IMPROVING CELLULAR AUTOMATA MODELING OF HIGH SPEED TRAFFIC FLOW

Renatus Mussa[1] and Victor Muchuruza[2]

ABSTRACT

The use of high velocity updates in cellular automata modeling regardless of initial vehicle speeds and their unbound deceleration rates is unsuitable when modeling traffic flow in high-speed roadways, particularly limited access facilities. To remedy the situation, a vehicle movement logic that uses kinematic equations is proposed. In this logic, a driver's decision to accelerate or decelerate is set to depend on the relative speed and available space gaps in relation to the lead vehicle. Special features of the proposed model are the ability of the vehicle to occupy multiple cells and dependence of the position update on the kinematic equations. The simulation model was tested on a 4.8-km long, single lane roadway in which traffic is not interrupted by presence of interchanges. The simulation modeling results indicated that the kinematic-based modeling approach reduced erratic acceleration behavior observed in the ordinary CA traffic models particularly when traffic is transitioning from free flowing to jammed conditions.

KEY WORDS

Cellular automata, traffic modeling, traffic flow

INTRODUCTION

The development of traffic micro simulation models has received considerable attention in the past few decades. An increasing number of researchers in numerous disciplines have tackled various aspects of microscopic simulation using either numerical simulations or analytical solutions. The microscopic simulation models built through these research efforts have been encouraging based on the fact that the models have been able to reproduce relatively accurate traffic flow relationships. One of the new areas of micro simulation that has gained considerable attention in both traffic science and engineering is cellular automata (CA). The CA systems are defined as dynamical systems which are discrete in both space and time. CA operate in a uniform regular lattice and are characterized by local interactions. Modeling of traffic flow using CA simulation was made possible through the assumption that the traffic stream is composed of identical entities which interact locally—i.e. the motion of a subject vehicle is only affected by neighboring vehicles on the road. The CA traffic models aim at modeling the actions and reactions of the vehicles as accurately as possible in a discrete fashion. By using property of CA rule 184, which is also referred to as traffic rule (Wolfram 1986) it was possible to simulate vehicle movements on the road. Nagel and

---

[1] Associate Professor, Department of Civil and Environment Engineering, FAMU-FSU College of Engineering, 2525 Pottsdamer Street 129, Tallahassee FL 32310, Phone: (850)410-6191, Fax: 410-6142, mussa@eng.fsu.edu
[2] Graduate Student, Department of Civil and Environment Engineering, FAMU-FSU College of Engineering, vmuchuruza@eng.fsu.edu

Schreckenberg (1992) were among the first researchers to recognize the capability of the CA rule 184 in traffic flow micro simulation. They modified this rule to enable vehicles to evolve with different velocities during simulation. Another form of CA traffic model was proposed by Fukui & Ishibashi (1996). The major difference between Nagel & Schreckenberg model and Fukui & Ishibashi model is that the former allows a gradual acceleration of the vehicle while the later allows abrupt increase in acceleration whenever there are empty spaces ahead. The advantages brought about by having gradual acceleration have made the Nagel & Schreckenberg model to have a widespread acceptance in the modeling community. Cellular automata modeling dicretizes the roadway into cells wither occupied by a single vehicle or are empty. Simulation and analytical results obtained from these models were able to reproduce basic traffic flow characteristics such as the formation of traffic jams and fundamental relation between speed, density, and flow.

CA models that use the logic proposed by Nagel & Schreckenberg was applied in developing TRANSportation SIMulation (TRANSIMS) software by the Los Alamo laboratory and other simulation tools that simulate urban networks (Nagel *et al.* 1997, Simon & Nagel 1998, Hafstein *et al*. 2003). The advantages of CA traffic models is based on their use of very simple vehicle position update rules and quick realization of numerical simulation due to the use of integer numbers. However, these models are deficient when modeling high speed traffic. For example: the failure of these models to mimic driver behavior at the transition from free flow to congested traffic flow conditions can reproduce unrealistic traffic operations in high-speed situations. In addition, the unbound deceleration component used in these models results can cause erratic jumps from high speeds to low speeds— e.g. a vehicle can decelerate from 85 mph (i.e., five cells per second) to zero mph in just one second. Unlike other microscopic simulators that use car-following logic, deceleration in CA is modeled by using a simple rule that forces a vehicle to slow to speeds equal to the amount space gaps ahead. Further, many prevailing CA models employ higher position updates that are independent of the vehicles' initial speeds—e.g. in one second a speed change equal to 27 kph (i.e., one cell per second) can be realized. This is equivalent to an acceleration rate of 8 m/sec^2.

Recent developments in the CA modeling has led to the introduction of velocity-dependent randomization and anticipation (e.g., Li *et al* 2001, Lárraga 2004), and slow-to-start rule for vehicles starting from rest (e.g., Benjamin *et al* 1996) in order to improve the vehicle movement logic in the model proposed by Nagel & Schreckenberg. Another improvement in CA modeling was suggested by Knospe *et al* (2002) in which the desire of the driver to attain smooth and comfortable driving is considered. Despite these efforts to improve the CA modeling, more realistic traffic flow can be achieved by enhancing the decelaration rules using in CA modeling. The study reported herein is an effort to improve CA modeling by evaluating the efficacy of a new deceleration rule.

The paper introduces an extension of probabilistic simulation of CA traffic model. In particular, an attempt is made to simulate traffic using field-derived vehicle and driver characteristics. Kinematic equations are introduced to improve stochastic and dynamics of vehicular traffic flow on high speed highways. Driver's decision to accelerate is based on the relative speed between the subject vehicle and the leading vehicle together with the available space ahead. Using this approach, the erratic nature of the ordinary cellular automaton traffic model is expected to be reduced especially in the transition phase from free flowing traffic to jammed traffic conditions. The new movement logic is tested on the single-lane uninterrupted traffic. The performance of the simulation model is verified by examination of macroscopic traffic characteristics—average speed, density, and traffic flow. The following section discusses the approach used in modeling. The section thereafter discusses the testing and verification of the model. At the end of the paper, conclusions and directions for future research is discussed.

MODELING APPROACH

For simplicity, all vehicles were assumed to have a common average length. Vehicle and driver entities were modeled as a single object comprising both properties of vehicles and drivers. At a minimum, the vehicle-driver object contained the basic integer-based attributes such as average speed, position, desired speed, current acceleration, and vehicle unique identification number. The roadway was discretized into cells which, at any instant, were either occupied by objects or were empty. Object oriented programming was used to program into a computer a single-lane mainline road with an entrance node and an exit node. To attain random traffic flow in the simulation, random numbers were used to assign the driver-vehicle parameters. Every driver was assigned a desired speed generated from the distribution of real-life speed data collected from a section of an interstate freeway in Florida. The use of the desired speed from the underlying speed distribution is a paradigm shift from the ordinary CA models that use a single value, i.e., speed limit, as the desired speed for all drivers. The simulation model keeps track of the number of vehicles in the system by taking into account the vehicles that enter and leave the simulation system. The movement of the vehicle in the simulation system depends on the number of empty cells ahead.

Three parameters were assumed to affect driver's choice of speed and hence the acceleration of the vehicles in the model. These were the desired speed, the following distance, and the relative speed. Introduction of relative speed into the model is an attempt to bridge the car following theory and the CA models. It is worthy mentioning here that in the logic proposed by Nagel & Shreckenberg (1992), the driver choice of speed is affected by the speed limit and the amount of gap ahead.

The first kinematic equation ($v_f = v_i + at$) and third kinematic equation ($v_s^2 = v_l^2 + 2a\Delta x$) were used to model the acceleration and deceleration of the vehicles. In these equations, v_f = the new speed (in ft/sec) of the subject vehicle after being accelerated at a ft/sec^2 in time t from an initial speed v_i. The parameter v_s = initial speed of the subject vehicle and v_l = initial speed of the leading vehicle. The parameter Δx = the distance between the rear bumper of the leading vehicle and front bumper of the subject vehicle (in ft). The third kinematic equation calculates the deceleration rate of the subject vehicle when it is moving faster than the leading vehicle—i.e., closing conditions. The position of the subject vehicle was updated by using the average speed, $\bar{v}$, and the elapsed time. The equation used was $x_f = x_i + \bar{v} \times t$ where x_f and x_i are the new and old positions of the subject vehicle, respectively. The advantage of using average speed in updating the vehicle's position is the reductions of over displacements of the vehicles in the simulation model because of the consideration of both the initial and final speeds of the vehicle. Conventional CA models use the final speed in updating the position of the vehicles.

The distance traveled by the subject vehicle, $x_{Follower}$, should be less or equal to the sum of the space headway and the distance, x_{Leader}, that the leader will travel in the next time step in order to ensure a crash-free movement, i.e., $x_{Follower} \le (spacing - s') + x_{Leader}$. The space headway is the clearance between the rear bumper of the leading vehicle and the front bumper of the subject vehicle in which *s'* = the minimum spacing that the driver is willing to maintain in congested traffic conditions. This minimum spacing (or bumper to bumper distance in jammed traffic conditions) for each driver was slightly varied about a mean minimum value. Observations of vehicle movements on real life roadways showed that drivers in the congested traffic conditions tend to keep a minimum safe spacing which is different for each driver but a minimum value of 3 meters was assumed. Utilizing the condition of the crash free movement, the final speed that the subject vehicle was therefore determined as $v_{f,Follower} = \min\left(v_i + a.t,\ 2 \times \left(x_{Leader} + spacing - s'\right) - v_{i,Follower}\right)$.

As discussed earlier, the modeling of the desire of the driver to accelerate was based on relative speed, the space headway, and the desired final speed that the driver wishes to accelerate to. A rule-based acceleration algorithm was devised, which enables the driver to choose the type of motion based on the state of the prevailing traffic state. Four prevailing traffic states were created, i.e., free flowing, dense equilibrium, congested, or emergency state. Driver action in each traffic state is shown in Table 1. Modeling of the rule-based acceleration logic employed *if-then* statements based on the relative speed and space headways.

Table 1: Rule-Based Acceleration Model

Traffic State	**Description**	**Subject driver's action**
Free-flowing	Road near empty, there is no influence of the leading vehicle.	• Accelerates to reach the desired speed. • Cruises at the desired speed
Dense equilibrium traffic	Approaching a relatively slow moving vehicle.	• Decelerates so that the relative speed is zero and seeks to maintain the desired following distance.
	Following the leading vehicle subject vehicle has a lower speed.	• Accelerates if the spacing is large enough. • Driver cruises keeping the desired following distance. • The relative speed oscillates around zero.
Emergency situation	The leading vehicle suddenly decelerates.	• Driver applies high deceleration rate to avoid collision.
Traffic Jam	Road nearly full of vehicles, the leading vehicle in a stop and go movement.	• Driver keeps the minimum following distance either cruising, accelerate or decelerate.

MODEL TESTING AND VERIFICATION

The simulation model was implemented in C++ programming language where the roadway and driver-vehicle objects were created. The simulation was tested on a 4850-m single-lane roadway. The roadway object was made up of 0.60-m cells—i.e. the total length of the roadway was 8000 cells. The use of small cell width enabled collection of several speed bins as well as improved the acceleration nature of the traffic. Average vehicle length of 6 meters was used; therefore the driver-vehicle object occupied multiple cells at one time. Inside the driver-vehicle object is where the vehicle acceleration algorithm was placed. The simulation model was characterized by the following parameters: acceleration rates of 1 m/sec^2 (when speed is greater than 105 kph) and 1.2 m/sec^2 (when speed is less than 104 kph), deceleration rates of 2.4 m/sec^2 and 4.8 m/sec^2 for normal and emergence maneuvers, respectively. A fluctuating safe minimum gap was set at a mean of 3 meters and a common variance of 0.3 m, average car length of 6 m and free flowing gap of 90 m was assumed. The desired speed of the driver was obtained from a real life speed distribution collected from a section of interstate freeway. The vehicle speeds were updated in parallel and a random value which reduced the speed of some of the vehicles by 1 m/sec was used to enhance stochastic behavior of traffic flow. This randomization is another paradigm shift from conventional CA models in which all vehicles are randomized at a particular time step. After the model compiled successfully, it was run to simulate traffic behavior using constant flow rates in different simulation runs. The free flow condition was characterized by generating a low traffic flow rate.

The model verification was performed by examining the correlations between macroscopic parameters collected at a virtual detection point following equilibration of the simulation system. The simulation was assumed to have reached equilibrium when the number of vehicles within the simulation system remained constant—that is, number of vehicles entering and leaving the system were equal. The virtual detection point was set at the middle of the roadway where microscopic metrics were collected every one second after equilibrium was reached. The time average statistics of the microscopic metrics (i.e. average speed, flow, and density) were collected after every 30 seconds.

Correlations between macroscopic statistics are shown in the fundamental diagrams depicted in Figure 1. Figure 1 shows that as the density increases the speed of traffic decreases almost exponentially. At low densities the speed of traffic is nearly constant; this is the region of free flowing condition where vehicle interactions are minimal. Correlation between speeds and traffic flow presented in Figure 1 looks similar to the correlations that are presented in HCM (TRB 2000) based on the real life traffic data collected from roadway sections experiencing uninterrupted flow conditions. Both saturated and unsaturated traffic flow conditions were observed in this correlation. However, in the transition area the traffic pattern is somewhat undefined. This is the region where vehicles enter or exit the congestion wave. The variation of the traffic density with flow is also depicted in Figure 1. This variation shows that maximum flow occurs when density is about 22 vehicles per kilometer—beyond this density value, traffic flow is unstable. Results displayed in the figures show scattered data points in the unstable flow region perhaps because aggressive and nonaggresive drivers produce varying headways in congested conditions. It is worthy mentioning that although static flow rate was used in each simulation run, the model itself allowed the headways to vary because of the acceleration logic used.

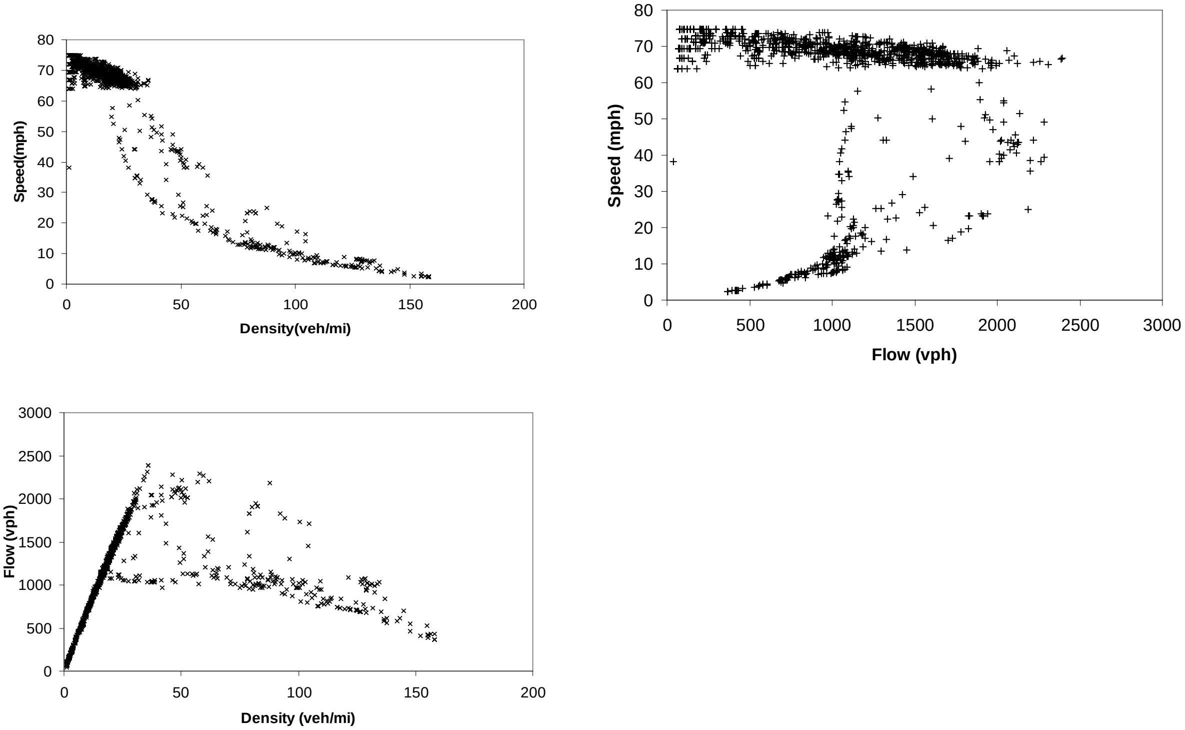

Figure 1: Fundamental Diagrams of Speed, Flow, Density Relationships

Comparison of the behavior of traffic in the model using kinematic equations and the acceleration logic used in convention CA was performed by changing the kinematic acceleration logic in the model to the conventional CA model acceleration logic. The logic used in the conventional CA models has unbounded deceleration rates, and the position update is done using the final speed of the subject vehicle independent of the initial speed in the given time-step. Using this modification, the lag vehicle position update function was: $x_f = x_i + v_f$ where $v_f = \min(v_i + a, v_{desired}, spacing - s')$. The position update was done in parallel and a randomization parameter introduced where all vehicles speeds were reduced by 1cell/sec. It is worthy mentioning that other parameters used in the kinematical based model remained the same The results obtained from using conventional CA rules are superimposed in the correlation plots obtained from kinematical based model and shown in Figure 2.

Examination of Figure 2 further shows that traffic flow characteristics obtained from using conventional CA rule only matches with the one that were obtained from kinematic-based rule in the free flowing and congested conditions. This may be caused by abrupt high decelerations of the vehicles present in the conventional CA model—i.e. vehicles can decelerate very quickly from high speed to very low speed. The kinematical based model allows gradual deceleration by considering relative speed of the subject vehicle and available space gaps in the rule-based acceleration model.

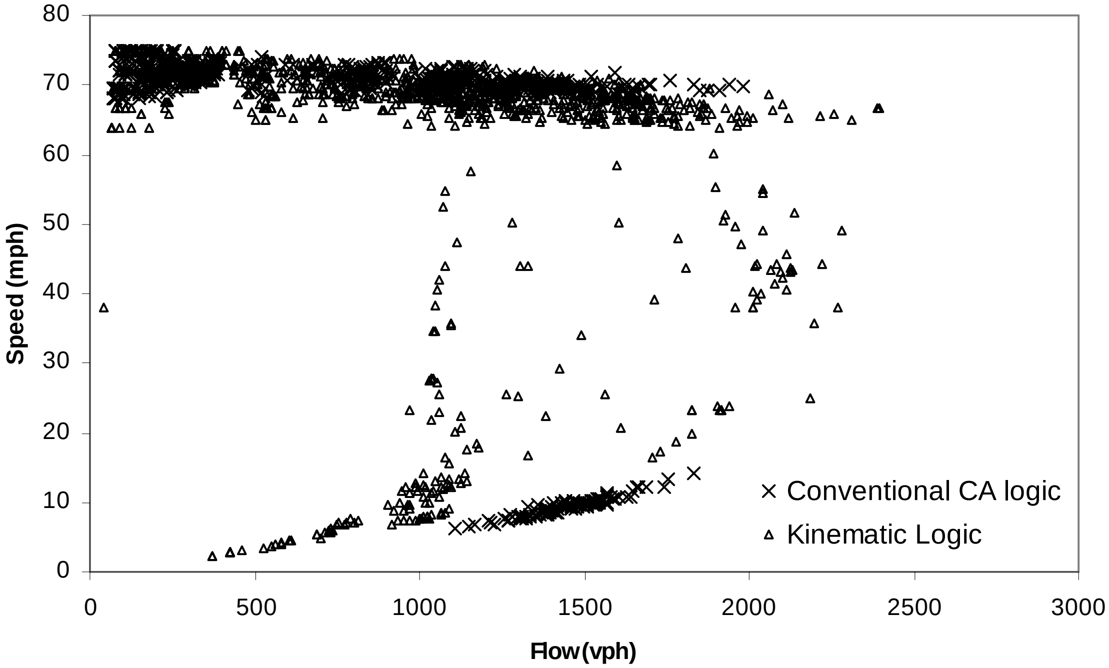

Figure 2: Correlation between speed and flow

Individual behaviors of all vehicles in the simulation model were examined using time-space trajectories plots. The observations of the vehicle trajectories showed that in the light traffic conditions when vehicle interactions are minimal, few or no traffic jams were formed at all. However, in dense traffic conditions, there was a considerable formation of the traffic jams. One interesting finding seen in Figure 3 is the back propagation of the jam. The dark spots observed in this figure indicate that the slope of the line decreases meaning that the speed of the vehicle has dropped. Closer tracing of the movement of a single vehicle revealed that when the driver is in the dense traffic condition, the driver might be in a stop and go motion most of the time. The length of the reduced slope may indicate the amount of time that the driver is in stop and go situation. A vehicle leaving a jam tries to accelerate faster to its desired speed (steep slope after dark spots) but since the traffic is still dense, the desired speed is hard to be attained and later the vehicle may be caught in another jam caused by deceleration of the leading vehicle. This may be the explanation for many dark spots after the onset of the first jam.

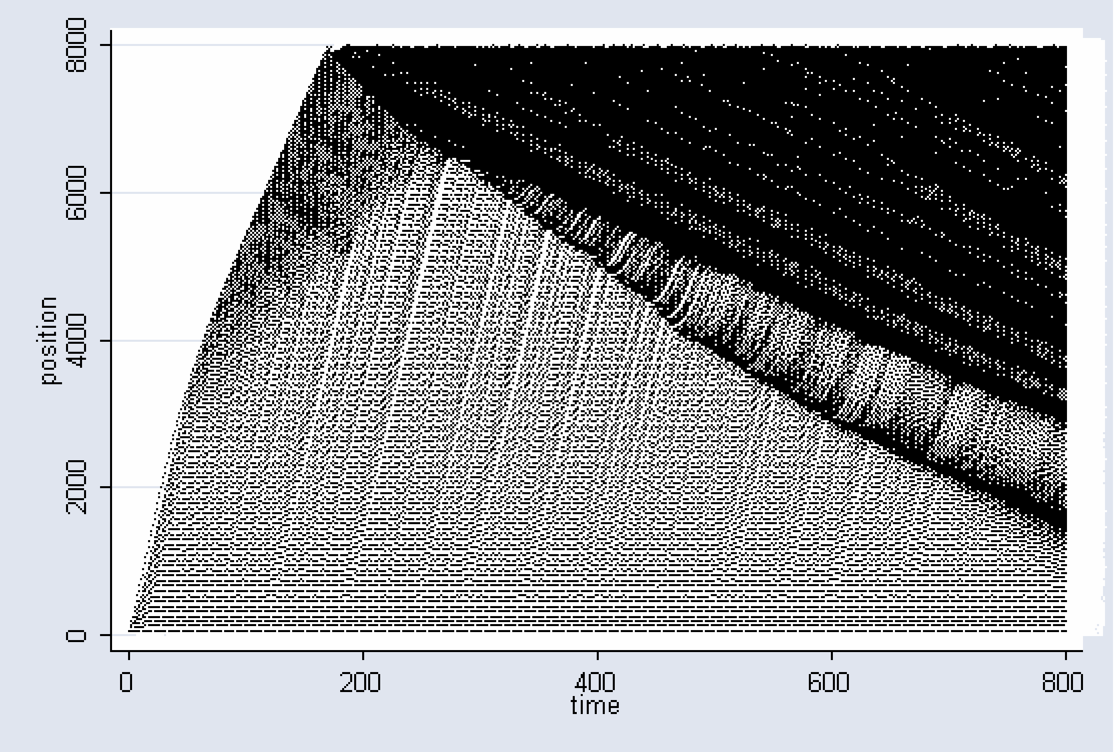

Figure 3: Jam formations in heavy traffic flow conditions

CONCLUSIONS AND LIMITATIONS

This paper introduced another form of cellular-based traffic simulation model that uses kinematic equations and rule-based acceleration logic. The modeling effort was part of the ongoing research on modeling traffic conflicts and crashes using CA micro simulations. The objective of the research reported herein was to improve the acceleration logic in the CA model in order to reduce unbounded deceleration rates. In the proposed model, a vehicle position on the highway was updated using kinematic equations. The results showed improvement in vehicle flow dynamics. The model was verified by analyzing the plausibility of the relationship between average speed, density, and flow rate. Time step trajectories of individual vehicles were also used to verify the formation of back propagation jams in dense traffic condition. Comparison of the proposed model results to the results of the conventional CA model showed that the proposed model faired better in depicting traffic flow in the transition from free-flowing to congested traffic conditions.

Although the simulation results reported herein showed interested pointers, work is still in progress to improve the ability of this model to represent traffic dynamics on high speed roadways such as freeways. The major limitation of this model is the use of the single lane of traffic which does not allow passing of vehicles. Part of the work currently in progress includes applying the model to multilane highways with on and off ramps and a mixture of different driver-vehicle entities that have different acceleration and reaction capabilities.

REFERENCES

Nagel, K ., and Schreckenberg, M. (1992). A Cellular Automaton Model for Freeway Traffic, *Journal Physique 2*, 2221-2229.

Fukui, M., and Ishibashi, Y. (1996). Traffic Flow in 1D Cellular Automaton Model Including Cars Moving with High Speed. *Journal of Physics Society of Japan 65,* 1868-1870.

Wolfram, S. (1986). *Theory and Application of Cellular Automata*. World Scientific, Singapore.

Li, X, Qingson, W., and Jiang, R. (2001). Cellular Automaton Model Considering the Velocity Effect of a Car on the Successive Car. *Physical Review E 64,* 066128, 1-4.

Lárraga, M. E., del Rio, J. A., and Schadschneider, A. (2004). New Kind of Phase Separation in a CA Traffic Model with Anticipation, *Journal of Physics A: Mathematical and General, 37 (12),* 3769- 3781.

Benjamin S. C, Johnson, N. F., and Hui, P.M. (1996). *Journal of Physics. A: Mathematical and General 29(12),* 3119-3127.

Knospe, W., Santen, L., Schadschneider, A., and Schreckenberg M. (2002). Towards a Realistic Microscopic Description of Highway Traffic. *Journal of Physics. A: Mathematical and General, 35 (15),* 3369- 3388.

Special Report 209: Highway Capacity Manual. (2000). 3rd Ed. Transportation Research Board, National Research Council, Washington, D.C.