ seconds occurs. The analysis of the comparison of the results of the simulation and those of the experiment proves the adequacy of the developed model. It was established that the change in the section entropy to the value within the limits of $7 \div 17$ bits leads to a driver's reaction which results into a change in a vehicle motion speed. These changes correspond to the experimental data obtained earlier.

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