TECHNOLOGIA I AUTOMATYZACJA MONTAŻU
kwartalnik naukowo-techniczny
ZESPOŁÓW • MASZYN • URZĄDZEŃ

Eduardo Valente[1], Camelia Avram[2], Adina Astilean[3], José Machado[4]

DOI: 10.7862/tiam.2022.1.2

A SYSTEMATIC APPROACH FOR MICROSCOPIC MODELS BASED ON CELLULAR AUTOMATA FOR ROAD TRAFFIC

SYSTEMATYCZNE PODEJŚCIE DO MODELI MIKROSKOPOWYCH OPARTYCH NA AUTOMATACH KOMÓRKOWYCH DLA RUCHU DROGOWEGO

Abstract

The transportation infrastructure is one of the most important resources for a country's economic and social well-being. The effectiveness of a country's street network will decide whether it develops further or stagnates. With the increasing number of vehicles on the road and the effects of urbanization, traffic roads are being subjected to a variety of requests and uses for which they were not designed, sized, or predicted. Because of the critical relevance of traffic roads, research must begin to lessen the effects of traffic jams in the streets, determine the appropriate number of traffic lanes, and integrate real-time traffic information into GPS systems. The goal of modeling a traffic-road system is to either build new traffic systems or gain a better knowledge of existing traffic systems so that they can be optimized. The accuracy, performance, stochastic and dynamic behavior of the model produced will be evaluated using a simulation of a genuine traffic system. This paper provides microscopic models based on cellular automation to replicate the behavior of various automobiles on a set of urban streets in Cluj Napoca city downtown. This model includes streets with multiple traffic lanes, various types of vehicles such as automobiles, buses, and trams, intersections with multiple possible upcoming streets controlled by traffic lights, bus stops inside and outside the traffic lane, tram stops inside the traffic lane, pedestrian crosswalks, and parking areas alongside and transversely with the right traffic lane of a street. TCA (Traffic Cellular Automata) is a proposed model that produces adequate findings in urban traffic theory. The results were obtained in both free-flow and traffic-jam conditions.

Keywords: Urban-traffic theory, cellular automaton, simulation, modeling, traffic-elements

Streszczenie

Infrastruktura transportowa jest jednym z najważniejszych zasobów zapewniających dobrobyt gospodarczy i społeczny kraju. Skuteczność sieci ulic danego kraju zadecyduje o dalszym rozwoju lub stagnacji. Wraz z rosnącą liczbą pojazdów na drogach i skutkami urbanizacji, drogi drogowe są przedmiotem różnych wymagań i zastosowań, do których nie zostały zaprojektowane, zwymiarowane ani przewidziane. Ze względu na krytyczne znaczenie dróg, badania muszą zacząć łagodzić skutki korków na ulicach, określić odpowiednią liczbę pasów ruchu i zintegrować informacje o ruchu drogowym w czasie rzeczywistym z systemami GPS. Celem modelowania układu ruch-droga jest albo zbudowanie nowych układów ruchu, albo uzyskanie lepszej wiedzy o istniejących układach ruchu, aby można je było zoptymalizować. Dokładność, wydajność, zachowanie stochastyczne i dynamiczne wytworzonego modelu zostaną ocenione za pomocą symulacji rzeczywistego systemu ruchu. W tym artykule przedstawiono mikroskopowe modele oparte na automatyzacji komórkowej w celu odtworzenia zachowania różnych samochodów na zbiorze miejskich ulic w centrum miasta Cluj Napoca. Model ten obejmuje ulice z wieloma pasami ruchu, różnego rodzaju pojazdy, takie jak samochody, autobusy i tramwaje, skrzyżowania z wieloma możliwymi zbliżającymi się ulicami sterowanymi przez sygnalizację świetlną, przystanki autobusowe wewnątrz i poza pasem ruchu, tramwaje przystanki wewnątrz pasa ruchu, pieszy przejścia dla pieszych oraz parkingi wzdłuż i w poprzek z prawym pasem ruchu ulicy. TCA (Traffic Cellular Automata) to proponowany model, który daje odpowiednie wyniki w teorii ruchu miejskiego. Wyniki uzyskano zarówno w warunkach swobodnego przepływu, jak i w korku.

Słowa kluczowe: teoria ruchu miejskiego, automat komórkowy, symulacja, modelowanie, elementy ruchu

[1] Eduardo Valente MSc, University of Minho; MEtRICs Research Center; Campus of Azurém; 4800-058 Guimarães; Portugal, e-mail: E_Valeeeente@live.com.pt

[2] Camelia Avram PhD, Technical University of Cluj Napoca, Cluj Napoca, Romania, e-mail: camelia.avram@aut.utcluj.ro, ORCID: 0000-0002-7394-5051.

[3] Adina Astilean PhD, Technical University of Cluj Napoca, Cluj Napoca, Romania, e-mail: adina.astilean@aut.utcluj.ro

[4] José Machado Dr. habil, PhD (corresponding author), University of Minho, MEtRICs Research Center; Campus of Azurém; 4800-058 Guimarães; Portugal, e-mail: jmachado@dem.uminho.pt, ORCID: 0000-0002-4917-2474.

1. Introduction

The continuous increase of the global number of vehicles circulating in the constant number of urban traffic roads has become one of the main problems for modern society. The impact generated by the saturation and consequent congestion of the traffic networks reflects directly and reduces the life quality for the citizens. The major disadvantages for the citizens of these blocks are waiting too much time, physical resources spent in excess, and the possible apparition of stressful situations. In this context computing simulations can have an important role, allowing different ways to control and manage urban traffic [7].

The most innovative solutions called ITS (Intelligent Transport Systems) employ the latest technological products and have a high market price. Its main goal is to collect information related to vehicular traffic roads in urban and suburban areas and their subsequent use to optimize and correct traffic circulation. The characte-ristics of this type of technology make it particularly suitable for the use of mathematical models and computer simulations with high computing capacity [4].

In fact, vehicular traffic is a complex system with features to the model. Indeed, it was one of the first simulated systems by the ancestors of digital computers in the middle of the twentieth century [8]. In general, a traffic model represents the behavior of a group of vehicles traveling on a road or a circuit. There are different modeling strategies according to the level of resolution required for the subsequent simulation; macroscopic, mesoscopic, and microscopic models [18]. In those simulations, the microscopic models based on cellular automata have been highlighted from the other principal computational models for vehicular traffic simulation, due to their capacity to represent the main traffic features using simple rules. In Germany, for example, an approach based on cellular automata is used to predict the traffic situation for the next hour, from the data obtained by sensors scattered around the road's country network [18].

Due to the extreme importance of the traffic-roads, research must be initialized to reduce the effects of traffic jams in the streets, sizing the optimal number of traffic lanes, and to implement in Global Position Systems information about the traffic conditions (the possibility of traffic congestions in each path, the existence or not of car-crushes, or works in the street) in real-time. Modeling a traffic-road system intends to design new traffic systems, or a better understanding of the existing traffic systems to optimize them. The simulation of a real traffic system will evaluate the accuracy, the performance, the stochastic and dynamic behavior of the model created.

The main target of this work is the creation of an urban traffic model using the cellular automaton approach. This model contains the main traffic elements present in urban traffic as streets with multiple traffic lanes, different types of vehicles as automobiles, buses, and trams, intersections with multiple possible upcoming streets controlled by traffic lights, bus stops inside and outside of the traffic lane, tram stops inside of the traffic-lane, crosswalks for pedestrians, parking areas alongside and transversely with the right traffic lane of a street.

Creating a systematic and easily changeable imple-mentation for different urban traffic scenarios is the biggest advance that the author intends to reach.

The concrete aims highlighted in this work are:

- Characterization of the urban traffic, explaining its main variables and relations among them.
- Overall framework of the cellular automata theory converging for TCA (Traffic Cellular Automata) theory and its implementation in the software UPPAAL [2, 16, 17].
- Detailing the construction process until the final model and its characteristics are considered.
- Definition of the entire group of Cluj-Napoca's streets implemented in the simulation.
- Simulation and validation of the results obtained by the model suggested.

2. Urban traffic theory

Historically, traffic congestion was thought to be a challenge that only existed in major cities. The traffic difficulties that plagued densely populated metropolitan areas began to spread to the suburbs over time. Advances in transportation technology have made it possible for more people to drive, as well as the busy modern lifestyle has resulted in traffic congestion issues even in tiny communities. With this chaotic environment in place, the need for solutions to improve road traffic circulation has arisen, and road traffic simulators play an important role [4].

A thorough understanding of road traffic dynamics is required to aid in the selection of the most efficient and appropriate strategies. Simulations that mimic the final effect of traffic change parameters may be particularly useful in improving road traffic circulation in this scenario [7].

Road traffic, in general, contributes to climate change and environmental degradation. Innovation in sustainable mobility will help to reduce environmental pollution [11].

Road traffic models and in particular the microscopic ones represent a fundamental resource in the management of road networks. Real progress in the study of traffic has been obtained with the introduction of the models based on cellular automata (CA) [1, 5, 6, 12, 15].

Because of their simplicity in simulating un-realistic vehicle behavior and the versatility of cellular automata to be implemented on a variety of platforms, traffic models based on cellular automata have a high computing efficiency. Parallel processing is a term that refers to the process of the other tiny traffic, on the other hand, car-following models, for example, are more computationally intensive, but they include more realistic driver behaviors and detailed vehicle characteristics [13, 10, 11, 19].

In this section, the fundamental concepts of the urban traffic theory will be presented. Firstly, the main physical variables involved in the traffic road problems (flow, average speed, and density) are shown, as well as different approaches to express those variables. Afterward, relational diagrams between these variables are depicted and their theoretical behaviors are exposed. A presentation of some microscopic models for traffic road simulation will close this chapter [7].

2.1. Fundamental concepts of the urban traffic flow (traffic parameters)

The traffic behavior can be evaluated by the following variables: flow (J), average speed ($\bar{v}$), and density (ρ). These parameters are called traffic parameters, i.e., those variables that help to determine the road condition at a particular time. Traffic flow is defined as the vehicles quantities which pass through a road section in each period and its unities are vehicles per time unit. The average speed is given by space units traveled by those vehicles per time unit. The density is determined by the number of vehicles per space unit [9, 18].

In this section different methods to calculate the urban traffic parameters are presented. The different expressions provide the necessary background for the utilization of urban traffic parameters in the course of this work [5, 7, 9, 13].

The traffic characteristics are ranging in time and space. To simplify these variations, commonly medial values for the traffic parameters are adopted. These medial values may be temporal or spatial values. Thus, there are different expressions for the traffic variables, when one traffic road is considered, in a one-time interval, is called temporal average, or a lane stretch in a time instant, is called a spatial average [5, 7, 9, 13].

2.2. Relational diagrams

Several empirical studies have been conducted to understand the behavior of vehicles on roads, i.e., the way that the variables presented in the previous section interact and how they are related. In this section, the principal diagrams that describe the relational behavior of the real traffic parameters are presented, such as the relation between the flow with the density, the flow with the speed, and density with the speed [5, 7, 9, 13].

Fundamental traffic diagram (Traffic flow & density)

The diagram that relates the traffic flow with the density is the principal diagram wildly used, due to its strong connection with the saturation level of the traffic lane. The diagram is called a fundamental diagram, has three different phases [3], and is displayed in Figure 1.

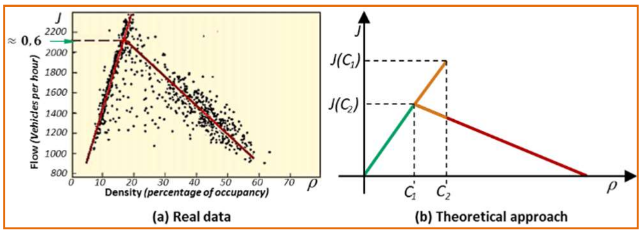

Fig. 1. Fundamental traffic diagram[1]

(i) Low-density region, called free traffic flow. This phase generically, allows the drivers to have the desired speed, approaching the maximum permitted speed. The diagram in this region has a linear growth with a density ranging from $0 < \rho < c_1$, presented in Figure 1(b). It can be also observed in Figure 1(a), the maximum flow in this region occurs approximately 2100 vehicles per hour or 0.6 vehicles per second.

(ii) Median density region, $c_1 < \rho < c_2$ Figure 1(b), where the traffic flow is not exclusively defined by density. The traffic configuration directly influences its flow and may cause a free or congested flow. In this region, the middle density is denominated meta-stable region.

(iii) High-density region, $\rho > c_2$, Figure 1(b), where the traffic flow drops as the density increases. The large concentration of vehicles causes them to cluster in traffic jams and a vehicle that leaves a place from the traffic jam will find congestion just ahead. This type of traffic is characterized by the behavior start and stop.

The meta-stable region of median density is characterized by the hysteresis effect. In the first phase, the drivers can maintain their speeds with $\rho > c_1$ (the direction a, Figure 2). This behavior continues until the density $\rho \le c_2$ when the distance between vehicles is no longer enough to allow movement. From this moment, when the driver decelerates, also causes a deceleration in the following vehicles, creating a traffic jam (direction b, Figure 2). On the other hand, (direction c, Figure 2) if the flow goes from congested to free; the density decreases, the traffic flow will increase linearly until it becomes a free flow (point d in Figure 2) [7].

Relation Flow & Speed

Another important relationship is the flow with the speed, shown in Figure 3, where V_f is the final average speed, it has a value slightly below the maximum traffic lanes speed since in a free flow, not all vehicles are permanently at maximum speed. The speed that provides a maximum traffic flow J_{max} is called optimal speed V_0 [7].

Also, can be observed in Figure 3, when the vehicles are circulating at maximum or minimum speed the traffic flow has the minimum value. This occurs, when the vehicles circulate at low speed, and traffic jams are created which, despite the high density, generate a low vehicles flow. When the vehicles are at high-speed little interactions occur between them, and consequently, the density is lower, generating a low vehicle flow. For this reason, the maximum traffic flow (J_{max}) occurs with a speed below the maximum value, at a point where the density of vehicles is bigger before the traffic jams start [7, 14].

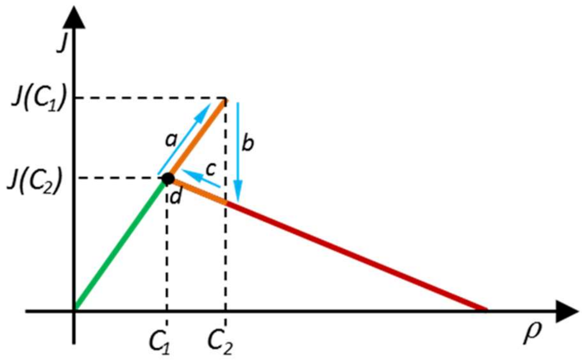

Fig. 2. Hysteresis effect[1]

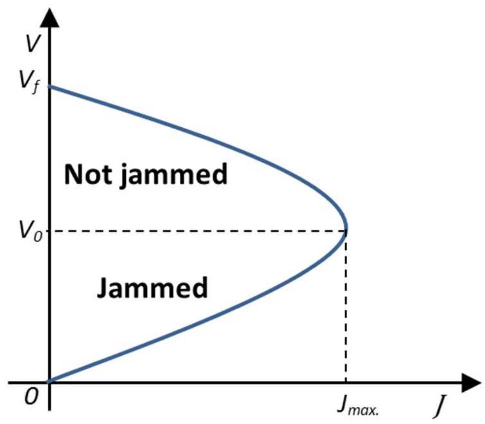

Fig. 3. Theoretical scheme of the speed-flow relation[1]

[1] Image adapted from [7].

Relation Density & Speed

The diagram presented in Figure 4, shows how the speed decreases with the traffic-lane saturation. Due to its monotonically decreasing behavior, some mathematical models represent this diagram only as a linear function.

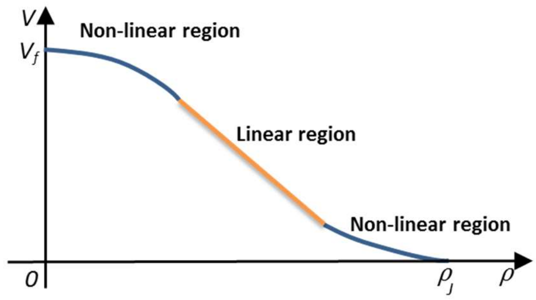

Fig. 4. Theoretical scheme of the density-velocity relation

2.3. Some models for simulation of vehicular traffic

Mathematical models for traffic simulation can be divided into three different approaches: Macroscopic, Mesoscopic, and microscopic models.

The macroscopic analyses describe the global behavior of traffic streams. Therefore, they relate the density, flow, and average speed parameters of the vehicles [18].

The mesoscopic models represent the behavior of a group of vehicles, i.e., bases its traffic analyses in a group of vehicles that behaves according to some logical grouping criteria: an expedition, congestion behavior, etc. [18].

Microscopic models are the ones that focus on the individual behavior of each vehicle to obtain the global behavior of a traffic road. They consider the interrelated parameters which determine the vehicle's dynamics. For example, knowing the acceleration of each vehicle at each time instant its position and speed can be known, after a time interval [18].

In the next section, a brief description of microscopic models is presented.

2.4. Microscopic Models

A type of microscopic modeling that has been largely used in traffic simulation is based on cellular automata, due to its versatility and simplicity. The first probabilistic model that reproduced the basic traffic conditions with the use of simple transition rules was proposed in [10].

One of the most studied models in traffic road simulation is the microscopic model, using the persecution model (car-following) which was developed at the end of the 1950s. This model has as a first objective the translation of speed variation of the tracker vehicle. The speed variation is a response function of the speed stimulus between a vehicle and the vehicle in its front, called leader vehicle. A schematic representation of a car-flowing model is presented in Figure 5 [7].

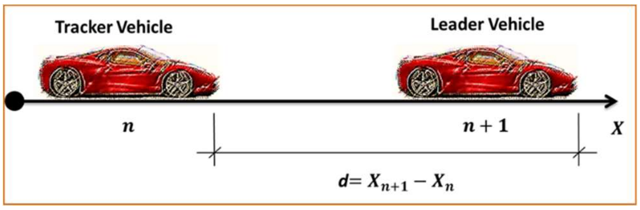

Fig. 5. Scheme of the car-following model

In general, the car-following modes are centered on the following relation:

[Response]n ∞ [Stimulus]n+1

The vehicle n = 1, 2, … can only accelerate or decelerate as a response to different flow conditions. The equation (1) represents the car-flowing model's vehicle's analyzed speed (v_n), the speed difference between it and the leader vehicle (Δv_n), and the distance between these vehicles (d_n) among others [14].

$$\ddot{x}_n(t) = f(v_n(t), d_n(t), \Delta v_n(t)) \tag{1}$$

Road layout and the physical environment

When cellular automaton analogy is applied to vehicular road traffic flows, the physical environment of the system represents the road the vehicles are driving on. In a classic single-lane setup for traffic cellular automata, the layout consists of a one-dimensional grid. Each cell can either be empty or occupied by exactly one vehicle (single-cell models). Another possibility is to allow a vehicle to occupy several consecutive cells (multi-cell models) (Nagel, 1996).

An example of the time-space dynamics of TCA is represented in Figure 6, where two consecutive vehicles i and j are driving on a 1D grid. A typical discretization scheme assumes ΔT = 1 s and ΔX = 7.5 m corresponding to speed increments of ΔV = ΔX/ΔT = = 27 km/h. The spatial discretization corresponds to the average length that a vehicle occupies in a traffic jam. (In this context, its width is not considered). The temporal discretization is based on a typical driver's reaction time [10].

In Figure 6, the time axis is oriented downwards, the space axis extends to the right. The TCA's configuration is shown for two consecutive time steps t and t + 1, during which two vehicles i and j propagate through the grid.

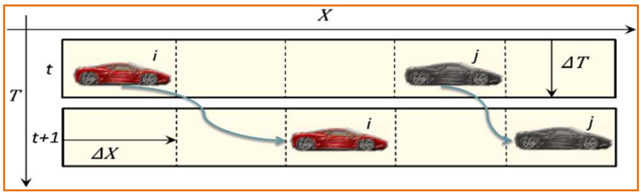

Fig. 6. Schematic diagram of a single-lane traffic cellular automaton (TCA)

With respect to the layout of the system, two main cases can be distinguished: closed and open systems. They correspond to periodic (or cyclic) versus open boundary conditions respectively. A closed system is usually implemented as a closed ring of cells and the number of vehicles is always conserved. An open system considers an open road.

Vehicle movements and the set of rules

The circulation of the individual vehicles in a traffic flow is described by a set of rules that reflects the car-following and lane-changing behavior, evolving in time and space. This set of rules included in TCA is consecutively applied to all vehicles in parallel. The system's state is changed through synchronous position updates of all the vehicles: for each vehicle, the new speed is calculated, after its position is updated according to its new speed and finally a possible lane-change maneuver is considered. It is furthermore assumed that a driver does not react to events between consecutive time iterations.

For single traffic-lane models, it is assumed that vehicles act as anisotropic particles, i.e., they only respond to frontal stimuli. The car-following stimuli are the states of the direct frontal neighborhood of each vehicle. The radius of this neighborhood should be large enough so that vehicles are able to move without collisions. Typically, this radius is equal to the maximum speed that a vehicle can achieve, expressed in cells per time step.

From a microscopic point of view, the process of a vehicle following its predecessor is expressed using the relation stimulus-response. Typically, this response is the speed or the acceleration of a vehicle. In TCA models, a vehicle's stimulus is mainly composed of its speed and the distance to its leader. As a direct response, the vehicle's new speed is adjusted. In a strict sense, this approach only leads to the avoidance of accidents. Some models incorporate anticipation stimuli. These forms of "anticipation" only consider leaders' reactions. When these effects are considered, the traffic flow is more stable and laminar avoiding abrupt braking and strong accelerations.

3. Uppaal modelling and simulation

This section is described the modeling process until the final UPPAAL model that covers and represents the study case.

Firstly, when the author faced the problem, simplistic models were created and as far as the project was developed the models became more complex. Some features such as places, transitions, functions, and channels from the simple models were changed or erased. Thus, each example present in this chapter defines a concrete problem and the models' evolution until the creation of the final model that contains all the features needed to implement in the study case.

The first subsection presents a model with one traffic lane and one automobile. In the second subsection, the complexity increases, and two models are presented to describe a traffic lane with several automobiles traveling. The third subsection is described the model which contains four traffic lanes connected by an intersection and the automobiles will choose the next street to continue their journey. A fourth model is a group of four traffic lanes connected in an intersection and are allowed to travel three different vehicles: automobiles, buses, and trams in free flow. The fifth subsection presents a model with traffic lanes where the three previous vehicles can circulate and be added to other traffic elements (bus and tram stops inside and outside of the traffic lane, crosswalks for pedestrians, parking areas, and traffic lights).

The author was always concerned with the creation of general models that can be easily extended or implement new situations and features. For this reason, the previous definition of the street cell using the function list was erased and in this new model, in similarity with the automobiles' definition was used the function typedef to create the streets in the global declarations.

3.1. Model with one traffic lane and one automobile

To implement this scenario in UPPAAL was necessary to develop two automata: the automaton street and the automaton automobile. An automobile only has two possible states: STOPPED or MOVING. The movement of the automobile is coordinated by the sensors at the beginning and at the end of the street which will define if the automobile is in or out of the traffic lane considered.

3.2. Model with one traffic lane and several automobiles

The model presented previously is extended with several features like changing traffic lanes, speed monitoring, acceleration/deceleration, and creating and managing queues.

The intersections are modeled as sections with multiple exits. For simulation purposes, vehicles will have two types of trajectories: random movement on the simulated map (at the end of each section with multiple exits – intersection – the next segment is randomly selected) and predefined path (at the beginning of the simulation for this type of automobiles the list with streets to follow is predefined)

This model has potentialities to be extended to new traffic scenarios and to be implemented in other types of vehicles and traffic elements.

Based on real-life road traffic measurements the average flow on the cells of analyzed streets is calculated and is used as weights in the UPPAAL model. The random choice of the next segment is weighted based on real-time road traffic measurements.

3.3. Street with multiple possible choices as an upcoming street with automobiles, buses, and trams moving in a free flow

Once the behavior of a traffic lane with several automobiles traveling with three possible next streets was already modeled, the next level of complexity is to create different types of vehicles. Two new classes of vehicles were defined: buses and trams. The difference between an automobile and a bus is its length. The bus is longer than an automobile and has a defined route to move by the pre-established bus stops. The tram is also bigger than an automobile and in similarity with a bus has a defined route to move by the tram stops.

In this model, we consider free-flow traffic (the bus or tram travel without stops) and traffic with predefined stops (on specific traffic lane cells with bus or tram stations).

The principal new feature considered in this model is that a bus will occupy two street cells and a tram will occupy three street cells. When a bus or a tram reaches an intersection with multiple next streets, they will always choose the same street to move in its predefined route. Therefore, to have multiple routes of trams or buses can be created different types of buses or trams in the simulation. Consequently, the simulation will have groups of buses or trams covering different areas of the city.

In this model and in all the subsequent models the automobiles will continue to have homogeneous distributions by the next possible traffic lanes: 50% in the case of two next possible streets and 33% when the intersection has three next possible streets.

Figure 7 is schematically represented the model with several automobiles, buses, and trams moving in a street, and at the end of the street is chosen another street. The distribution of the traffic flow with the rules admitted for buses, trams, and automobiles was explained, and they are depicted in this scheme. The first automobile (black) which arrives at the intersection (blue rectangle) will continue to travel in the street ID 1, the second automobile to reach the intersection (green) will choose the street ID 2, the third automobile (blue) will choose the street ID 3, and this cycle of choice will continue for the subsequent automobiles. In the case of the buses which arrive at the intersection, they will always continue to move in the street ID 2. The trams which arrive at the intersection will have similar behavior to the buses but instead of choosing the street ID 2, they will always choose the street ID 3.

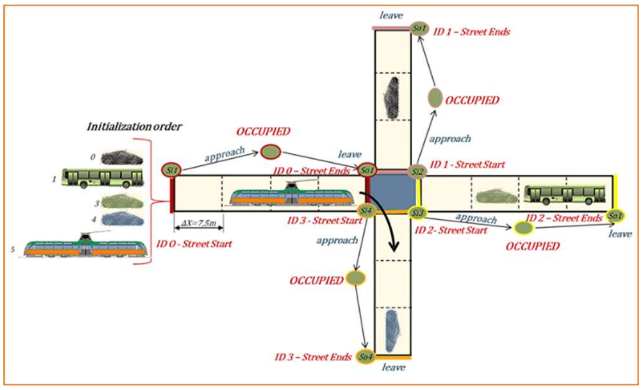

Fig. 7. Schematic representation of the model traffic lane with several automobiles, buses, and trams traveling with three possible next streets

Also, should be considered the buses that are not in service or buses that are traveling on long-distance trips and assume trucks equal in size to the buses. For this reason, in the subsequent models, buses with random destinations as automobiles will be considered. This percent of traffic elements is small, but to be as accurate as possible buses that are not included in the bus stop and have no predefined route will be considered, including long-distance buses and trucks.

This new model, contrarily to the previous model, is constituted by four templates: street, automobile, bus, and tram because it considers three different types of vehicles.

In the global declarations firstly is declared the number of automobiles, buses, trams, and streets, using the function typedef. In this model, it will be present three automobiles, one bus, one tram, and four streets.

The automaton street will be the "brain" of the simulation has all the information regarding the traffic conditions, set of rules and consequent transition rules, and possible interactions between the different vehicles.

Figure 9 shows the configuration of the street automaton for the model one traffic lane and different vehicles traveling with three possible next streets.

Figure 10 and Figure 11 present the bus and tram automaton respectively. In the red oval are highlighted the differences between them and the automobile automaton.

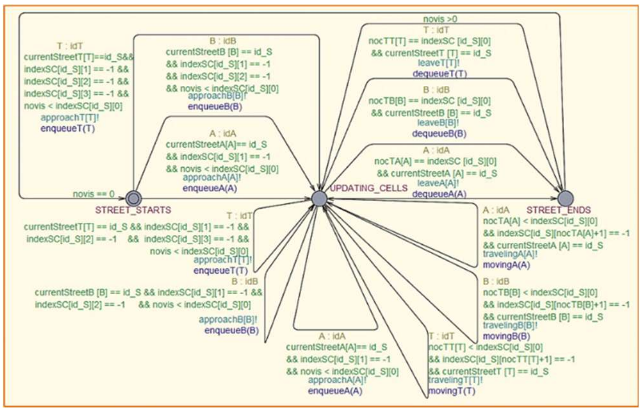

Fig. 9. Street automaton for the model traffic-lane with automobiles, buses, and trams

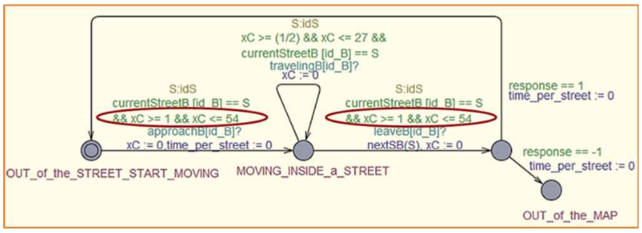

Fig. 10. Bus automaton for the model traffic-lane with different vehicles traveling with three possible next streets

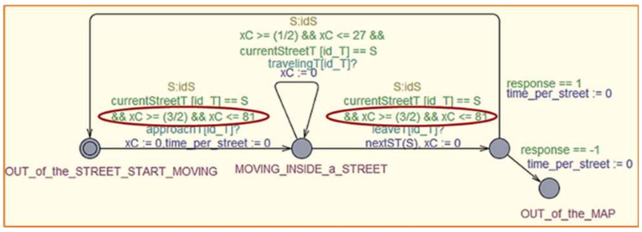

Fig. 11. Tram automaton for the model traffic-lane with different vehicles traveling with three possible next streets

For the streets considered in the case study, the traffic behavior is not exclusively influenced by the state of the street cells, as considered in the previous model. The vehicles interact with others traffic elements present in the street as crosswalks, bus stations, and tram stations. In this new model are added this interaction between vehicles and the traffic elements contained in the group of the streets of this case study.

The automobiles can interact with the following traffic elements implemented:

- Crosswalks for pedestrians.
- Parking placed transversely on the right side of the traffic lane.

- Parking placed alongside on the right side of the traffic lane.

The buses can interact with the following traffic elements implemented:

- Crosswalks for pedestrians.
- Bus stops inside of the traffic lane.
- Bus stops outside of the traffic lane, on the right side of the traffic lane.

The trams can interact with the following traffic elements implemented:

- Crosswalks for pedestrians.
- Tram-stops inside of the traffic lane.

3.4. Global declaration of the model containing different traffic-elements

To implement these traffic elements were needed to instantiate in the matrix indexSC, new negative numbers which will have a different meaning than an empty cell, affecting the behavior in the vehicles. The elements present inside of the street (crosswalks, bus stops inside of the street, and tram stops inside of the street) were coded in the respective street ID, with a negative number.

However, to create the traffic elements outside of the street were necessary to define adjacent streets to implement the exit movement that a vehicle will execute for the adjacent street where is located the traffic-element. The implementation rule is the following: if a traffic lane has in its right side an exterior traffic element (parking places transversely, parking places alongside and bus-stops outside of the street) the street ID-1 will have the respective negative digit of the traffic element and in the street, ID-2 will be necessary to create the border of the street that will give information that the vehicle cannot move to another street ID on the right.

Summarily, the different negative digits that a matrix indexSC can have will give the instructions for an interaction between a vehicle and a traffic element. The meaning (the traffic-element) of the negative digits is the following: (description of the matrix number of cells per different street with different traffic elements)

-1 - Empty cell,

-2 - Bus station inside of the traffic lane,

-3 - Tram station inside of the traffic lane,

-4 - Crosswalks for pedestrians,

-5 - Possible Park place alongside for automobiles in the right side of the street,

-55 - Border of a parking place alongside for automobiles with the right side of the street,

-6 - Possible Park places for automobiles in transversal with the right side of the street (the right place),

-66 - Border of a park places for automobiles in transversal with the right side of the street (the right place),

-7 - Possible Park places for automobiles in transversal with the right side of the street (left place),

-77 - Border of a park places for automobiles in transversal with the right side of the street (left place),

-22 – Bus station outside of the right side of the street,

-222 - Border of a bus station outside of the right side of the street,

-8 - Street's end and cells without meaning for the simulation.

The succeeding Figures will be explained how to encode the different configurations of the traffic lanes containing different traffic elements in the matrix indexSC.

3.5. Implementation of traffic elements inside of the traffic lane

This simulation contains traffic elements inside of a street that will affect the traffic circulation for the respective vehicle. The traffic elements inside of the street considered are bus stops, tram stops, and crosswalks for pedestrians.

In Figure 12 the generic configuration of a bus stop inside of a street is presented. In this example, the street is constituted with four cells (the first element of the matrix) and the street cell which contains the bus stop is encoded with the digit -2. All the other cells are encoded with -1, (empty cells) and the last element of the matrix (-8) means that is the end of the street.

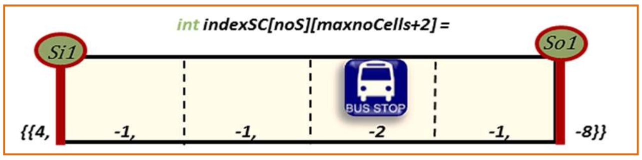

Fig. 12. Bus stop inside of the traffic lane implemented in the matrix indexSC

In Figure 13 the generic configuration of a tram stop inside of a street is presented. In this example, the street is constituted with four cells (the first element of the matrix) and the cell with a tram stop is encoded with the number -3. All the other cells are encoded with -1 and the last element of the matrix (-8) means that is the end of the street.

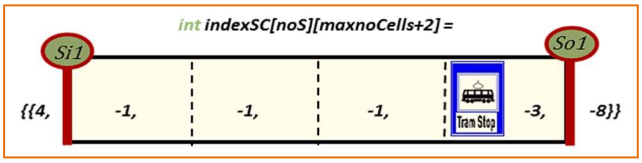

Fig. 13. Tram stop inside of the traffic lane implemented in the matrix indexSC

In Figure 14, a traffic lane with a crosswalk for pedestrians is presented. In this example, the street is constituted with four cells (the first element of the matrix) and the cell with a crosswalk is encoded with the number -3. All the other cells are encoded with -1 and the last element of the matrix (-8) means that is the end of the street.

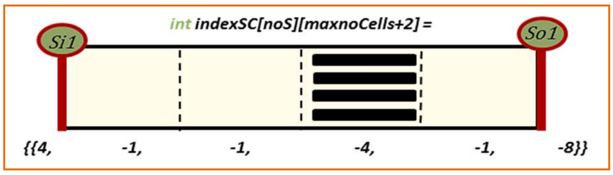

Fig. 14. Crosswalk encoded in the matrix indexSC

These three previous traffic elements inside of the traffic-lane (crosswalks, bus, and tram stop inside of a street) when the vehicles are moving, created the necessity of control variables, to restore the traffic element inside of the street's cell (inside of the matrix indexSC) in the same position. In Figure 14, the eighteen control variables generated in the global declaration are presented. At the beginning of the simulation, all the variables are set with the value 0 and now that interacts with the respective traffic element, its value will change for 1.

In Figure 15 the generic configuration of a parking area transversely with the right side of a street is presented. In this example, the street is constituted with four street cells (first element of the street ID 2) and all the other street cells are encoded with -1, (empty cells) and the last element of the street ID 2 (-8) means that is the end of the street. Once in this microscopic model, the width of the street and the vehicles are not considered, two adjacent traffic lanes for implementation of the parking area were created.

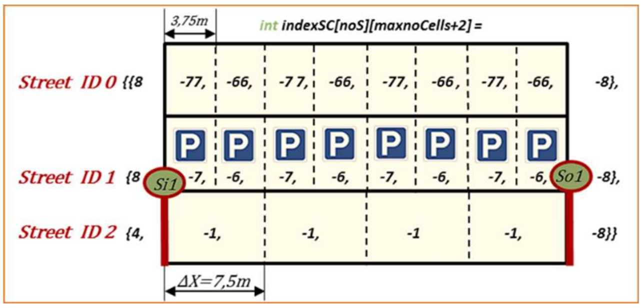

Fig. 15. Parking area for automobiles in transversal with the right side of a traffic lane

In Figure 16 the generic configuration of a parking area in parallel with the right side of a street is depicted. In this example, the street is constituted with four street cells (first element of the street ID 2) and all the other street cells are encoded with -1, (empty cells) and the last element of the street ID 2 (-8) means that is the end of the street. Once in this microscopic model, the width of the street and the vehicles are not considered, two adjacent traffic lanes for implementation of the parking area were created.

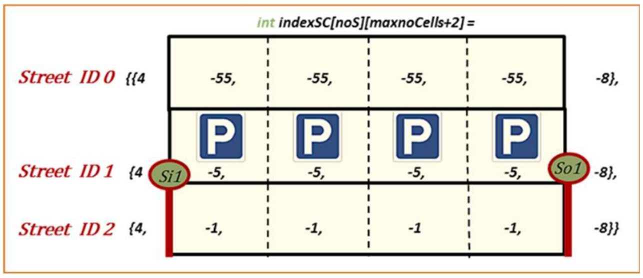

Fig. 16. Parking area for automobiles alongside the right side of a traffic lane

In Figure 17 the generic configuration of a bus stop outside of the traffic lane on the right side of a street is depicted. In this example, the street is constituted with four street cells (first element of the street ID 2) and all the other street cells are encoded with -1, (empty cells), and the last element of the street ID 2 (-8) means that is the end of the street. Once in this microscopic model, the width of the street and the vehicles are not considered were created two adjacent traffic lanes to implement the boarding area and unloading area.

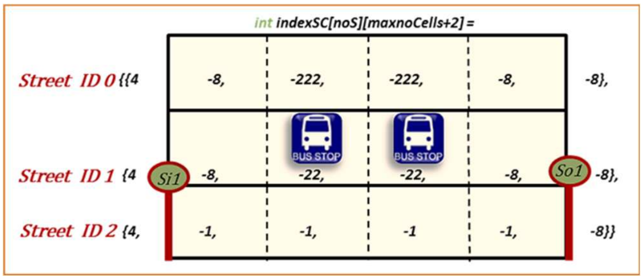

Fig. 17. Bus stop outside of the right side of a traffic lane

3.6. Automaton Automobile

The automaton automobile only evolves from the initial location if it was detected an automobile by the sensor Si1 present at the beginning of a street. The channel approachA will be activated and the clock time_cellA[id_A] will have a value between 0.5 times unites and 27-time units which is the time necessary to cross one street's cell with 7.5 meters with a range of velocity between 1 and 50 km/h.

After entering a street, the automobile will receive the channel travelingA from the street automaton always that the street's cell in its front is free and will update its position inside of the street. And if the cell in its front is a crosswalk the channel stopped_in_NCCWA is activated. In a crosswalk was admitted that the clock time_cellA[id_A] will have a value between 0.5 times unites and 50-time units because the automobile can be forced to stop if pedestrians were crossing the traffic lane. In the place INTERACTING_INSIDE_a_STREETbefore PARKING two situations can occur: If there are no parking places on the right side of the street the automobile reaches the end of the street, or if exist possible parking places in its right and if the driver desires to park the vehicle will be parked during a period. When an automobile reaches the last street's cell, the channel leaveA will be activated and the function nextCA will be updated. This function has the algorithm of choice between the possible next streets. If the value of the auxiliary variable response is 1 the value of the currenStreetA will be updated and the automobile continues to move inside of the considered map but in another street ID. If the value of response is equal to -1 means that there are no possible next streets, and the automobile will be out of the map remaining blocked in the place OUT_of_the_MAP. In the second case when an automobile evolves for one of these places: parked PARKED_ALONGSIDE or PARKED TRANSVERSELY RIGHT or PARKED_TRANSVERSELY_LEFT the automobile will stop during a period. If the automobile is parked alongside a parking place the time consider for the clock time_cellA[id_A] is between 7200 and 10800-time units, which correspond to a parking time between 2 or 3 hours. If the automobile is parked in a transversal parking place the time consider for the clock time_cellA[id_A] is between 21600 and 28800-time units, which correspond to a parking time between 6 or 8 hours. This last interval of parking time can be considered for the people that are going to work during a normal workday. After having been parked the automaton evolves to the place INTERACTING_INSIDE_a_STREET_after_PARKING and in this place the automobile can interact with other vehicles and traffic- elements but if in the same street that it was parked exist free parking places, the automobile cannot park again. This behavior is like the real driver's behavior because after being parked for a period the driver normally wants to continue his trip and not park again a few meters further in the same street. Thus, after leaving the street where the automobile was parked and if the automobile is traveling in another street with free parking places it can park again.

Figure 18 shows the configuration of the automaton automobile for the model of several vehicles' interaction with different traffic elements.

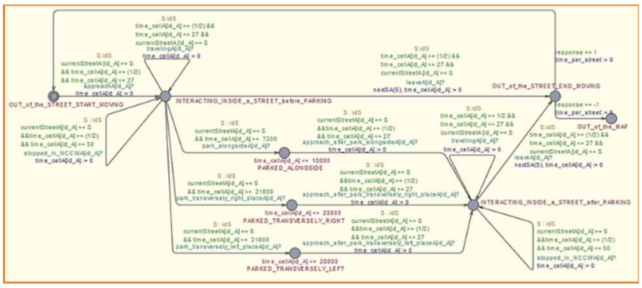

Fig. 18. Automaton automobile for the model several vehicles interaction with different traffic-elements

3.7. Automaton Bus

The automaton bus was reconfigured and has five places:

- OUT_of_the_STREET_START_MOVING: when a bus is moving in a direction to the beginning of the street.
- MOVING_INSIDE_a_STREET: when a bus was detected by the sensor Si1 and since there is inside of the street traveling interacting with other vehicles and traffic-elements.
- STOPPED_in_BUS_STATION_OUTSIDE_of_the_STREET: when a bus is stopped outside of the street to board and unload passengers.
- OUT_of_the_STREET_END_MOVING: when a bus was detected by the sensor SO1.
- OUT_of_the_MAP: when a bus was detected by the sensor SO1 and there are no possible next streets and is out of the considered map.

The automaton bus-only evolves from the initial location if it was detected a bus by the sensor Si1 present at the beginning of a street. The channel approachB will be activated and the clock time_cellB[id_B] will have a value between 1-time unit and 54-time units which is the time necessary to across two street's cells with 7.5 meters with a range of velocity between 1 and 50 km/h.

After entering in a street, the bus will receive the channel travelingB from the street automaton always that the street's cell in its front is free and will update its position inside of the street. If the cell in its front is a crosswalk the channel stopped_in_NCCWB is activated. In a crosswalk was admitted that the clock time_cellB[id_B] will have a value between 0.5 times unites and 50-time units because the bus can be forced to stop if pedestrians were crossing the traffic lane. If the cell in its front is a bus stop inside of a street the channel stopped_in_bus_Station_inside_Street[id_B] is activated. In a bus stop inside of the street and in accord with the book "Transit Capacity and Quality Service Manual" the following values for the busiest bus stops may be adopted, considering their location: 60s downtown, 30s peripheral zone very busy and 15s typical peripheral zone. In all the bus stops was admitted that the clock time_cellB[id_B] will have a value between 60 times unites and 30-time units which corresponds a bus stops located downtown and in peripheral zones of the city in similarity with the study case. In the place MOVING_INSIDE_a_STREET two situations can occur: if there is no bus stops on the right side of the street the bus reaches the end of the street, or if exist a bus stop outside of the street the bus is forced to go out of the traffic lane and the automaton evolves to the place STOPPED_in_BUS_STATION_OUTSIDE_of_the_STREET. When a bus reaches the last street's cell, the channel leaveB will be activated and the function nextCB will be updated. This function has the algorithm of choice between the possible next streets. If the value of the auxiliary variable response is 1 the value of the currenStreetB will be updated and the bus continues to move inside of the considered map but in another street ID. If the value of response is equal to -1 means that there are no possible next streets, and the bus will be out of the map remaining blocked in the place OUT_of_the_MAP. In the second case when a bus evolves for the place STOPPED_in_BUS_STATION_OUTSIDE_of_the_STREET the bus will stop during the period previously explained. After having been stopped the bus evolves to the place MOVING_INSIDE_a_STREET and in this place the bus can interact with other vehicles and all the traffic- elements even if in the same street that it was stopped outside of the street in a bus stop exist another bus stop outside of the street.

Figure 19 shows the configuration of the automaton bus for the model of several vehicles interacting with different traffic elements.

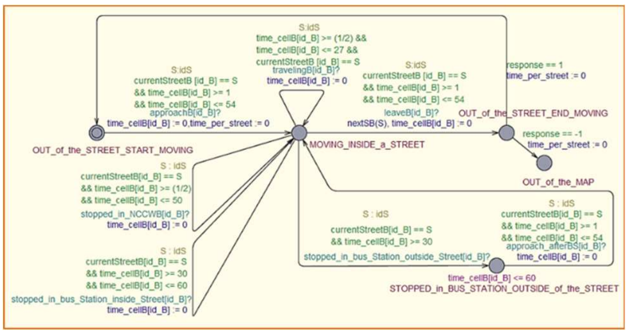

Fig. 19. Automaton bus for the model several vehicles interaction with different traffic elements

3.8. Automaton Tram

The automaton tram has four places:

- OUT_of_the_STREET_START_MOVING: when a tram is moving in direction to the beginning of the street.
- MOVING_INSIDE_a_STREET: when a tram was detected by the sensor Si1 and since there is inside of the street traveling interacting with other vehicles and traffic-elements.
- OUT_of_the_STREET_END_MOVING: when a tram was detected by the sensor SO1.
- OUT_of_the_MAP: when a tram was detected by the sensor SO1 and there are no possible next streets and is out of the considered map.

The automaton tram only evolves from the initial location if it was detected a tram by the sensor Si1 present at the beginning of a street. The channel approachT will be activated and the clock time_cellT[id_T] will have a value between 1.5 times unites and 81-time units which is the time necessary to across three street cells with 7.5 meters with a range of velocity between 1 and 50 km/h.

After entering a street, the tram will receive the channel travelingT from the street automaton always that the street's cell in its front is free and will update its position inside of the street. If the cell in its front is a crosswalk the channel stopped_in_NCCWT is activated. In a crosswalk was admitted that the clock time_cellT[id_T] will have a value between 0.5 times unites and 50-time units because the tram can be forced to stop if pedestrians were crossing the traffic lane. If the cell in its front is a tram stop inside of a street the channel stopped_in_tram_Station_inside_Street[id_T] is activated. In all the tram stops was admitted that the clock time_cellT[id_T] will have a value between 30 times units and 60 based on the same values for the buses. In the place MOVING_INSIDE_a_STREET when a tram reaches the last street's cell, the channel leaveT will be activated and the function nextCT will be updated. This function has the algorithm of choice between the possible next streets. If the value of the auxiliary variable response is 1 the value of the currenStreetT will be updated and the tram continues to move inside of the considered map but in another street ID. If the value of response is equal to -1 means that there are no possible next streets, and the tram will be out of the map remaining blocked in the place OUT_of_the_MAP.

Figure 20 shows the configuration of the automaton bus for the model of several vehicles interacting with different traffic elements.

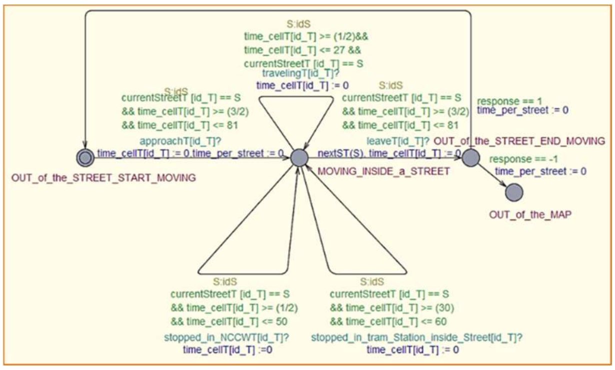

Fig. 20. Automaton tram for the model several vehicles interaction with different traffic elements

Some relevant features of this model:

- The physical environment is a two-dimensional grid of rectangular cells. The street cells, the crosswalk cells, the bus stop cells, the tram stop cells, the alongside parking cells are equal in size (7.5 meters in length). The transversal parking cells have a different size (3,75 meters in length) and for this reason, this model has a non-homogeneous grid of cells.
- It is a multiple cells model because an automobile occupies one street cell, a bus occupies two street cells, and a tram occupies three street cells in each time iteration.
- The possible states of the cell are thirteen: be occupied by an automobile, a bus, or a tram, be empty, to contain a crosswalk, to contain a bus stop inside of the street, to contain a tram stop inside of the street, to contain a parking place alongside with right side of the street, to contain a left parking place transversely with the right side of the street, to contain a right parking place transversely with the right side of the street and to contain a bus stop outside of the right side of the street.
- variables and the matrix idexSC to extend the size of the neighborhood is different for each cell and this model is not anymore anisotropic because the automobiles and buses also receive stimulus from the right side.
- This model is a dynamic system with a closed number of automobiles buses, trams, and streets, being the evolution in space and time depending on different rules to satisfy the real traffic rules.
- The time is a stochastic feature, and its choice is completely nondeterministic. In an instant t, a vehicle can circulate in a cell at the velocity of 50 km /h and in the instant t+1 it can move at 2 km/h. This model has presented heavy breaks and accelerations even if the street is completely free.
- It is a realistic model, once considering different types of vehicles (automobiles, buses, and trams).
- This model can be easily extended. The number of streets and vehicles can be easily changed, is only necessary to define in global declaration those the map, define the inputs of the traffic flow in the simulation (vectors currentStreetA, currentStreetB and currentStreetT), define the next upcoming streets for the different vehicles (matrices indexMap AUTOMOBLIE, indexMapBUS, and indexMapTRAM), set up the variables responsible to count the number of cells traveled (nocTA, nocTBF, nocTBB, nocTTF, nocTTM, and nocTTB) for each vehicle, and define the matrix indexTL.

In fact, this model has the potentialities to simulate different traffic scenarios. It can be largely improved but due to the time restriction for this project the author defined a list of possible next improvements in this model.

4. Simulations

Figure 21 presents the map chosen for simulation to validate all the complex presented features. The map is inspired by Cluj Napoca downtown. Some of the designed features previously presented are artificially added to the city model for tests and validation purposes.

To implement the considered scenario 90 automobiles, 10 buses, and 9 traffic lanes were declared. Intersection A is completely considered, and a part of intersection B is also included.

An extensive list of interrogations that can be used in this type of simulation was previously presented in [17]. Based on the interrogations in UPPAAL we can establish the variation of the number of automobiles inside of the traffic lanes.

The left traffic lane before intersection A, of the street Piața Mihai Viteazu (direction street George Barițiu) is constituted by 8 street cells which is also the maximum number of vehicles allowed to travel. This street has an input of traffic flow of 30 automobiles and 5 buses. At the end of this street, all the buses mandatorily will continue their trip in the right traffic lane of the street Piața Mihai Viteazu (direction Street Dávid Ferenc). The automobiles will be equally distributed by the left and right traffic lane of the street Piața Mihai Viteazu (direction Street Dávid Ferenc) and in the Street Piața Mihai Viteazu (direction street George Barițiu) left traffic-lane after the intersection A.

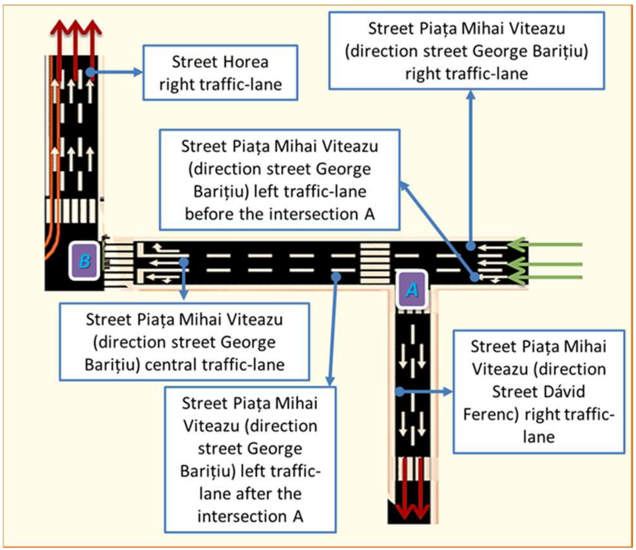

Fig. 21. Representation of the considered map in the simulation in UPPAAL

Figure 22 presents the variation of the number of automobiles inside of this traffic lane. Can be observed that the number of vehicles inside of this traffic lane never exceeds 10 vehicles. During the time considered the number of vehicles is not floatable, continuing the entire simulation in a traffic fluid regime.

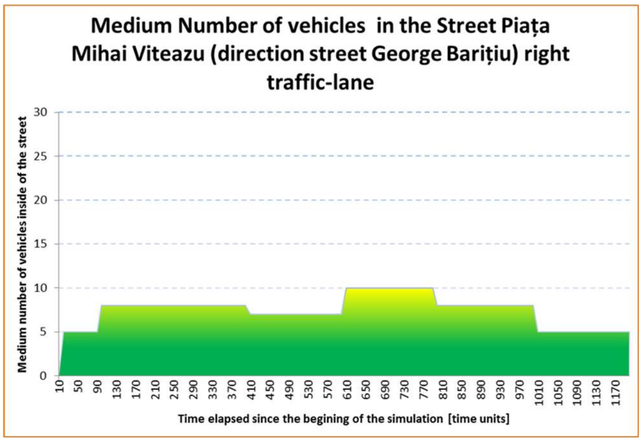

Fig. 22. Evolution of the medium number of vehicles in the street Piața Mihai Viteazu (direction street George Bariţiu) right traffic-lane

Figure 23 presents the variation of the number of automobiles inside of this traffic lane is presented. Can be observed that the number of vehicles inside of this central traffic lane of the street Piața Mihai Viteazu never exceeds 15 vehicles. During the time considered the traffic behaves in a fluid regime.

In Figure 24 the variation of the number of automobiles inside of this traffic lane is presented. Can be observed that the number of vehicles inside of this traffic lane of the street Piața Mihai Viteazu never exceeds 6 vehicles. During the time considered the traffic behaves in fluid regime until 370 time units elapsed and after the traffic started to get congested until 800 time units. Due to the small length of this street, it will have a moment of peak traffic corresponding to the maximum number of vehicles inside traveling. When a big group of vehicles left the street and is propagating to the others traffic lanes the number of vehicles inside starts to be smaller and interacting again in a fluid regime.

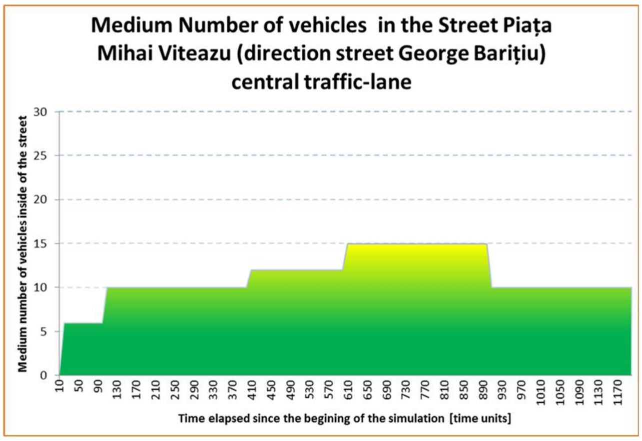

Fig. 23. Evolution of the medium number of vehicles in the street Piața Mihai Viteazu (direction street George Bariţiu) central traffic-lane

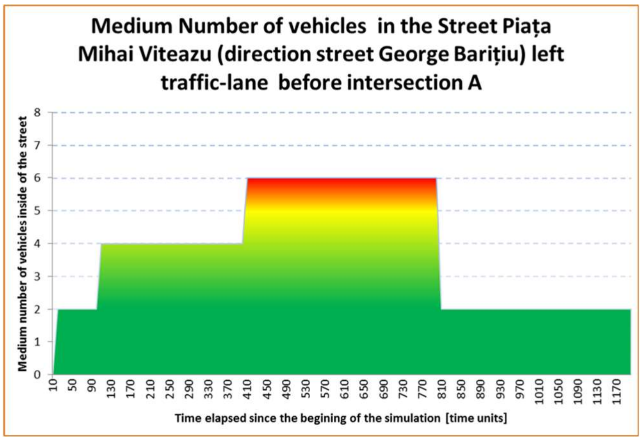

Fig. 24. Evolution of the medium number of vehicles in the street Piața Mihai Viteazu (direction street George Bariţiu) left traffic-lane before the intersection A

The right traffic-lane, of the street Horea, is constituted by 14 street cells which is also the maximum number of vehicles allowed to travel. This traffic lane will receive 33% of the number of automobiles (10 automobiles) and 5 buses which started the trip in the Street Piața Mihai Viteazu (direction street George Bariţiu) right traffic-lane before the intersection B. At the end of this street, all the automobiles are considered outside of the map.

In Figure 25 the variation of the number of automobiles inside of this traffic lane is presented. Can be observed that the number of vehicles inside of this traffic lane never exceeds 10 vehicles. During the time considered the traffic behaves in the fluid regime and pre-congested regime.

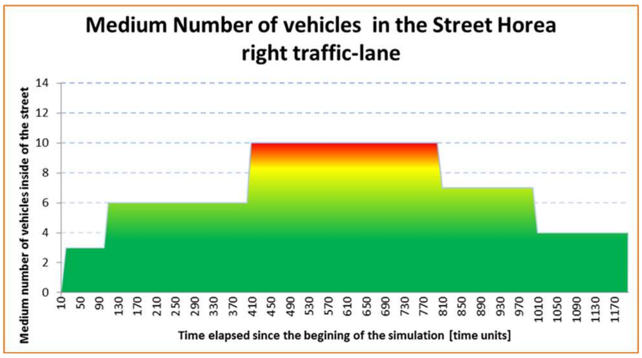

Fig. 25. Evolution of the medium number of vehicles in the Street Horea right traffic-lane

These results were obtained by queries implemented in UPPAAL graphical interface Verifier. The results obtained with the model proposed are appropriate in the context of the urban traffic theory.

5. Conclusions

The cellular automata allow the observation of different phenomena, managing to dissect its components in individual variables, and can understand how local changes affect the whole grid of cells.

Using microscopic models brings a large amount of data to analyze. In an urban area, where are several elements involved in road traffic, is compulsory to analyze the interactions between them to reduce traffic jams, fuel costs and to improve the quality of life.

It would be interesting to implement different kinds of vehicles like ambulances, fire trucks, and police automobiles with high priority than the others, works in the street, bus and tram schedules, and crosswalks controlled with traffic lights.

Implementing the adaptive safety distance for a vehicle depending on the chosen value of velocity, and the distance that splits it from the vehicle in front (number of free cells in its front) based on the functions presented previously would be also an interesting topic to analyze. With this implementation will be created smooth transitions of the values of velocity between two consecutive street cells.

References

[1] Alur, R., Dill, D.L., ”A Theory of Timed Automata,” In Theoretical Computer Science, vol. 126, 183-235, 1994.

[2] Behrmann, G., David, A., Larsen, K.G. “A tutorial on UPPAAL”. In Proceedings of the 4th international school on formal methods for the design of computer, communication, and software systems (SFM-RT’04). LNCS 3185, 2004.

[3] Chowdhury, D., Santen, L.; Schadschneider, A., “Statistical physics of vehicular traffic and some related systems,” Physics Reports, v. 329, pp. 199-329, 2000.

[4] Clark, J., Daigle, G., “The importance of simulation techniques in its research and analysis”, Proceedings of the 1997 Winter Simulation Conference, USA, 1997.

[5] Daigle, G., Clark, J., "The Importance of Simulation Techniques In Its Research And Analysis," in Winter Simulation Conference, pp. 1236-1243, 1997.

[6] Hanumappa, D., Ramachandran, P., "Cellular Automata Model for Mixed Traffic Flow with Lane Changing Behavior", Modelling and Simulation in Engineering, vol. 2021, 2021.

[7] Lima, E.B., “Modelos microscópicos para simulação do tráfego baseados em autômatos celulares.”, Dissertação de Mestrado em Computação, Universidade Federal Fluminense, Niterói, Brazil, 2007.

[8] Lindberg, T., Peterson, A., Tapani, A., “A simulation model of local public transport access at a railway station”, RaillLille 2017, International Conference on Railway operations modeling and analysis, pp. 922-944, 2017.

[9] May A.D., “Traffic Flow Fundamentals”, Prentice Hall, 1997.

[10] Nagel, K., Schreckenberg, M., “A cellular automaton model for freeway traffic”, Journal de Physique I, France, pp. 2221-2229, 1992.

[11] Nguyen, J., Powers, S.T., Urquhart, N., Farrenkopf, T., Guckert, M., “An overview of agent-based traffic simulators”, Transportation Research Interdisciplinary Perspectives, Volume 12, 2021.

[12] Regragui, Y., Moussa. N., “A Cellular Automata Model for Urban Traffic with Multiple Roundabouts”, Chinese Journal of Physics, Physical Society of the Republic of China, 2018.

[13] Rodaro, E., Yeldan, O., “A multi-lane traffic simulation model via continuous cellular automata”, 2018.

[14] Rothery, R., et all “Traffic flow theory. Transportation Research Board (TRB)”, Special Report, pp. 165, 1998.

[15] Tian, J., Zhu, C., Jiang, R., “Cellular automata approach to synchronized traffic flow Modelling”, 2018.

[16] Vaandrager, F., “A First Introduction to Uppaal”, Institute for Computing and Information Sciences, Radboud University Nijmegen, Netherlands.

[17] Valente, E., Avram, C., Machado, J., Aştilean, A., "An Innovative Approach for Modelling Urban Road Traffic Using Timed Automata and Formal Methods", Jour. of Advanced Transportation, vol. 2018, Article ID 6269526, 15 pages, 2018.

[18] Vico, F.J., Basagoiti, F.J., García-Platas, R., Lobo, D., “Modelado y simulación del tráfico en vías urbanas y periurbanas en base a la estimación de tiempos de recorrido”, ETSI Informática, Universidad de Málaga and Tecnologías Viales Aplicadas, TEVA, SL, Malaga, 2005.

[19] Zhao, H.T., Zhao, X., Jian-Cheng, L., Xin, L.Y., “Cellular automata model for Urban Road traffic flow Considering Internet of Vehicles and emergency vehicles”, Journal of Computational Science, Volume 47, 2020.