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A Study Of Vehicular Traffic Flow Modeling Based On Modified Cellular Automata

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Abstract: *Traffic flow micro simulations are popular for the planning of transport problems due to their temporal and spatial resolution. Cellular automata (CA) model are mathematical idealizations of physical systems in which space and time are discrete, and physical quantities take on a finite set of discrete values .In this paper , we are exploring the usefulness of CA to traffic flow modeling. A CA model is applied to a single-lane highway with a ring topology. Also two-lane traffic flow with lane changing is discussed. Simulations results show the ability of this modeling paradigm to capture the most important features of the traffic flow phenomena.*
Key words: *Cellular Automata, Lane Changing, Micro Simulation, Traffic Flow.*

I. INTRODUCTION

The role of the cars in everyday activities has become not only a comfort but also an essential need for contemporary life style. Traffic flow simulation plays a vital part in transport planning, it also represents the final link between the description of travel demand, the emergence of flow of densities, volumes, and travel speeds. Many scientists have tried numerous methods to develop various mathematical models (such as the car following model, the cellular automaton model, the particle-hopping model) in order to describe, explain and subsequently optimize traffic flow. This CA model belongs to the group of microscopic models but they use discrete time and space in the calculations. CA models are extremely simplified program for the simulation of complex transportation systems. From the perspective of traffic flow, it is possible to relate the cell states with the significant quantities such as travel time, vehicle speed, throughput, etc. CA models have the distinction of being able to capture micro-level dynamics and relate these to macro level traffic flow behavior.

II. LITERATURE REVIEW

The first application of the CA for simulation of traffic flows on streets and highways was introduced by Nagel and Scheckenberg [1]. CA are dynamic models developed to describe transportation phenomena .Updating obeys a finite set of local interaction rules that can have probabilistic influence. Rules of interaction can be designed for complex highway topologies, such as multilane highways [2]. In this paper,we present a CA probabilistic model for traffic simulation. The model extends the work of Nagel and Schreckenberg [1] who first introduced CA for traffic simulation and applied them in Los-Alamos-National-Laboratory [3]. Rules of interaction in Nagel and Schreckenberg, are modified to better capture driver reactions to traffic that are intended to preserve safety on the highway. As a result, a safety distance parameter is included in the model. This parameter is related to other safety analysis, as those presented in Alvarez and Horowitz [4], Godbole and Lygeros [5],, Carbaugh et al. [6] for manual and automated highway systems. By appropriately tuning this parameter, different traffic situations of manual, automated and mixed traffic can be considered. Although the CA model can be applied to multiple lane highways, in this paper a one-lane highway with a ring topology is used. The goal is to show the ability of the CA model paradigm to capture the basic phenomena of traffic flow. This closed boundary approach has been used by other authors, such as Li and Shrivastava [7], to analyze traffic flow stability. The two-lane cellular automata model based upon the single-lane CA introduced by Rickert et al. was examined [8]. A 2D extended version of the 1D Fukui-Ishibashi model, elaborated by Wang et al [9], was presented for single-lane traffic to take into account the exchange of vehicles between the first and second lane. A simple lattice-based exclusion model which can be considered as a crude representation of traffic on a two-lane motorway was introduced[10].Effect of an aggressive lane-changing behavior on a two-lane road in presence of slow vehicles and fast vehicles has been further studied [11]. A highway traffic flow model with blockage induced by an accident vehicle was introduced in which both symmetric and asymmetric lane-changing rule were adopted [12]. Simulation results presented confirm that this CA model can reproduce most common regimes in traffic free flow, transition flow and congested flow [13]. The relations derived from the density / velocity and density / flow curves are in agreement with the empirical fundamental diagrams that describe these relations in traffic analysis. The influence of the variation of speed on the flow is also found to be a factor of great importance in traffic synchronization.

III. TRAFFIC MODEL CLASSIFICATIONS

There are three types of traffic flow models.

- Microscopic models (Car following models, cellular automata models)
- Mesoscopic models (Gas Kinetic models)
- Macroscopic models (LWR models)

Microscopic models:. Microscopic modeling considers the individual vehicle's physical status and the factors that control human driving behavior. The movement of individual vehicles is governed by the driver's behavior, the road topology, the status of surrounding vehicles, and the headway distribution. Each vehicle in the traffic may be described by a set of parameters that includes position, actual speed, desired speed, route choice, and willingness to pass the other vehicles. It is very difficult to derive analytic and deterministic equations to precisely describe microscopic traffic phenomenon and quantify all the factors that control human driving behavior. Therefore, computer-based simulations are preferred over analytic models in this case. However, computational complexity increases rapidly with the number of vehicles being considered, and therefore, real-time simulation requires a tradeoff between complexity and computation costs.

Mesoscopic Models: Mesoscopic models represent a compromise between the accuracy of a microscopic model and the computational efficiency of a macroscopic model. These models are often used when real-time simulation with a high level of detail is needed [14].

Macroscopic models: Macroscopic models describe traffic with aggregate variables such as traffic density, mean speed, and volume. The use of such variables reduces the computation requirements for macroscopic modeling, making real-time calculation quite feasible. However, macroscopic models cannot estimate travel time, turning movements at intersections, fuel consumption, and control parameters on a short time scale [15].

IV. CELLULAR AUTOMATA (CA)

Cellular automata are mathematical idealizations of physical systems in which space and time are discrete, and physical quantities take on a finite set of discrete values. A cellular automaton consists of a regular uniform lattice, usually finite in extent, with discrete variables occupying the various sites. The state of a cellular automaton is completely specified by the values of the variables at each site. The variables at each site are updated simultaneously, based on the values of the variables in their neighborhood at the preceding time step, and according to a definite set of "local rules" [2]. Performance metrics are generally obtained through computer simulation of the evolution of the cellular automaton over time. The transportation simulation group at Los Alamos National Lab have developed the Transportation Analysis Simulation System (TRANSIMS) [16] are co-operating with The Centre for Parallel Computing at University of Cologne in using cellular automata for the micro simulation of traffic flow.

4.1. The Advantages of CA Traffic Flow Model

The use of the cellular automata in modeling has certain advantages, as compared to other types of models. The most important of its advantages are the following:

- The model is simple. And it is easy to be achieved on the computer.
- It can re-create all kinds of complicated traffic phenomena and reflect the properties of traffic flow.
- The roads are divided into plenty of minute lattices. The conditions of cars turning are simplified as traveling in straight lines. It can simplify the parameters of roads.
- CA model is a dynamic model, which consists of limitless discrete of space, limited discrete of state, all discrete time is integer.
- Once the local interactions between the cells are solved, the system can be increased up to any size, without any other modeling problems.
- The results of the scientific research and the experiments reported in the scientific literature prove that the traffic simulation with cellular automata is an interesting and useful research topic.

4.2. Fundamental Diagram

The fundamental diagram describes the connection between density and flow rate on the road. When the density is low, that is, vehicles are far from each other, the flow increases linearly with increasing density. When the density reaches certain value, vehicles start to 'interact' with each other, drivers become cautious and lower their velocities to maintain a safe distance to the vehicle ahead. The lowering of velocities causes the flow to decrease. As the density still increases, vehicle velocities get lower and finally a point is reached when traffic is completely jammed and the flow rate drops to zero. The diagram (b) in Fig.1 shows the qualitative velocity-dependence of vehicles on the density. In the theory of traffic flow, it is supposed that the average flow

rate (Q(ρ)) is related to the density (ρ) and the average velocity of vehicles (V (ρ)) **as** $\mathbf{Q(\rho) = \rho\, V(\rho)}$.
The fundamental diagram in Fig.1 is only qualitative and refers to a situation with vehicles moving with equal distances to each other and with the same velocity.

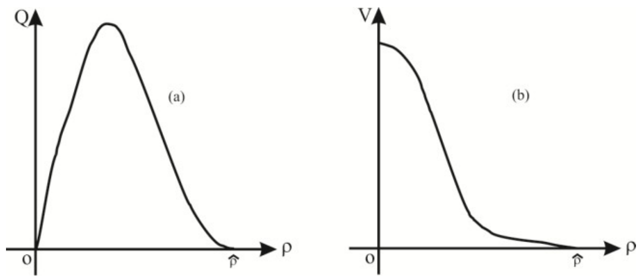


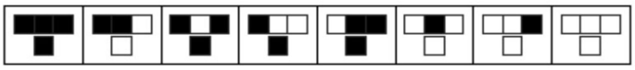
Fig.1. Qualitative forms (a) of the fundamental diagram (Q = flow, ρ = density, V = velocity) and (b) of the related dependence of the "maximal and out of danger" velocity of vehicles on the density. Here ρ^ denotes the maximal possible density of vehicles in traffic flow.

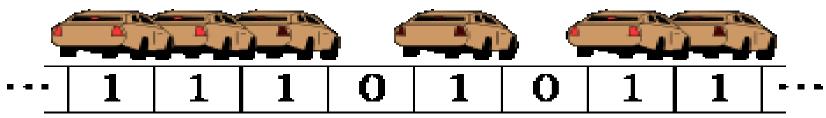
V. CA Models Using Rule 184

In each step of its evolution, the Rule 184 automaton applies the following rule to determine the new state of each cell, in a one-dimensional array of cells:

current pattern	111	110	101	100	011	010	001	000
new state for center cell	1	0	1	1	1	0	0	0

or it can also be expressed in the diagram below





According to rule 184, the evolution of a particular cell depends on its two immediate neighbors, i.e. the cells in front of and behind it. Black or "1" indicates that the cell is occupied by a "vehicles" and white or "0" indicates "empty spaces". In this diagram, "vehicles" are moving to the right. If the "vehicle" has an "empty space" in front of it, it will move one unit to the right. Otherwise, it will remain in its original cell. To further illustrate, in Box 3 and 4, there is a left black cell and white central cell at initial time step. At the next step, the vehicle in the left black cell is trans-located to the centre, since the initial central cell is empty. In Box 2 and 5, the central cell is occupied by vehicle and the right cell is empty and does not block the vehicle in the central cell. At next iteration step, the vehicle in the central cell proceeds and empty cell is obtained.
Under this rule, the number of filled cell, which indicates the occupancy by a vehicle, does not change, or the density of 1's is conserved.

1. Acceleration of free vehicles	IF (v < vmax) THEN v = v + 1
2 .Slowing down due to other cars	IF (v > gap) THEN v = gap
3. Stochastic driver behavior	IF [(v > 0) AND (rand < pnoise)] THEN v = v − 1
4. Driving	The new velocity v_n for each car n has been determined forward by v_n cells: $x_n \rightarrow x_n+v_n$.

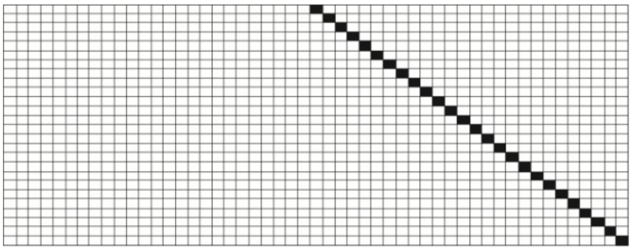


Fig.2. The simulation result of rule 184 after 25 time-steps

VI. NaSch MODEL – KAI NAGEL AND MICHAEL SCHRECKENBERG MODEL

In Nagel's paper, a simplified approach of CA model is adopted. In this model, a simple single-lane CA is set up. To describe the state of a street using a CA, the street is first divided into cells of length 7.5 m. This corresponds to the typical space (car length + distance to the preceding car) occupied by a car in a dense jam. Each cell can now either be empty or occupied by exactly one car. Each vehicle is characterized by its current velocity v which can take the values $v = 0, 1, 2,... ,v_{max}$.

Here v_{max} corresponds to a speed limit and is therefore the same for all cars (in the simplest case). The maximum velocity is defined to be 5 cell length, which corresponds to 37.5/s or 135 km/h .The number of unoccupied cells between two consecutive vehicles is defined as "gap". In a single-lane CA model for traffic flow, the following rules are applied in each iteration, which corresponds to 1 second of real time.

The simplest rule set, which leads to a realistic behavior, has been introduced in 1992 by Nagel und Schreckenberg [8]. It consists of 4 steps that have to apply at the same time to all the cars (parallel or synchronous dynamics).

6.1 Forward rules

In each of the iterations, the following 3 steps are carried out sequentially. In step 1, the vehicle is accelerated by 1 cell-length if its velocity is smaller than vmax. This is based on two assumptions that 1) Drivers always try to maximize their speed and 2) The acceleration of vehicle is constant at 7.5m/s^2 for all vehicles traveling at all speeds below vmax.

Step 2 states a safety measure. It forces vehicles which travel at v greater than gap to slow down to v = gap. Step 3 takes other factors that may slow the driver down, such as less smooth roads, into account. P_{noise} is a predefined parameter representing the probability with which the vehicle is slowed down by 1 unit, such that $0< p_{noise} <1$. In each of the iterations, a random number generator generates a number, which is then compared with p_{noise}. When (v > 0) AND (rand < p_{noise}), v is decreased by 1 cell-length. Note that in this model, v is an integer number of cell-length, i.e. multiples of 7.5 m/s.

VII. MODIFIED NAGEL CA MODEL

The model presented here is a probabilistic CA. It consists of N vehicles moving in one direction on a one -dimensional lattice of L cells arranged in a ring topology. The number of vehicles is fixed. Each cell is either empty or is occupied by just one vehicle traveling with velocity, v that takes values ranging from 0 to v_{max} . The typical length of a cell (Δx) is around 7.5 m. It is interpreted as the length of a vehicle plus the distance between vehicles in a jam, but it can be suitably adjusted according to the problem under consideration. The time step (Δt) is taken to be 1s. Therefore, transitions are from $t \rightarrow t + 1$. This time step is on the order of human's reaction time. It can also easily modify. With these values of Δx and Δt, $v = 1$ corresponds to a vehicle moving from one cell to the downstream neighbor cell and translates into 27 km/h. The maximum velocity is set as $v_{max} = 5$, which is equivalent to 135km/h. Units in position x denote the number of cell in the lattice; in velocity v, number of cells per unit time, and in time t, number of time steps.

Let v_i and x_i denote the current velocity and position of vehicle i and v_p and x_p be the velocity and position of the vehicle ahead (preceding vehicle) at a given time , $d_i = x_p - x_{i-1}$ denotes the distance (number of empty cells) in front of the vehicle in position x_i.

State transitions are defined with the following set of rules, which are applied simultaneously to all vehicles.

S1 : Acceleration : If $v_i < v_{max}$ the velocity of vehicle i is increased by one.

$$v_i \rightarrow \min (v_i + 1, v_{max}).$$

S2: Randomization : If $v_i > 0$, the velocity of vehicle i is decreased randomly by one with probability R.

$$v_i \rightarrow \max (v_i - 1 ,0) \text{ with probability R.}$$

S3: Decelaration : If round $(d_i + (1 - \alpha) v_p) < v_i$, the velocity of vehicle i is reduced to round $(d_i + (1 - \alpha) v_p)$.

$v_i \rightarrow \min(v_i, \; \mathrm{round}(d_i + (1 - \alpha)\, v_p))$, where the function round truncates its argument to the closest integer.

S4: Vehicle Movement : Each vehicle is moved forward according to its new velocity determined in steps 1 to 3.

$$x_i \rightarrow x_i + v_i$$

Rules S1, S2 and S3 are designed to update velocity of vehicles; rule S4 updates position. According to this, state updating is divided into two stages, first velocity and second position. Rule S3 is the main modification to the model in Nagel and Schreckenberg that will be referred to as the NaSch model.

VIII. SIMULATION RESULTS

To simulate the CA model of the previous section, a closed system with $L = 10^4$ cells, representing a one-lane loop, is used. N vehicles are randomly distributed on the lane around the loop with an initial speed taking a discrete random value between 0 and vmax. Since the system is closed, the average density, $\rho = N / L$, remains constant in time. Different values of N, R and α were simulated. Each run was simulated for $T = 6 * L$ time steps. To analyze results, the first half of the simulation was discarded to allow the system to reach its steady state. For each simulation, a value for parameter α was established to set the desired degree of safe distance among vehicles.

For example, the value α = 0 corresponds to minimal safety requirements allowing vehicles to occupy neighboring cells at high speeds. A convenient way to demonstrate that the model reproduces traffic flow behavior is to plot the fundamental diagrams, that is, the relation between flow and density.

Fig.3 shows the fundamental diagram obtained for different values of α and a fixed value of R = 0.4. Each plot in Fig.3 is composed by the results of many simulations using the same value of R and values of number of vehicles N ranging from 0 to L. The value of N / L for each simulation is in the horizontal axis, while the average flow for that run of N is in the vertical axis. Fig.5 also illustrates the impact of the driving strategies coded in α. The maximum flow changes with the inverse of α, i.e. smaller values of α imply larger flows.

It is interesting to note that values of α = 0.25 and α = 0.5 lead to forms of the diagram which are significantly different from the other cases, indicating a mixed condition where the maximum flow is attained with a non-maximal velocity. This is due to the presence of platoons of vehicles traveling at high speed in a synchronized fashion. The value of the density for maximum flow ρ_m decreases with smaller values of α, when α ≤ 0.5. It is also note that for low densities and all values of α , the slope of the fundamental diagrams is similar, indicating that vehicles travel at near maximum speed, while the slope in the congested region is only equal for values of α ≤ 0.5, indicating a similar velocity behavior for this situation.

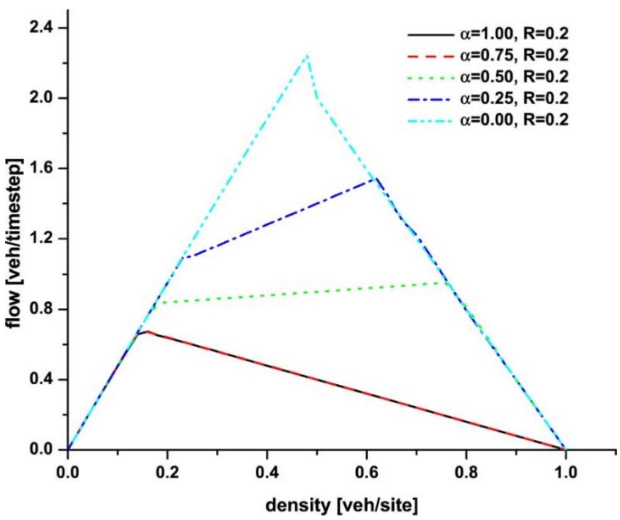


Fig.3. Fundamental diagram for different values of safety factor α, and noise R = 0.4.

Fig.4 shows the velocity diagram corresponding to the same simulation conditions as in Fig.3.Here note that due to the presence of rule S2 the velocity does not reach the value of v_{max}.

The effect of the parameter R, that represents the probability of traffic disturbances, is shown in Fig.5, where the induced velocity reduction due to large values of R can be appreciated. The greater its value, the smaller the flow, for the same density values. The location of ρ_m is pushed to the left for greater values of R.

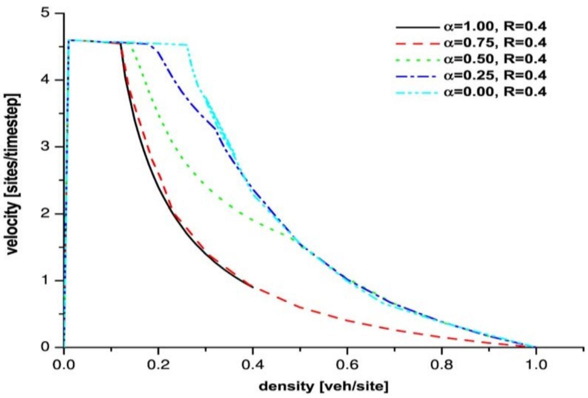


Fig.4. Relationship between mean velocity and density for R = 0.4 and different values of α.

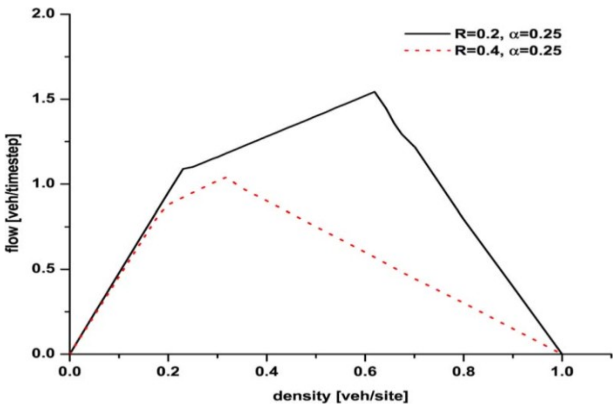


Fig.5. Fundamental diagram for safety factor α = 0.25 and different values of R.

Fig.6 corresponding to R = 0.2 shows that for α ≥ 0.5 the fundamental diagram is the same as in Fig.5. This indicates that when inter-vehicle distance is large, a probability of disturbances does not alter traffic flow.

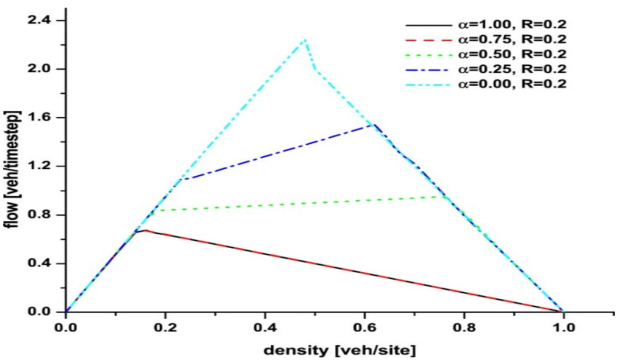


Fig.6. Funamental diagram for different values of the safety parameter α and R = 0.2

By comparing the maximum flow and the maximum speed variance for α = 0 and α = 0.25, it is noted that the maximum flow for α = 0 is 12% higher than for α = 0.25. However, the maximum speed variance at α = 0.25 is 50% smaller than for α = 0. This is a consequence of the safety distance factor. When this factor is higher, there exists a smaller propagation of fluctuations that prevent variations of speeds by the formation of platoons or clusters of vehicles.

IX. TWO LANE CA MODEL

The single lane model is very inadequate for realistic modeling purposes. In reality, vehicles would be moving in a multi-lane road. The next logical step after modeling single lane traffic is to model two-lane traffic. Nagel and Schreckenberg [9] introduced a two lane model consisting of two parallel single lane models with periodic boundary conditions and four additional rules defining the exchange of vehicles between the lanes. A basis for modeling the lane changing is as follows.

Rule 1: Check ahead your current lane if another car is in your way.
Rule 2: Check ahead on the other lane if it is better there.
Rule 3: Check back on the other lane if you would get in the way of another vehicle.
Rule 4 : Based on the result of the first three rules, decide whether to remain on the same lane or change to the other lane.
Using these rules and the algorithm for the one-lane model, we can add the following algorithm for lane changing:

Incentive Criteria Rule : $d_n < \min\{v_n + a, v_{max}\}$

Improvement Criteria Rule : $d_{n,other} > d_n$

Safety Criteria Rule : $d_{n,back} > v_{max}$

where $d_{n,other}$, $d_{n,back}$ denote the number of empty cells between the n[th] and its two neighbor vehicles in the other lane at time t, respectively. If all rules are satisfied then the vehicle will change lanes.

X. CONCLUSION

In this paper, we explored the usefulness of cellular automata to traffic flow modeling. We extended some of the existing CA models to capture interesting characteristics of traffic flow that have not been possible to model using either conventional analytical models or existing simulation techniques. Using CA models, we were able to examine higher moments of traffic flow, which we show to behave in a rather unexpected fashion. We also showed that CA models are more amenable to modeling multi-lane traffic. Lane changing rules and behavior can be explicitly accounted for in the model. The impact of these rules and behaviors becomes then easier to examine. Simulation results illustrate that this model captures the essential features of traffic flow encoded in the fundamental diagram, while preserving simplicity that allows rapid simulation that can prove useful for application to large scale traffic networks.

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