Розглядається взаємодія транспортних засобів на автомобільній міжміській дорозі. Модель керування автомобілями є тут ідеалізованою, близькою до автоматизованої інтелектуальної транспортної системи 4-го покоління. Кожен автомобіль має бажану програму руху, незалежну від мотивів водія, яка обґрунтована за мінімальними витратами ресурсів і дотриманням бажаного розкладу. Різноманітність програм впливає на їх небажану зміну. Ставилась мета виявити залежність дійсної швидкості автомобіля від параметрів транспортного потоку. Основною задачею було виявити прямий параметр для зміни програми руху. Обґрунтовано використання імітаційних моделей на основі кліткових автоматів. Розроблено новий клітковий автомат, який є ковзним вікном з початком відліку, яким є автомобіль-спостерігач. Кількість об'єктів в полі поповнюється періодично і є сталою. Усі клітинки зліва і справа початку відліку автомата утворюють інформаційне поле, або загальну довжину автомата. Висота автомата залежить від виду магістралі, яка моделюється. Правила переміщення об'єктів в сітці автомата на кожній ітерації є скінченні, сталі й подібні до автомата Шрекенберга, за виключенням рандомізації, яка в цій моделі зводиться до мінімуму. Такий автомат відображає відносні швидкості автомобілів потоку відносно спостерігача, а також має можливість відтворювати прискорення. На кожній ітерації обчислюється зміна швидкостей автомобілів потоку. Алгоритм імітації запрограмовано на Делфі. Виконано приклад моделювання руху автомобіля на трасі міжнародного значення Е-471. На відрізку цієї траси довжиною 20 км було змодельовано транспортні потоки з різною густиною і різним розподілом швидкостей. Виявлено квадратичні кореляційні залежності вимушеної зміни бажаної швидкості автомобіля-спостерігача від середньої зміни швидкостей автомобілів потоку. Ступінь узгодження теоретичної залежності з емпіричними даними є дуже високий. На основі отриманих залежностей було обґрунтовано вибір прямого діагностичного параметра транспортного потоку

***Ключові слова:** транспортний потік, магістраль, клітковий автомат, ковзне вікно, відносна швидкість, інтелектуальна транспортна система*

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DEVELOPMENT OF VEHICLE SPEED FORECASTING METHOD FOR INTELLIGENT HIGHWAY TRANSPORT SYSTEM

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1. Introduction

Due to the rapidly growing volumes of goods transportation in recent years, the number of trucks and road trains, as well as their average speed is constantly increasing. This leads to negative consequences, such as traffic congestion, deterioration of the environmental situation around transport networks, increase in the number of road accidents on the, including fatal ones. Improvement of the road network does not always solve these problems. Experts in transport management consider it more effective to use intelligent transport systems (ITS). These systems can regulate the movement of vehicles. This prevents road incidents, ensures the most cost-effective modes of vehicles and reduces delays in goods delivery in cities and during intercity transportation. A very important element of ITS is the means of forecasting the vehicle speed. It is known that it depends on road and transport conditions, aside from a subjective factor. Road conditions are usually defined, and information about them is available over at least one transport cycle. For example, through online service the driver can build the shortest route between the specified points on desired roads, quickly learn about technical conditions of roads, weather, route parameters. Based on this, it is possible to calculate the optimum motion program, which provides minimum resource consumption and timely implementation of the transport task [1]. However, so far nobody forecasted traffic density on highways with the correct accuracy, and also determined the mutual influence of traffic participants on the forced average speed. Therefore, in practice, the time of arrival at the destination point is reserved, and the transport process is scheduled with time windows [2]. However, transport conditions are more dynamic, dependent on a large number of subjective factors, poorly predictable. In this regard, for forecasting the vehicle speed on the highway, it is necessary to have several secondary attributes of traffic, which functionally depend on changes in the speed of any vehicle. In this study, the parameter that can be the basis for predicting the speed of the chosen vehicle is experimentally substantiated. But at the same time, the prospects for ITS development on transport networks, which would make possible such forecasting were considered. Applying theoretical dependencies in conditions of spontaneous decision-making by highway traffic participants makes no sense.

Experiments, namely simulation, are the most effective means of such research. In some cases, this is the only way to identify and predict transport conditions on the road. Therefore, evolving a simulation method is a relevant task in the development of information transport systems.

2. Literature review and problem statement

The majority of modern studies are aimed at creating intelligent vehicles moving in intelligent transport networks. For example, there are known projects of autonomous vehicles and their organized following [3]. However, optimal movement programs are neglected since the purpose of these ITS was only to improve road safety. Similar studies related to the driver's assessment of the road-transport situation and speed choice are made in [4]. However, such a direction of ITS improvement can not be considered promising, since it has already been shown in [5] that the driver, as the most inertial link of the driver-vehicle-road-environment system (DCRE), makes choice depending on an information field, which is not always favorable. All studies on ITS are quite reasonable, especially because over 70 % of all accidents are caused by the human factor [5]. In [3, 6], there is evidence that limiting the scope of driver's decisions is more promising than the study of physiological features of the decision-making process. In this regard, when constructing a vehicle motion forecasting model, it is necessary to step away from random factors associated with the subjective choice of the operator.

The analysis of studies on forecasting the vehicle speed on the highway is made in [7, 8]. Providing accurate estimates of speed and its relation to traffic flow parameters is the main task of transport simulation. A closer look at the nature of this task indicates that speed is, in fact, the result of vehicle interaction with other traffic participants. For many years there have been various simulation approaches to address this problem. In general, simulation of traffic flow in order to solve the main problems of its development is divided into three conditional levels, namely macrolevel, mesolevel and microlevel. Macrolevel models describe the whole traffic flow, taking into account the totality of all vehicles. A significant characteristic of this model is traffic volume. This type of model is most appropriate for the analysis of a large transport system, such as highway and interregional transport networks. However, macromodels are unsuitable for evaluating a particular parameter because of high error.

In the car-following models [8], an important assumption is stated that there is a connection between the movement of the follower and leader vehicles. As the theory developed, models of this group took into account the driver's response time, the motion of multiband roads and motion stability were studied. However, in order that micromodels reproduced a real picture of vehicles interaction, they need to be supplemented with studies on rational driver's behavior, which, as noted, is the unpromising direction. Therefore, traffic flow research can be intensified by clearly describing the impact of each particular vehicle on the entire traffic flow, as shown by the example of automation of road facilities in [9]. One way to eliminate human error and delays in the follower vehicle is to replace the driver with sensors and appropriate computer control system. Therefore, the number of works aimed at developing autonomous intelligent cruise control systems (AICCS) is growing. In particular, in [10] the automated vehicle control system is proposed. The influence of the system on traffic flow is also studied and comparison of its properties with the driver behavior models is made. The disadvantage of such control is the lack of information exchange between vehicles, as well as interaction with other systems. It is found that AICCS efficiency is higher than that of the driver behavior models. For this, computer simulation is used. In addition, several emergency situations are simulated, including emergency stop and drive shutdown. The simulation results demonstrate AICCS efficiency and potentially beneficial effect on traffic flow. However, the simulation model described is unsuitable to simulate a wider range of tasks, such as substantiating the ITS properties, since it requires large volumes of data.

The review of known studies in the generation of vehicle speed forecasting models is performed in [11]. Unlike previous studies, GPS satellite navigation systems are now used for speed measurement, which gives a fairly positive result in data accumulation. A great prospect of such use is mentioned in [12]. It is also proved by the facts [9] that visual observation is almost not used in research. It is known that traffic conditions and safety are mainly influenced by road conditions, traffic volume and structure. Moreover, these indicators form the nature of the information load on the driver. It is also indicated that information indicators of the driver's perception field are closely interrelated [12]. This greatly complicates the development of an ITS model, which is based on a human driver behavior model. Therefore, all subjective factors need to be eliminated from the simulation model.

The paper [13] also states that the relative speed of other flow participants plays an important role in the information support of the driver. It is found that the level of driver's mental stress during information perception depends on two factors: the value and amount of information. The amount of information depends mainly on speed and traffic volume. However, it would be wrong to assume that the most valuable information is the one that more influences the driver's decision-making on traffic safety. The choice of energy-saving modes, especially when transporting goods by heavy vehicles, is not less important.

The studies [14, 15] show that GPS data transmitted from the vehicle via cellular technologies can provide most of the performance information desired by road agencies. However, obtaining enough data in a cost-effective way is difficult, unless the method of transport conditions assessment is changed.

Another source of data for the investigated ITS is the extensive highway monitoring and control system of WSDOT (Washington State Department of Transportation). Output data from each of the ITS devices analyzed in this study presented different images (options) of cargo flows for the same roadway section [16]. In addition, ITS data often cover various (non-adjacent) roadway segments and systems or geographic areas. The result of such a wide variety was the task of integration, which is much more difficult than originally expected. In general, the study found that the integration of data of all ITS devices potentially offers both a more complete and more precise description of cargo and transport flows. On the other hand, integration of information flows in the ITS leads to system overload and extremely bulky databases that can not be processed promptly.

The project [16] explores the process of converting signals from onboard transponders of road trains into useful data for describing the highway performance. The possibility to use electronic transponders of trucks (also known as tags) is identified. The purpose is to describe whether the time of truck movement increases due to highway congestion. As a result, the traditional approach to route analysis based on average travel time control is rejected. However, these studies have no theoretical basis. And changes in vehicle speed were recorded only in absolute terms, based on traffic density, which may not be enough.

As is known, speed is one of the key traffic parameters [17]. If possible, drivers move at speeds that are rational for a particular type of trip. However, the subjective factor leads to the fact that the concept of "desired speed" has become too blurry to be described on the basis of technical and organizational factors. In real flows, speed distribution is quite significant and depends on their density. Homogeneity of traffic flow is almost never achieved and reaching the same speed even for the same vehicles is rather difficult. Hence the complexity in the development of such traffic models and patterns that would satisfy the absolute majority of traffic participants. However, the solution to this problem can be approached through continuous monitoring of speed modes and study of determining factors. In [7], for example, the theoretical approaches to the classification of speed, its interrelation with other primary traffic parameters, as well as factors influencing the speed modes of individual vehicles in the traffic flow are considered. However, the main focus is on the research of instantaneous speeds on straight sections of the street-road network of settlements. This is one of the main features characterizing traffic safety in cities and can not be applied to long-distance traffic.

Effective and informative way to simulate the movement of a set of vehicles on the highway is cellular automata [17]. On the basis of the microsimulation approach, a number of them have been developed. A separate class is called transport cellular automata (TCA). TCA allow tracking the dynamics of both a single vehicle and the flow in general, and getting initial data to estimate speed, travel time, time in traffic jams [18].

The studies [19] deal with using advanced numerical and intelligent tools to forecast vehicle speed using time series. It is clear that the uncertainty caused by the driver's behavior and various external disturbances on the road will affect vehicle speed. Therefore, it is important to develop technical means to overcome the risk of unpredictability associated with the vehicle speed profile on highways. In the study, the authors propose an intelligent tool, called the evolutionary least learning machine (E-LLM), to forecast the sequence of vehicle speed. For the practical assessment of E-LLM efficiency, the authors use driving data collected on city roads of San Francisco. However, there are no data on the use of E-LLM on highways, and the proposed method is only suitable for long-term speed forecasting.

The concept of the analysis of sliding windows time series (SWTS) is used by researchers to prepare databases for speed forecasting [17]. A number of known approaches, such as autoregression method, backpropagation neural network, evolutionary extreme learning machine, extreme learning machine, as well as the radial basis function neural network, are intended to estimate the efficiency of the proposed methodology. Through a comprehensive comparative study, the authors noted that E-LLM is a powerful tool for forecasting vehicle speed profiles. The results of the current study can be useful for automotive engineers. In this case, there is the need for fast, accurate and inexpensive tools capable of forecasting the vehicle speed. Such a forecasting horizon can be used to develop effective intelligent controllers of power units, as is done, for example in [19]. For operational vehicle control in the highway flow, it is too large-scale.

The cellular automaton is an extremely simplified program for simulating complex transport systems, where speed is more important than model accuracy. In the cellular automaton, space and time are divided into discrete cells and steps. Only transported units perform cell exchange with adjacent cells directly within one time step. The Cellular Automaton model is defined by the rules that control these exchanges.

The paper [17] describes a new concept of the cellular automaton principle for traffic flow simulation. This model uses the time-oriented vehicle model. The model more precisely corresponds to the actual driver's behavior than the corresponding Nagel-Shrekenberg one. The properties of discrete time and space are preserved. Also, the updating process can be performed for each vehicle independently. This model achieves fairly good compliance with the observed real traffic flow. The paper shows that the degree of compliance with reality depends on the vehicle model used. For different traffic flows, it can give significant errors.

The new concept of the model combines realistic simulation with high computing performance [19]. Traffic models based on cellular automata are effective due to simplicity in describing complex traffic models and easy implementability for parallel computing. However, such models require adaptation in each particular study. Other micromodels, such as models of the follower vehicles (computer), are more expensive, but more realistic as reflect the driver's behavior and detailed vehicle characteristics. In [20], the hybrid of these two categories is proposed, which determines the traffic model based on continuous cellular automata. This approach could be used to simulate vehicle movement in the ITS.

There are many various systems for transport network simulation. Among them, AIMSUN (Aimsun SLU, Spain), PA-RAMICS (Paramamics Microsimulation, Great Britain), AUTOBAHN (Z-Software, Germany), IHSDM (Turner-Fairbank Highway Research Center, USA), INTEGRATION (M. Van Aerde and Assoc., Ltd., USA), PLANSIM-T (Los Alamos National Laboratory, USA), FLEXSYT-II (Public Works and Water Management Transport Research Center, Netherlands), TRANSIMS (Los Alamos National Laboratory, USA), SimTraffic 6 (Trafficware, USA), VISSIM (PTV System, Germany), MITSIM (MIT, USA), etc. [21, 22]. The authors of [23] made an overview of the traffic simulation systems and proved the need to develop a distributed traffic simulation system. Such a simulation system will reflect transport networks of large cities with a large number of vehicles, as well as reduce financial costs of system support. The system realizes the possibility to model the driver's route choice before and during the trip [24]. The AIMSUN computer system, which includes four different algorithms of dynamic route selection, the editor of the travel cost calculation function and the option of travel cost calculation proceeding from information about previous routes, is considered to be the most advanced. Different drivers will use different route selection criteria: from constantly choosing the same route to changing the route according to traffic conditions. In [22], it is noted that vehicle behavior models in the AIMSUN system are defined by functions of several parameters. This approach allows simulating the movement of different types of vehicles (vehicles, buses, trucks, etc.), which can be grouped into classes. A common drawback of all the systems is the need to store and process a large amount of input data, which increases nonlinearly with simulation scales, time boundaries of models when it comes to large highway transport networks, and the dependence of the accuracy of flows description on a large number of random factors. In the end, not all of these software tools are linked to the online data flow and they do not provide for ITS development. Also, no less significant drawback is that all software tools can not reflect acceleration and deceleration of individual traffic subjects due to the methods incorporated in them. Because of this, many maneuvers reproduced by the systems are not realistic enough.

So, for the development and implementation of ITS of the fourth and subsequent generations on the highway, it is necessary to have an operational forecast of speed on specified sections of the transport network. Forecasting of the speed of a particular vehicle based on the study of secondary traffic flow characteristics such as density and relative speed was not performed in previous studies. Instead, due to the development and implementation of autonomous transport systems on highways, the problem of increasing the accuracy of forecasting the growing volume of traffic parameters, which are extremely variable in time and space, is exacerbated. In order to eliminate these two obstacles to the development of effective ITS, it is necessary to justify the model of intelligent vehicle interaction with the flow. Also, there are no clear conclusions about the choice of parameters for traffic flow control on the highway. Density and volume are traditionally used, but there are no appropriate means for accurate measurement of them.

3. The aim and objectives of the study

The aim of the study is to develop a method and obtain results that prove the need to measure and apply relative speed as a sign for changing the mode of a particular vehicle in the ITS.

To achieve the aim, the following objectives need to be accomplished:

– to develop a simulation model of the relative motion of a given vehicle;

– to perform machine experiments for flows with different densities and distribution of desired speeds;

– to establish a relationship between the relative speed of the flow objects and the speed of the chosen observer vehicle.

4. Substantiation of the method and algorithm of simulation

The simulation model is a modified cellular automaton with two-way vehicle movement. From classical known models, basic principles are adopted [18]:

1) locality of rules: a new state of a cell can be influenced only by the elements of its environment and, possibly, the cell itself;

2) homogeneity of the system: none of the grid areas lattice area can differ from another due to any features of the rules; boundary conditions for the initial and finite state of the model are also introduced;

3) finiteness of the set of possible cell states – the nece essary condition to perform a finite number of operations in order to obtain a new state of the cell;

4) simultaneous transition to a new state for all cells – permissible values in all cells are changed once, at the end of iteration, and not in the calculation [19].

In addition to traditional, new assumptions and simulation rules are applied that make it easier to achieve the aim of the study.

In this option, the cellular automaton is a two-dimensional grid. The grid height corresponds to the number of highway lanes (including oncoming). The length of the grid is the "information field" of the observer vehicle (OV), that is, the finite constant number of cells behind the OV and the finite constant number of cells in front of the OV. This field is caused by the use of devices for assessing the road transport situation. In practice, it can be implemented using radars, lidars, infrared sensors and other means the OV can be equipped with [11]. With the help of such devices, it is possible to estimate the presence and relative coordinates of other traffic participants, moving both along with the OV and on oncoming lanes. In this case, the two-dimensional coordinate system, in which the OV is the reference point is applied. Each automaton cell can be occupied with a traffic flow object or free, except for the initial one, which is always occupied. The OV speed should correspond as much as possible to the desired motion program $V_{0.d}(x)$, where $0 \leq x \leq L$ is the absolute coordinate of the reference cell; L is the length of the two-dimensional grid. However, the grid can be forcedly changed due to maneuvers performed by other traffic participants. The number of non-empty automaton cells depends on the predefined traffic density, as well as the size of the "information field": the number of back cells – R_b and the number of front cells – R_f of the OV.

Vehicles are reflected in the automaton, depending on their dynamic dimensions in the form of a certain number of the filled cells. If the length of one automaton cell is 10 m, and the time of one iteration is 0.1 s, the movement of an object by one cell corresponds to a change in speed relative to the OV by 1 m/s. The displacement length to be displayed by this simulation is several tens of times greater than the length of the information field R_b+R_f. The main interest of these studies is the determination of relative speeds and relative displacements. In this regard, all vehicles involved in the traffic flow are considered as single-cell, two-cell or maximum three-cell objects, without significant accuracy reduction. This corresponds to the dynamic dimensions of the vehicle, respectively, 10, 20 and 30 m. On intercity highways, these dimensions are actually measured in the range from 7.5 to 27±2 m. Our assumption does not reduce the adequacy of the model due to the scale of simulation. Modern observation systems, for example lidar-based, are able to "see" a transport situation at a distance of about 300–400 m. According to the studies, this is not the limit of their capabilities and a longer distance should be expected [11]. In addition, these means become more available and are already mounted on the 4th generation ITS. Thus, if the size of one automaton cell is 10 m, the automaton can consist of about 30 cells in front of and the same behind the OV. If traffic participants are vehicles with a smaller static dimension, then such objects usually have higher dynamics. So, their dynamic dimension can be equated to the size of 1–3 automaton cells on a scale without significant loss of accuracy. The error of such an assumption is the smaller the greater the length of the simulated route. Thus, at a 20,000 m run, the cell size is 0.05 %. This means that the vehicle, performing such a run, will be displayed by the automaton after 2,000 iterations. All this applies to the vehicles reflected by one, two or three cells. It is also accepted that the height of the cell corresponds to the width of one lane. The filled cell means that the lane is completely occupied with the vehicle in the given section.

The automaton records the relative speed of the vehicle. Its numerical value depends on the OV speed:

$$V_{r.i} = V_i - V_0, \quad i = 1,\dots N_c, \tag{1}$$

where V_i is the absolute speed of the i-th vehicle, m/s; V_0 is the absolute speed of the OV, m/s; N_c is the number of traffic participants moving along with the OV.

For oncoming vehicles, speed is determined from the expression:

$$V_{r.y} = V_y + V_0, \quad y = 1,\dots N_a, \tag{2}$$

where V_y is the absolute speed of the oncoming vehicle, m/s; N_a is the number of traffic objects, moving along the oncoming lanes relative to the OV.

The relative speed of the i-th vehicle calculated by (1) can be a negative value if its absolute value is less than V_0. Hence, the filled cells can move in the information field to the right if the desired vehicle speed is higher than the desired OV speed, or to the left, if the desired speed is lower. One step in the cellular automaton simulation is discrete time that corresponds to 0.1 s. Thus, movement of the filled cell one position to the right or left corresponds to a change by 10 m for 1 s. Paired or tripled cells move simultaneously.

If, as a result of the simulation, it turns out that the i-th cell should move beyond R_b or R_f, it means the i-th vehicle disappears from the OV information field. A new or several new objects that have random speeds are generated in the side of the information field opposite to disappearance in order to maintain a given flow density and, therefore, experimental integrity. If the cell disappears on the left, outside R_b, then a new filled cell with the same dimensions appears near the right border of the information field and has a random speed $V_i \leq V_0$. If the cell i disappears on the right, outside R_f, then a new filled cell appears on the left and will have a random speed $V_i \geq V_0$. Thus, a constant number of filled cells is maintained in the information field from step to step. Similarly, cells arise and disappear from the information field on other with-flow and oncoming lanes of the cellular automaton.

Each filled cell or a set of cells at each iteration is characterized by the following values:

$X_{step.i}$ – current coordinate relative to the OV;

$\Delta X_{step.i}$ – change of the current coordinate relative to the OV;

$V_{step.i}$ – absolute speed;

$V_{step.r.i}$ – relative speed;

$V_{d.i}$ – desired speed caused by the rational mode in the given road conditions and condition of compliance with the transport schedule;

$\Delta V_{step.i}$ – deviation from the desired speed;

$j_{max.i}$ – maximum permissible acceleration/deceleration due to driving safety and dynamic characteristics of the vehicle.

In these notations, $step$=0…S is the number of iteration, that is, discrete time interval of simulation, i=0..N_c is the number of the object that moves along with the OV, i=1..N_a is the number of the object on the oncoming lane of the automaton.

Rules of transition of the filled cells depend on events that necessarily occur in the vehicle, if there are suitable conditions. The number of such events is finite, however, at least 5. The sequence of these events for all cells is justified on the basis of their priority and traffic safety conditions.

1. Braking. At the zero step of the automaton, all the vehicles within the information field have the same current speed and are equidistant from each other. However, the desired speed of a group of vehicles is a random variable, characterized by the Erlang distribution law, or exponential, depending on the road category [9]. The cells located to the right of the others and having the desired speed lower than that of the OV need to be moved to the left by the number of cells that corresponds to the difference

$$\Delta X_{step.i} = V_0 - V_i, \tag{3}$$

but not more than the maximum allowed deceleration $j_{\max.i}$.

Moving to the left should be done regardless of whether there are free cells on the left. This rule follows from the fact that the leader vehicles always have a priority on the road, but they are limited in braking rate. Therefore, performing the braking procedure, it is necessary to forcedly recursively move all the filled cells that are in the way of the i-th one to the left. This procedure, based on the calculation of displacements (3), should be performed by the order of coordinates from right to left. Since the procedure is rather complicated and its modeling differs from those known in the field of cellular automata, we give the pseudocode of the procedure performed for each cell having $\Delta V_{step.,i}$<0.

procedure CheckBracking; //braking possibility check procedure

begin

01 nulling of the source array ΔX

//maximum deceleration check

02 if ($-\Delta V_{step.i}$<=$j_{\max}$) then

03 $j_{\max}$:=$\Delta V_{step.i}$

04 else $j_{\max}$:=$j_{y.\max}$;

//if the maximum deceleration condition holds, the object moving on the left relative to the OV moves one position to the left:

05 if $j_{\max}$<0 then

06 for z:=1 to ($-j_{\max}$) do

07 begin

08 $X_{step,z}$:=$X_{step,z}$–1;

09 ΔX_z:=ΔX_z–1;

10 $V_{step,z}$:=$V_{step,z}$–1;

end;

//if the coordinate of the moved cell is occupied with the object z, then this object needs also to be moved by the cell to the left. To do this, the element of the array ΔX_z is reduced by 1. Viewing of all such cells from right to left is carried out:

11 for z:=N_c downto 0 do

12 begin

13 if (($X_{step,z}$=$X_{step,i}$) and (i<>z)) then

14 ΔX_i:=ΔX_i−1
end;
end;
//for all objects having elements of the array ΔX_z<0, their current coordinate, speed and speed difference are changed by the value of ΔX_i
15 for i :=N_c downto 0 do
16 if ((ΔX_i<0) and (i<>z)) then
18 begin
19 $X_{step.i}$:=$X_{step.i}$+ΔX_i;
20 $V_{step.i}$:=$V_{step.z}$;
21 $\Delta V_{step.i}$:=$V_{d.i}$–$V_{step.i}$;
end;
end;
end; //end of the procedure.

2. *Acceleration*. The current speed of the i-th object is less than desired, that is>$V_{step.i}$<$V_{d.i}$, it needs acceleration, which is acceptable for such a maneuver, but does not exceed $j_{\max.i}$. This can be done if there is free space in front of this object. After the acceleration, the object takes a speed, depending on whether it is desired or not and whether there is an obstacle to further relative motion. If there are no free cells in front of the accelerating object, then acceleration does not occur. If there are so many free cells that ($V_{d.i}$–$V_{step.i}$)≤ΔX_i, where ΔX_i is the number of free cells, then the object acquires a speed equal to the predecessor speed. If ($V_{d.i}$–$V_{step.i}$)>ΔX_i, then the object acquires the desired speed. The pseudocode of this procedure is as follows:

Procedure Acceleration; //acceleration procedure
begin
01 for i :=N_c downto 0 do
02 if $\Delta V_{step.i}$>0 then
03 begin
//check of front free cells by the CheckFreeCell function:
04 if CheckFreeCell(i)<$j_{x.\max}$ then
05 acceleration:=CheckFreeCell(i)
//acceleration by a certain number of cells is performed
//if acceleration is not limited by an obstacle ahead, it is carried out at maximum
06 else acceleration :=$j_{x.\max}$;
//coordinate, object speed increases by an admissible value, and the difference between the desired and current speeds decreases by this value:
07 $X_{step.i}$:=$X_{step.i}$+acceleration;
08 $V_{step,i}$:=$V_{step,i}$+acceleration;
09 $\Delta V_{step,i}$:=$\Delta V_{step,i}$– acceleration
end;
end. //End of the procedure

3. *Overtaking or lane change.* These maneuvers are modeled in the cellular automaton under favorable conditions and in the absence of restrictions. Overtaking is permissible in the absence of a solid line between lanes and if there is at least one lane in each direction. Overtaking is prohibited on the highway. The rules of overtaking in this automaton are as follows. Acceleration of the object should not exceed the permissible maximum. Overtaking begins if there is no approaching object on the oncoming lane at a safe distance (remind that the speed of the oncoming object in this automaton is about twice the absolute speed of the OV).

Overtaking is performed if there are at least two free cells in front of the predecessor object. Free cell check is carried out in the same way as for the acceleration procedure. If all these requirements are met, overtaking is performed automatically regardless of the driver's possible behavior. After overtaking, the object acquires the desired speed or the predecessor speed. The procedure of lane change, or vertical cell movement in the automaton, differs from overtaking by the fact that it is necessary to calculate the number of free cells behind the object. In the absence of obstacles, maneuvering is possible.

4. *Constant motion to the left* is carried out if the object already has the desired speed or the current speed, which is lower than the OV speed. In this case, free cell check is not performed. Moving to the left is carried out by the number of cells ($V_{step.i}$–$V_{d.i}$). All objects following the i-th object also move to the left by the corresponding number of cells. The procedure is performed similarly to the braking procedure. The speed of all objects moved to the left is equal to the speed of the i-th one.

5. *Constant motion to the right* is performed if $V_{step.i}$>V_0. Before this motion, free cells are found on the right.

6. *Correction of object coordinates relative to OV coordinates.* All the above procedures 1–5 apply not only to the objects under observation but also to the OV itself. Therefore, they may lead to a situation where the OV coordinate namely X_0 is not zero and/or its speed is different from the desired one. In this case, it is necessary to reformat the information field, that is, the automaton, displacing it by 0–X_0 and recalculate ΔV_0=$V_{0.i}$–V_0. This value is a function that needs to be defined after S simulation steps:

$$\Delta V_{0.\Sigma} = \sum_S \Delta V_{step.0}. \tag{4}$$

As a result of correction of the OV speed and coordinates, some automaton objects may appear outside the information field. They need to be removed from the next simulation step and replaced with new ones.

Upon transition to the next iteration, the same control parameters are transferred and the numerical value of the functional is calculated:

$$\Delta V_{i.\Sigma} = \sum_{i=1}^{N_c} \Delta V_{step.i}. \tag{5}$$

The algorithm of simulation consists of the above procedures (Fig. 1) and is implemented in Delphi 10.2 environment.

5. Experiments for different transport conditions

The developed method and algorithm for traffic flow simulation was applied on an example on the E-471 Kyiv-Chop highway. The highway has two lanes, one in the opposite direction. Road category – 2. The flow density varies within 15...150 vehicles/km. The flow included 100 % of cars. The exponential law of distribution of desired vehicle speeds was adopted with the following parameters: expectation – 16 m/s, standard deviation – 3.5 m/s. Maximum acceleration of vehicles – 5 m/s^2, maximum deceleration – 3 m/s^2. The section of the E-471 route, namely, Stryi-Pisochne, was considered. Length – 20 km. The road is straight, with constant cross-section. Maximum speed allowed – 25 m/s. There are almost no crossings and adjunctions. The actual average speed of vehicles on this route according to Google Map – 16.6 m/s.

Initial data varied as follows: the relative speed of the vehicles differed from the desired OV speed (Table 1).

Table 1

Example of the series of prepared initial data for the flow density of 25 vehicles/km

No.	$\overline{V}$	η_V	σ_V	Δx_{av}	ΔV_{av}
1	25.000	0.000	0.0000	0.0000	–5.000
2	24.938	0.040	0.2500	0.1172	–4.938
3	24.625	0.081	0.6191	0.5156	–4.625
4	24.375	0.082	0.8062	0.7031	–4.375
5	24.063	0.125	0.9979	0.8203	–4.063
6	23.688	0.127	1.1383	0.9766	–3.688
7	23.250	0.172	1.2383	1.0313	–3.250
8	22.750	0.176	1.2383	1.0313	–2.750
9	22.250	0.180	1.2383	1.0313	–2.250
10	21.750	0.184	1.2383	1.0313	–1.750
11	21.250	0.188	1.2383	1.0313	–1.250
12	20.750	0.193	1.2383	1.0313	–0.750
13	20.250	0.198	1.2383	1.0313	–0.250
14	19.750	0.203	1.2383	1.0313	0.250
15	19.250	0.208	1.2383	1.0313	0.750
16	18.750	0.213	1.2383	1.0313	1.250
17	18.250	0.219	1.2383	1.0313	1.750
18	17.750	0.225	1.2383	1.0313	2.250
19	17.250	0.232	1.2383	1.0313	2.750
20	16.750	0.239	1.2383	1.0313	3.250
21	16.313	0.184	1.1383	0.9766	3.688
22	15.938	0.188	0.9979	0.8203	4.063
23	15.625	0.128	0.8062	0.7031	4.375
24	15.375	0.130	0.6191	0.5156	4.625
25	15.188	0.066	0.4031	0.3047	4.813
26	15.063	0.066	0.2500	0.1172	4.938

The estimates were introduced for the initial data:

1) speed variation factor:

$$\eta_V = \frac{V_{\max} - V_{\min}}{\overline{V}}, \tag{5}$$

where $V_{\max}$, V_{min}, $\overline{V}$ are the maximum, minimum and average speeds of objects in the automaton field, respectively;

2) standard speed deviation σ_V;

3) mean deviation from the expectation:

$$\Delta x_{av} = \frac{1}{N_c}\sum\left|x_i - \overline{x}\right|, \tag{6}$$

4) absolute deviation of the average speed of objects from the OV speed ΔV_{av}.

Consider, for example, according to Table 1, the average flow speed of 20.25 m/s with a standard deviation of 1.25 m/s. With a traffic density of 16 vehicles/km in the OV information field of 480 m, there will be 8 vehicles+OV+on the oncoming lane. The distribution of their speeds will be as follows: 20; 22; 21; 21; 20; 20; 19; 19; 18. Fig. 2 shows the example of five iterations for the given initial data.

The information field of the automaton is asymmetric: 16 cells behind (160 m), in front – 32 cells (320 m). This means that the initial group of vehicles moving in a column due to the speed difference is scattered along the cellular automaton and, in the end, 4 of them go beyond the review limits. However, the presence of three vehicles with speeds lower than the OV desired speed, namely 19, 19, 18 m/s, leads to the total OV delay on the route of 1 m/s on the length of 20 km.

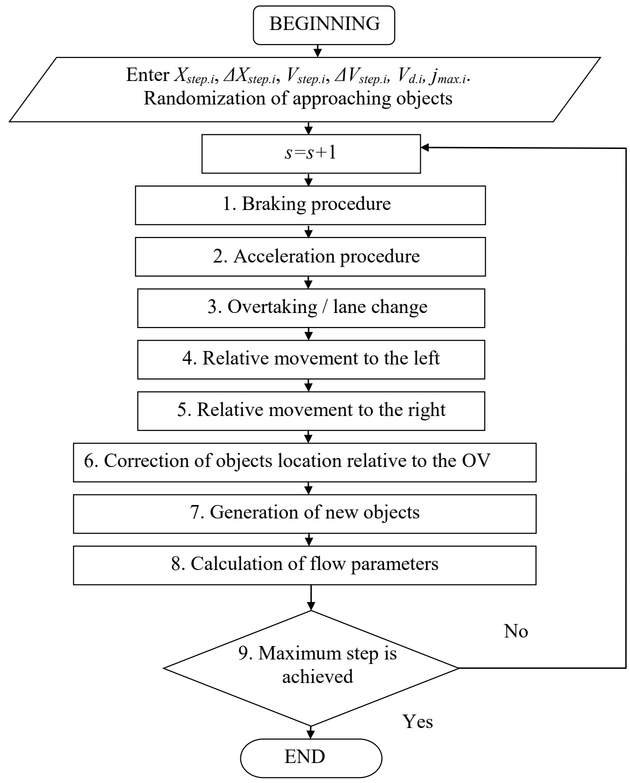

Fig. 1. Block diagram of the simulation algorithm of traffic flow on the two-lane road with allowed overtaking

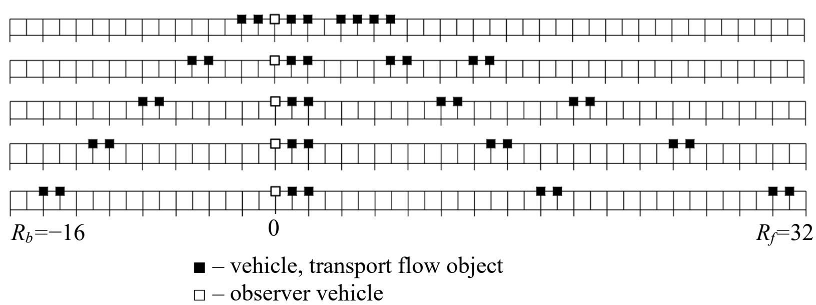

Fig. 2. Scheme of five simulation steps of cellular automaton

These data were entered into the program and dependences of average vehicle delays with the desired speed of 20 m/s with respect to the relative speed of other traffic participants were obtained (Fig. 3).

6. Establishing a relationship between the relative speed of the flow objects and the change in the speed of the chosen observer vehicle

The obtained simulation results for various arguments ΔV_{av} lead to changes in the actual speed of the OV in relation to its planned speed. Denoting this value as y and ΔV_{av} as x, the following regression equations can be obtained:

– for a flow density of 40 vehicles/km:

$y = 0.06x^2 + 0.2917x + 0.4109;$

– for a flow density of 28 vehicles/km:

$y = 0.0297x^2 + 0.1908x + 0.0869;$

– for a flow density of 16 vehicles/km:

$y = 0.00653x^2 + 0.425x + 0.7113.$

The coefficients of the regression equation are obtained using the "trend" function in Excel 2007 spreadsheets, which performs the construction of the regression equation on the basis of empirical data using the least-squares method. The reliability of empirical approximation for all three dependencies is greater than 0.97, indicating a good agreement between the theoretical dependence and empirical data. The obtained dependences are graphically shown in Fig. 3.

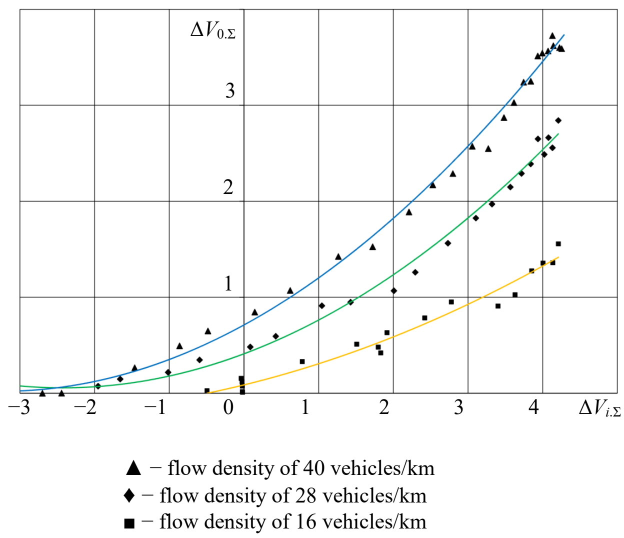

Fig. 3. Experimental results of the simulation of changes in the OV speed depending on changes in the flow parameters, and theoretical approximation

All dependencies are described by parabolas. However, for a flow density of 16 vehicles/km, the parabola asymptotically approaches the abscissa for $\Delta V_{i,\Sigma} = -0{,}5$.

7. Discussion of the simulation results of traffic flow on the highway

The dependences of $\Delta V_{0,\Sigma}$ on $\Delta V_{i,\Sigma}$ obtained as a result of the simulation can be divided into two parts. The first part, for which $\Delta V_{i,\Sigma} > 0$, the second one, for which $\Delta V_{i,\Sigma} < 0$. The first part reflects the situation when "fast" vehicles of the traffic flow force the OV to increase speed to eventually adhere to the given average desired speed. This is because the OV has to perform overtaking or lane change. However, such accelerations of the OV are made when the total speed increase of all *i*-th vehicles, which are in the OV information field, is greater than 0.2, 0.45, 0.7 m/s for different traffic flow densities. The higher the flow density, the less the effect of acceleration of other traffic participants on the OV.

The second part of the dependence (Fig. 3) reflects the situation when the OV has to reduce speed due to the effect of "slow" vehicles. In these situations, the vehicles of the flow constrain the OV at certain timepoints. The increase in the density of "slow" vehicles has a greater impact on the number of forced OV accelerations.

The dependences in Fig. 3 also have such a property that with increasing flow density their character becomes more and more non-linear, especially in the region of $\Delta V_{i,\Sigma} < 0$. The dependence of the forced change of the OV on the influence of the transport flow can be adequately described by the obtained regression equations.

Technical means for determining the relative speed allows following the schedule. However, delays increase rapidly when the average flow speed becomes lower, that is, when there are "slow" vehicles in the flow, which force all others, including the OV, to change the current speed. Telemetric means of the OV, including means for determining the relative speed of vehicles in the flow, telecommunication means can be used to correct the schedule. Knowing V_{av}, with the known flow density, it is possible to forecast the desired speed for any desired distance of the route.

The studies, however, concerned those highways that did not have adjunctions, distribution, expansion, or narrowing, forced stops of traffic flows. This restriction can be removed further using two-dimensional cellular automata. A significant limitation for the implementation of the results is the understanding of the desired speed of vehicles in the flow and its distribution. For objective application of this term, it is necessary to expand the scope of the study, involving the patterns of transport processes occurring on highways.

8. Conclusions

1. Using the active observer method in the highway traffic simulation model allows perceiving rather large volumes of input data, since it only reflects the dynamics of the situation around a given information field. The developed simulation method takes into account all accelerations/decelerations of the vehicle, reflects a sufficiently large highway distance in detail without involving distributed means. Also, with the help of the method, the opportunity to get rid of minor maneuvers on the highway, which take additional computing resources of the automaton is obtained. All maneuvers of traffic objects are carried out according to the method based on the principle of objective expediency. This is consistent with the concept of creating ITS on highways.

2. For the simulation of the highway traffic flow, it is enough to use observation data from one vehicle. The vehicle carrying such observations shall be equipped with means for measuring own instantaneous speed, coordinates, relative speed of the object and estimating the flow density. Such data are enough to perform simulation on a highway of any length. The simulation performed on the E-471 route reveals the possibility of obtaining relative speeds of objects at any flow density on the highway.

3. The results of the simulation show the significant impact of changes in vehicle speeds on the speed of other flow subjects. The dependence is quadratic. Part of the dependence corresponds to the negative value of the argument. This means that even if the desired speed of the OV is lower than the average speed of the flow, "slow" vehicles affect the OV. Consequently, in the ITS, vehicle speed forecasting can be carried out with a relative speed of all vehicles that are in its information field.

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