Construction of Cellular Automata Lattice Based on the Semantics of an Urban Traffic Network

Vedran Ivanac[1], Bojana Dalbelo Bašić[2], and Zvonimir Vanjak[1]

[1] Telegra, Software R&D Department,
Plesivicka 3, Sveta Nedelja, Croatia
{vedran.ivanac,zvonimir.vanjak}@telegra-europe.com
[2] Faculty of Electrical Engineering and Computing
University of Zagreb, Unska 3, 10000 Zagreb, Croatia
bojana.dalbelo@fer.hr

Abstract. In this paper, we propose a construction process that enables the transformation of an urban traffic network using a cellular automata lattice. An abstract network hierarchy is defined which allows us to describe the important properties of an urban traffic network layer by layer. The cellular automata lattice is extended with three additional types of cells that permit the modelling of conflict points at intersections. A supporting model of vehicle behaviour based on traffic cellular automata is also extended with rules that allow vehicles to move properly within the extended cellular automata lattice.

Keywords: cellular automata, construction, intersection, urban traffic network, cellular lattice, conflict points.

1 Introduction

Traffic simulation is used to model and simulate the flow of vehicles in a road network. Traffic simulators are most commonly applied in the planning stages of the construction of transportation networks, the prediction of traffic flow characteristics, traffic signal optimisation, the analysis of environmental impacts, and the evaluation of transportation scenarios [1]. Depending on the level of detail, simulation models may be macroscopic, mesoscopic, or microscopic. Microscopic models describe traffic flow with a high level of detail by modelling the behaviour of each vehicle in the flow [2]. Traffic microsimulation based on cellular automata is very effective in simulating vehicular traffic [3, 5–7]. Traffic cellular automata (TCA) models are capable of reproducing elementary events in traffic flow, such as the breakdown of free flow, stop and go waves, and traffic jams. The main component of cellular automata is the cellular lattice that is used to represent the road surface. Most analyses focus on defining the rule set of TCA models and evaluation of these TCA models on simple road network configurations. However, problems arise when traffic microsimulation based on

G.C. Sirakoulis and S. Bandini (Eds.): ACRI 2012, LNCS 7495, pp. 795–806, 2012.

cellular automata is used to simulate traffic flow on real traffic networks. Unlike simple traffic networks in the shape of a single straight road or a circular road, highway and urban traffic networks include many additional elements that affect the flow of traffic. Moreover, urban traffic networks contain junctions, traffic lights, roundabouts, and bus stops that make them more complex then highway traffic networks. Therefore, TCA microsimulation that enables the simulation of traffic flow on urban traffic networks must have the following components:

- **A semantically correct network representation** – All important characteristics and properties of the urban traffic network are contained in the definition of the cellular lattice.
- **Vehicle behaviour supporting model** – A model that understands the characteristics and properties of urban traffic networks contained in thenetwork representation.

An optional but desirable feature of network representation is the ability to be described on a higher level of abstraction, enabling the cellular lattice to be derived instead of constructed manually.

This paper is organised in seven sections. Following this introduction, Section 2 discusses the related works, while Section 3 defines basic traffic cellular automaton. Section 4 describes the important characteristics and properties of urban traffic networks. Section 5 presents an abstract network hierarchy with an extended definition of the cellular lattice and a behaviour model. Section 6 presents an example of the transformation of a real urban traffic network into a cellular lattice. This is followed by the conclusions in Section 7.

2 Related Works

In the field of traffic simulation, a broad scope of models describes the behaviour of traffic flows [2]. Maerivoet and De Moor [4] categorised TCA as deterministic, stochastic, and slow-to-start, depending on the ability to simulate different types of vehicle behaviour. Nonetheless, traffic microsimulation based on TCA that is capable of representing a complex traffic network as a cellular lattice has been successfully implemented [5, 6]. Chopard et al. [5] applied TCA to the city of Genova, representing roads with a set of one dimensional (1-D) cellular lattices and intersections with rotaries. Esser and Schreckenberg [6] described a road network as a composition of nodes and edges representing crossings and roads. Edges enable the modelling of multi-lane roads with turning sections, and transfer edges enable the merging of traffic flows to be modelled. A node describes only the connections between edges, modelling the intersections as black boxes. A similar network representation is used in TRANSIMS [7]. Ruskin and Wang [8] focused on simulating traffic flows on unsignalised intersections, which they represented as the intersection of two 1-D cellular lattices. Zhang and Chang [10] extended this idea by representing an intersection with a 2-D lattice that enables the simulation of a mixed traffic flow of vehicles and people in an intersection.

3 Definition of a Basic Traffic Cellular Automaton

Traffic cellular automata (TCA) are based on a theory of cellular automata (CA) introduced by Wolfram [11]. The cellular automaton is defined as the following 4-tuple [4]:

$$CA = (\zeta, \Sigma, \Omega, \delta), \quad (1)$$

where the cellular lattice is represented by ζ, the set of possible cell states by Σ, the cell neighbourhood by Ω, and the transition rules by δ. The cellular lattice represents the space on which the CA is computed. This underlying structure can be finite or infinite in size, consisting of cells in rectangular, hexagonal, or other topologies. The dimensionality of the lattice can be 1 (an array of cells), 2 (a grid of cells), or higher. The cells are all equal in size, and each cell can be in only one state from the set of possible states at one time step. Transition rules define the evolution of a cell through discrete time steps based on the current cell state and the states of the cell's neighbourhood. The CA evolve in time and space as the rules are subsequently applied to all the cells in parallel.

Nagel and Schreckenberg [9] introduced a stochastic traffic cellular automaton (STCA) model that is capable of reproducing the important properties of real traffic flow. The forward motion of vehicles is described by the following set of rules:

1. Acceleration: $v_i(t) \leftarrow min(v_i(t-1)+1, v_{max})$;
2. Deceleration: $v_i(t) \leftarrow min(v_i(t), gap_i(t-1))$;
3. Randomisation: $\xi(t) < p \Longrightarrow v_i(t) \leftarrow max(v_i(t)-1, 0)$;
4. Movement: $x_i(t) \leftarrow x_i(t-1) + v_i(t)$.

Each cell i is either empty or occupied by one vehicle with a discrete speed $v_i \in \{0, ..., v_{max}\}$. The variable gap_i defines the number of empty cells in front of the vehicle at cell i. $\xi(t)$ is a uniform random generator, and p is the probability that defines the level of stochastic noise, which is important for reproducing speed fluctuations due to human behaviour or external conditions.

The analogy of the cellular automaton to vehicular road traffic flow is based on representing a physical road with the cellular lattice. A 1-D lattice of cells represents one traffic lane in which cells may either be empty or occupied by a vehicle. For each traffic cellular automaton model, a discretisation scheme is defined in accordance with space and time.

4 An Urban Traffic Network

An urban traffic network is a traffic network in a city area featuring different types of roads, intersections, and interchanges in which traffic flow is regulated by traffic signs and traffic signals. The elements of an urban traffic network [12–15] define spatial topology, signalisation and basic traffic rules. For the purpose of defining semantically correct network representations, the following important characteristics and properties of these three elements are selected:

- **Spatial topology**
  - **Roads** – There are different types of roads, including freeways, arterial roads, collector roads, and local roads. Roads have length, traffic lanes with spatial configurations, and assigned signalisation. Roads connect two junctions and can be uni- or bi-directional.
  - **Intersections** – Areas in which two or more roads intersect. The important properties of intersections include the spatial configurations of lanes and of conflict points, roads connected to intersections, and the level of control. Control in an intersection may be maintained by basic traffic rules, traffic signs, or traffic lights.
  - **Interchanges** – Points of access for vehicles to enter or leave a freeway. The important properties of interchanges include the length of enter/exit lanes and the location of interchanges on roads.
- **Signalisation**
  - **Traffic signs** – Traffic signs may be classified into the three main categories of regulatory, warning, and informative signs. The important properties of these signs are their class, meaning, and location within the network.
  - **Traffic signals** – Traffic signals solve the problems at conflict points in intersections using the principle of time sharing. Traffic signals are defined by cycle, cycle length, phases in cycle, the location of each traffic signal relative to the intersection and the traffic lanes in the intersection.
- **Basic traffic rules** – Elementary rules that apply to traffic without signalisation.

5 A Cellular Lattice for Urban Traffic Networks

In the Nagel and Schreckenberg model [9], the network representation is one traffic lane in the shape of a 1-D array of cells, but this is not particulary applicable to urban traffic networks. In this section, a cellular lattice for urban traffic networks is presented as part of an abstract network hierarchy representing urban traffic networks as cellular lattices with extensions.

5.1 Abstract Network Hierarchy

Traffic networks may be viewed at different levels of abstraction. In this way, the network representation may be modelled layer by layer until the cellular lattice on the last layer is defined. Each layer has more detail and defines additional semantics of the urban traffic network. From top to bottom, there are five layers, including the network, the graph, the segment, the inner segment, and the cell layer. The benefit of an abstract network hierarchy is that it requires definition only in the upper layers of the hierarchy, while transformation algorithms can generate the cellular lattice in the cell layer.

- **Network layer** – The network layer is the top layer that represents the grounds of the abstract network hierarchy. It holds all the entities below it and describes the network as a black box.

- **Graph layer** – The graph layer is the layer below the network layer that describes the traffic network as a graph. The graph layer consists of nodes and links that represent vertices and edges. The nodes describe the semantics of the junctions, and the links describe the semantics of the roads between the junctions.
- **Segment layer** – The segment layer describes the network as a collection of connected segments. Every node and link from the graph layer is built from segments so that connections from the graph layer become connections between segments. The main purpose of the segment layer is to achieve uniformity and create logical entities that have the same rules and semantics. Fig. 1 shows how the nodes and links from the graph layer are presented in the segment layer. Each node always has one segment, and each link may have at least one segment, depending on the road configuration and the traffic rules.

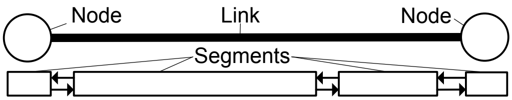


Fig. 1. Segments of the segment layer

- **Inner segment layer** – The inner segment layer defines semantics in more detail than simply the connections between junctions. Each segment is comprised of lanes, connectors, signs, and conflict points. Fig. 2 presents an example of inner segment structures, where the segment on the left is a typical example of a segment in a link, and the segment on the right is a typical example of a segment in a node. The lanes represent traffic lanes from a real traffic network so that each lane has its own length and neighbouring lanes. The number of lanes in the segment is the same as the number of lanes in the part of the real traffic network that the segment represents. Connectors facilitate the connections of lanes from different segments. Each connector has one or more pins where each lane in the segment may connect with its beginning and end. Connectors mediate between the defined connections of segments in the segment layer and the lane connections from the inner segment layer. Lanes from two different segments are then connected based on the information in the connectors during the process of abstract network construction. Conflict points describe lane overlaps and enable the modelling of traffic regulation within the abstract traffic network. The three types of conflict points are divergent points, cross points, and merge points. A divergent conflict point describes a situation where two or more lanes begin at the same point, a merge conflict point describes a situation where two or more lanes end at the same point, and a cross conflict point describes a situation where two or more lanes cross each other. Every traffic rule that affects traffic flow can be defined by the signs in a particular segment.
- **Cell layer** – The cell layer contains a cellular lattice that uses the semantics defined in the upper layers for its construction. Every lane within the inner

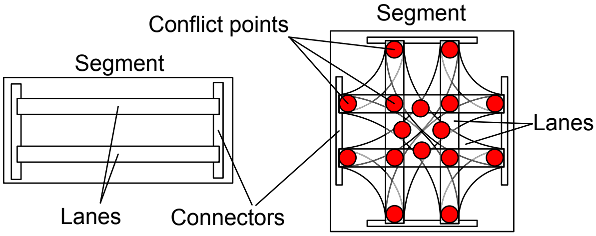


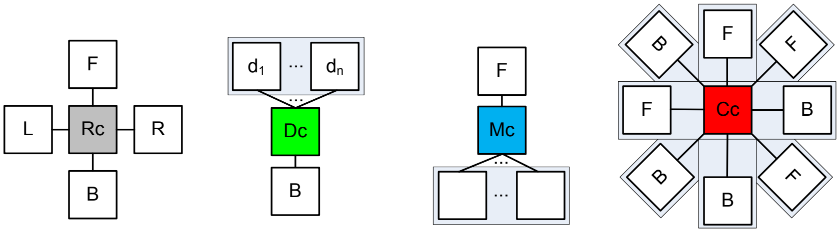
Fig. 2. Examples of the inner structure of segments

segment layer has a 1-D array of cells that are interconnected. Each cell represents a part of the physical road surface in a traffic lane. Information about the connections between lanes is used to connect the cells outside the array so that all cells in the cell layer are connected in a lattice that defines a real urban traffic network. To be able to define all the semantics from the upper layers, the basic definition of a cellular lattice has been extended.

5.2 Extended Definition of a Cellular Lattice

The basic definition of a cellular lattice defines it as a collection of cells of a single type that each have a state and a neighbourhood. The extended definition of a cellular lattice extends the definition of the cell type and its neighbourhood. The neighbourhood of the cell type varies, but it allows every cell to be its neighbour, regardless of the cell type. Apart from the existing type of cell, the road cell, there are three new types of cells called conflict point cells, resulting in the following list of cell types:

- **Road cell** – The road cell represents a cell type from the basic definition of a cellular lattice and enables modelling of a plain road surface. Fig. 3(a) presents a road cell with its von Neumann neighbourhood in the front-back and left-right directions.
- **Diverge cell** – The diverge cell enables the modelling of a diverge conflict point. It has a neighbourhood only in the front-back direction and more than one front neighbour, as shown in Fig. 3(b). It has one front neighbour cell with a key d_i for every possible direction; it provides information about the destination node of the leading direction of that cell so that a vehicle can select a front cell based on its preferred route.
- **Merge cell** – The merge cell enables the modelling of a merge conflict point. It has one back cell for each direction and one front cell, as shown in Fig. 3(c). The merge cell also regulates the priorities of merging vehicle flows.
- **Cross cell** – The cross cell enables the modelling of a cross conflict point. Each lane is represented with a direction containing a pair of front and back cells relative to the cross cell, as shown in Fig. 3(d). Those cells are the neighbours of the cross cell. The priority of passing through the cross cell is determined by the position of the direction relative to the other directions of the cross cell.



(a) Road cell (b) Diverge cell (c) Merge cell (d) Cross cell

Fig. 3. Type of cells in an extended cellular lattice

5.3 Vehicle Behaviour Supporting Model

In urban traffic networks, vehicles must be able to change lanes, navigate through the network, comply with traffic signs and rules, and choose directions at intersections that correspond with their routes. In this case, the STCA model is used as a base for the extensions. A lane change extension enables a vehicle to change lanes on multi-lane [7, 16] or bi-directional roads [17, 18]. It enables the simulation of situations including passing a slower vehicle, changing lanes before an intersection in accordance with the route of the vehicle, and entering or exiting a highway [6, 7]. When simulating vehicles complying with traffic lights, an abstract flag [6] or traffic control algorithm [7] is used. The same concepts of lane changes and compliance with traffic lights are used in this paper, but different concepts are presented in the case of traffic rules.

Traffic rules are divided into basic rules and rules modelled through traffic signs that override and extend the basic rules. These rules can also be divided by the layers on which they are defined; for instance, on the segment layer, rules that limit speed and lane changes are defined, while on the cell layer, rules that prioritise vehicle passing are defined. Priority rules are defined at the conflict points on an intersection. The priority of direction in conflict points depends on the spatial position of direction relative to other directions and on traffic signs, such as stop and yield signs. Based on these concepts, each vehicle must evaluate an occupied status for cells in front of the vehicle when calculating the front gap in a forward movement model. If the cell is a conflict point cell, the occupied status requires the following additional calculation:

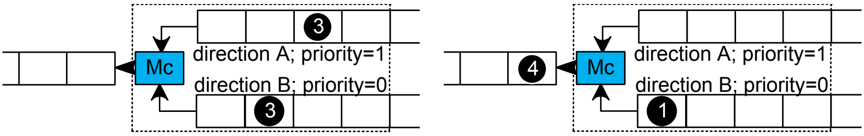
- **Diverge cell** – A diverge cell does not have defined priorities. If a stop sign is placed within the diverge cell, then the cell is occupied if the speed of the vehicle that evaluates the status of cell occupation is greater than zero.
- **Merge cell and cross cell** – In merge cells and cross cells, the cell's status of occupation is based on a pass acceptance algorithm.

Pass acceptance algorithm (PAA)

```
Input: (c, d, s) conflict point cell c, direction d in which is
the vehicle that evaluates PAA, and the zone of the conflict s.
```

```
Output: calculated cell's c occupied status.
if (c is occupied by vehicle) return true;
else
    for each(direction z in c.directions)
        if(z.priority > d.priority){
           find vehicle v upstream of a cell c in the direction z;
           if((vehicle v exist) && (distance(v.cell, c) <= s))
                return true;
        }
return false;
```

The addition of traffic signs changes the priorities of the directions in conflict point cells. Yield and stop signs reduce the priority of a particular direction. The pass acceptance algorithm does not offer a logical solution for preventing and resolving the deadlocks, that may occur between cross cells. Such deadlocks may be prevented by applying deadlock resolvers [19, 20].



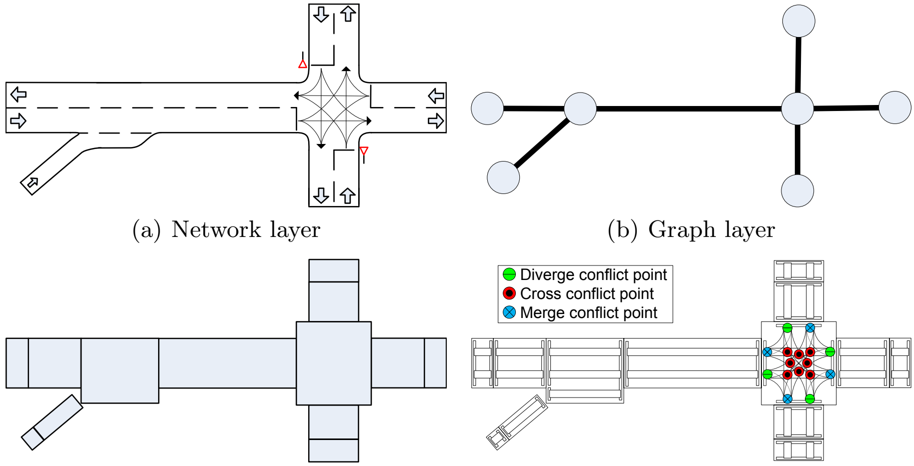
(a) iteration(t) (b) iteration(t+1)

Fig. 4. Example of using the pass acceptance algorithm in a merge cell

Fig. 4(a) depicts part of a cellular lattice with a merge cell and two directions with different priorities. Each vehicle has a speed of 3 cells per iteration and must pass a merge cell. During the vehicle's process of calculating a new position for the next iteration, it uses the pass acceptance algorithm (PAA) to determine the occupied status of a merge cell. In this case, the vehicle v_2 travelling in direction B has a lower priority than the vehicle v_1 travelling in direction A. Therefore, the PAA will return true for v_2 and false for v_1, and v_2 will slowdown and v_1 will pass a merge cell, as shown in Fig. 4(b).

6 An Example of the Transformation of a Real Traffic Network into an Extended CA Lattice

This section will demonstrate how a real traffic network is transformed into an extended cellular automata lattice by using an abstract network hierarchy. In this example, the network part (Fig. 5(a)) comprises two bi-directional roads that cross at a signalised intersection. The horizontal road has an interchange with one entry ramp and has priority over the vertical road. Lines with arrows at the intersection and arrows on lanes show the possible directions of vehicle movement.



(a) Network layer (b) Graph layer

(c) Segment layer (d) Inner segment layer

Fig. 5. Upper layers within the abstract network hierarchy

The next step includes using a graph layer to describe part of a real traffic network. Fig. 5(b) presents a description of the traffic network in a graph layer, in which roads are represented by links, while intersections and interchanges are represented by nodes. The boundaries of the network are also represented by nodes.

The entire network is then described as a set of interconnected segments. Every node is represented by one segment, and each link is represented by one or more segments, depending on road configuration. Fig. 5(c) presents a description of the network in a segment layer, where the connections between segments are based on the connections in the graph layer.

In the inner segment layer, each segment's inner structure is defined with connectors, signs, conflict points and lanes. The number and position of these connectors depend on the number of the segment's neighbours. The graph and segment layers describe the connections in the traffic network, but the space dimension is described with lanes in the inner segment layer. Each segment has lanes whose number and length depend on the space that the segment represents in the real traffic network. On the inner side of the segment, a connector links the lanes, but on the outer side of the segment it connects with the other connector. Conflict points describe overlaps between the lanes and the priorities of the lanes. Fig. 5(d) shows the inner structure of segments with connectors, conflict points, and lanes.

The cell layer does not require description because it can be produced from the information defined in the upper layers and the discretisation scheme. Information from the upper layers describes the number and type of cells that are used and how they interconnect. Fig. 6 shows the extended cellular lattice in a cell layer with a zoomed view of an intersection. The lanes were transformed into 1-D cellular lattices, with the exception of the lanes in the intersection. Because the intersection was defined by lanes and conflict points, special types of cells were used. Gaps between the cells are used to present a cell layer, and arrows are used to describe the connections between the spaced cells. Fig. 6 does not show the connections between cells in neighbouring lanes; however, in this example, each cell in the segment that does not belong to the intersection segment also has a left and/or right neighbour cell. Based on the position of the lanes in the intersection and the signs at the intersection, priorities for directions in special types of cells were calculated.

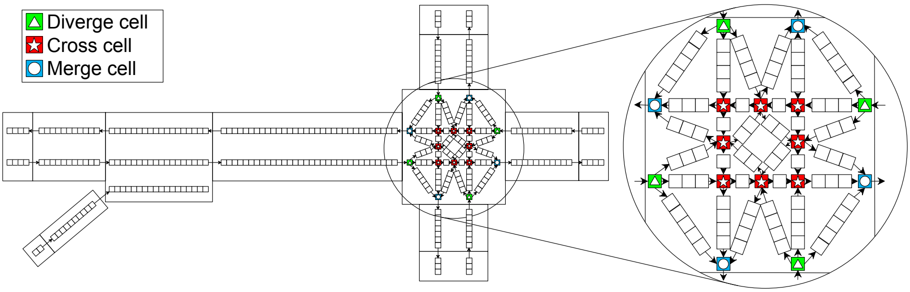


Fig. 6. Cell layer

7 Conclusion

We have successfully defined a methodology for representing urban traffic networks in traffic cellular automata (TCA) by using an abstract network hierarchy and extending the definition of a cellular lattice. We have also defined and selected the important properties of an urban traffic network and defined how these are incorporated into the layers of an abstract network hierarchy. In our example, an abstract network hierarchy is used to describe the important properties of an urban traffic network. An extended cellular lattice was built using the information from layers in the abstract network hierarchy. This offered us the option of using graphical tools that accurately describe the layers of the abstract network hierarchy and allow for the automatic creation of an extended cellular lattice. By extending a cellular lattice with three additional types of cells, we showed how the semantics of intersection and conflict points can be presented in TCA. A simulation tool is in the process of a development that will validate and calibrate the proposed model of an urban traffic network.

Acknowledgments. The authors would like to thank Edouard Ivanjko, Hrvoje Gold, Matija Piskorec and Jan Snajder for their helpful comments and suggestions. This work has been supported by Telegra-Europe and the Ministry of Science, Education and Sports, Republic of Croatia, under Grant 036-1300646-1986.

References

1. Boxill, S., Yu, L.: An Evaluation of Traffic Simulation Models for Supporting ITS Development. Technical Report 167602-1, Texas Southern University (2000)
2. Hoogendoorn, S.P., Bovy, P.H.L.: State-of-the-art of Vehicular Traffic Flow Modelling. Special Issue on Road Traffic Modelling and Control of the Journal of Systems and Control Engineering, 283–303 (2001)
3. Hafstein, S.F., Chrobok, R., Pottmeier, A., Wahle, J., Schreckenberg, M.: Cellular Automaton Modeling of the Autobahn Traffic in North Rhine-Westphalia. In: Troch, I., Breitenecker, F. (eds.) Proc. of the 4th MATHMOD, North Rhine-Westphalia, pp. 1322–1331 (2003)
4. Maerivoet, S., De Moor, B.: Cellular Automata Models of Road Traffic. Physics Reports 419, 1–64 (2005)
5. Chopard, B., Dupuis, A., Luthi, P.: A cellular automata model for urban traffic and its application to the city of Geneva. In: Proc. of Traffic and Granular, pp. 154–168. Springer (1997)
6. Esser, J., Schreckenberg, M.: Microscopic Simulation of Urban Traffic Based on Cellular Automata. International J. of Modern Phys. C 8, 1025–1036 (1997)
7. Nagel, K., Stretz, P., Pieck, M., Donnelly, R., Barrett, C.L.: TRANSIMS traffic flow characteristics (1997)
8. Ruskin, H.J., Wang, R.: Modelling Traffic Flow at an Urban Unsignalised Intersection. In: Sloot, P.M.A., Tan, C.J.K., Dongarra, J., Hoekstra, A.G. (eds.) ICCS-ComputSci 2002, Part I. LNCS, vol. 2329, pp. 381–390. Springer, Heidelberg (2002)
9. Nagel, K., Schreckenberg, M.: A cellular automaton model for freeway traffic. J. Phys. I France 2, 2221–2229 (1992)
10. Zhang, X., Chang, G.L.: A CA-based Model for Simulating Vehicular-Pedestrian Mixed Flows in a Congested Network. In: The 90th Annual Meeting of the Transportation Research Board, vol. 16, pp. 1–20 (2011)
11. Wolfram, S.: Statistical Mechanics of Cellular Automata. Rev. of Modern Phys. 55, 601–644 (1983)
12. AASHTO, A Policy on Geometric Design of Highways and Streets, American Association of State Highway and Transportation Officials, Washington, DC (2001)
13. Mahmoud El-Sherbiny, Y.: Design of urban traffic areas. Journal of Engineering and Applied Sciences 6 (2011)
14. Evans, H.K.: Traffic engineering handbook, Institute of traffic engineers, New Haven, Connecticut (1950)
15. Mathew, T.V., Krishna Rao, K.V.: Introduction to Transportation Engineering. NPTEL (May 2006)
16. Nagel, K., Wolf, D., Wagner, P., Simon, P.: Two-lane traffic rules for cellular automata: A systematic approach. Phys. Rev. E 58, 1425–1437 (1998)

17. Simon, P.M., Gutowitz, H.A.: A Cellular Automaton Model for Bi-Directional Traffic. Phys. Rev. E 57, 2441 (1998)
18. Moussa, N.: Simon-Gutowitz bidirectional traffic model revisited. Phys. Letters A 372, 6701 (2008)
19. Chopard, B., Luthi, P.O., Queloz, P.A.: Cellular automata model of car traffic in a two-dimensional street network. Journal of Phys. A 29, 2325–2336 (1996)
20. Doniec, A., René, M., Espié, S., Piechowiak, S.: Dealing with multi-agent coordination by anticipation: Application to the traffic simulation at junctions. In: EUMAS, pp. 478–479 (2005)