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RESEARCH OF CONGESTIONS IN URBAN TRANSPORT NETWORK USING CELLULAR AUTOMATON MODEL

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Abstract. The growing demand for transport and communication services leads to more and more important, traffic related and closely associated problems, especially in the city centre, such as traffic congestion, air pollution, noise and some others. When modelling traffic flows in the Kaunas city centre, the simulation models of crossroads were created based on the principle of cellular automaton model, taking into consideration such relevant traffic indicators as the average speed of traffic flow in different streets, traffic intensity, congestions and distributed flows. Operation of cellular automaton model is associated with the improved approach of further vehicle model. Modelling of microscopic traffic flows is based on the brake light–cellular automaton (BL–CA) model. Random functions were made discreet and autocorrelation values of these functions were calculated in this work. Fundamental macroscopic traffic characteristics were obtained. Numerical dependences of the average traffic speed and traffic flow, traffic density and traffic flow, the average traffic speed and density were determined, with a help of which the demand parameters of transport network were evaluated in the Kaunas city centre in certain time intervals.

Keywords: congestion, transport network, flow speed and intensity, cellular automaton model.

1. Introduction

Today's metropolitan life style requires both collective and individual mobility. For this reason, traffic flows are very important to the national economy. The growing demand for transport network leads to new traffic problems, such as road safety, traffic congestions and air pollution. These problems are closely connected, consequently, there is a constant traffic flow analysis to reduce indicators and research of new models to find the best transport system model (Çalışkanelli *et al.* 2009; Kapski *et al.* 2008; Nagatani 2005, 2006; Verhoef, Rouwendal 2004; Wen 2008; Žiliūtė *et al.* 2010).

Intensity and discontinuity of traffic flow is particularly felt in larger cities, especially in their centres. Various regulations of the European Union, the Republic of Lithuania and the initiated projects emphasize the necessity of information collection related to traffic flows, and the installation importance of mathematical models of traffic flows, their use, integration, evaluation and prediction (Jauneikaitė, Carreno 2009; Jović, Đorić 2010; Liu 2007; Nagel, Nelson 2005).

In urban centres traffic density is high enough, with such characteristics as low speeds, frequent acceleration and deceleration stop. Over the past decade traffic flow analysis based on cellular automata has increased (Barlović 2003; Lárraga, Alvarez-Icazza 2010). These models can help to simulate large transport network systems accurately enough. Using the cellular automaton (CA) model it is possible to describe the complex, global and coherent systems and nonlinear phenomena using simple rules. CA models are discrete, which, by their nature, are strictly determined and obeying various laws, but their behaviour can be so complex that it is sometimes difficult to distinguish it from stochastic processes, and the same process may seem chaotic and unpredictable (Boumediene *et al.* 2009; Gowri, Sivanandan 2008; Lárraga *et al.* 2005).

CA models are superior to the other traffic flow models for their simplicity because they are single-dimensional, hardware implementations; they can restore traffic evolution in time of road traffic systems with characterization of traffic flow features; represent the discrete dynamic system, consisting of factors such as discrete grid, cell's state in the grid, cell's neighbourhood, movement in the grid.

2. Modelling of Traffic Flows in Transport Network

For simulation of traffic flows in transport network the transport system supply and demand is necessary for sources and aggregations of transport network. The model consists of some main elements: zones, nods, connectors, manoeuvres, connecting elements, stops, public transport routes. Nodes indicate the allowed manoeuvre directions and priorities (main, secondary road), street connections are described by the length, number of lanes, speed restrictions on traffic, the traffic throughput (Dell'Acqua, Russo 2010; Dragčević *et al.* 2008). Modelling has been performed in several stages (Fig. 1).

The result of each stage modelling serves as initial data to features modelling. The result of demand modelling is the initial data in the network model, and network modelling results may be initial data of the demand model. OD matrixes in the demand model are evaluated in a way to restore trip times and traffic flows in joints.

Based on the obtained results (trip duration, traffic intensity, traffic flow speed) a state of traffic flows in the concrete parts of transport network system was evaluated. Traffic modelling is based on a number of rules, which are included both into the network and the demand models. With data about transport network

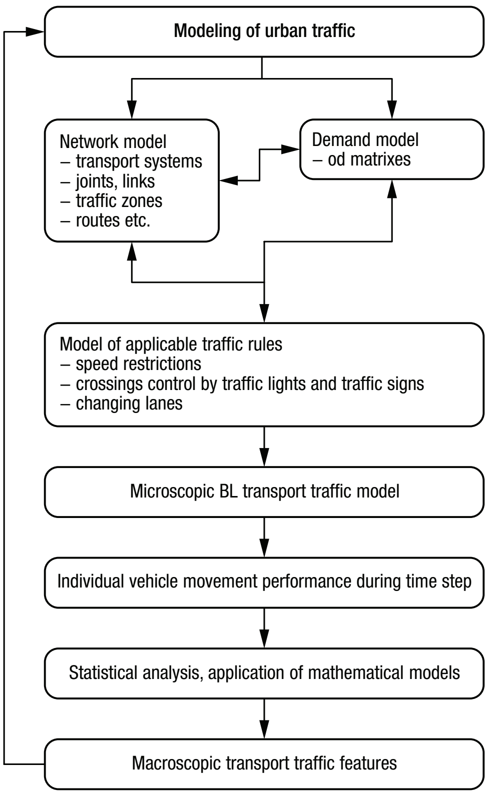

Fig. 1. Modelling scheme of urban transport network

system the microscopic traffic modelling based on BL model was performed, and in the result, characteristics of movement of the individual vehicles during the time step were obtained. Later, the statistical analysis of data was carried out and the mathematical techniques for the evaluation of modelling results were applied. From the transport network configuration the macroscopic characteristics of urban traffic were obtained.

2.1. Traffic Flow Measurement

The road network of Kaunas region was determined by geographic and natural situations. Kaunas is one of the largest cities in the centre of the country – the main routes from Vilnius, Alytus, Marijampolė, Šakiai, Jurbarkas, Raseiniai, Šiauliai, Panevežys and Ukmergė directions meet there. Traffic flows are mostly formed at the exits and entrances to the city center, where the streets of high-speed meet, which are characterized by high traffic volume – Savanorių Ave, Jonavos St. and Karaliaus Mindaugo Ave, Veiverių St. Vehicle flows moving along them are distributed to several smaller streets of smaller capacity in the Old Town (Šv. Gertrūdos St., Gimnazijos St., Birštono St., Šauklių St.) forming congestions in them (especially in peak hours). The street network of the Old Town is uneven, width of streets varies from 6 to12 meters (even 15 meters wide).

In order to assess the actual load of the existing traffic lanes of street segments and crossroads, the traffic-flow measurements at the crossroad of the main streets of Kaunas city centre were carried out (Fig. 2).

The Old Town is situated in the river valley, built-up by perimeter where traffic flow cause significant noise and pollution. The corridor of Šauklių – Šv. Gertrūdos – Gimnazijos Streets is crowded most of the day; it drastically divides the Old Town and causes significantly adverse impact on the spatial structure, buildings and people.

Based on data of the modern investment project of management system of integrated traffic, performed several years ago, the max flow is at Šv. Gertrūdos – Gimnazijos St. crossing and makes up 3904 vph. Currently, the max traffic flow in the Old Town is represented by the street sections between Birštono and Gimnazijos St. (five lanes) and Šv. Gertrūdos and Šauklių St. (four lanes). Here, the routes from all parts of the city meet – Savanorių Ave, Karaliaus Mindaugo Ave, Jonavos St. and also Vilijampolė bridge connecting the routes of Vilijampolė district. The other smaller streets of the Old Town are completely unsuitable for motor traffic. The attempts to introduce one-way traffic were not successful and did not improve situation.

In 2010 researchers of the *Institute of Transport Problems of Kaunas University of Technology* carried out the measurements of traffic flows. Vehicles were registered on April 13, 14 and 15 during the morning rush hours from 7:00 to 9:00, during the day time or not rush hours from 11:30 to 13:30 and during evening peak hours from 16:00 to 18:00 with 15-minutes time intervals. Vehicles were separated into different classes and different traffic directions (BX1, BX2, BY1, BY2, BZ1,

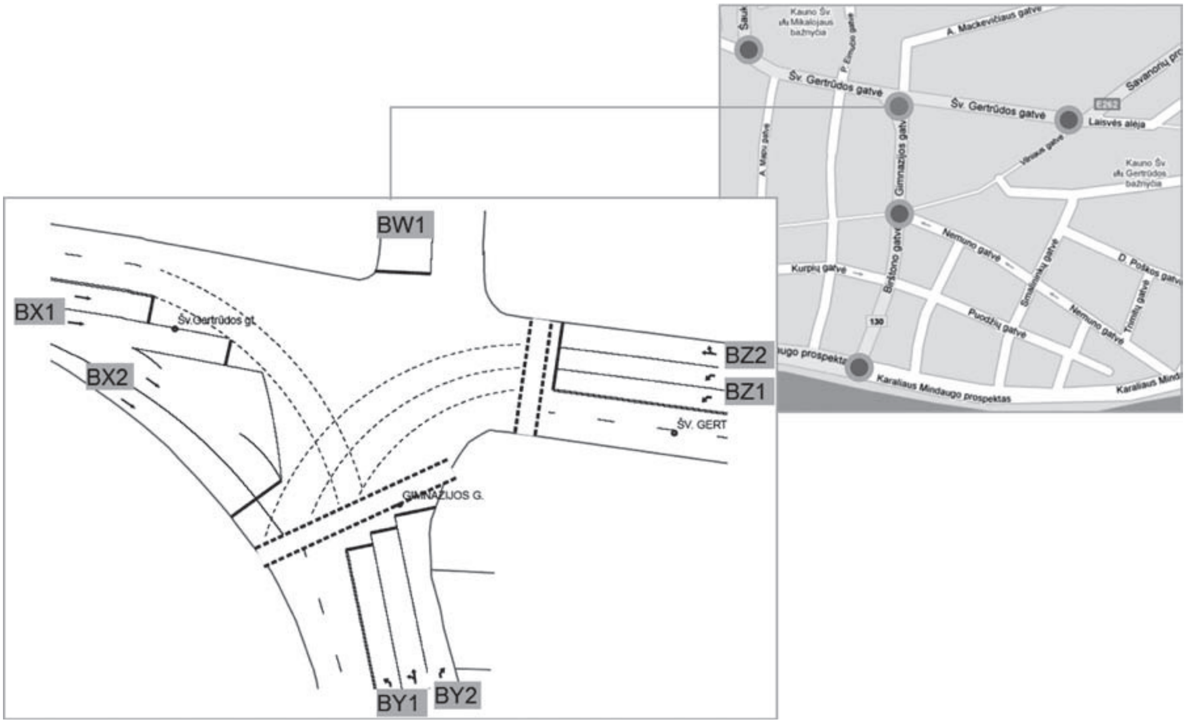

Fig. 2. The most problematic area because of congestions in Kaunas city is the crossing of Gimnazijos St. – Šv. Gertrūdos St.

BZ2, BW1 (Fig. 2): motorcycles, mopeds, bicycles, cars, taxi cars, special cars, shuttle vans and other minibuses, light trucks, special light trucks or vans, trucks, multi-axial trucks, buses, city bus service, shuttles tri-axial.

2.2. Simulation of Transport Network

CA is a dynamic abstract system, time step is $\Delta T = 1\text{s} = (t + 1) - t$ and space is large-grained (Fig. 3). Time axis is pointed downward; space axis extends to the right. CA configuration is given for t and $t + 1$ time intervals, during which two vehicles n and $n + 1$ move along the grid. The road is discretized into cells with the length $\Delta X = 1.5$ m, vehicle acceleration is equal to 1.5 m/s^2, acceleration from 0 up to 100 km/h takes 19 s. Vehicle may take a few cells in turn, every cell is empty or it contains one vehicle from N in the transport system.

BL–CA model consists of rules (Knospe *et al.* 2001) used to simulate a complex physical process, taking into account initial conditions of the system. Every n^{th} machine is defined by two parameters: position $x_n(t)$ and speed $v_n(t)$ at time moment t. Every next time step $t + 1$ speed of n^{th} vehicle depends on distance $d_{n,n+1}(t)$ till next n+1 vehicle moving in front of it, which is defined

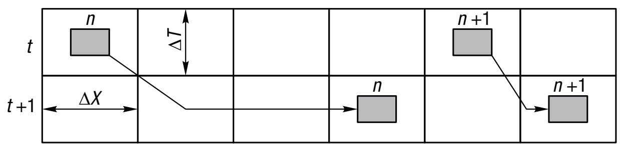

Fig. 3. Schematic operating diagram of one lane cellular automaton (CA) in grid L

by the amount of empty cells. Assessment of the distance $d_{n,n+1}(t)$ allows to determine whether nth vehicle will stop and activate brake lights and to predict how far $n + 1$th vehicle will move during the next time step $t + 1$.

The actual distance between n and n +1 vehicle is then defined by the Eq (1):

$$d_{n,n+1}^{fact.}(t) = d_{n,n+1}(t) + \max(v_{n+1}^{\min}(t) - d_{safe}, 0), \quad (1)$$

where: $d_{n,n+1}(t)$ – distance between the front bumper of n^{th} vehicle and the rear bumper of $n+1$ vehicle; d_{safe} – constant safe distance.

Min movement speed of $n+1$ vehicle moving in front of:

$$v_{n+1}^{\min}(t) = \min(d_{n+1,n+2}(t), v_{n+1}(t)) - 1. \quad (2)$$

Brake lights $b_n(t) \in \{0.1\}$ (0 – turned off, 1– turned on) are the components of predicted movement and allows to respond to the obstacles in front of.

Probability that the n-th vehicle brake, due to n+1st vehicle lights turned on, is determined by the equation:

$$p(t) = p\big(v_n(t), b_{n+1}(t)\big) = \begin{cases} p_b, b_{n+1}(t) = 1, t_n^h(t) < t_n^s(t); \\ p_0, v_n(t) = 0; \\ p_d, \end{cases} \quad (3)$$

where: $p_b = 0.96$ – probability of braking, controlling a back-spreading wave of the brake lights turned on and restoring a synchronized traffic movement; $p_0 = 0.5$ – probability that the vehicle will start moving slowly, $p_d = 0.1$ – probability of deceleration, creating possibility for a sudden formation of traffic congestion;

$t_n^h(t) = \frac{d_{n,n+1}(t)}{v_n(t)}$; $t_n^s(t) = \min(v_n(t), h)$; h – time of the lights turned on.

In parallel the BL–CA rules of the same model were applied to all cells and vehicle movement from one cell to another were carried out simultaneously over a single time interval.

Movement of n^{th} vehicle in the system over a time step $t+1$:

$$x_n(t+1) = x_n(t) + v_n(t+1). \tag{4}$$

There are two changes of traffic lane: mandatory and discretionary. In the first case the vehicle is forced to change the lane, for example, when it needs to leave the road or, according to the rules, the vehicle has to follow the lane at the right shoulder.

In the second case the vehicle changes the lane at its own discretion.

Vehicles $m \in N$ are in the left lane, vehicles $n \in N$ are in the middle lane, vehicles $k \in N$ are in the right lane, and all three lanes are defined by the set $j \in$ {*left*, *straight*, *right*}. Movement to the left lane, when n^{th} vehicle is in the *straight* lane, is described by the following actions:

- $j_n(t)$ = *straight*;
- check whether a lane change is possible: if $b_n(t) = 0$ and $d_{n,n+1}(t) < v_n(t)$, and $d_{n,m+1}^{fact.} \geq v_n(t)$, and $d_{m,n}(t) \geq v_m(t)$, then $j_n(t)$: = *left*;
- changing of lane: if $j_n(t)$ = *left*, n^{th} vehicle changes lane to the left;
- return to the right lane, when n^{th} vehicle is in *straight* lane:
- $j_n(t)$ = *straight*;
- check whether a lane change is possible: if $b_n(t) = 0$ and $t_{n,k+1}^h > 3$, and $(t_{n,n+1}^h(t) > 6$ or $v_n(t) > d_{n,n+1}(t))$ and $d_{k,n}(t) > v_k(t)$, then $j_n(t)$ = *right*;
- changing of lane $j_n(t)$ = *right*, n^{th} vehicle changes lane to the right.

Judgment on a suitability of the lane changing model is based on certain macroscopic observations. Their example is the lane change frequency, taking into account different densities, the flows of each and all traffic lanes, critical density at which traffic in each lane collapses (Angel *et al.* 2005).

Measurements of the grid of CA models were based on two possible initial conditions: homogeneous initial conditions (evaluated according to studies carried out in the central part of Kaunas city), or compact super-congestion.

In the first case, all the vehicles were uniformly distributed in the grid and this means uniform intervals of movement forward.

In the second case, all the vehicles were concentrated one after another with zero intervals. Going from one global density to another, by using equivalent method, the vehicles were adiabatically added (or eliminated) to the already homogeneous or blocked state. Initial conditions corresponding to the first method were always set for experiments.

2.3. Mathematical models

As the result of the latest research the reference (Jablonskytė 2010) widely discusses general vehicle traffic models, analysis of their components, possibilities and conditions of their integration and differentiation, application possibilities, requiring no definition of microscopic characteristics of the traffic flow during the trip, under acceleration and deceleration conditions.

Emphasis is placed on the need of application of universal criteria and their identification.

Suppose we have a random function $X(t)$ (Fig. 4). Consider its two sections – the random variables – $X(t)$ *and* $X(t')$ obtained by capturing the different moments of time t and t'.

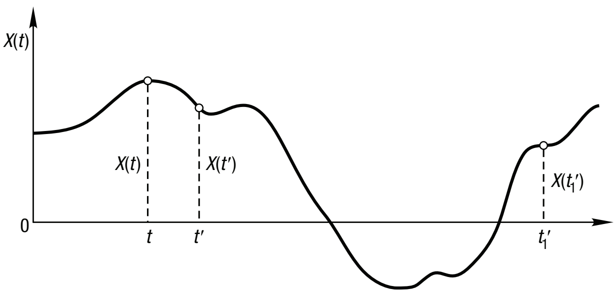

Fig. 4. Random function (Jarner, Tweedie 2001)

When the value of t and t' is close, the variables $X(t)$ *and* $X(t')$ are associated with close dependence: if variable $X(t)$ acquires any value, it is highly probable that the variable $X(t')$ will acquire value close to that one. It follows that with the increasing interval between sections t and t', the dependence between the variables $X(t)$ and $X(t')$ may be lost.

Degree of dependence of variables $X(t)$ *and* $X(t')$ can be characterized by their correlation moment, which is the function of two arguments t and t'. This function is called the correlation function.

Thus, the correlation function of the random function $X(t)$ is called not random function of two arguments $K_x(t, t')$, which for each pair of time values t *and* t' is equal to the correlation moment of obtained sections:

$$K_x(t,t') = M\left[X^0(t), X(t')\right], \tag{5}$$

where: $X^0(t) = X(t) - m_x(t)$, $X^0(t') = X(t') - m_x(t')$.

Suppose, that $t' = t$, then:

$$K_x(t,t) = M\left[X^0(t)^2\right] = D_x(t), \tag{6}$$

where: $D_x(t)$ – dispersion of obtained section.

Thus, there is no need to consider dispersion as the random feature. For investigating the essential character points of the random function it is sufficient to consider only its average and correlation function.

Instead of the correlation function $K_x(t, t')$ we may use the rationed correlation function:

$$r_x(t,t') = \frac{K_x(t,t')}{\sigma_x(t)\sigma_x(t')}, \tag{7}$$

which determines correlation coefficient of variables $X(t)$ and $X'(t)$. When $t' = t$ is the rationed correlation function and is equal to 1.

$$r_x(t,t) = \frac{K_x(t,t)}{[\sigma_x(t)]^2} = \frac{D_x(t)}{[\sigma_x(t)]^2} = 1. \quad (8)$$

When $X = (x_1, x_2,\ldots,x_n)$ – n-dimensional random vector with the vector of mean values $M = (m_1, m_2, \ldots, m_n)$, then the vector's correlation function is (Jarner, Tweedie 2001):

$$K = \begin{vmatrix} E(x_1-m_1)^2 & E(x_1-m_1)(x_2-m_2) & \ldots & E(x_1-m_1)(x_n-m_n) \\ E(x_2-m_2)(x_1-m_1) & E(x_2-m_2)^2 & \ldots & E(x_2-m_2)(x_n-m_n) \\ \ldots & \ldots & \ldots & \ldots \\ E(x_n-m_n)(x_1-m_1) & E(x_n-m_n)(x_2-m_2) & \ldots & E(x_n-m_n)^2 \end{vmatrix}. \quad (9)$$

The random vector X is normal, if its n-dimensional probable density is described by formula:

$$p(X) = \frac{1}{(2\pi)^{\frac{n}{2}} |K|^{\frac{1}{2}}} e^{-\frac{1}{2}(X-M)K^{-1}(X-M)^{T'}}, \quad (10)$$

where: $|K|$ – determinant of the correlation matrix K of vector X.

Vector X is the vector of values of random process $X(t)$ in points $t_1, t_2,\ldots,t_n$, thus $X = (x(t_1), x(t_2),\ldots,x(t_n))$. The process $X(t)$ is considered to be stationary and normal process and is completely characterized in correlation theory, or the multidimensional normal distribution function is defined, if moments of its first two rows are known.

3. Results and Discussions

The results of investigation showed that the crossing Gimnazijos St. – Šv. Gertrūdos St. (Fig. 5) is mostly crowded during the morning rush hour from 7:45 to 8:00 and during evening peak hours from 17:00 to 17:15. The prevailing group of the mixed traffic flow was cars, making 70÷80%. The other group of vehicles of lower manoeuvring speed and at first glance seeming insignificant, influences the velocity of flow and the capacity of traffic lane.

The max flow was recorded in BX1 and BY1 directions in all three periods investigated. During the morning rush hour traffic intensification was in BX1 direction, the highest number of cars from 7:30 to 8:15 was 180 vehicles per hour. A number of buses, trolley buses, minibuses and trucks during that period was quite stable. The morning rush hour starts at 7:30 and lasts till 8:15.

During the day and evening peak there was no pulsation in this direction – a number of cars, buses, trolley buses, trucks and minivans over 15-minutes intervals was almost invariable. In the morning a number of vehicles travelling straight (from Šauklių St. towards Savanorių Ave) was significantly higher than of those turning to the right (from Šv. Gertrūdos St. to Gimnazijos St.). Over two hours 1942 vehicles passed in these directions, i.e. 1299 vehicles travelled straight and 643 vehicles turned right. About 80% of all vehicles going straight were passenger cars, the cars turning right made up 90%.

Assessing the results presented, it could be concluded that during the day a number of vehicles going straight is nearly twice higher than those turning left. During these two hours 1240 vehicles were going straight and 679 vehicles were turning left. In the evening peak, like in the morning and afternoon peak hours, 80% of vehicles travelling straight and 90% of those turning left were passenger cars. During evening peak hour a number of buses and trolley buses, going from Šauklių St. towards Savanorių Ave, have increased significantly in comparison with the day period. During this period, 80 buses and trolley buses were recorded.

The most acute flow direction in sense of capacity at the Gimnazijos St. – Šv. Gertrūdos St. crossing is

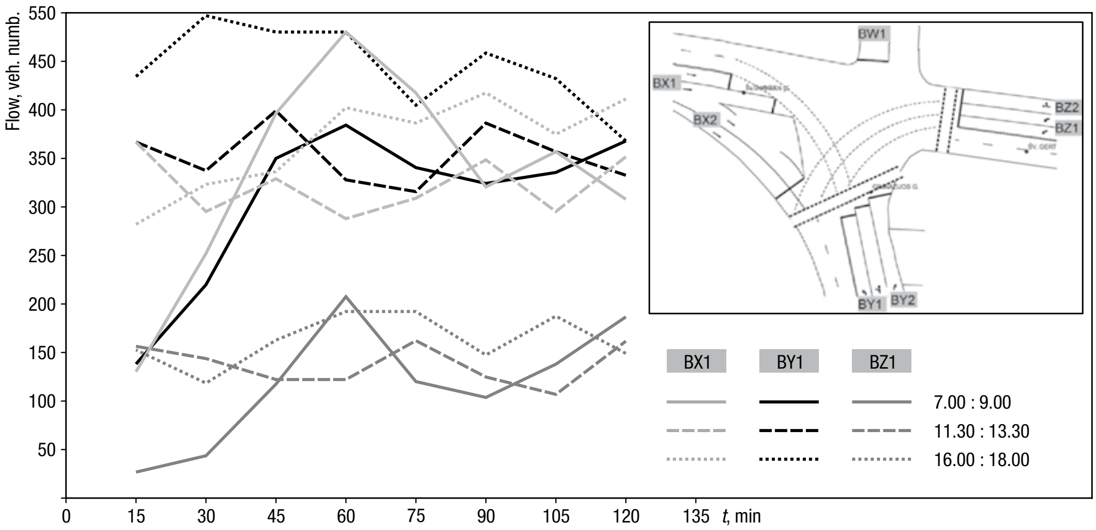

Fig. 5. Registered traffic during the morning, afternoon and night peaks at the Gimnazijos St. – Šv. Gertrūdos St. crossing

the direction BY1 (Gimnazijos St. flow turning to Šv. Gertrūdos St.): in a period 17:15÷17:30, 425 vehicles ran in this direction. It is the largest flow value, defined during the research, indicating a low capacity of this group of lanes.

Simulation of microscopic traffic flows is based on BL–CA model because of the possibility to restore road traffic evolution in time and space. The model to evaluate the distances between moving vehicles, the average vehicle speed in separate road segments, lengths of turns due to stop at prohibited traffic lights, etc. was set up.

Assessing changes of the vehicle speed in road segment of one lane, it was found out that average speeds are almost identical under the same traffic conditions and do not depend on random realization. But modelling sections of transport systems with few or more lanes provides a completely different behaviour, and sequential realizations of several simulations have also given completely different results.

Trying to solve the problem possibilities of vehicles the turnings left and right were taken into account. When a certain number of vehicles are turning left or right, behaviour of BL–CA model is obtained even. If the restrictions, mentioned earlier, are included into the model, behaviour of the model is similar to different traffic flows in case of one lane and also in cases of few or more lanes.

Evaluating lane-changing rules with the help of the CA model, several conditions describing this manoeuvre were determined. It was found that the vehicle is typically changing lanes during successive time intervals. In order to avoid that, a coincidence of lane change was introduced, thus, unrealistic effects that appear in transport system were destroyed. The analysis of individual vehicles movement in the transport system gave information about the drivers' behaviour. Vehicles autocorrelation and approximated autocorrelation functions are presented in Fig. 6. Autocorrelation was defined taking into consideration the average movement speed of individual vehicles over time interval which is equal to one minute, strong correlation among the speed of individual vehicles was then defined. The value of autocorrelation function α = 1.899 was determined by the least-squares method, where confidence interval is (0.1214; 0.2813) and confidence level is 0.99. Empirical values of autocorrelation functions were approximated by the obtained phenomenon:

$$K_{vv}(t) = \frac{1}{1+\left(1.899+t\right)^2}. \quad (11)$$

Correlation disappears when traffic density in transport system is very small, i.e. 0÷10%. Strong correlations were obtained at small time intervals (Fig. 4), this explains the intense movement of vehicles in transport system, when distances between them are minimal or vehicles in the system move in small groups.

Macroscopic characteristics: densities, flows and average speeds in CA grid L, obtained from local measurements with an artificial loop detector of unit length. To ensure that no vehicle could 'avoid' the detector be-

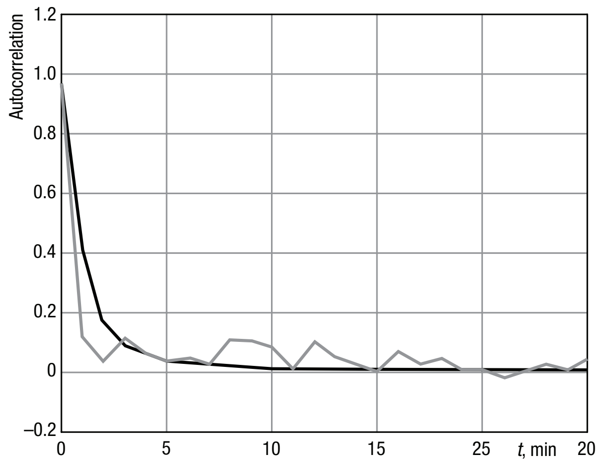

Fig. 6. Autocorrelation function of the vehicle speed (black curve), when the average speed is estimated every minute. Approximated autocorrelation function (grey curve)

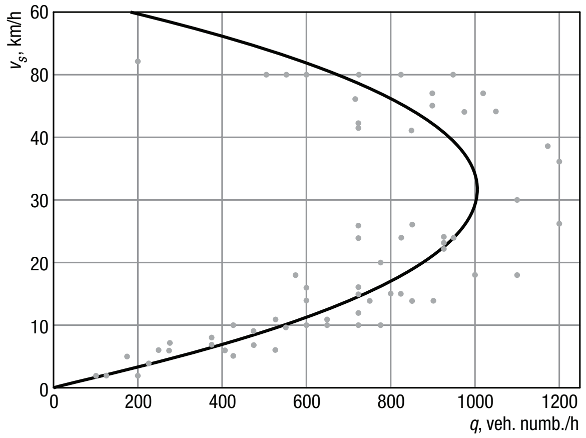

Fig. 7. Fundamental diagram of the average traffic speed and traffic flow

tween consecutive time intervals, local measurements of traffic flows and densities over certain time interval T_{mp} were done. An average flow speed is derived using the main ratio of traffic flow theory (Kerner 2010; Nagel, Nelson 2005):

$$q = kv_s, \quad (12)$$

where: q – traffic, veh.numb./h; k – traffic density, veh. numb./km; v_s – average flow speed, km/h.

Diagram of the average traffic flow speed and traffic flow in Gimnazijos St. segment, corresponding to the fundamental Kerner diagram, is presented in Fig. 7. Dependence of an average traffic speed and traffic flow in Gimnazijos St. is square:

$$v_s = -1.0161q^2 + 63.976q\,. \quad (13)$$

With free movements of vehicles, traffic flow speed increases until a threshold of traffic congestion, then the traffic starts to diminish, while traffic intensity is growing quickly. With the growth of traffic flow, an average flow speed in system cuts up to ~ 3 km/h, which means a great congestion of vehicles in transport system and almost immobile vehicles.

4. Conclusions

The analysis of traffic flows in urban transport network and formation of illustrated congestions which appear for a variety of reasons such as urban services, inadequate transport infrastructure and inadequate street intersections; lack of trunk-streets of continuous traffic; irrationally used carriageways of congested streets were presented.

The largest traffic flows in Kaunas city appear at the exits and entries to the city centre, where streets of high capacity, characterized by high traffic volume meet – Savanorių Ave, Jonavos St. and Karaliaus Mindaugo Ave, Veiverių St. Vehicle flows moving down them are distributed to several smaller streets of lower capacity of the Old Town (Šv. Gertrūdos, Gimnazijos, Birštono, Šauklių Streets) causing congestions on them (especially in peak hours).

The results of traffic-flow measurements showed that the Gimnazijos St. – Šv. Gertrūdos St. crossing (Fig. 5) is mostly crowded during the morning rush hour from 7:45 to 8:00 and during evening peak hours from 17:00 to 17:15. The prevailing group of the mixed traffic flow is cars, making 70–80%. The most acute traffic flow direction in terms of the capacity is crossing Gimnazijos St. flow, turning to Šv. Gertrūdos St.: 425 vehicles run in this direction at 17:15÷17:30.

The programme tool for simulation of microscopic traffic flows and evaluation of their parameters in microscopic and macroscopic scales, highlighting the traffic flow modes and defining of transition boundaries between the traffic modes has been compiled. Correlated vehicles speeds lead to movement of vehicles in a stable transport system, where the confidence level is 0.99.

With application of the distances between moving vehicles, average vehicle speeds in individual road segments and the microscopic cellular automaton model in nonlinear dynamic system, evaluating row lengths formed at traffic lights prohibited, the relationship between traffic flow and traffic density, traffic flow and average flow rate has been determined.

According to the traffic congestion dynamics the Fundamental Kerner diagram has been created, causing the relevance of the model to simulate the urban transport network system.

With definition of a separate vehicle dynamic characteristics and technical parameters, test results and the created software tool should be assessed as initial data in investigating or predicting congestion formation at nano-level.

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