Simulating car accidents with Cellular Automata traffic flow model

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Abstract
This paper applies Cellular Automata (CA) simulation to describe the influence of a car accident in a multi-lane traffic flow model. The model consists of a main road with 3 lanes each way and two-lanes crossroads. Thus, it was also required to consider traffic lights in the model. Cars, trucks and buses completed the environment. Results considering a car accident in this complexity environment are presented.

Keywords: Cellular Automata, Urban Traffic flow model, Car accident simulation

1 Introduction
Nowadays, it is observed a considerable urbanization world-wide and an increasing growth of cars and the traffic jams. Traffic jams is one of the main components of quality-of-life in some big cities, and, decreasing them, is an important challenge. The use of computational techniques to model the traffic flow is one of the most important tools to improve the flow inside and outside cities.

Among several methods to traffic flow simulations, the ones based on the use of Cellular Automata (CA) have received an especial attention of researchers. Some papers from the 1990’s presented the bases concerning the use of CA for traffic flow [1,2,3,4,5]. These results considered the basic acceleration, deceleration, velocity randomization and velocity update rules. A review considering road traffic flow can be found in[6]. It shows that most of the concerns are related to acceleration, deceleration and lane changes for freeways.

Makowiec and Miklaszewski [7] added supplementary rules to the traditional model such a way to increase the mean velocity. It is expected that most of drivers want to travel as close as possible to the maximum allowed speed. The CA is a

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very useful and efficient method, and can be applied to online simulation of traffic flow, as presented in [8]. In [9] it was derived the critical behavior of a CA traffic flow model by means of an order parameter breaking the symmetry of the jam-free phase. Fuks [10] considered a deterministic CA model and derived a rigorous flow at arbitrary time.

Other important aspect, is the jamming caused by the reduction of the number of lanes. This reduction can be due to repairing, accidents and even because it is part of the road design. Studying the road capacity, Nassab et. al. [11] considered a road partial reduction from two lanes to one lane. The blockage of one lane, caused by an accident car, was recently studied in [12].

This paper considers the study of a car accident in an urban environment. By urban environment it is required to consider: (i) multi-lane traffic flow; (ii) crossroads; (iii) traffic lights; (iv) trucks; (v) buses and; (vi) bus stops. The presence of buses and bus stops requires specific rules which are proposed in this paper. These rules are important to the traffic flow in urban areas. Moreover, considering the aforementioned elements altogether is also an important novelty introduced in this work.

The article is organized as follows: Section 2 gives a brief review on the basic concepts of CA and illustrates some its applications. Afterwards, in Section 3, it is defined the proposed model for traffic flow micro-simulation. Results of micro-simulation, considering the occurrence of an accident, are shown in Section 4 and, finally, in Section 5 are presented the conclusions and possible future work.

2 Cellular Automata

Studies on the potential of CA started around 1950’s by von Neumann and Ulam [13]. CA is, in short, the mathematical model discrete in time, space and states. Its fundamental unit is called cell. This kind of model is based on two simple components: local rules and neighborhood. Local rules are responsible for calculating the next state of the cell, based on the influence of its neighborhood. Only with those components CA can reproduce (simulate) dynamic complex systems, ranging from biology to chemical reactions [13].

The simplest case of elementary CA is an one-dimensional array of a cells, where each cell can assume the values 0 or 1. Consider \( a_i^t \) as the state of the cell of index \( i \) at the moment \( t \), an example of local rule \( \delta \) for this elementary CA is [13] [14]:

\[
\begin{align*}
  a_i^{t+1} &= \delta (a_{i-1}^t, a_i^t, a_{i+1}^t).
\end{align*}
\]

Formally, CA is defined by a tuple \( A = (S, d, n, \delta) \), where \( S \) is set of states that one cell can assume, \( d \) is the dimension, \( n \) is the influence of the neighborhood structure over a cell \( a \), and \( \delta \) is the local rule. In a uniform CA model the same \( \delta \) function is applied over all cells, but it is possible to have different local rules for distinct sets of cells, in this case has a non-uniform or hybrid CA [15]. CA may also include stochastic elements, such as probabilistic local rules, as shown below:

\[
\begin{align*}
  \delta (.) &= \begin{cases} 
    s_1, & \text{if } p \\
    s_2, & \text{if } 1 - p
  \end{cases}
\end{align*}
\]
where $p$ is the probability of occurrence of the state $s_1 \in S$. The update of the cells may occur in a synchronous or asynchronous form. The CA is classified as synchronous if all cells are updated at the same time, but, if some parts of the model are updated at different times the CA is classified as asynchronous.

The best known application, based on CA, is the "Game of Life", created in 1970 by Conway [13] [16]. In this game each cell is a unicellular organism that can assume one of two states: 0 - dead or 1 - alive. The local rules of this game are:

- **(R1) Under population:** any living cell will die if it has less than two live neighbors;
- **(R2) Overcrowding:** any living cell will die if it has more than three live neighbors;
- **(R3) Perpetuation:** any cell will remain for the next generation if it has two or three neighboring
- **(R4) Reborning:** any dead cell will revive if it has exactly three live neighbors;

Other examples of applications based on CA are well documented in the literature, see, for instance, [17,18,19].

### 3 Model Definition

The model of urban traffic flow is implemented based on a two-dimensional Stochastic Cellular Automata, called Urban Traffic CA - UTCA. UTCA has resources capable of simulating the features of an urban traffic as main roads, secondary roads, traffic lights and bus stop. Moreover, it is possible to generate events that cause traffic jams, such as stopped vehicles and accidents. The sub sections below will detail the proposed model.

#### 3.1 Maps definitions

The cell of the model can assume one of two states: 0 - empty, 1 - occupied. All cells of the model are square with side equal to 5.5 meters. This measure represents the average sized car in the Brazil, taking into account the distance between cars. The properties of cells are defined as a triple: $c_{i,j} = \{pd, sd, vmax\}$, where: (i) $pd$ is the predominant direction; (ii) $sd$ is the secondary direction; (iii) $vmax$ is the speed limit. The predominant direction means: the direction in which the vehicle will stay longer; and, by secondary direction the change route or direction, such as lane-changing or street change. The speed limit determines how many cells can be advanced forward, at most, per iteration. Each direction $d$ has a code, and their respective sift in the axis $x$ and $y$, as can be illustrated in the Figure 1. Moreover, it allows a vehicle to move forward up to 3 cells. To indicate that a cell is not available for transit and the end of road (cell where vehicle is removed from model), two triples, $\{0,0,0\}$ and $\{9,9,9\}$, are used, respectively.

#### 3.2 Environmental rules

These are the rules that change a set of cells to implement some desired characteristics. One of the most important feature in urban traffic is the presence of traffic lights. Consider the complementary set of traffic lights $T_1$ and $T_2$, where the cells affected by these sets are defined as $T_1 = \{(x_1,y_1), (x_2,y_2), \ldots, (x_n,y_n)\}$.
Similarly, consider $T_2$, where, for example, $T_1$ is the set of traffic lights in the main road and $T_2$ in the secondary road. The complementarily, then, is defined by: $T_1(\text{Green}) \Rightarrow T_2(\text{Red})$, $T_1(\text{Yellow}) \Rightarrow T_2(\text{Red})$, $T_2(\text{Green}) \Rightarrow T_1(\text{Red})$, $T_2(\text{Yellow}) \Rightarrow T_1(\text{Red})$. The Equation 3 shows how the traffic lights can be modeled.

\[
\begin{align*}
\text{(RT)} : & \quad T(\text{Red}) \implies v_{\text{max}} = 0 \\
& \quad T(\text{Yellow}) \implies v_{\text{max}} = 1, \forall (x,y) \in T \\
& \quad T(\text{Green}) \implies v_{\text{max}} = v_{\text{max}}
\end{align*}
\]

As mentioned, the model contains features that may cause breaks in some regions, is broken by vehicles or accidents. Consider the set $A = \{(x_1, y_1), (x_2, y_2), \ldots, (x_n, y_n)\}$ as the location of the cells where the incident occurs, at time $t_0$ with $k$ iterations long. Additionally, consider $\text{cod}(A,t) = \text{cod}(A,t_0-1)$ as the cell triple code before the incident. Since the cells not available for transit is represented using \{0, 0, 0\}, then, the presence of stopped vehicle is modeled as:

\[
\begin{align*}
\text{(RA)} : & \quad \text{cod}(A,t) = 000, \quad \text{if } t \leq t_0 + k \\
& \quad \text{cod}(A,t) = \text{cod}(A,t_0-1), \text{ otherwise}
\end{align*}
\]

At the beginning and the end of each road there is one sensor. These sensors are responsible for capturing the statistics, such as, number of vehicles (flow) and their speeds.

### 3.3 Vehicles definitions

The model implemented has three types of vehicles: small vehicles, like cars, and large vehicles, such as buses and trucks. Small vehicles occupy only one cell, while large vehicles occupy three cells in length and the width of one cell.

Currently, the model considers that large vehicles can only move in the main roads and can not switch lanes or routes. Buses and trucks differ, themselves, by the fact that buses have to stop at bus stops. The vehicle models have the following...
structure: (i) kind of vehicle: 1 − car, 2 − bus or 3 − truck; (ii) vehicle location \((x, y)\); (iii) lane change indicator \((t_1)\); (iv) vehicle current speed \((vel_i)\); (v) time of the vehicle last stopped \((t_2)\); (vi) sensor identifier \((sid)\). The feature \((iii)\) is applied only when the vehicle is a car and indicates how many iterations from the vehicle changed lane for the last time. This serves to prevent the car change its lane by consecutive times. Because of this, the model does not allow a vehicle leaving right lane and go to left lane, whereas there is a central lane, instantly.

Consider a vehicle \(v_i\) in the set \(V = \{v_1, v_2, \ldots, v_i, \ldots, v_n\}\) at the moment \(t\). The location of the vehicle may be recovered by the expression:

\[
\text{loc}_i = \begin{cases} 
[x_1, y_1] = \text{posi}(v_i), & \text{if } v_i = \text{car} \\
[x_1\ x_2\ x_3] \ ' = \text{posi}(v_i), & \text{otherwise} 
\end{cases}
\]

Consider the location of all vehicles as \(\text{LOC} = \text{posi}(V)\). The function \(\text{dir}_i = \text{direc}(v_i)\), where \(\text{dir}_i = [xd, yd]\) for small cars, indicates the vehicle moving, according to the Figure 1. For instance, a vehicle is moving to the east, the function \(\text{direc}()\) will be \([xd, yd] = [1, 0]\) and \([xd, yd] = [-1, 1]\) for northwest moving. The current speed of the vehicle \(vel_i\) is accessed through the function \(\text{speed}(v_i)\).

The maximum speed that a vehicle can achieve depends on its type and its location at time \(t\), as small cars tend to be faster than large vehicles in urban traffic. The speed is computed as cells/iteration, of \(c/i\). The speed limit is calculated by the function \(v_{max_i} = \text{velocmax}(v_i, \text{loc}_i)\). The Equation 6 defines the rule for local acceleration. This rule represents the intention of the driver to speed up as possible, i.e., the speed limit of the road will be respected.

\[
(R1) : \text{vel}_{(i,R1)} = \min(\text{vel}_{(i,t)} + 1, v_{max_i}).
\]

However, we know that drivers may, so seemingly random, reduce vehicle speed. Consider \(\alpha\) as the probability of a slowing down, then the local rule for this event is given by 7.

\[
(R2) : \text{vel}_{(i,R2)} = \max(\text{vel}_{(i,R1)} - 1, 0), \text{ if } \text{rand} < \alpha_i.
\]

The previous local rule is a representation of a natural factor in the urban transit system and, in some way, can contribute to the rise in congestion. Another condition for the deceleration of the vehicle is the existence of obstacles on the road. The \(n_{free_i} = \text{gap}(v_i)\) function is responsible for identifying the maximum number of free cells in which the vehicle can move in a given direction \(d\), according to the Figure 1. The local rule for the downturn by obstacles is given by Equation 8.

\[
(R3) : \text{vel}_{(i,R3)} = \min(\text{vel}_{(i,R2)}, n_{free_i}).
\]

The rule \(R3\) simulates, to some extent, the vision of the driver, it means, the maximum that he can move is a combination of factors: the road speed limit, maximum speed that the vehicle can reach and the next obstacle.

Furthermore, it is defined in the model rules for local buses to consider the bus stops. Consider \(S = \{(x_1, y_1), (x_2, y_2), \ldots, (x_n, y_n)\}\) the set of cells located in a bus stop. For a bus \(v_i\), consider \(t_0\) the moment where \(\text{loc}_i \in S\) and \(k\) the stop duration,
with a probability \( \varphi_i \), the following sentence is true:

\[
(9) \ (RS) : \begin{cases} 
vel(i,i,t+1) = 0, & \text{if } loc_i \in S, \text{ rand } < \varphi_i, \ t < t_0 + k \text{ and } v_i = \text{bus} \\
vel(i,i,t+1) = vel(i,R_3), & \text{otherwise}
\end{cases}
\]

Finally, the movement of the vehicle \( v_i \) given the direction \( d \) of displacement \( dir_i \) can be calculated by:

\[
(10) \ (R4) : loc_i,t+1 = loc_i + vel_i,t+1 \ast dir_i.
\]

4 Simulation Results

4.1 Simulated scenarios

Ten runs were performed for each proposed scenario. Each of these scenarios simulate the transit of a town that starts the 05:00 a.m. and ends at 10:00 p.m. Here is the description of each scenario: (i) Scenario 1: No accidents happened; (ii) Scenario 2: the accident took place between 11:30 a.m. and 12:30 a.m., in the second block of the road; (iii) Scenario 3: an accident occurred between 4:30 p.m. and 5:30 p.m., in the third stretch of the road; (iv) Scenario 4: an accident occurred between 10:00 a.m. and 11:00 a.m., in the first block, and; (v) Scenario 5: an accident occurred between 10:00 a.m. and 11:00 a.m. in the fourth section of the route. The layout of the modeled map, with its main components, can be seen in Figure 2.

All these scenarios take into account the main road towards west-east. The main roads have 3 lanes, while the secondary roads have only 2. The entry of vehicles in the model, vehicle density, is given in the following way:

(i) West-east Main roads: Probability of at least 10% of a vehicle entering the model outside the time of greatest movement. This probability increases linearly up to 70% between the hours of 7:00 a.m. to 8:00 a.m.. And, 50% between the hours of 12:00 a.m. to 1:00 p.m.

(ii) East-West Main roads: Probability of at least 10% of a vehicle entering the model outside the time of greatest movement. This probability increases linearly up to 50% between the hours of 12:00 a.m. to 1:00 p.m.. And, 70% between the hours of 4:00 a.m. to 5:00 p.m.

(iii) Secondary streets: Probability of at least 10% of a vehicle entering the model outside the time of greatest movement. Inreasing 30% in the hours between 7:00 a.m. and 8:00 a.m., 12:00 and 1:00 p.m., and, 4:00 p.m. and 5:00 p.m..

For all scenarios are carried out 30% of large vehicles (between bus and trucks), and, all simulated accidents occurred on the central lane of the west-east main road, but in different blocks. It was considered that in the main roads speed limit is 60 km/h (or 3 cells per iteration), while the secondary roads is 40 km/h (or 2 cells per iteration). The maximum speed that a large vehicle (bus or truck) can reach is 40 km/h, cars and 60 km/h.
4.2 Results

The results will be displayed below, are according to the average speed obtained by the vehicles. It will show the results according to scenario 1, where no accident occurred, in the others.

In the first graph of Figure 3, it can be observed that, even though the accident occurred in the second block, it affects the average speed of the first block; which is the period between 11:30 a.m. and 12:30 a.m.. In the Second Graph of Figure 3, the same effect is observed, i.e., although the accident had happened in the third block, its effect spread out till the first one, which is the period between 4:30 p.m. and 5:30 p.m.. In the third graph there is a curious effect. It is not clear whether or not there was an accident. This is because it is a time where, normally, the average speed of vehicles has decreased naturally over the period which is from 10:00 a.m.. Finally, the fourth graph, unlike what occurred in the third, the accident that occurred in the fourth block affected the speed of the first. It can be assumed that the accident occurred in the fourth block affected the entries and exits of other roads.

In the first and third graphs of Figure 4 it was observed that the accident occurred in the second block leads the average velocity to almost zero, thus, affecting also the first block. The same effect can be observed in the second graph of the same figure, i.e., in the period 4:30 p.m. to 5:30 p.m. the average speed was near zero. As the third graph of Figure 4, the effect of the accident in the first block can not be detected in the second. Finally, the effect of the accident in the fourth block spread out to the first and second blocks (fourth graph of the same Figure).

In the first and third graphs of Figure 5 it can be observed that: accidents in the previous blocks have no effect as sharp as in subsequent blocks. To prove this we note that the second and third graphs show an average speed close to zero.

Finally, in Figure 6, the first, second and third graphics show what was done previously, that is, the events in blocks shall not create a very abrupt end when compared to the event occurring in later blocks.
5 Conclusion and Future Directions

This study have investigated the use of Cellular Automata for modeling urban areas traffic flow. For that, new rules were proposed to include the presence of traffic signs, buses, bus stops and accidents. The results showed that the approach can be used effectively to study the traffic in urban areas, as well as the effects of accidents and their consequences in traffic as a whole.

References


Fig. 3. Results for the first block to the main road towards west-east. The continuous line represents the result for the scenario without accidents. The dotted line represents the result for the scenario where there was an accident.

Fig. 4. Results for the second block to the main road towards west-east. The continuous line represents the result for the scenario without accidents. The dotted line represents the result for the scenario where there was an accident.
Fig. 5. Results for the third block to the main road towards west-east. The continuous line represents the result for the scenario without accidents. The dotted line represents the result for the scenario where there was an accident.

Fig. 6. Results for the fourth block to the main road towards west-east. The continuous line represents the result for the scenario without accidents. The dotted line represents the result for the scenario where there was an accident.