UDC 519.6

CELLULAR AUTOMATA IN APPLICATION TO TRAFFIC FLOW SIMULATION*

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The paper deals with mathematical modeling of traffic flows on urban road networks using cellular automata theory. The proposed multilane model allows to simulate traffic on various complex road networks and includes drivers with different strategies of lane changing.

Various kinds of average characteristics (such as, for instance, the capacity of the crossroad) can be obtained using the program package based on the model.

Computations show that the created program package can be used to set up optimal traffic lights regimes on complicated road fragments and to simulate the consequences of road accidents that might be necessary for real-time online modeling of city traffic in order to develop the measures to avoid traffic jams and evaluate the efficiency of these measures. Besides that, the program package allows to predict the consequences of various decisions regarding road infrastructure changes.

Keywords: mathematical modeling, traffic flows, microscopic models, cellular automata

Citation: Chechina A. A., Churbanova N. G., Trapeznikova M. A. 2018. Cellular automata in application to traffic flow simulation. *Problems of Computational and Applied Mathematics.* 6(18): 5–12.

1 Introduction

Since K. Nagel and M. Schreckenberg had proposed application of von Neumann's cellular automata (CA) theory to traffic flow modeling in 1992 [1], a lot of scientists chose this approach in their research due to its simplicity and flexibility (see, for example, [2]– [9]). The main advantages of microscopic models, which include cellular automata models, are the following features: consideration of each separate vehicle motion, the possibility of rarefied flow simulation, the possibility of different drivers behavior description. The paper deals with the original multilane model based on Nagel-Schreckenberg one-dimensional CA model. In the created model the algorithm of progressive movement along the road is supplemented by the rules of changing lanes as well as some rules describing different driver strategies. Modern computer systems allow to perform large-scale simulations on road networks of big cities.

2 The proposed model and its numerical implementation

Traffic flow models based on cellular automata theory are fully discrete. The road is divided into equal cells, each cell can either contain a vehicle, or be empty. The distance along and across the road is measured in the number of cells. Time steps are usually equal to 1 second, the speed of the vehicle is the number of cells the vehicle can overcome during one time step. Each time step the cell state update is made according to certain logical rules. First of all conditions for changing lanes are checked:

*The research was supported by Russian Foundation for Basic Research (grants 18-51-41001 and 18-01-00405) and by Agency for Science and Technology of the Republic of Uzbekistan (grant MRU-OT-30/2017).

1. A vehicle is located in a domain where lane change is allowed;
2. Lane change leads to increase of speed (decrease of density) or is necessary to reach the destination;
3. A target cell is empty;
4. The safety condition is satisfied – on a target lane the distance behind is greater or equal to the maximal velocity, in front it is greater or equal to the concerned vehicle velocity;
5. Lane change takes place with some probability.

Then the movement occurs on the selected lane in accordance with the rules of Nagel-Schreckenberg.

The Computation module is written in C/C++ and involves Glut library for the alternative visualization means used to debug the program, and MPI library for parallel calculations. The Computation module is organized as separate sub-programs simulate traffic on different types of road elements in parallel, with data exchange on the boundaries.

Such structures as the straight road with and without traffic lights (Fig. 1), the on-ramp (Fig. 2), the straight road with a widening (Fig. 3) can be considered as basic elements of the road.

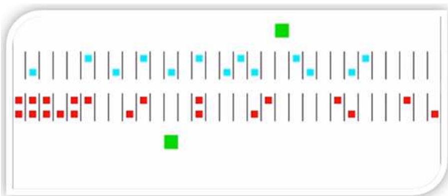

Figure 1 Modeling traffic flow on the straight road

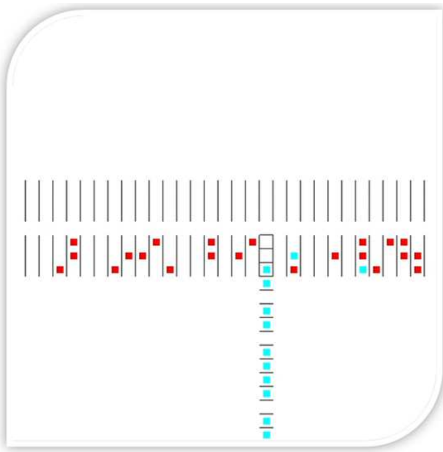

Figure 2 Modeling traffic flow on the on-ramp

Other important road elements are T-type signalized intersection (Fig. 4) or X-type signalized intersection (Fig. 5). The smaller squares represent cars, the larger squares — traffic lights. Cars have different colours according to their planned destinations. Each road type can have any number of lanes.

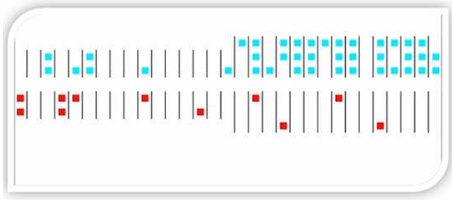

Figure 3 Modeling traffic flow on the straight road with the widening (from two to three lines in each direction)

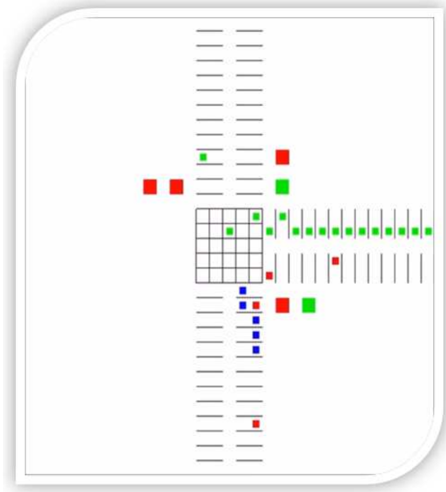

Figure 4 Modeling traffic flow on T-type intersection

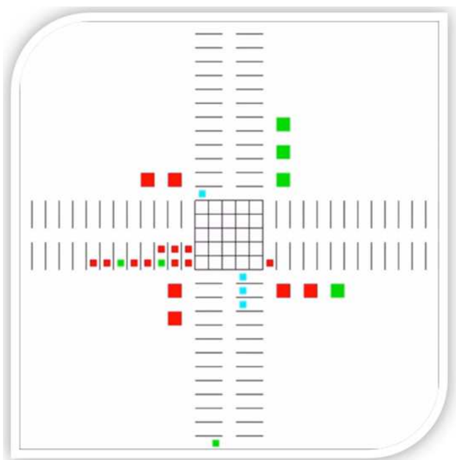

Figure 5 Modeling traffic flow on X-type intersection

The proposed approach has both advantages and disadvantages: on the one hand, simple logical algorithms allow to take into consideration different characteristics of vehicular traffic, such as, for example, driving strategies; on the other hand, discrete speed and acceleration introduce certain limitations into a model. Also, the fixed size of a cell (usually 7.5 meters) makes it difficult to model heterogeneous traffic that includes long vehicles, such as trucks and buses. Nevertheless, it is possible to overcome these difficulties (to a certain point, at least) for the tasks where it is needed.

Numerical realization of the model is represented as an original program package created by the authors and called CAM-2D — "Cellular Automata Model – 2-Dimensional". It consists of two modules: User Interface and Visualization module (for setting initial conditions and model's parameters and calculations of visual representation) and Computation module (for calculations).

Having modules simulating various types of roads, we can create numerous road networks, matching real road networks of the city or a district. Different kinds of problems can be solved using CAM-2D, for example, the investigation of the dependence of the crossroad capacity on the traffic lights regimes [10], or the influence of changes in road infrastructure on the traffic situation.

3 Test problems

Several numerical experiments were carried out in order to verify the proposed model. The first one is the problem about accidents on the road. Accidents can be also simulated using CAM-2D (see Fig. 6). Road accidents can not happen inside the model due to the safety rules: a car always slows down approaching an obstacle or another car in the lane, and it does not change its lane if the gap in the target lane is not enough to do it safely. But it is possible to model consequences of an accident that might be necessary for real-time online modeling of city traffic in order to develop the measures to avoid traffic jams and evaluate the efficiency of these measures. It is also possible to evaluate how much the capacity of a road will decrease after the accident.

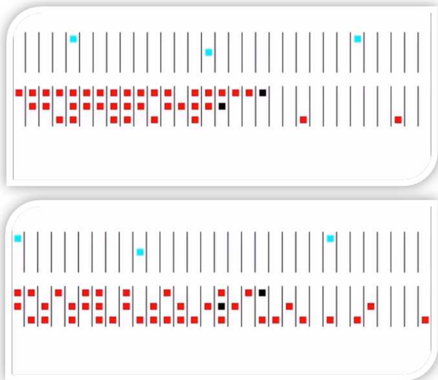

Figure 6 Modeling traffic flow on the straight road with an accident – different driver strategies can be taken into account

Drivers possess different driving styles: ones are more determined, change lanes more easily (Fig. 6, the bottom picture), others are more cautious, they wait for a larger gap to move to the neighboring lane (Fig. 6, the top picture). Their behavior influences the overall situation on the road. To reflect that, the following driver types were included in the model: "cautious"drivers change lanes only if the gap between the target cell and the first occupied cell up-stream is larger than the maximum speed; "aggressive"drivers change lanes if the gap between the target cell and the first occupied cell up-stream is larger than the actual speed of the vehicle which is situated in the first occupied cell; "cooperative"drivers can be either cautious or aggressive. The percentage of cooperative drivers in the system can vary. These drivers slow down if they see a traffic jam before an obstacle or a road bottleneck on the neighboring lane. If there is a jam before the obstacle on the neighboring lane, and there are drivers that want to change their lane, cooperative drivers stop and let them pass, even if those cars from the other lane can not move immediately, because the target cell is occupied by another car. For details, see [11].

As the second test the problem of velocity field patterns for a road with on-ramp was analyzed. Traffic structures in real data obtained in different parts of the world are always similar and look like stripes of a lower velocity on time-space diagrams (see Fig. 7). Ox is time in hours and minutes, Oy – the distance in km, the colour corresponds to the vehicles' speed. Red regions have lower speeds, yellow regions — higher speeds.

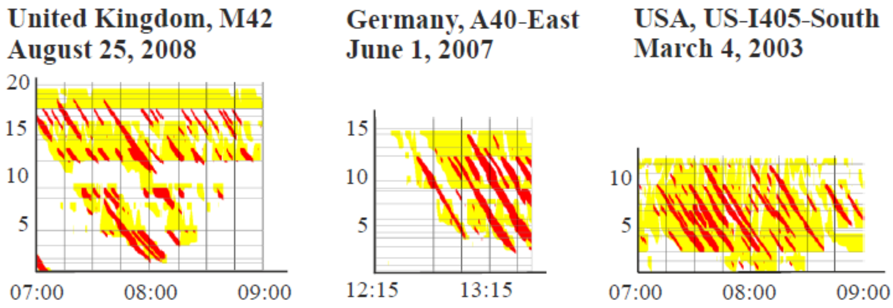

Figure 7 Experimental time-space patterns in traffic flows. The data are taken from [12]

In order to compare test predictions with these data and to see if the model reproduces said patterns, the following situation has been simulated: on the intersection of two roads, one of which is the main road with priority pass, and the other is a secondary road, where drivers have to wait for a large enough gap in the flow on the main one to enter, there is a constant flow on the main road and a varying flow on the secondary. The vehicle velocity at different points of the road at different time moments was calculated. Results were averaged out for easier comparison (Fig. 8–10). Ox is time in minutes, Oy – the distance in km, the colour corresponds to the vehicles' speed. Red regions have lower speeds (congested flow, traffic jams), blue regions — higher speeds (free flow). The distance of 3.5 km on Oy corresponds to the location of the on-ramp. The inflow on the main road and on the on-ramp are different in the presented figures. Besides, in all three cases after the time point of 100 min the input flow on the on-ramp drops down to zero and no more cars enter it till the end of the computation.

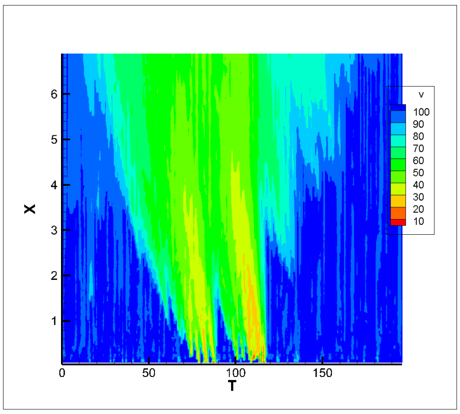

Figure 8 Time-space pattern in test predictions. The inflow on the main road is 21 veh/min, the inflow on the on-ramp is 2 veh/min

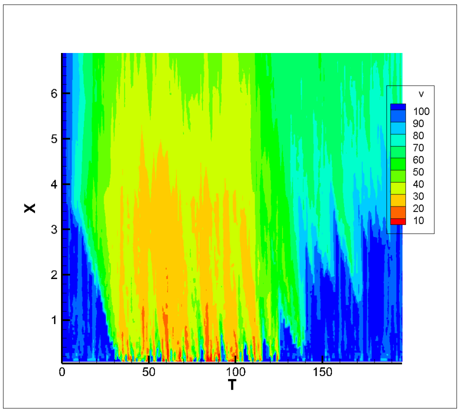

Figure 9 Time-space pattern in test predictions.The inflow on the main road is 22 veh/min, the inflow on the on-ramp is 6 veh/min

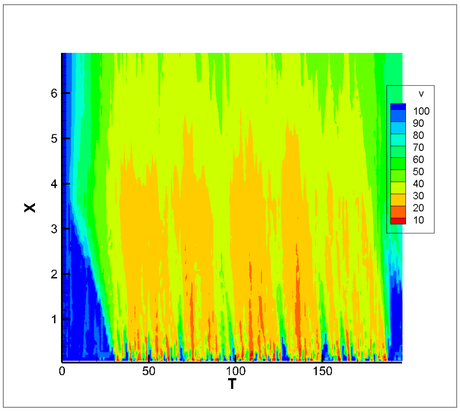

Figure 10 Time-space patterns in test predictions. The inflow on the main road is 25 veh/min, the inflow on the on-ramp is 9 veh/min

As is seen in the figures, the stripy structures for the velocity on time-space diagrams, similar to experimental, are obtained by the simulation. The influence of the on-ramp inflow can be observed. If the on-ramp inflow is large enough (Fig. 10), then the width of the stripy structure zone expands in both directions: up–stream and down–stream.

4 Concluding Remarks

The created mathematical model and the program package CAM-2D allow to simulate traffic flows on road networks, to solve different problems of traffic management and can be used as a basis for developing a practical tool for the traffic simulation in cities.

The results obtained agree with experimental data.

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Received November 8, 2018

УДК 519.6

ИСПОЛЬЗОВАНИЕ КЛЕТОЧНЫХ АВТОМАТОВ ПРИ МОДЕЛИРОВАНИИ ТРАНСПОРТНЫХ ПОТОКОВ*

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Работа посвящена математическому моделированию транспортных потоков на сетях городских дорог с использованием теории клеточных автоматов. Предложенная многополосная модель позволяет моделировать поток транспорта на различных сетях и включает в себя моделирование различных стратегий поведения водителей при перестроении из полосы в полосу.

Использование пакета прикладных программ, основанного на предлагаемой модели, позволит получить различные осредненные характеристики движения (такие, например, как пропускная способность перекрестка).

Вычисления показывают, что созданный пакет программ может быть использован для поиска оптимального режима работы светофора на сложных дорожных

*Работа выполнена в рамках Грантов РФФИ № 18-51-41001 и № 18-01-00405 и Гранта Агентства по науке и технологиям Республики Узбекистан № MRU-OT-30/2017.

фрагментах и для моделирования дорожных аварий, что может быть необходимо для моделирования в реальном времени городского трафика с целью принятия мер по устранению заторов и оценки эффективность этих мер. Кроме того, программный пакет позволяет прогнозировать последствия различных решений, касающихся изменений в дорожной инфраструктуре.

Ключевые слова: математическое моделирование, транспортные потоки, микроскопические модели, клеточные автоматы

Цитирование: *Чечина А. А., Чурбанова Н. Г., Трапезникова М. А.* Использование клеточных автоматов при моделировании транспортных потоков // Проблемы вычислительной и прикладной математики. — 2018. — № 6(18). — С. 5–12.

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Поступила в редакцию 08.11.2018