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

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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. Example traffic network was transformed and capacity of a minor street in a two-way yield controlled intersection was measured under different vehicle flow parameters. Results show that simulation on extended cellular lattice is capable of reproducing relationships between vehicle flows at intersections.

Keywords: Cellular automata, intersection, urban traffic network, cellular lattice, conflict points, street capacity, simulation.

1 INTRODUCTION

Traffic simulation is used to model and simulate the flow of vehicles in a road network. Depending on the level of detail, simulation models may be macroscopic, mesoscopic, or microscopic [1]. In this work we use microscopic models that describe traffic flow with a high level of detail by modelling the behaviour of each vehicle in the flow. Traffic microsimulation based on cellular automata is very effective in simulating vehicular traffic [2–5]. 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 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 the network representation.

This paper is organised in six sections. Following this introduction, Section 2 discusses the related works, while Section 3 presents an abstract network hierarchy with an extended definition of the cellular lattice and a behaviour model. Section 4 presents an example of the transformation of a real urban traffic network into a cellular lattice. Section 5 presents results of measuring capacity of a minor street on the two-way yield controlled intersection under different values of traffic flow parameters. This is followed by the conclusions in Section 6.

2 RELATED WORKS

In the field of traffic simulation, a broad scope of models describes the behaviour of traffic flows [1]. Maerivoet and De Moor [6] 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 [3, 4]. Chopard et al. [3] 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 [4] described a road network as a composition of nodes and edges representing crossings and roads. A similar network representation is used in TRANSIMS [5]. Ruskin and Wang [7] focused on simulating traffic flows on unsignalized intersections, which they represented as the intersection of two 1-D cellular lattices. They investigated capacity of streams at an unsignalized intersection and proposed methodology of measurement. Zhang and Chang [8] 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 A CELLULAR LATTICE FOR 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.

3.1 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

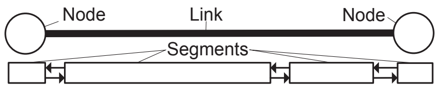


FIGURE 1
Segments of the segment layer

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. Figure 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.

- **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. Figure 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 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

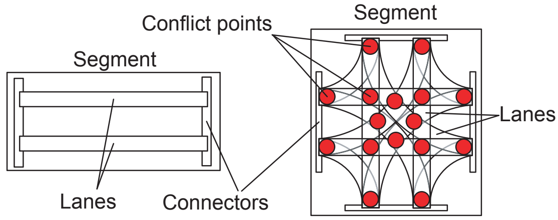


FIGURE 2
Examples of the inner structure of segments

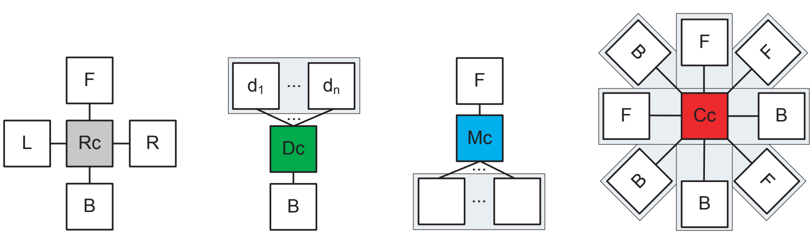
more lanes end at the same point, and a cross conflict point describes a situation where two or more lanes cross each other.

- **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 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 and 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.

3.2 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. Figure 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 Figure 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.



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

FIGURE 3
Type of cells in an extended cellular lattice

- **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 Figure 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 Figure 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.

3.3 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 stohastic TCA model is used as a base for the extensions. A lane change extension enables a vehicle to change lanes on multi-lane [5, 14] or bi-directional roads [15]. 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 [4, 5]. When simulating vehicles complying with traffic lights, an abstract flag [4] or traffic control algorithm [5] is used.

Vehicle behaviour supporting model use the Diverge-Cross-Merge (DCM) algorithm (Algorithm 1) to understand semantics of an intersection. That include understanding of priority rules defined in conflict cells. Priority of direction in the conflict cells depends on the spatial position of direction relative to other directions and on traffic signs, such as stop and yield signs. The vehicle will decide to enter an intersection if the time gaps between other vehicles in conflict directions are larger then the critical time gap t_c. Critical time gap t_c defines the minimum gap that the vehicle in a minor stream needs for deciding to enter intersection. The DCM algorithm is called when the vehicle is evaluating occupancy status of a diverge conflict cell. The occupancy status of a diverge cell depends on the result of the DCM algorithm. The DCM algorithm evaluates occupancy status of the cells in the intersection, searching for the vehicles that are in the conflict with the vehicle that called DCM. Area of search depends on critical space gap g_c that is calculated based on critical time gap t_c and maximum speed of vehicles v_{max} as $g_c = t_c * v_{max}$.

4 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.

Algorithm 1: DCM algorithm

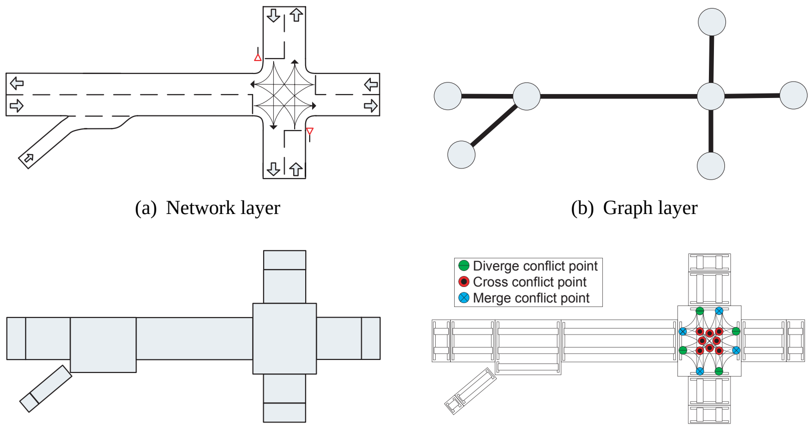
```
input  : Diverge cell dc, vehicle v and critical space gap gc
output: Occupied status of the diverge cell dc
cur = dc;
while true do
    if cur is cross or merge cell then
        vehDir = getDirectionIndex(cur, v); dirs = cur.directions;
        foreach direction d with priority over vehDir in dirs do
            search upstream of the direction d until gc is reached or
            first vehicle conVeh is detected;
            if conVeh exists and conVeh drives to cur then return false;
        foreach direction d with no priority over vehDir in dirs do
            search upstream of the direction d until merge cell is
            reached or first vehicle conVeh is detected;
            if conVeh exists and conVeh drives to cur then return false;
    if cur is merge cell then return true;
    cur = front neighbour cell of cur;
```

In this example, the network part (Figure 4(a)) comprises two bi-directional roads that cross at an unsignalized 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.

The next step includes using a graph layer to describe part of a real traffic network. Figure 4(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. Figure 4(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



(a) Network layer (b) Graph layer

(c) Segment layer (d) Inner segment layer

FIGURE 4
Upper layers within the abstract network hierarchy

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. Figure 4(d) shows the inner structure of segments with connectors, conflict points, and lanes.

Information from the upper layers describes the number and type of cells that are used and how they interconnect. Figure 5 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.

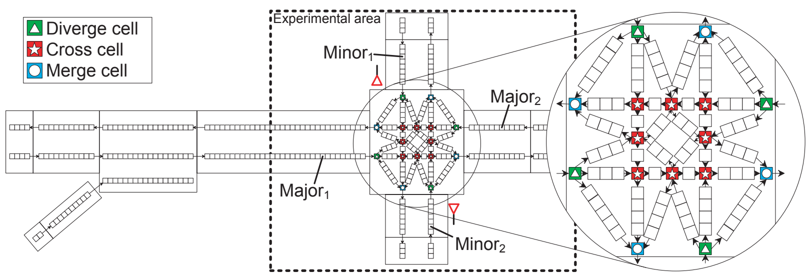
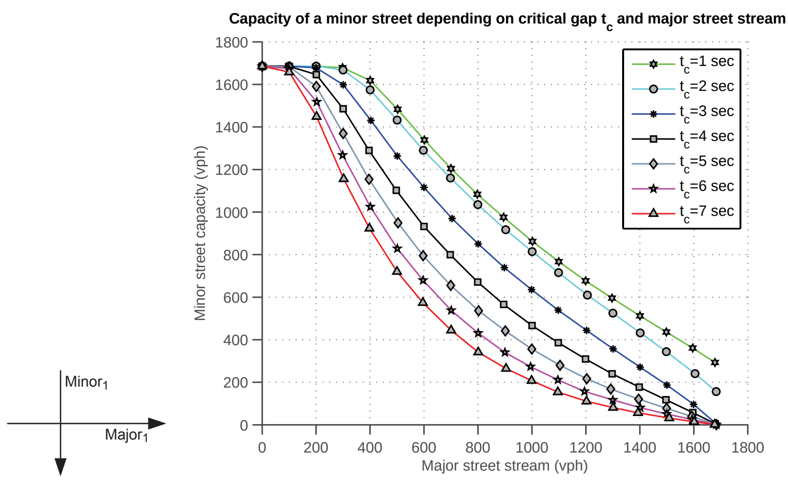


FIGURE 5
Cell layer

5 RESULTS OF SIMULATION

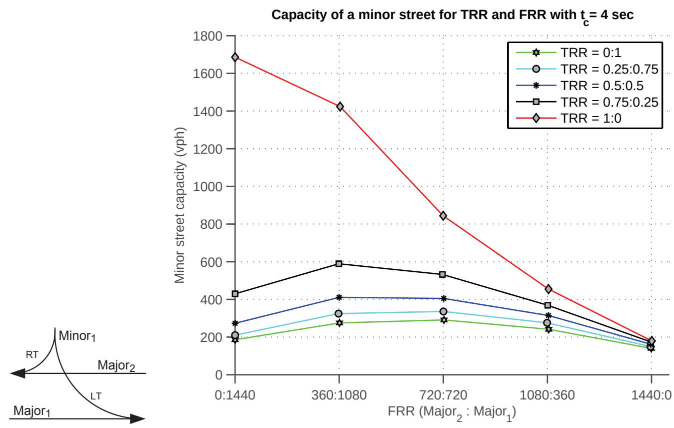
Based on the extended CA lattice of traffic network in Figure 5 and proposed vehicle behaviour supporting model, capacity of a minor street in two-way yield controlled intersection was investigated under different values of traffic flow, turning rates, and critical time gap t_c. Network was represented with cells of $\Delta s = 1[m]$ length and each iteration in the simulation was represented with $\Delta t = 1[s]$. Experiments were carried out for each parameter configuration in duration of 12 hours (equivalent to 43200 iterations) and repeated 10 times to assure that standard deviation is small enough. Each vehicle had length of $l_v = 5\, cells$, maximum speed of $v_{max} = 15\, cells/\Delta t$ (equivalent to 54 km/h) and acceleration $a = 3\, cells/\Delta t^2$. Vehicles were generated on the beginning of 200 meter long approach roads using Poisson distribution with different λ values ($\lambda = 0.1$ is equivalent to 360 vph). Driver behaviour was modelled with critical space gap g_c where aggressive drivers have lower g_s then rational and conservative drivers.

Experiment 1 in Figure 6(a) consists of vehicles in a minor $Minor_1$ and a major stream $Major_1$ that drive straight ahead, conflicting in one point at intersection. Total number of vehicles per hour in the minor stream was 2000 vph, to assure that a queue of vehicles always exists. The experiment measured capacity of the minor street under different flow of vehicles in the major street (from 0 to 1800 vph in steps of 100 vph) and different critical time gap t_c (from 1 to 7 seconds in steps of 1 second). Figure 6(b) shows results of the



(a) Vehicle streams (b) Results

FIGURE 6
Experiment 1 - Capacity of a minor street depending on critical gap and major street stream



(a) Vehicle streams (b) Results

FIGURE 7
Experiment 2 - Capacity of a minor street for TRR and FRR with $t_c = 4\,[s]$

simulation, indicating that critical time gap and major flow affects capacity of the minor street. Capacity of a minor street decreases with increase of critical time gap, but also with increase in flow of vehicles on the major street.

Experiment 2 in Figure 7(a) consists of left and right turning vehicles in the $Minor_1$ stream and vehicles in two major streams $Major_1$ and $Major_2$ that drive straight ahead at the intersection. *Turning rate ratio* (TRR) defines ratio between right and left turning rate of $Minor_1$ stream. Total number of vehicles per hour in major streams was always 1440 vph and in a minor stream it was 2000 vph. *Flow rate ratio* (FRR) defines ratio between vehicle flows in $Major_2$ and $Major_1$ streams. In experiment 2 critical headway is $t_c = 4\,[s]$. Figure 7(b) shows result of simulation, indicating that both FRR and TRR affects capacity of minor street. Capacity of minor street decrease with decrease of TRR. Drop of capacity is caused by more left turning vehicles that are in conflict not only with $Major_2$ stream but also with $Major_1$ stream. Because left turning vehicles are in conflict with two streams the probability of large enough gaps to occur is smaller then for right turning vehicles. From the results of simulations, capacity increase as FRR is closer to 1. Results from the experiments show that with the proposed model it is possible to reproduce conflicts between vehicle streams at an intersection.

6 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. 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. 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. We used developed simulation tool to simulate vehicle flows on two-way yield controlled intersection. Results show that simulation on the extended cellular lattice is capable of reproducing relationships between vehicle flows at intersections.

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