SIMULATIONS OF VEHICULAR TRAFFIC BY CELLULAR AUTOMATA

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ABSTRACT

The present paper studies simulation of traffic flow in urban environment, microscopic traffic flow simulation models of street' crossroads are made. The behaviour of cellular automata (CA) models is analyzed by means of such as indexes queue lengths at crossroads with traffic signals, flow rates, average velocities on different roads. The following indicators characterize traffic situations in a road network.

Keywords: traffic flow, cellular automata

1. INTRODUCTION

The contemporary metropolitan life style requires a collective and individual mobility. For this reason, traffic flows are crucial to the economy. The growing demand for transport networks conditions the emerging of traffic problems: traffic safety, traffic congestion, air pollution. These issues are closely related to each other. Consequently, there are continuous studies and explorations of traffic flow models in order to find the best model of transport system. Traffic flow is a system far from equilibrium, therefore, it is necessary to describe transition conditions between free flows, synchronized, congested or jammed platoons [4, 7, 12]. During the last decade traffic flow analysis was based on cellular automata. A rather accurate simulation of large scale traffic networks is possible by means of these models.
Cellular Automata (CA) is a convenient tool for modelling complex, global and continuous natural systems as well as nonlinear phenomena containing large number of simple identical components which interact locally through application of simple rules. CA models are considered as simple due to their simplicity, one-dimensionality. CA models are discrete models which are strictly determined by their nature and obey the laws of various rules. However, models' behaviour can be so complex that it is sometimes difficult to distinguish from stochastic processes and the processes may seem chaotic and unpredictable. These models are advantaged in respect of the other traffic flow models for the following reasons: their simplicity because their dimension is equal to one and have an easy hardware realization; they can restore the realistic and complex evolution of traffic situations in time

and space where the properties of traffic flow can be characterized; models represent a discrete dynamic system consisting of the following factors: discrete lattice grid, state of the cells' in the lattice, neighbourhood of cells, moving rules of particles in the grid.

Nagel and Schreckenberg proposed a fundamental model of CA by means of which real traffic flow characteristics, such as a sudden appearance of traffic congestion in the traffic jam, can be restored. Nagel and Schreckenberg's cellular automata (NS-CA) traffic model consists of three rules [12,13]: 1) acceleration and braking rule; 2) randomization rule; 3) vehicle movement rule. The first rule defines the increase and decrease of speed in order to avoid vehicle collisions. The second rule determines random speed fluctuation which is generated due to varying human behaviour or external factors. The actual movement of the vehicle is defined in the third rule. As a result of noise in the NA-CA model, traffic jams can form at any traffic flow density, even at a free-flow regime if an accident in traffic occurs, it means that deceleration may occur in different traffic flow regimes [15].

Different transport CA models are based on NS-CA. Stochastic noise [6, 13], slow-to-start [5, 11, 15], velocity-dependent randomization (VDR-CA)[1,3], brake-light (BL-CA) [9] rules etc. were included in order to stabilize the range of vehicle movement. Therefore, nowadays traffic flow models can be dealt with adequately various aspects.

Though the single-lane models provide quite good analysis of traffic flows, it is not sufficient to represent the real world traffic situations. However, two-lane traffic models based on cellular automata have been suggested in order to incorporate the rules able to deal with multi-lane traffic systematically [10].

Most of researches on cellular automata models for traffic flows have been done for traffic systems with periodic boundary conditions. Open boundaries are needed in order to restore real evolution of traffic flows in time and space accurately in cases when the number of vehicles can change [8].

2. TRAFFIC VDR-CA AND BL-CA MODELS

In single-lane CA models, the road is divided into an orderly lattice grid consisting of distinct cells. Usually the length of every cell equals to 7.5 m. Each cell has one state (empty or busy). The cell can be occupied by one *j* vehicle of *N* vehicles located in the system. The value of the sites evolves synchronously in discrete time steps according to a particular set of rules. The value of a vehicle site is determined by the previous values in the neighbourhood of sites around it. The speed every vehicle is mediates in interval $v_j \in \{0,1,2,..,v_{\max}\}$, time step is one second. The maximum speed of a vehicle equals to 5 cells/time step which corresponds 37.5m/s.

Velocity – dependent randomization cellular automata (VDR-CA) model is based on the rules of NS-CA [15] model only additional stochastic noise rules are introduced [1, 3]:

$$\begin{cases} v_j(t-1) := 0 \Rightarrow p'(t) := p_0, \\ v_j(t-1) > 0 \Rightarrow p'(t) := p_d. \end{cases} \tag{1}$$

$p'(t)$ - a stochastic noise parameter which depends on the vehicle speed; p_0 - slow-to-start probability, p_d - slowdown probability.

Barlovic et al. evaluated fact that there are only two different parameters of noise (p_0 and p_d), but they ignored the more general case when there are noise parameters for each possible speed [2].

Knospe et al. suggested to incorporate brake lights of vehicle in CA model [9] which includes an anticipation effect. The above mentioned anticipation effect leads to stabilization zone of free-flow regime. Transport BL-CA model describes random spontaneous breaking and “slow-to-start” behaviour. Basically some elements were included in the BL-CA model by means of which synchronized traffic flow can be restored unexpected collisions can be avoided. The above mentioned model consists of many rules which are used for modelling complex physical process taking into account the initial conditions of the transport system. Traffic BL-CA model is described by multiplex and complex rules listed below [10]:

1. Stochastic noise:

$$\begin{cases} b_{j+1}(t-1)=1\_and\_g_{t_j}(t-1)<t_{s_j}(t-1) & \\ v_j(t-1)=0 & \Rightarrow p(t):=p_b, \\ else & \Rightarrow p(t):=p_0, \\ b_j(t):=0, & \Rightarrow p(t):=p_d, \end{cases} \quad (2)$$

Where:

$b_j(t)$ - denotes the state (0 or 1) of the brake light of the j[th] vehicle at the time step t;

$g_{t_j}(t)=d_{s_j}(t)/v_j(t)$ - denotes the time of the j[th] vehicle needed to reach the leading vehicle at the time step t;

$t_{s_j}(t)=\min\{v_j,h\}$ - denotes an interaction horizon of the j[th] vehicle at time step t;

$d_{s_j}(t)=x_{j+1}-x_j$ - denotes space gap between jth and (j+1)[th] vehicles at time step t;

$v_j(t)\in[0,v_{\max}]$ - denotes the speed of the j[th] vehicle at the time step t;

h - denotes the interaction range of the brake light;

p_b - braking probability;

p_0 - slow-to-start probability;

p_d - slowdown probability.

2. Acceleration:

$$(b_j(t-1)=0\_and\_b_{j+1}(t-1)=0)\_or\_g_{t_j}(t)\geq t_{s_j}(t) \Rightarrow v_j(t):=\min\{v_j(t+1),v_{\max}\}, \quad (3)$$

3a. Effective space gap:

$$d^*_{sj}(t):=g_{s_j}(t-1)+\max\{\min\{v_{j+1}(t-1),d_{s_{j+1}}(t-1)\}-d_{s_s},0\}, \quad (4)$$

Where:

$\min\{v_{j+1}(t-1),d_{s_{j+1}}(t-1)\}$ - denotes the anticipated speed of leading vehicle.

3b. Braking:

$$v_j(t) := \min\{v_j(t), d^*_{s_j}(t)\},$$
$$v_j(t) < v_j(t-1) \qquad \Rightarrow b_j(t) := 1, \tag{5}$$

4. Randomization:

$$\xi(t) < p(t), \xi(t) \in [0,1]$$
$$\Rightarrow p(t) = p_b\_and\_v_j(t) = v_j(t-1) + 1 \Rightarrow b_j(t) := 1,$$
$$v_j(t) := \max\{0, v_j(t) - 1\}, \tag{6}$$

Where:
$\xi(t) \in [0,1]$ - denote a random number drawn from a uniform distribution.

5. Vehicle movement:

$$x_j(t) := x_j(t-1) + v_j(t) \tag{7}$$

Where:
$x_j(t)$ - denotes the position of the j^{th} vehicle at the time step t.

The same rules are applied to all cells in parallel and the vehicle movement from one cell to another is implemented simultaneously in one time step. Though single-lane traffic CA models define traffic situations quite well but they are insufficient for two-lane and multi-lane traffic network modelling.
Lane-changing rules have to be introduced in order to extend VDR-CA and BL-CA models to multi-lane traffic. Besides the rules that are applied to the single-lane traffic CA model, there is also a rule for lane-changing. The lane-changing rule is applied to all traffic CA models in a similar manner [4,14].

3. MODELLING AND ANALYSIS OF SIMULATION RESULTS

The previously discussed VDR-CA and BL-CA models are applied to simulation and analysis of the real crossroads of a city in Lithuania (Fig.1). Vehicles access to transport system is modelled in accordance with Markov's queuing theory. Movement and manoeuvrability of vehicles in this transport system are based on the items described in the previous chapter.
Microscopic traffic flow models reflecting the crossroads operation by traffic-lights and traffic flow evolution in time and space are created. It is considered that traffic-lights have additional sings for turning right. Furthermore, some more conditions of traffic flow evolution in VDR-CA and BL-CA models are involved: the drivers stick to traffic regulations; vehicles cannot turn around on the way; random stops in the event of an accident are possible; overtaking of the vehicles are possible only on the left turn. Vehicles usually move on a pre-selected road lane. Additional lane changes are possible in special cases: because of congestions on the carriageway; because of change of the road; because of an ease stop over the stop line. If the crossroads is free, vehicles will come to crossroads, it means that there are no other

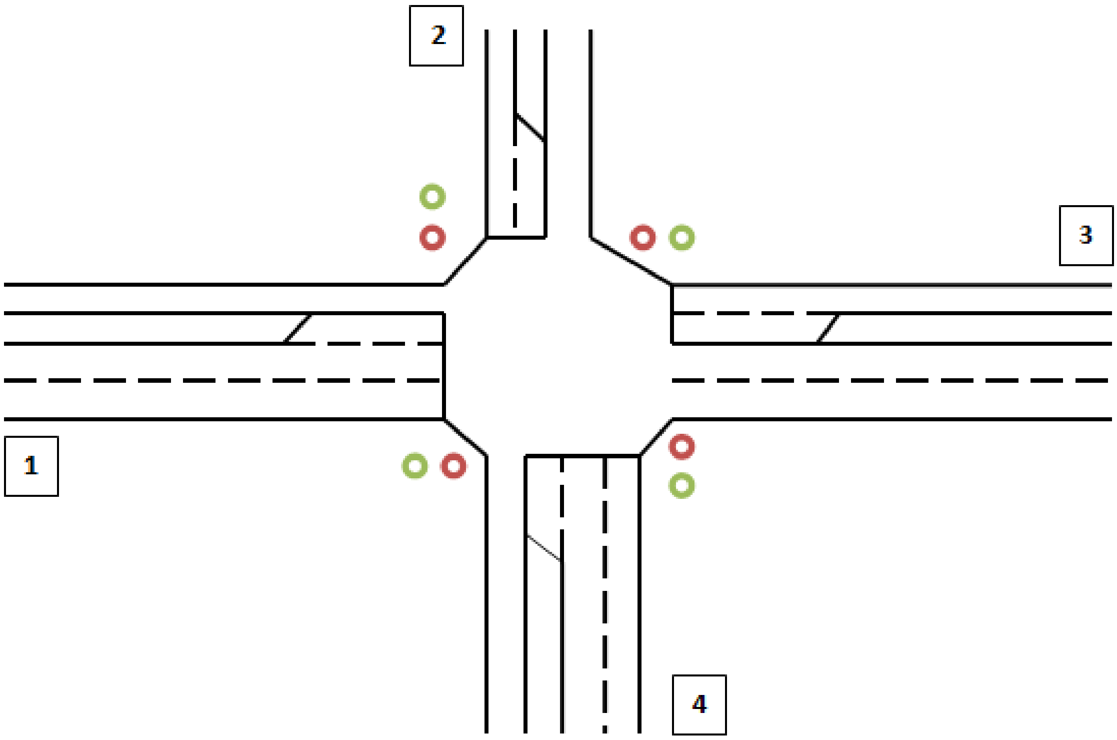

Figure 1 –Schematic representation of transport system

vehicles which can block the movement. Vehicles stand in a queue over the stop line, if the traffic lights are red, if there is any obstacle on the right.
When the VDR-CA model is applied, the single cell's length equals to 5 meters, the time step is one second, the maximum velocity of the vehicle is $v_{max} = 3$ cells/time step = 54 km/h, the length of the vehicle corresponds to the length of the cell.
In BL-CA model the length of the cell is 1.5 meter, the time step is one second as in VDR-CA model, the maximum car's velocity is $v_{max} = 10$ cells/time step = *54 km/h*, the length of the vehicle equals to three cells' length.
Distances between vehicles at the time step t are estimated on the basis of the previously discussed VDR-CA and BL-CA models. The average velocities of vehicles in the traffic system on different road segments are measured, the length of queues over the stop line and at the red traffic lights is also computed.
On the one-lane road segment (1 and 3 streets) the flow mean velocity is almost identical to VDR-CA and BL-CA models under the same initial conditions. However, other forms of traffic system behaviour are obtained when two-lane (2 and 4 streets) road segment is explored. The results of sequent simulations are so different all the time on both VDR-CA and BL-CA models. All simulation results depend on the random generation of models. The problem was solved by taking into account vehicle dislocations of the right and left turns at the crossroads. In case of VDR-CA and BL-CA the behaviour of flow mean velocities became more even when there was a defined amount of vehicles moving on the left and right turns. At high traffic flow VDR-CA and BL-CA models behave similarly in both one-lane and two-lane case.
The result, two-lane case, flow mean velocities from 1 to 3 and from 4 to 3 streets, of 5-minute periods, the traffic intensity 500-600 veh/h, and 650-800 veh/h, are depicted in figure 2 and figure 3. Traffic flow characteristics were studied in morning and evening rush hours.

In VDR-CA model depending on the velocity, vehicles are subject to various randomizations. A metastable transport system is resulted when slow-to-start probability is significantly higher than the slowdown probability. This has the effect of a diminished outflow from a traffic jam. In BL-CA model backward propagating speed wave is well fitted for real traffic evolution in time and space.

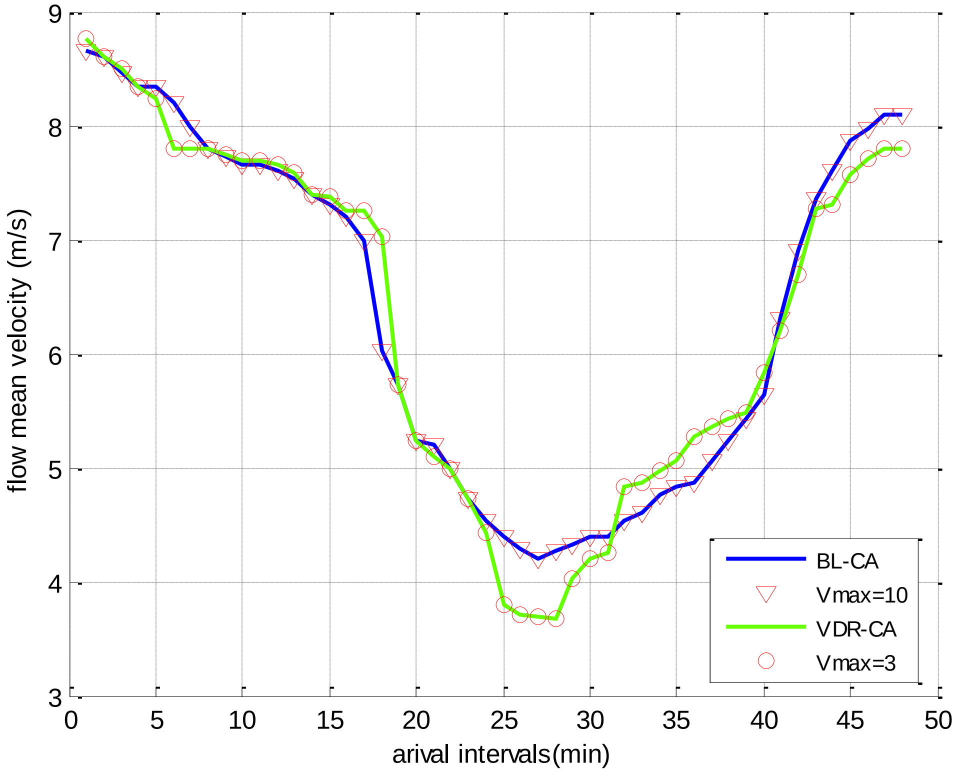

Figure 2 – Flow mean velocity during rush hours from 1 to 3 street

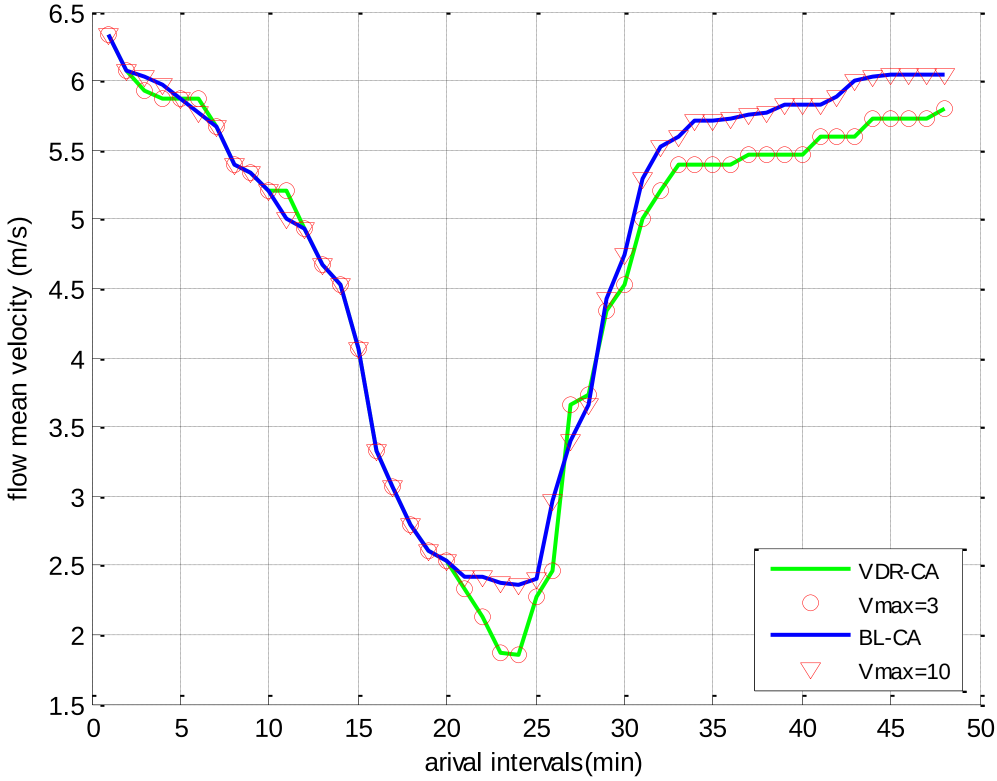

Figure 3 – Flow mean velocity during rush hours from 4 to 3 street

Another parameter characterizing traffic flows is the queue lengths. The formation of vehicle queues over the stop line at the red traffic lights was researched. Such results of simulations distort the real situation of transport system. A similar problem as discussed previously was noticed. Results of the queues forming at the red traffic lights are depicted below in figure 4 and figure 5 (stop line on 1st road and stop line on the 4th road).

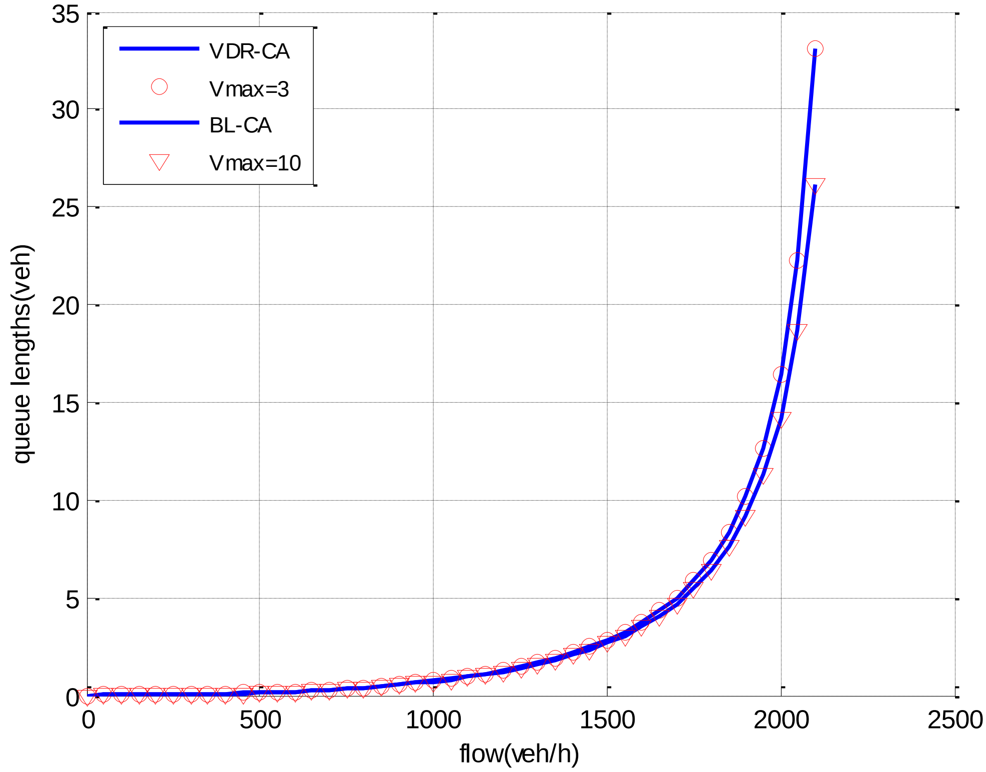

Figure 4 – Formation of queue length over the stop line on the 1st road

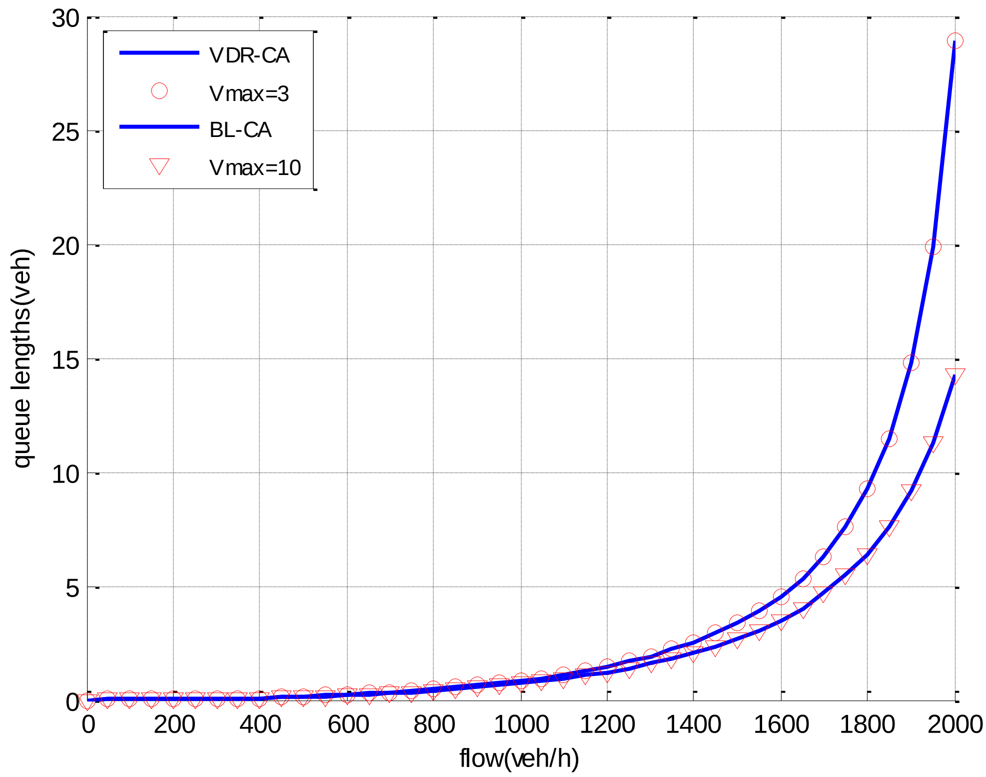

Figure 5 – Formation of queue length over the stop line on the 4th road

The results are similar in case of both cellular automata models applied. An exponential relationship between traffic flow and the formed vehicular queue lengths over the stop line at the red traffic lights was obtained. The queues do not appear at small traffic flow rates, as it is seen in figure 4 and figure 5. When traffic flow density is slowly increasing, the lengths of vehicles series are heavily growing up. In case of the extensive traffic flow, congestion part is obtained, convergence speed of exponential function suddenly grows up. Greater difference between the models is observed only in case of very intense traffic. Higher vehicle queue lengths are in case of VDR-CA model, when traffic is in congestion mode. The cause thereof is smaller flexibility of the model comparing with BL-CA model and selections of parameters.

4. CONCLUSIONS

Traffic cellular automata models (VDR-CA and BL-CA) have been chosen to evaluate traffic flow characteristics. Flow mean velocity fluctuation in time and road space has been defined and the fact that queue length over the stop line at the red traffic lights is formed exponentially has been established.

Simulation results showed that VDR-CA and BL-CA models suit quite well in. BL-CA model excellently represents vehicle dynamics as well as acceleration or deceleration of vehicles for various external factors. Results of applying VDR-CA model for transport system demonstrated that vehicle characteristics of dynamics in accelerating, decelerating or stopping are a little bit rougher than applying BL-CA model for the same transport system. Consequently, BL-CA model is a better solution due to its anticipation effects.

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