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DYNAMIC CONTROL OVER TRAFFIC FLOW UNDER URBAN TRAFFIC CONDITIONS

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This article deals with solving topical issues of improving traffic effectiveness in major cities. The main traffic problem in major cities is a decrease in the throughput capacity of a street-road network and an increase in unpredictable travel time. The conducted study determined that the main reason for a decrease in the throughput capacity of a street-road network is the existence of traffic congestion modes and the formation of a "shock wave" with its spreading toward the oncoming traffic flow. To solve this problem, the dynamics of a change of parameters of a transport flow based on detection of the feature of the formation of a "shock wave" in a dense flow was simulated in the research. The analytical dependence on the rate of a density change under complicated traffic conditions on road sections makes it possible to determine the place of the "shock wave" formation to prevent its occurrence. The most common methods only affect the elimination of traffic congestions, which increases transport delays. To eliminate the congestion state on the open line of a street network, it was proposed to introduce dynamic traffic control. The feasibility of the above type of control is proved by simulating the impact of a change in the speed of traffic flow on its intensity. Theoretical models of traffic dynamics were developed for the street-road network section of the length of 1,500 m. The results of the simulating experiment on the urban open line that is 380 m long proved the adequacy of the model. The obtained results prove the possibility of decreasing intensity on the approach to congestion by reducing the speed of motion. This method of traffic control affects the end of a "shock wave", rather than its front to prevent congestion. The research results affect an increase in network throughput

Keywords: traffic, throughput capacity, density change rate, shock wave, dynamic control

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1. Introduction

Solving the problem of traffic (TR) control in major cities requires increased attention because traffic jams remain a social and state problem. A decrease in the throughput capacity of the traffic network is related to the existence of congestions on complex sections of a street-road network (SRN) and has certain consequences for the traffic process in the cities. In case of an increased density of the urban traffic flows (TF), there is a need to develop control measures to ensure the network efficiency and environmental safety of cities.

The accumulated world experience in creating and implementing the TR control systems shows their significant impact on the TR performance indicators. Namely: decreasing transport delays – 15–40 %; increasing throughput capacity of the SRN – 10–15 %; decreasing number of road accidents – 15–20 %; reduction of environmental pollution – 20–25 %.

The most common technologies of TR control (with the fixed plans of control and network management) do not make it possible to obtain certain results, because spatial relations between traffic situations on certain SRN elements have a complex character, which depends on the topology of the traffic network of cities and parameters of the TF. That is why the application of adaptive methods of situational control allows a significant reduction of the impact of uncertainty of transport flow parameters on the control quality. The most effective method of control in cities is the method of dynamic control, which belongs to the technology of situational control. This method involves controlling the TF motion to decrease the intensity of problem areas of SRN, which will contribute to the elimination of traffic congestion. This approach is an alternative to the method of TF control at city intersections using a timer, which is not effective in a dense flow. Implementation of the TR control method under consideration requires the development of a mathematical model of the control object to determine the place, time, and method to influence it.

Well-known transport models provide an effective result under ideal traffic conditions and require improving when used for urban traffic. This problem needs to be solved, which emphasizes its relevance and expediency in the field of urban TR control.

2. Literature review and problem statement

The fight against congestions on urban roads around the world is extended under objective circumstances of an increase in the level of population automobilization. The methods can be both administrative, and scientifically practical. The introduction of the passing payment was considered the most effective approach in London, Stockholm, and Singapore [1]. However, this did not lead to positive consequences, because this controlling measure initially received no support, and in subsequent years the state of congestions returned to the original level. That is why it is necessary to solve these problems based on theoretical research with the introduction of their results in the TR process.

The reason for decreasing the efficiency of SRN functioning is the result of the irrational loading of its elements. Traffic congestion, which is a queue of road vehicles (RV) on the open line of a network, complicates the TF motion and increases the level of the SRN load. To ensure the efficiency of the transport network functioning, the existing measures to prevent the transition of the TF on open lines of the SRN into the congestion state, which can be determined by two main directions, were identified [2]. These directions contain information on the parameters of the TF, forecasting random disturbances or obstacles on a road, and optimizing the throughput capacity of the urban traffic network. It is this approach that implements the TF control with the help of operating control devices on the SRN. They include road signs, traffic light devices, and markings. The most common measure is traffic light regulation, the parameters of which must be consistent with the parameters of the TF on the open road line. However, such measures are characterized by the complexity of implementation under conditions of dense TF, because the direction of the controlling influence on the beginning of the TF, that is, its “front”, is not effective in control. Then, based on the analysis of measures, it is possible to conclude that it is necessary to develop a new approach to prevent traffic congestion on the SRN.

Congestion states of TR arise for many reasons, the basis of which is the inefficiency of traffic flow control. Further research is aimed at the analysis of the basic traffic models, on which control algorithms are formed. The results of the study [3] prove the impact of management strategies on the basic TR parameters, the description of which is associated with the fundamental diagram of the TF. This relationship is major in understanding the relationship between the parameters of the TF and the TR control.

In paper [4], when studying congestions on the SRN, the author proposed the concept of a “synchronized flow” and based on it, separated two qualitatively different TF states (phases): the phase of so-called “synchronized traffic” and the phase of “wide moving traffic jams”, which should be distinguished in the congested mode of the traffic flow. The main statement of the concept of a “synchronized flow” is the hypothesis about the existence of a stable state of the TF. This means that in the areas of the TF stability, all vehicles move to keep a safe distance and at the same constant speed, which is chosen relative to the flow density, without taking into consideration a set of current speeds of the RV. This approach provides the direction and grounds for theoretical research into the physical nature of processes in the TF. However, the issues of practical determining the TF parameters remained unresolved. Analysis of the TF models revealed two approaches for the description of traffic congestions:

1. Based on the properties of the TF itself according to the classification of phase transitions [4], as well as the classification proposed by scientists at the Los Alamos National Research Center [5].

2. Based on external reasons – the influence of different “bottlenecks” [6]. By bottlenecks, the author implies the combination of SRN sections with a different number of traffic lanes and, consequently, with different throughput capacity. Thus, the theory of bottlenecks was developed to construct their classification, which determines the need to study the problem of “reverse phase transition” to the TF. However, this is related to objective difficulties, because traffic congestion occurs quite quickly, and dissipates slowly and uncontrollably. That is why the way of preventing congestion will be more effective than its elimination. To do this, it is necessary to consider the models of the TF by the following features: application area; the level of detailing a simulation object; deterministic or stochastic; continuous or discrete [6].

Deterministic models include the models based on functional dependences between the basic parameters of the TF – intensity (N), speed (V), density (q) and the distance between the RV while moving in a flow. In stochastic models, the process of the TF motion has a probabilistic character of the description of the interaction of the basic parameters, which makes it difficult to use them in the TR control algorithms.

The main requirements for the application of models in the TR control systems are the adequacy of models to the control object and the promptness of their implementation.

When choosing control models, well-known transport models of the TF are preferred. This approach is used in papers [7, 8]. The description of the first macroscopic models (hydrodynamic), in which the TF is treated as a similar flow of compressed liquid, deserves attention [7, 8]. The first microscopic models (following the leader), describing the motion of each car and the model of cell machines, are also known [9]. In today’s practice of modeling traffic flows, commercial software products based on micromodels [10], which are mostly represented by modifications of the “following the leader” model, have become widely spread. It should be noted that the latest studies have fundamental violations of the continuity of the LWR models for different transport flow states [11, 12]. The variant to overcome these violations may be the description of the state of a transport flow in general based on macro models of the TF. However, in well-known transport models, there is no description of the TF transition from the stable state to the probabilistic in the event of a congestion TR state [13]. In addition, the description of parameters of motion of a separate RV in a high-density flow requires more accuracy and promptness according to the basics of micro-models of the RV during the motion in the TF.

All this suggests that it is necessary to apply deterministic models for the TR control algorithms because they are the basis for mathematical maintenance of the control system. However, it is advisable to obtain a description of the causes of “shock waves”, while the issues of their consideration in control algorithms to prevent congestion on the SRN remain unresolved. This approach requires the development of a description of the TF congestion state. All this makes it possible to state that it is necessary to formalize the description of the interaction of the TF parameters under conditions of urban traffic taking into consideration the identified difficulties in modeling.

3. The aim and objectives of the study

The aim of this study is to develop a model of interaction of the TF parameters for dynamic TR control in urban environments. This will provide an opportunity to prevent congestion to increase the throughput capacity of the RSN.

To achieve the aim, it is necessary to solve the following tasks:

– to develop the model of dynamics of a change in parameters of a transport flow during formation of a "shock wave" under complicated urban traffic conditions with carrying out the experiment;

– to substantiate the appropriateness of implementation of dynamic traffic control on open road lines by means of modeling the influence of a change in the traffic motion speed on intensity.

4. Development of the models of interaction of parameters of a transport flow under complicated urban traffic conditions

The processes that take place in a TF at passing through "bottlenecks" were studied. At a slight loading of the RSN section, when the TF motion occurs in the unrelated mode, each driver has an opportunity to choose the motion speed within the speed range permitted in this section. However, at an increase in loading of the RSN section, the TF density increases and transfers into an interrelated mode of motion. At the same time, each RV driver obeys the conditions of the TF motion, which affects the lack of possibility of choosing the speed of motion and implementation of maneuvers on a driveway. An increase in the TF density is not a problem until the moment when flow intensity reaches the maximum value. At the same time, the level of RSN servicing under specific road conditions changes, after which there is a decrease in the speed of traffic motion and the transition of the TF to an unstable state. This leads to a change in the conditions of the RV motion and the occurrence of features of a dense TF state, which affects the motion cessation and transition to the traffic congestion mode. Traffic congestion on the local RSN section may cause congestion spreading around the network if the intensity of the RV arrival at a complex section does not change.

Analysis of continuous models revealed contradictions that imply that TF speed $V(x, t)$ at point x and in time t is density function $P(x, t)$. Then

$$V(x,t)=V\big(p(x,t)\big), \quad (1)$$

where $V(p(x, t))$ is the speed of flow motion at density $p(x, t)$.

Apparently, the speed of flow motion under normal conditions approaches $V(p)$. However, this conclusion does not correspond to the situation in the transport network when there are congestion states of a transport flow, where the TF speed is equal to 0, and density acquire the maximum value, which contributes to the process of formation of a "shock wave", which requires additional research.

Comparative analysis of continuous and discrete models allowed the identification of the complexity of the presentation of analytical continuous models for control algorithms, so it is necessary to improve the known models in the process of research.

We formed an approach to the construction of a macro model of a TF, which is aimed at a formalization of the interaction of macro-parameters of the TF to describe a "shock wave" formation in the TF, because this process complicates traffic, reduces the throughput capacity of the SRN and increases transport delays during the motion. The TF motion under difficult conditions for traffic control systems was formalized as follows [14].

The RV mode of motion is stable on the SRN section in the absence of any external influences, including controlling influences. If there are regulation facilities in the section, the transport flow is subject to their influence, the result of which is a change in the motion mode. Taking into consideration the continuity of the TF parameters, their relations in a specific cross-section x of the SRN open road can be described by a known dependence [15]:

$$V(x)=V_{\max}-k\cdot q(x), \quad (2)$$

where $V(x)$ is the TF speed on cross-section x of the SRN section, m/s; $V_{\max}$ is the maximum permitted speed of motion on the given SRN section, m/s; k is the coefficient that characterizes a change in the speed of motion in the section from $V(\max)$ to $V(x)$ at maximum density from $q(x)$ to $q(\max)$:

$$k=\frac{V_{\max}-V_{\min}}{q_{\max}}, \quad (3)$$

where $q(x)$ is the TF density in cross-section x of the SRN section, cars/km.

Then, by differentiating (2), we determined the TF density in a certain cross-section of the open road line. It is carried out by the following dependence:

$$q(x)=q_{\max}\cdot e^{-\rho\cdot 10^{-7}(x-S)^2}, \quad (4)$$

where $q_{\max}$ is the maximum TF density, which corresponds to throughput capacity of the SRN section, car/km; e is the base of natural logarithm; S is the length of the SRN section, m; x is the coordinate of a cross-section in the SRN section; ρ is the coefficient determined by boundary values of the TF density on the SRN section that can be determined from the following expression

$$\rho=\frac{\ln\left(q_{\max}/q_{\min}\right)\cdot 10^{7}}{S^{2}}, \quad (5)$$

where $q_{\min}$ is the minimal TF density that corresponds to minimal flow intensity on this SRN section, cars/km.

Subsequently, to determine the character of a change in intensity, density, and speed of the TF along the length of the open road, the following boundary values of the TF density were accepted: $q_{\min}$=5 cars/km; $q_{\max}$=100 cars/km. It is necessary to study a change in TF density on the SRN section of the length of 1,500 m (maximal length of the open road section by normative documents), where a traffic light device was eventually installed. The diagram of a change in the TF density according to (4) throughout the SRN section takes the following form (Fig. 1).

Apparently, the TF density increases from the beginning of the section and reaches the maximum value at the cross-section with the coordinate of 1500 m. At this cross-section, there is a decrease in the TF density, which actually characterizes the process of vehicles passing one another in the RV queue, which accumulated before the intersection. The graph of changes in the motion speed along the length of the open road line in the presence of traffic light regulation, according to (2), takes the following form (Fig. 2).

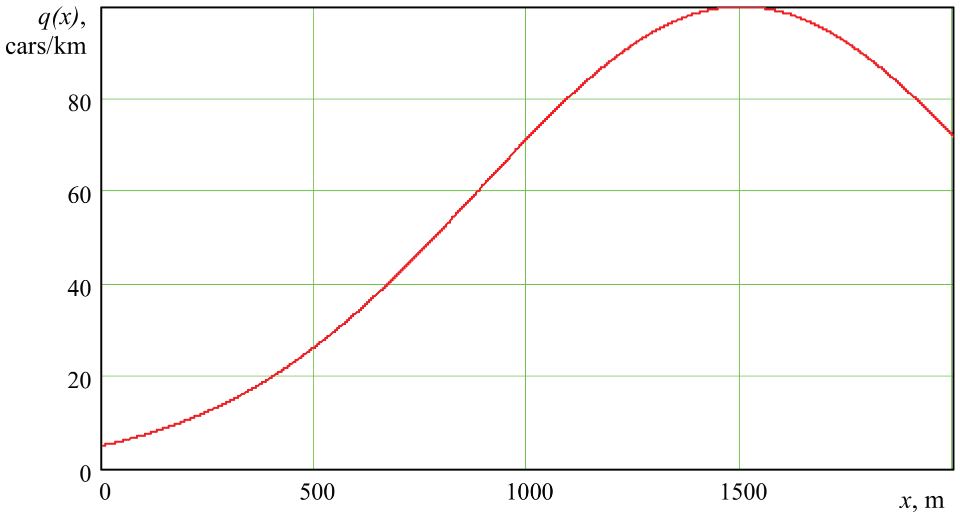

Fig. 1. Change in the TF density on the SRN section

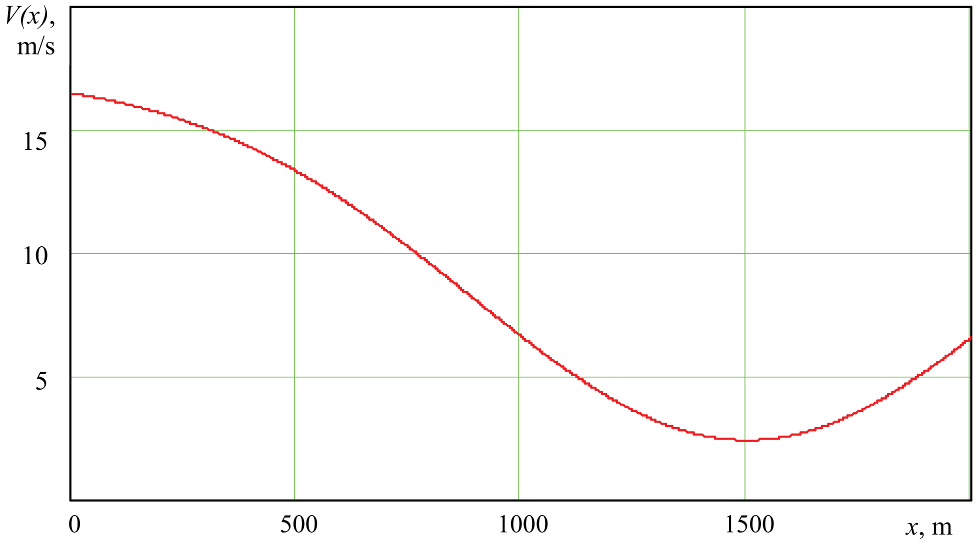

Fig. 2. Change in TF speed in the SRN section

The obtained results show that at distance from the beginning of an open road section, the motion speed decreases to the minimum value. Thus, the TF density and its speed along the length of the SRN are non-uniform and characterized by "critical" values in a certain section. At the same time, the minimum motion speed and the maximum flow density, which can be observed in the section, are characteristic of the congestion state of the TF. The obtained result corresponds to the actual behavior of the TF, as congestions occur at the end of the open road line and spread towards oncoming traffic flow.

Then, based on determining the TF density and speed on the SRN section (2), (4), the TF intensity was obtained as the product of these parameters:

$$N(x)=V_{\max}\cdot q_{\max}\cdot e^{-\rho\cdot 10^{-7}\cdot(x-S)^2}-k\cdot q_{\max}\cdot e^{-2\cdot\rho\cdot 10^{-7}\cdot(x-S)^2}. \qquad (6)$$

Graphical interpretation of dependence (6), a change in TF intensity along the length of section (S) takes the following form (Fig. 3).

The determined nature of a change in the TF intensity along the length of the open road line differs from the known models of changes in TF density and speed. At fixed parameters of the SRN area, an increase in the TF intensity is observed 500 m before its completion and begins to decrease further in the flow direction. This fact proves the assumption that regular traffic congestions, which are accompanied by the accumulation of RV on the SRN section, are formed at the end of the SRN. Thus, the obtained model of determining the transport flow intensity in a dense flow (6) is adequate for actual processes on the SRN.

Further studies are related to the impossibility of determining the speed of the TF motion at its maximum density by means of macro modeling. That is why it is necessary to proceed to the micro models of car motion. It is possible to determine the number of cars that are at a given moment of time in the SRN open line, having length S, by integrating expression (4). Then, the number of cars (n) is determined as:

$$n=\int_0^S q(x)\,\mathrm{d}x, \qquad (7)$$

where S is the length of the SRN section, m.

RV accumulation on the SRN section leads to a change in TF density over time at each point. To determine the nature of the RV accumulation on the SRN section, differentiation of density by time was carried out. It was accepted in the research that the number of the RV accumulated on the SRN section is determined by the TF intensity at its inlet and outlet:

$$\Delta n=\left[N(x)-N(x+\Delta x)\right]\cdot\Delta t, \tag{8}$$

where Δn is the magnitude, by which the number of the RV on the SRN section will change, cars; $N(x)$ is the TF intensity at the section inlet with coordinate x, cars/h; $N(x+\Delta x)$ is the TF intensity at the outlet of the section with coordinate $x+\Delta x$, cars/h; Δt is the time measurement pitch, s.

Then according to (4), the TF intensity can be expressed by the product of its density by speed;

$$\Delta n=\left[V(x)\cdot q(x)-V(x+\Delta x)\cdot q(x+\Delta x)\right]\cdot\Delta t, \tag{9}$$

where $q(x+\Delta x)$ is the TF density in the cross-section of the line with coordinate $x+\Delta x$, cars/km.

If the TF speed can be determined by dependence (2), then the number of the RV accumulated on the SRN section can be determined as:

$$\Delta n=\begin{bmatrix}\left(V_{\max}-k\cdot q(x)\right)\cdot q(x)-\\-\left(V_{\max}-k\cdot q(x+\Delta x)\right)\cdot q(x+\Delta x)\end{bmatrix}\cdot\Delta t=$$

$$=\begin{bmatrix}V_{\max}\cdot q(x)-k\cdot q(x)^2-\\-V_{\max}\cdot q(x+\Delta x)-k\cdot q(x+\Delta x)^2\end{bmatrix}\cdot\Delta t. \tag{10}$$

Based on the fact that a change in the number of RV on the open road line leads to a change in the TF density on the same section, it is possible to write down:

$$\Delta q\cdot\Delta x=\begin{bmatrix}V_{\max}\cdot q(x)-k\cdot q(x)^2-\\-V_{\max}\cdot q(x+\Delta x)+k\cdot q(x+\Delta x)^2\end{bmatrix}\cdot\Delta t. \tag{11}$$

After algebraic transformations, we have:

$$\frac{\Delta q\cdot\Delta x}{\Delta t}=V_{\max}\cdot\left[q(x)-q(x+\Delta x)\right]+$$
$$+k\cdot\left[q(x+\Delta x)^2-q(x)^2\right]; \tag{12}$$

$$\frac{\Delta q\cdot\Delta x}{\Delta t}=V_{\max}\cdot\left[q(x)-q(x+\Delta x)\right]+$$
$$+k\cdot\left[\left(q(x+\Delta x)-q(x)\right)\cdot\left(q(x+\Delta x)+q(x)\right)\right]. \tag{13}$$

Then:

$$\frac{\Delta q\cdot\Delta x}{\Delta t}=\left(q(x)-q(x+\Delta x)\right)\times$$
$$\times\left(V_{\max}-k\cdot\left(q(x+\Delta x)+q(x)\right)\right); \tag{14}$$

$$\frac{\Delta q}{\Delta t}=\frac{\left(q(x+\Delta x)-q(x)\right)\cdot\left(k\cdot\left(q(x+\Delta x)+q(x)\right)-V_{\max}\right)}{\Delta x}; \tag{15}$$

$$\frac{\Delta q}{\Delta t}=\frac{q(x+\Delta x)-q(x)}{\Delta x}\times$$
$$\times\left(k\cdot q(x+\Delta x)+q(x)-V_{\max}\right). \tag{16}$$

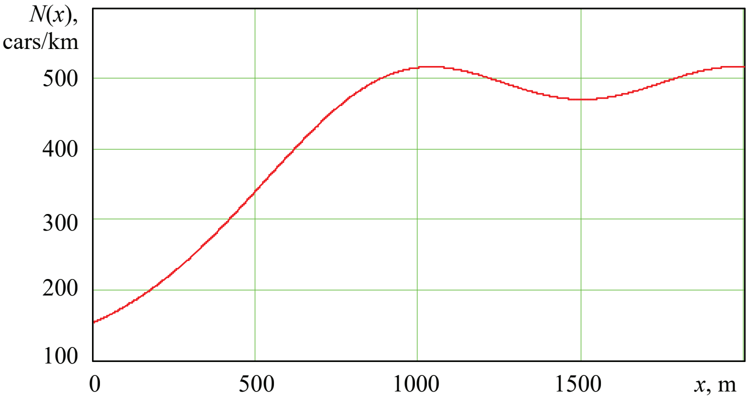

Fig. 3. Graph of change in the TF intensity on the SRN section

The resulting expression (12) determined a change in the TF density in time on a certain cross-section of the open road line. Considering the infinitely small magnitude of the cross-section of the open road line $\Delta x\to 0$, we obtained ${}^{\mathrm{d}q}\!/_{\mathrm{d}x}$ at $q(x+\Delta x)=q(x)$, instead of the first fraction in the right part of the equation. In fact, magnitude ${}^{\mathrm{d}q}\!/_{\mathrm{d}x}$ is the characteristic of the rate of a change in the TF density in cross-section x of the SRN section. To determine it, carry out differentiation (13):

$$\frac{\mathrm{d}q}{\mathrm{d}x}=-2\cdot q_{\max}\cdot\rho\cdot 10^{-7}\cdot(x-S)\cdot e^{-\rho\cdot 10^{-7}\cdot(x-S)^2}. \tag{17}$$

The result of a change in the rate of the TF density for the SRN section was obtained in the form of the graph (Fig. 4).

To plot the graph of the resulting dependence (Fig. 4), we used the normalized values of function [−0.1; 0.1], which reflect the rate of a change in density along the length of the SRN section and detect its non-uniformity. Then, the highest rate of density increase is observed not at the outlet of the section, but closer to the traffic lights location (1500 m). This makes it possible to argue that in case a congestion formation starts, the RV queue will be accumulated as quickly as possible not at the end of the road open line, but at a distance from it. It is likely that this is the place on the open road line, where the flow density starts to increase, and the speed is not yet decreased. After the boundary of the SRN section, the rate of a density increase at a certain point in time is negative in character, which indicates that the RV queue dissipates within some time and the TF density decreases. After determining ${}^{\mathrm{d}q}\!/_{\mathrm{d}x}$ using expression (17), expression (16) takes the following form:

$$\frac{\Delta q}{\Delta t}=\frac{\mathrm{d}q}{\mathrm{d}x}\cdot\left(2\cdot k\cdot q(x)-V_{\max}\right). \tag{18}$$

Transition to infinitely small time interval $\Delta t\to 0$ makes it possible to obtain a derivative of density by time, determined by the following dependence:

$$\frac{\mathrm{d}q}{\mathrm{d}t}=\frac{\mathrm{d}q}{\mathrm{d}x}\cdot\left(2\cdot k\cdot q(x)-V_{\max}\right). \tag{19}$$

When replacing the term of expression $V_{\max}-k\cdot q(x)$ with the TF speed in the specified cross-section of the SRN area, we obtained:

$$\frac{\mathrm{d}q}{\mathrm{d}t}=\frac{\mathrm{d}q}{\mathrm{d}x}\cdot\left(k\cdot q(x)-V(x)\right). \tag{20}$$

Thus, we determined the density change rate on the SRN section, the graph of which is shown in Fig. 5.

The obtained result is the macro model of change in the main parameters of the transport flow at the motion in a dense flow based on determining the TF density change rate at the transition to the traffic congestion mode.

To verify the correctness of theoretical research and the adequacy of the resulting macro models, we developed a simulation model of traffic flow motion for the simulation experiment. Software for the simulated model of the TF behavior was implemented in the integrated environment of application development Delphi 7.0. The open road section of the thoroughfare in the city of Kharkiv (Naukova Avenue), Ukraine, was chosen as the object of experimental research. The section parameters are the following: section length – 380 m; section width – 28.0 m; road cover state – excellent; curves in the plan – absent; longitudinal slopes – 41 ‰. The selected open road line has unsatisfactory motion parameters in rush hour – at the TF intensity on the section of 3,286 cars/h, the section passing time is 526 s, which results in the formation of congestion modes of TF motion. Experimental measurements of the TF intensity on the open road line were carried out by the field method on weekdays during the morning and evening rush hours.

The TF parameters, at which there are unsatisfactory conditions of passing the section with the congestion formation, were selected for the experiment. Increasing TF intensity at the constant regulation cycle leads to RV accumulation at stop-lines, and they do not pass each other during the permitting traffic light signal (Fig. 6), which results in the formation of the RV queue.

Comparative analysis of values of section passing time, obtained by experimental research on the actual SRN and by means of simulation is shown in Table 1.

The obtained result proved the adequacy of the developed simulation model for determining the RV speed in a flow, because the mean relative deviation of the values of the time of passing the studied SRN section does not exceed 5 %. Consistency of empirical and theoretical (by the model) distribution was assessed for confidence probability P=0.95 and permissible error α=0.05 [16]. Thus, the proposed simulation model can be used to determine the parameters of the "shock wave" formation process.

This approach provides an opportunity for further research of spatial-temporal changes in the basic parameters of the TF motion under urban conditions. All this suggests that the density change rate, rather than density itself describes adequately the TF behavior in the congested motion mode.

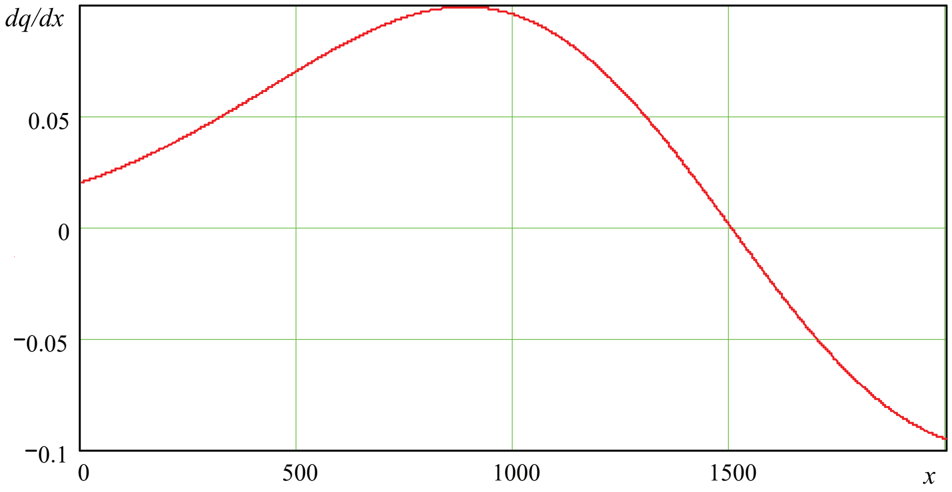

Fig. 4. Graph of change in density on the SRN section

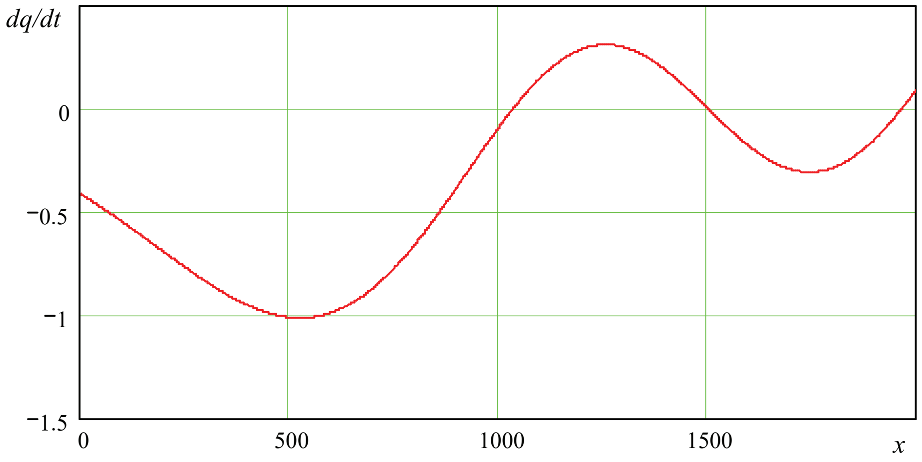

Fig. 5. Graph of density change rate on the SRN section

Table 1

Comparative analysis of section passing time in the maximum traffic loading period

No. of experimental measurement of the passing time	Time of section passing (experimental studies), s	Time of section passing (simulation model), s	Absolute deviation, s	Relative deviation, %
1	546	543	3	0.55
2	542	524	18	3.32
3	611	522	89	14.57
4	484	514	30	6.20
5	602	547	55	9.14
6	538	535	3	0.56
7	547	546	1	0.18
Mean values	552.86	533.00	19.86	4.93

Fig. 6. Formation of a shock wave in a transport flow

5. Substantiation of the feasibility of introducing a change in the high-speed motion mode of traffic flow in the urban street-road network

The resulting macro model of the TF proves that it is necessary to influence the TF parameters at the end of a "shock wave" (at the beginning of an open road line), rather than at its beginning (at the end of an open road line). This provides an opportunity to determine correctly the controlling actions of the automated TR control system to prevent the occurrence of the traffic congestion mode, which is formed at an increase in the TF density. Thus, the effect of a "shock wave" in relation to the TF implies a sharp speed decrease on the lane at shortening the safety intervals between cars. That is, the resulting description of the TF motion in a dense flow differs from the well-known models of the column mode of the TF motion. The determined difference affects the congestion and shock waves formation.

The determined control parameters have the features of directed control, so the situational TR control technology has a number of advantages related to the prediction of a change of the SRN state [17]. The dynamic traffic control has the same principle. The efficiency of the transport network is ensured by means of prevention of negative situations. The presented approach does not require a response to the situation by means of local control. It is necessary to implement the method of dynamic control, in which the traffic motion mode changes by the TF intensity or density, based on a closed control circuit. The controlling impact under this method is the determined speed of motion at the beginning of the SRN open line. The introduction of dynamic control is an alternative to the SRN expansion and affects the improvement of the safety and efficiency of the traffic process in general [18]. That is why it is proposed to change the TF speed mode on the SRN section to restrict access to the RV accumulation place and prevent the "shock wave" formation.

The merits of using dynamic control were identified by applying the methods of road traffic simulation. At the same time, the impact of a change in the speed of motion on the TF intensity on the RSN section was explored. To determine the speed of the RV approaching a complex area, we selected the macro model of the TF motion [19, 20], which includes controlling parameter (u) determining the value of the TF motion speed on the SRN highway:

$$V(q,u)=V_{\max}\cdot u\cdot e^{-\left(\frac{q}{q_{\max}}\right)^2\frac{u+1}{4}}, \qquad (21)$$

where $u\in(0;1)$ is the level of the controlling parameter influencing the speed of motion.

There are certain conditions to observe during simulation: the value of the maximum density of the TF $q_{\max}$=50 cars/km [21], and the speed of free motion $V_{\max}$=60 km/h (permitted speed of motion in a city [22]). A change in the TF, depending on the density at different levels of the controlling parameter is shown in Fig. 7.

The model was implemented under the condition that the level of controlling parameter implies that a decrease in motion speed on the open road line is not more than 20 km/h from the permitted [22]. Simulation results were obtained at three levels of the controlling parameter u=1.0; 0.83; 0.67, which corresponds to motion speed $V_{\max}$=60 km/h; $V_{\max}$=50 km/h; $V_{\max}$=40 km/h (Fig. 7).

Analysis of obtained simulation results proves that the controlling parameter makes it possible to change the existing high-speed mode on the SRN section only at a certain TF density. Thus, at a flow density of 100 cars/km, the action of the controlling parameter loses its influence on the TF speed, and then the SRN density increases, and the speed drops to zero. The obtained result is explained by the existence of mutual obstacles when drivers are forced to reduce sharply the speed of motion. Thus, the connected and the congested modes of TF motion appear.

To determine the TF intensity taking into consideration the selected macro model (21), we obtained the analytical dependence of intensity on the influence of the controlling parameter u on the TF speed (V):

$$N(q,u)=q\cdot V\cdot u\cdot e^{-\left(\frac{q}{q_k}\right)^2\frac{u+1}{4}}. \qquad (22)$$

Fig. 8 shows the graph of change in TF intensity, depending on density at q_k=50 cars/km at different levels of controlling parameters u.

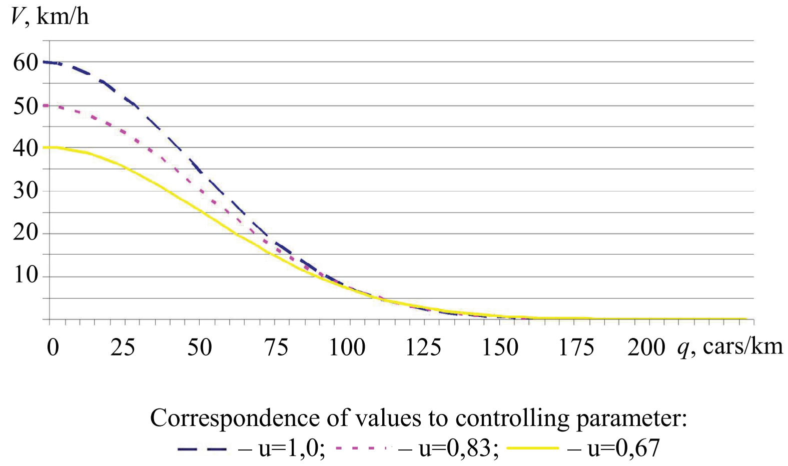

Fig. 7. Graph of change in the motion speed and flow density at different levels of controlling parameter *u*

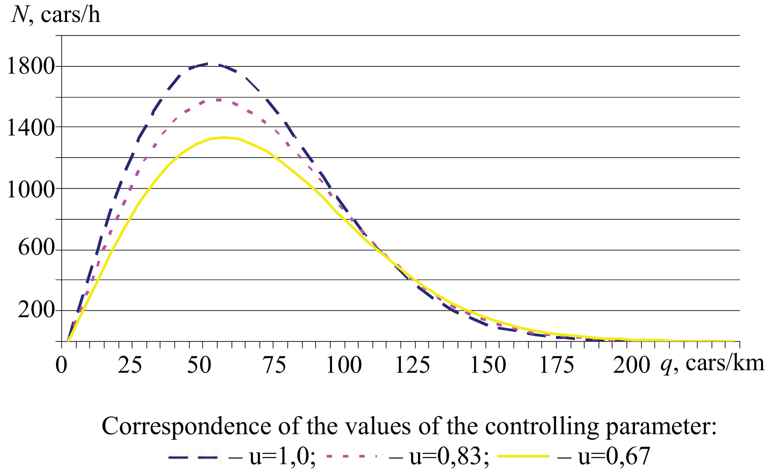

Fig. 8. Graph of change in TF intensity depending on density

Analysis of the results allowed arguing that the controlling parameter of a change in the speed of motion also has an impact on intensity when the SRN density changes in the range of 0–100 cars/km. A further increase in density leads to the TF transition to a congested state and it is no use changing the speed because intensity drops rapidly to 0. This proves that it is necessary to control the TF intensity by changing the speed mode of motion on the road line sections, where the TF density is not yet critical. Such values of the TF intensity are observed on approaches to the congestion place. That is, we obtained an effective method to prevent the formation and propagation of a "shock wave". This proves the appropriateness and necessity of developing the dynamic control of the TF by means of reducing its speed on the SRN sections with complicated traffic conditions.

The resulting models belong to the type of continuous macro models of the TF, according to which the TF "tail" has a lower density at a higher speed. There are difficulties in determining the parameters of dynamic control because, at an insignificant time interval (<30 s), the changes in parameters are so significant that their derivative is not obtained analytically. That is why there is a need to develop micromodels of the RV motion in the flow of high density in the presence of "bottlenecks" on the SRN.

6. Discussion of the results of simulation of the TF parameters to prevent congestion on the SRN

The study resulted in obtaining a description of a change in speed and intensity depending on the TF density (2), (4), (6), Fig. 1–3. At the same time, the length of the SRN section, at the end of which there is a traffic light device, was taken into consideration. The nature of a change in parameters indicates that there are certain maximums and minimums of density and speed functions at the end of the section. The determined nature of a change in intensity along the length of the section differs from the known models because it makes it possible to determine the distances, at which traffic congestions begin to form.

The model of a change in the TF density on a certain SRN section (17), Fig. 4, was obtained by means of mathematical transformations (11) to (16). This innovative approach allowed the development of a model of a density change rate (20), Fig. 5, depending on the speed of the TF motion by differentiating (18), (19). Theoretical and experimental studies indicate that a "shock wave" begins its formation at the distance equal to a third of the road section. The simulation experiment, conducted on the simulation model, proves the correctness of obtained theoretical results. When developing models, we determined the coordinate of a change in the rate of TF density equal to 1,000 m (at the section length of 1,500 m), and in the simulation experiment – 220 m (at the section length of the 380 m). The adequacy of the simulation model was obtained based on the indicator of the relative deviation of the actual section passing time from the model one (5 %). That is why to prevent the occurrence of a "shock wave", it is necessary to direct the controlling influence not to its beginning, but rather to its end.

To implement this approach to the prevention of the "shock wave" formation, it was proposed to apply dynamic control of the speed of TF motion to reduce the intensity of the approach to a high-density section. The impact of a decrease in speed on intensity was proven (21), (22), Fig. 7, 8. This proves that the controlling influence should be formed and directed to the TF when intensity changes in the range from 8 cars/km up to 100 cars/km, that is, at the beginning of the section.

However, it should be noted that this approach has certain limitations, which are related to the necessity to install additional technical regulation devices Today, such devices include controlled road signs with variable information of the determined level of motion speed of motor vehicles. No shortcomings of the application of dynamic control were identified.

It is planned to develop this research in the area of the introduction of dynamic control in the TF control systems in cities. The prerequisite for the implementation of dynamic control is mandatory approbation of the procedure for determining its parameters [23]. At the same time, it should be obligatory to take into consideration the length of the SRN road line and the duration of the traffic light cycle at an intersection.

7. Conclusions

1. The obtained results of simulation of dynamics of a change in basic parameters of the traffic flow allowed revealing not only the nature of the "shock wave" formation in the congested traffic mode but also the place of their occurrence. The simulation was carried out at a fixed length of the section based on determining the interaction of speed, density, and intensity. The complexity of their interaction during the motion in urban conditions is related to a change in safety distance between the road vehicles and appearance of congested traffic mode. The emergence of a "shock wave" is the cause of unjustified traffic flows stops on the street-road network. The description of the process of the "shock wave" formation was obtained based on determining the density change rate. The simulation experiment of the traffic flows motion on the street-road network section of Kharkiv was carried out and proved the adequacy of the developed simulation model (5 %).

2. Modeling the results of the controlling parameter on the traffic flow in the form of decreased speed of motion prove the adequacy of applying dynamic control with a change in the traffic flow motion mode. The proposed approach to the realization of dynamic adaptive control in the case of the traffic congestion mode has the features of situational management. A series of advantages in case of prevention of the unstable traffic flow state influence an increase in the throughput capacity of the street-road network and a decrease in the road vehicles downtime. Application of dynamic traffic control as a part of the traffic control system in cities is an alternative to the street-road network expansion in order to organize a stable mode of traffic flow motion. The implementation of dynamic control is based on measuring the traffic flow parameters by transport detectors in real time. Information on a change of the traffic mode should be sent to traffic participants by applying multi-position road signs.

The proposed approach to increasing the throughput capacity of the street-road network makes it possible to improve the components of traffic efficiency. A decrease in time of road vehicles traveling around cities without stopping is of strategic importance for the logistic process of passengers and cargo delivery. Formalization of controlling influences on reducing the traffic flow intensity and speed has a positive effect on traffic safety. Thus, the introduction of the proposed solutions to the traffic control system in cities is a promising direction for the improvement of the transportation process.

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