A CA-based Model for Simulating Vehicular-Pedestrian Mixed Flows in a Congested Network

Xin Zhang (Corresponding Author)
Department of Civil and Environmental Engineering
University of Maryland, College Park, MD 20742
Phone: (301)-405-2638
Fax: (301) 405-2585
Email: zhangxin@umd.edu

Gang-Len Chang
Department of Civil and Environmental Engineering
University of Maryland, College Park, MD 20742
Phone: (301)-405-2638
Fax: (301) 405-2585
Email: gang@umd.edu

Submission Date: 7/31/2010
Word Count: 6135+ 16 (14 figures + 2 tables) × 250 = 10135

Paper submitted for the 90th annual meeting of the Transportation Research Board
January 2011, Washington D.C.

ABSTRACT

In design of evacuation plans for major metropolises, it should be recognized that a potentially large number of evacuees depend either on transit or other modes for evacuation, or need to walk over a distance to access their cars. In the process of approaching some designated pick-up points or intermediate destinations, the massive number of pedestrians may incur tremendous burden to vehicles in the roadway network. Hence, development of a simulation tool, capable of replicating the realistic road condition for both the pedestrian and vehicle flows under the chaotic situation, is an imperative task. Such a simulation tool should be able to account for individual behaviors as well as all kinds of interactions, including conflicts between pedestrians, between vehicles, and between pedestrians and vehicles. Despite the increasing use of traffic simulation as the primary analysis tool, effective mechanisms to simulate the mixed vehicle-pedestrian flows under congested environments remains at its infancy. In this study, we attempt to address this vital subject with the Mixed-Cellular Automata (MCA) method. Our proposed simulation model has integrated the strengths of the CA method with some probabilistic functions, offering a realistic mechanism to reflect the competing and conflict interactions between vehicle and pedestrian flows. Although the development remains at its preliminary stage, our experimental results clearly indicate that failing to account for the impact of mixed flow interactions in a congested traffic system could result in far underestimate of the delay, travel time, and system throughput.

1. INTRODUCTION

In design of evacuation plans for major metropolises, it should be recognized that a potentially large number of evacuees depend either on transit or other modes for evacuation, or need to walk over a distance to access their cars. In the process of approaching some designated pick-up points or intermediate destinations, the massive number of pedestrians may incur tremendous burden to vehicles in the roadway network. Hence, development of a simulation tool, capable of replicating the realistic road condition for both the pedestrian and vehicle flows under the chaotic situation, is an imperative task. Such a simulation tool should be able to account for individual behaviors as well as all kinds of interactions, including conflicts between pedestrians, between vehicles, and between pedestrians and vehicles

In review of simulation literature, it is clear that many traffic simulation programs for different purposes have been developed. Examples of simulation tools developed over the past several decades are INTRAS [1], CARSIM [2], INTEGRATION [3], THOREAU [4], PARAMICS [5], DYNASMART [6], MITSIM [7], TRANSMIS [8], INTELSIM [9], CORSIM [10], AIMSUM [11], ARCHISIM [12], CELLSIM [13], VISSIM and TRANSMODELER.

Depending on the embedded logic for replicating the traffic flow characteristics, one can classify all existing simulation programs developed with classical traffic flow theory into three distinct categories: macroscopic [14, 15] [16, 17], microscopic [18-22] [23-26] and mesoscopic [27, 28] models. Since the properties of pedestrian flow and its interaction with vehicles have not been adequately addressed by the traffic flow community, most existing traffic simulation programs are not capable of realistically replicating the interactions between the mixed pedestrian-vehicle flows.

Instead of grounding the logic on a well-established traffic flow theory, some researchers have explored the Cellular Automata (CA) methodology to develop low-fidelity micro-simulation models that can account for the interactions between pedestrian and vehicle flows by dividing both the time and the space into discrete units and update the flow movements with a set of local rules. Due to its simplicity for computer implementation, such models are quite efficient for large-scale network simulation [29] or online simulation [30].

Examples of simulation model developed with such a method include a pioneering stochastic CA model (NaSch model) to study the 1-dimensional vehicle traffic in 1992 [31], and its later extensions to replicate various vehicle traffic phenomenon [32-41]. Some researchers also extended these CA-based simulation models to multi-lane roadways by incorporating some deterministic [42] or stochastic [43, 44, 45] lane-changing rules. In order to overcome the shortcomings of applying cellular automata (CA) and car following (CF) theories independently, Bham et al. presented a traffic simulation model, CELLSIM, that integrates CA and CF models in the simulation process [46].

With respect to the simulation of the pedestrian flow dynamics, some researchers proposed the use of the LG (Lattice Gas) models and the FF (Floor Field) models. The LG model [47-72] belongs to the CA model and is its special case, which is most suitable for bi-directional flow studies. The floor field concept was introduced by Schadschneider et al. [73, 74] to enhance the CA modeling methodology, which was inspired by the process of chemotaxis as used by some insects [75]. Friction and repulsion [76, 77] parameters are later introduced to the floor field model to represent the hesitation and reaction of the pedestrians.

One of the pedestrian flow simulation issues reported in the CA-application literature is the diagonal movement. Although some studies have addressed this issue [78], most of existing CA-based simulation models view the diagonal move in the same manner as with the lateral or parallel movements. However, such a simplification could yield unrealistic results for simulating massive pedestrian flows over a long walking distance.

On the subject of mixed pedestrian-vehicle flows over a congested network, only very limited number of studies has been reported in the literature. Among those, Helbing and Jiang [79] proposed a macro model to investigate analytically the oscillations and delays of pedestrian and vehicle flows. Jiang and Wu [80, 81] explored a simple lattice gas model to study the vehicle and pedestrian flows in a narrow channel. All such models presume that the moving directions of both types of traffic flows are given. Muhammed and Noland [82] studied the pedestrian traffic with VISSIM, where vehicle and pedestrian modes actually are operated independently and controlled by the traffic signals at potential conflicting areas. The inevitable conflict between vehicle and pedestrian flows over a congested network, which could incur a chaotic state especially during emergency evacuation, has not been addressed yet by any existing traffic simulation model.

Note that the conflicts between vehicle and pedestrian flows often occur at those areas without adequate control devices, e.g., parking areas, un-signalized intersections. For example, Figure 1 gives a road network with one intersection, which has 2 OD-pairs for the vehicles and 2 OD-pairs for the pedestrians. Assuming that the pedestrians stick to the rules that crossing can only occur at the intersection, Figure 1 depicts several possible paths for each OD-pair and the potential conflict locations. There are three types of potential conflicts: between pedestrians and pedestrians, between vehicles and vehicles, and between pedestrians and vehicles.

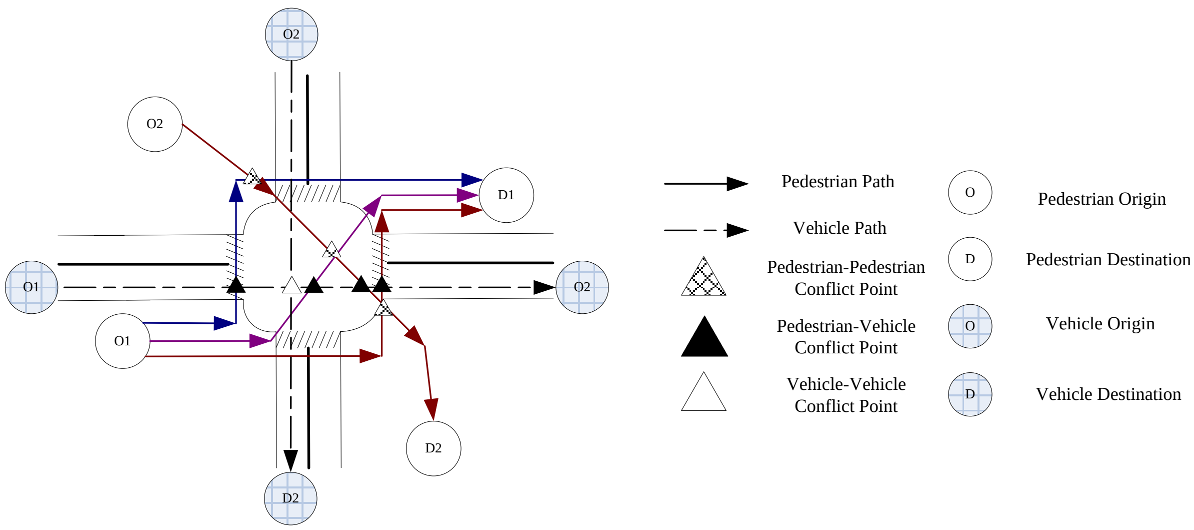


Figure.1. Example of Mixed Flows at an Intersection

In modeling the mixed flow dynamics and their complex interactions, several critical issues as indicated below need to be addressed:

1) How to model the real-time way finding decision of the pedestrians and drivers. First one needs to identify a route from his/her origin to destination, and then based on the real-time road condition to make necessary adjustments

2) How to model pedestrian and vehicle movements along any possible directions. In Figure 1, the pedestrians may make diagonal moves at the intersection or at any other locations. Although the vehicles are confined by the boundaries of lanes at road segments, they are likely to take diagonal movements when making turns at intersections.
3) How to model these three types of potential conflicts as depicted in Figure 1. Under most circumstances, the conflict is solved by one individual yield to the other. In most existing simulation models, the vehicle-vehicle and pedestrian-pedestrian conflicts have been well addressed. However, few have dealt with the pedestrian-vehicle conflicts.
4) How to model the dynamic driving and walking behaviors of each individual. In most simulation models, an individual's driving or walking decision doesn't always vary with encountered traffic conditions. Under the mixed-flow scenario where a driver is conflict with a crossing pedestrian, the longer the individual has been waiting behind the line, the less likely for the person to yield to the pedestrian. Thus, a dynamic behavior mechanism associated with the waiting times needs to be modeled in the simulation of evacuation traffic flows.

In this study, we attempt to address these issues one by one in the following sections with the Mixed-Cellular Automata (MCA) model that will take the following steps to simulate the mixed vehicle-pedestrian flows:

1) For each vehicle, update the position at the current time interval t, based on the direction and speed of the former time interval $t-1$.
2) For each pedestrian, update the position at the current time interval t, based on the speed of the former time interval $t-1$.
3) For each vehicle, determine its target position for the next time step $t+1$ at the current time interval t based on the static floor field model.
4) Check whether there are any potential vehicle-vehicle conflicts, in other words, whether there are more than one vehicles sharing the same target position, and solve the conflict by adjusting target cells.
5) For each pedestrian, determine his/her target position for the next time step $t+1$ at the current time interval t.
6) Check whether there are any potential pedestrian-pedestrian conflicts, or whether there are more than one pedestrian sharing the same target position, and solve the conflict by adjusting the target cells.
7) Check whether there are any potential vehicle-pedestrian conflicts, or whether there are both pedestrians and vehicles sharing the same target position, and solve the conflict by adjusting the target cells.
8) Reposition the target cell of an individual to his/her current cell with a probability term to model the hesitation of an individual when attempts to move during extremely congested conditions.

A position update procedure, including the diagonal movements, will be presented below for the Step 1) and Step 2), and a static field model will be applied to Step 3) and Step 5). For Step 4), Step 6) and Step 7), a competition factor concept is proposed and the conflicts are solved via competitions. The competition factor is modeled as a function of the waiting time where its two parameters of the function can be adjusted to represent the different levels of aggressiveness and patience of the individual.

2. Mixed CA Model

Model formalization

The MCA model applies the formal definition of Cellular Automata (Weimar 1998) for both the vehicles and the pedestrians. To simulate the evolution of both vehicle and pedestrian flows over the network, this study first creates two layers of lattices. Consider the set of $(L^v, S^v, N^v, L^p, S^p, N^p, f^{p,v})$, where the superscript v denotes the vehicle cells and p denotes the pedestrian cells, and:

L^v : Set of vehicle cells of the lattice

S^v : Set of states of the vehicle cell,

N^v : Set of neighbors of the vehicle cell

L^p : Set of pedestrian cells of the lattice

S^p : Set of states of the vehicle cell,

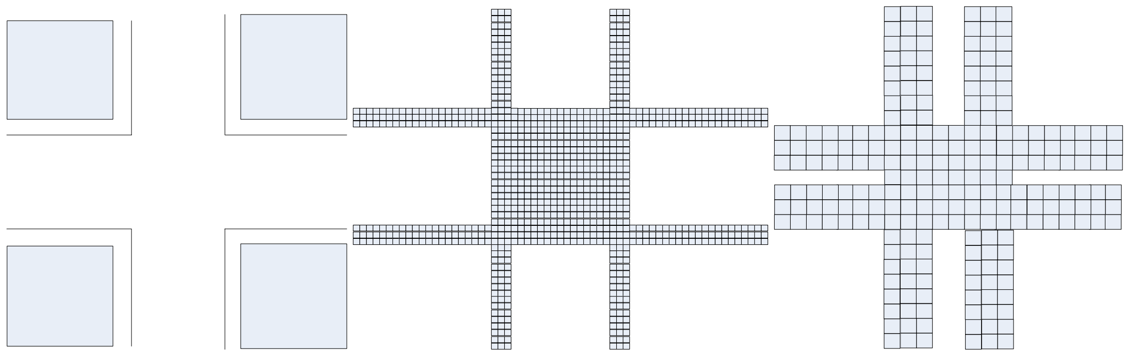
N^p : Set of neighbors of the vehicle cell

$f^{p,v}$: Transition function.

Our proposed model has the following key features:

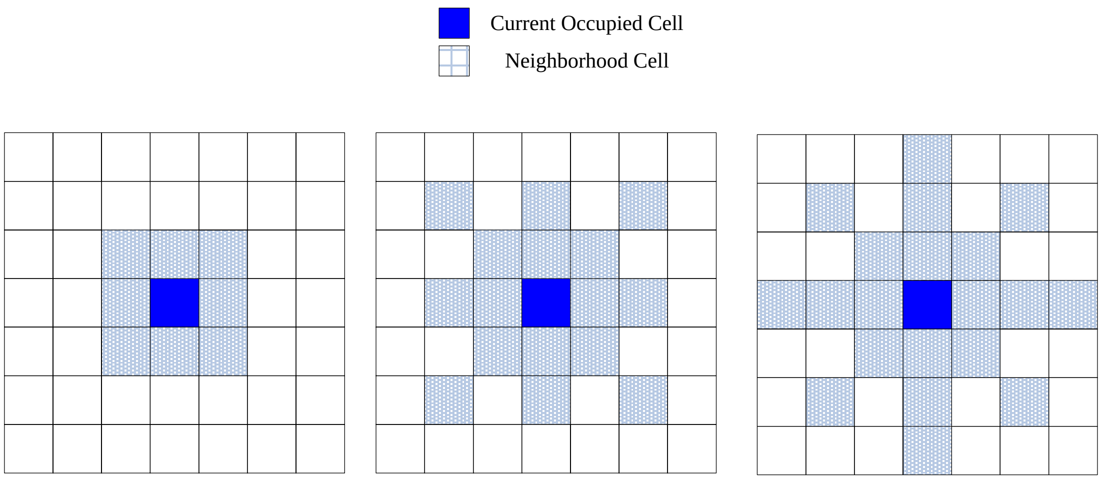
- The study area is divided into two overlapped layers of rectangular grids, and their cell sizes are determined by the space a vehicle and a pedestrian can occupy. Each cell can only hold one vehicle or pedestrian.
- The maximum speed of a pedestrian is 1 pedestrian cell per time step.
- The vehicle or pedestrian always moves in a straight line at each time step.
- Pedestrians are grouped by their origins and destinations, and given a floor field for their needs
- Pedestrians will always try to move to the neighborhood closest to their final destinations
- Some random terms are used to reflect the non-deterministic decision behavior.

In our model, the lattice is two-dimensional, so $L^v(i, j)$ gives the coordinates of the vehicle cell (i, j) and so is with $L^p(i, j)$. Taking a simple intersection in Figure 2(a) for example, Figure 2(b) presents the pedestrian cell lattice and Figure 2(c) illustrates the vehicle cell lattice. There are two possible states for each cell, $S^v = \{0,1\}$ or $S^p = \{0,1\}$ indicating whether the cell is occupied or not at a certain stage. The neighborhood of a cell, varying with the maximum velocity of an individual is defined as all the cells reachable within one time step of the speed. Figure 3 shows the neighborhood of different maximum velocities from 1 cell to 3 cells per time step. Transit function $f^{p,v}$ deals with conflicts and be able to check both layers and generate a feasible transition.



(a) (b) (c)

Figure.2. Cell Lattice Representation of an Example Intersection



Maximum Velocity = 1 Maximum Velocity = 2 Maximum Velocity = 3

Figure.3. Neighborhood Cells for Different Maximum Velocities

Position update for the diagonal movement:

Most CA models referred in the literature above simulate the diagonal movements in the same way as with vertical and horizontal movements. However, in reality, the distance of diagonal moves are longer than vertical or horizontal moves. For example, in Figure 4, a vehicle moves at a speed of 4 cells/time interval. For vertical moves, it traverse 4 cells per unit time, while for diagonal moves, it can only traverse 4/1.5=2.66 cells per unit time since the diagonal movements is 1.5 times the horizontal/vertical movements. Most CA models don’t account for such a difference, and thus could move the individual at an unrealistic speed. To provide a realistic representation of such a diagonal move, we propose the following maximum speed reservation technique:

1. First, move the target individual to the new position with the current moving velocity.
2. To keep the position still right on the grid, we need to perform a repositioning process. Two candidate points are selected as shown in Figure 4. A probability is assigned to each for selection. The probability is determined by the distance between the current position and the candidate point.
3. The maximum speed for the current interval is adjusted by the amount we have rounded up to eliminate the error created in the repositioning process.

In Figure 4, the velocity of the individual is 4 cells per time step. Thus, if undergoing a diagonal move, he/she will fall between the point C between cell A and cell B. However, in the CA model, the position of each individual should be exactly in a cell rather than somewhere between cells. By applying the procedure above, the probability of the individual falls on point A or point B can be calculated as: $P(x_{i,t} = A) = \dfrac{d_{AC}}{d_{AC} + d_{BC}}$, $P(x_{i,t} = B) = \dfrac{d_{BC}}{d_{AC} + d_{BC}}$ where, $P(x_{i,t} = K)$ is the probability the individual falls on point K, and d_{mn} is the distance from the point m to the point n . In either case, the maximum velocity of the next time interval can be calculated as: $v_{i,t}^{\max} = v_{i,t-1}^{\max} + d_{AC}$ and $v_{i,t}^{\max} = v_{i,t-1}^{\max} - d_{BC}$, respectively, where $v_{i,t}^{\max}$ is the maximum speed of the individual i at time step t.

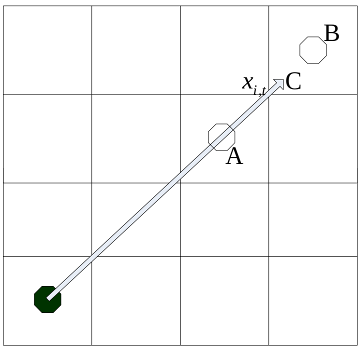


Figure.4. Example of Diagonal Moves

Static Floor Field

To model the real-time way-finding behavior, one needs to update the perceived shortest path to the final destination at every simulation time-step. This process often causes a great computing burden to the system. Rather than globally updating the paths, we adopt the notion of a static floor field (Burstedde and Schadschneider, 2001) for a real-time decision, based on the local neighborhood information. A value is assigned to every cell to represent the shortest path distance from that cell to the final destination. Usually cells with lower values are closer to the destination and thus the floor fields in the neighborhood of an individual can help decide where to move since they always prefer to move to a cell with a lower value than the current one. Notice that if a path contains diagonal moves, the path length should reflect the difference from a vertical or horizontal move. Thus, we assign a value 1.5 rather than 1 if we encounter such a move. Figure 5 gives an example of the static floor fields, given the upper-right destination cell. Assuming that the individual resides in the current cell, the arrow line denotes the shortest path to the destination cell. Since the path consists of 2 diagonal and 3 upward moves, the distance is 2*1.5+1*3=6, which is defined as the floor field value.

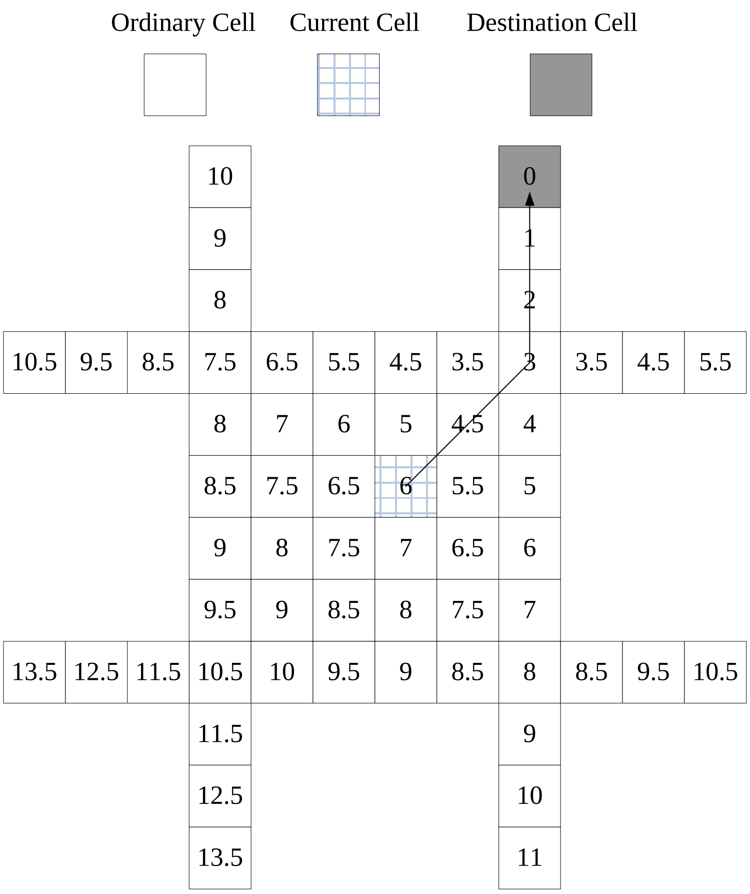


Figure.5. Static Floor Field of an Example Intersection

It is reasonable to assume that an individual will decide the target cell to move, based on the floor field values at each time interval. Two assumptions are made here regarding the decision making process:

(1) An individual only attempts to move to an unoccupied cell or remains still at a given time interval; and

(2) An individual has a larger probability to move to a cell closer to the destination.

To model the probability of moving to a certain neighborhood cell or remaining still, we define a utility function $U_{(i,j)->(k,l)}$ for the possible movement from cell (i, j) to cell (k,l). The utility function represents the gain from the choice made. Given the utility functions of all the possible movements, one can express the probability of a particular movement from cell (i, j) to cell (k,l) as follows:

$$P_{(i,j)->(k,l)} = \frac{e^{U_{(i,j)->(k,l)}}}{\sum_{\forall (k',l') \in \Gamma(i,j) \cup (i,j)} e^{U_{(i,j)->(k',l')}}} \qquad (1)$$

In Equation (1), $P_{(i,j)->(k,l)}$ is the probability of an individual moves from cell (i, j) to cell (k,l) and $\Gamma(i, j)$ is the set of unoccupied neighborhood cells of the cell (i, j). Equation (1) implies that an individual is more likely to take a movement of a higher utility.

In order to link the utility function to the static floor fields, we interpret the gain as the reduced distance toward to the destination due to the movement. Thus, the utility function can be expressed with Equation (2):

$$U_{(i,j)->(k,l)} = \alpha(M_{i,j} - M_{k,l}) \qquad (2)$$

In Equation (2), $U_{(i,j)->(k,l)}$ is the utility an individual gained by moving from cell (i, j) to the cell (k,l), $M_{i,j}$ is the floor field of cell (i, j), and α is an adjustable parameter.

For example, in Figure 6, the bold number in each cell is the floor field value and the number in brackets denotes the cell index. Consider an individual in cell (5) who is making a choice of movements out of 9 possible options: moving to 8 directions or remaining still. By setting $\alpha = 1$, one can use the above equation to compute the probability of moving up to each of these 9 directions. The probabilities for moving to each of these nine movements are shown in the set $(0.07, 0.2, 0.31, 0.04, 0.2, 0.11, 0.01, 0.02, 0.04)$.

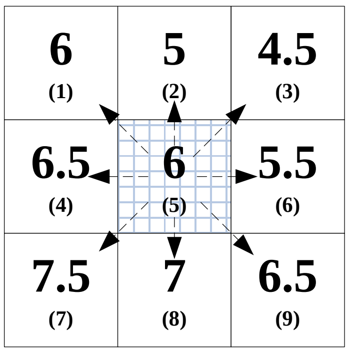


Figure.6. An Example of Decision Making for the Next Movement

Competition factor:

Whenever there are more than one individual targeting the same cell, a conflict and competition will take place. The individuals compete for the cell. In this study, we employ the competition factor attached to each competitor to approximate the likelihood for an individual to win the competition. In general, the more waiting time an individual has endured, the more aggressive he will be. When a vehicle-pedestrian conflict happens, the same mechanism is used. By denoting the competition factor and the current waiting time of the individual i at time step t as $\mathrm{K}_{i,t}$ and $W_{i,t}$, then the competition factor is a function of the current waiting time, that is; $K_{i,t} = f_i(W_{i,t})$. While the exact functional form should be estimated from the field data, we adopt a linear relationship as follows in this study; $K_{i,t} = K_{i,0} + \alpha W_{i,t}$. $K_{i,0}$ can be interpreted as the initial aggressiveness of the individual i, and α as the patience factor. Hence, a larger α implies a rapid increase in aggressiveness, and thus is less likely to yield to others.

Pedestrian-Pedestrian conflict

If multiple pedestrians are targeting the same cell, they shall compete the opportunity of moving based on their current competition factors. For example, in Figure 7, three pedestrians are competing the same cell, and the probability of the i-th pedestrian will win is $P_i = \frac{K_{i,t}^p}{\sum_{i'} K_{i',t}^p}$.

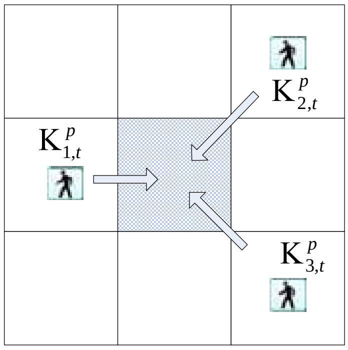


Figure.7. Example of Potential Pedestrian-Pedestrian Conflicts

Vehicle-Vehicle conflict

Since the vehicle speed at a time interval may exceed one cell per time step, all cells from the current position to the target position should be checked to see if any other vehicle may use one of these cells towards its target position. Once all the potential conflicting vehicles are identified, we can adopt a similar approach described previously in solving the pedestrian-pedestrian conflict. For example, in Figure 8, three vehicles are in a potential conflict, and the probability of the i-th vehicle will win is $P_i = \frac{K_{i,t}^v}{\sum_{i'} K_{i',t}^v}$.

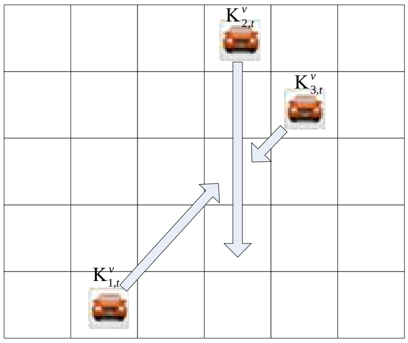


Figure.8. Example of Potential Vehicle-Vehicle Conflicts

Pedestrian-Vehicle conflict

For each vehicle in the simulation process, one needs to check whether there exists any conflict with pedestrians along its trajectory. Using the same notion for resolving the conflict, we can compute the probability of a vehicle moving along all pedestrian cells in its trajectory one at a time.

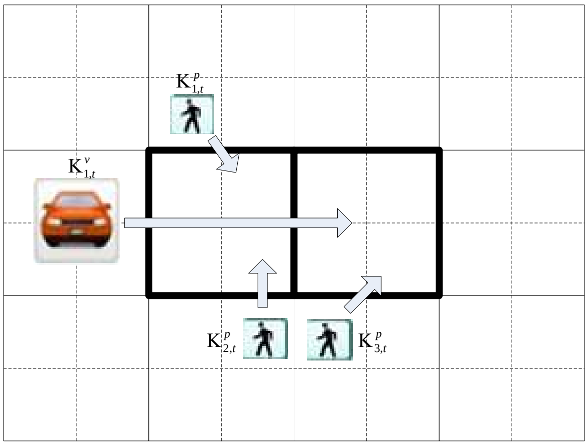


Figure.9. Avoid Potential Pedestrian-Vehicle Conflicts

For example, in Figure 9, the vehicle's trajectory includes two vehicle cells in the bold borders. The first bold vehicle cell overlaps with four pedestrian cells, two of which are also the target cells for two pedestrians, respectively. Thus, the vehicle is in conflict with the two pedestrians. Similarly, the vehicle is also in conflict with another pedestrian in the second bold cell. In our procedure, the vehicle has to compete with the pedestrian cell by cell. In the example above, the vehicle compete with the two pedestrians in the first cell, and then go on to the second cell if it wins. For a given cell, its winning probability of moving forward, P_i, can be calculated as: $P_i = \dfrac{K_{i,t}^{v}}{K_{i,t}^{v} + \sum_j K_{j,t}^{p}}$

3. Driver Behavior Analysis

To capture the impact of various driver behavior patterns on the actual traffic conditions, Figure 10 presents an example segment of roadway with a crosswalk. Pedestrians are assumed to cross the crosswalk from both sides and the vehicles are moving in both north and south directions. Assuming that all pedestrians have an identical competition factor function, Figure 11 presents the interrelationship between the waiting time and the resulting competition factors of three driver types under our adopted simulation mechanism.

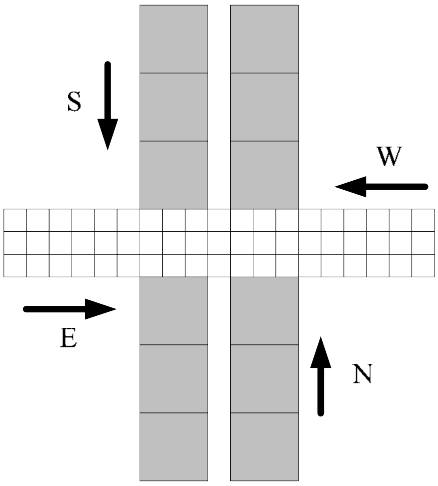


Figure.10. A Two-way Road with a Crosswalk

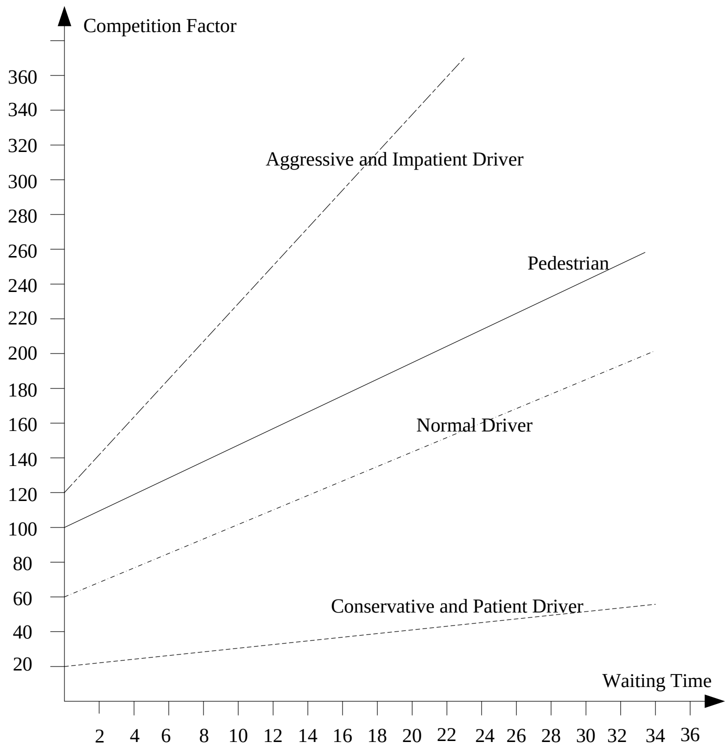


Figure.11. Competition Factors of Individuals

Figure 12 presents the simulation results with respect to the intersection throughput under these three types of driver populations. The numerical results indicate the following relations:

(1) Fewer vehicles can go through the intersection under higher crossing pedestrian flows. There is a sudden drop of vehicle throughput from the no-pedestrian to the low-pedestrian throughput cases, mostly because of the transition from the continuous flow to the stop-and-go traffic conditions.

(2) When the pedestrian flow level reaches a certain threshold, the vehicle flow drops to zero, which indicates a total blockage of vehicles by the pedestrians

(3) Aggressive and impatient drivers are more likely to win the competition of a certain cell over the rival pedestrians, thus more vehicles can go through the conflict zone within the same time window

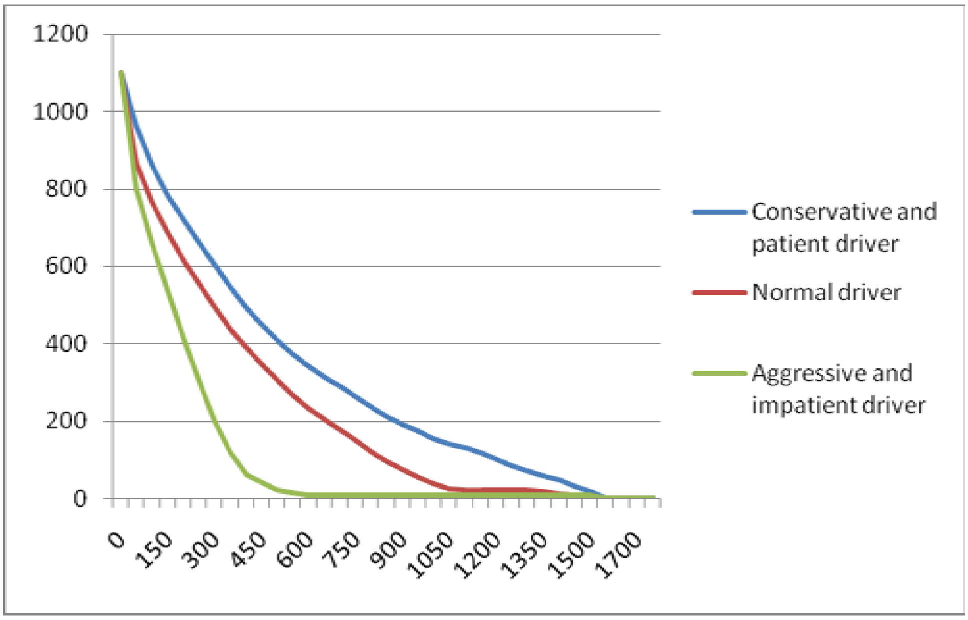


Figure.12. Throughput Information of Different Driver Behaviors

4. Numerical Example

To illustrate the needs of accounting for vehicle-pedestrian interaction in simulating a mixed-flow network, we apply our model to the road network between the entrance gate on US1 and the Stamp Union of the University of Maryland, College Park (See Figure 13). The vehicle and pedestrian demands are listed in Table 1, where the behavior of pedestrians and driver types are assumed to follow these in Figure 11. The distribution of the different driver types is depicted in Figure 14.

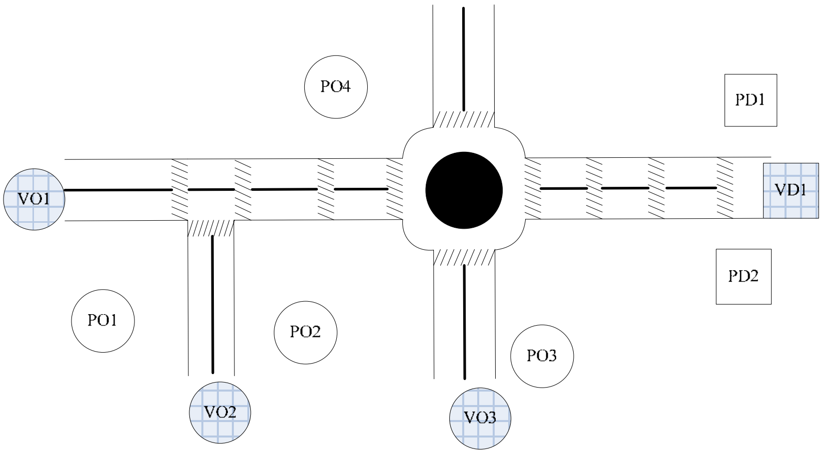


Figure.13. The Road Network between Gate and Stamp Union

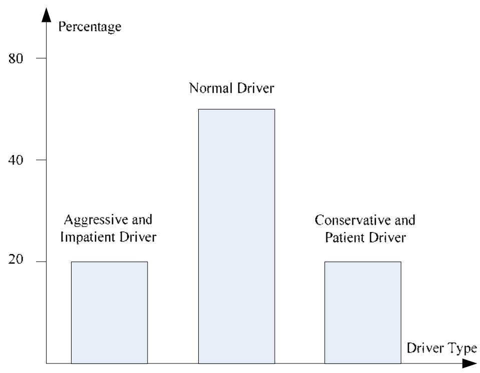


Figure.14. Distribution of Different Driver Behaviors

TABLE 1 Vehicle and Pedestrian Demand

	Origin	Destination	Demand
Pedestrians	PO1	PD1	200 ped/hour
		PD2	200 ped/hour
	PO2	PD1	200 ped/hour
		PD2	200 ped/hour
	PO3	PD1	200 ped/hour
		PD2	200 ped/hour
	PO4	PD1	200 ped/hour
		PD2	200 ped/hour
Vehicles	VO1	VD1	300 veh/hour
	VO2	VD1	300 veh/hour
	VO3	VD1	300 veh/hour

The analysis results presented hereafter are based on the following two simulation experiments:

(1) One hour simulation with our proposed mixed-flow model; and

(2) One hour simulation using the commercial traffic simulation software, Transmodeler 2.5

Transmodeler 2.5 can only model pedestrians on the crosswalks, so we assume the pedestrians will always take the shortest paths and set the path flow on the crosswalks as the accumulated path flows. The average measures of effectiveness over 10 replications with these two simulation methods are listed in Table 2:

TABLE 2 Measures of Effectiveness of the Two Simulations

	Mixed-Flow Simulation		Trans-modeler Simulation	
	Pedestrians	Vehicles	Pedestrians	Vehicles
Total Throughput	927	421	1042	652
Average Delay (s)	15.14	126.51	13.58	79.21

As expected, by considering all possible conflicts within a mixed flow traffic system, both individual and vehicles will experience much longer delay than those from simulation programs without adequately accounting for this vital issue. This overall system throughput under such a traffic system is likely to be overestimated with existing simulation models.

5. SUMMARY AND CONCLUSION

This paper has presented a simulation model to simulate the mixed vehicle-pedestrian traffic movements. The proposed model divides the space into discrete cells and develops a set of rules to emulate local and global interactions between the individual vehicle and pedestrian. The floor field concept is applied to model an individual’s way-finding process toward his/her current target cell. This proposed method dynamically updates paths without overburdens the computation. The concept of competition factor is put forward in this model to resolve the conflict issues among individual pedestrians and vehicles. A linear function of waiting time is used to model the aggressiveness and patience of an individual. Also, unlike most previous CA models, our proposed model has accounted for the diagonal movements in a network, making the mixed-flow movements more realistic and practical

An illustrative example presented in the paper seems to indicate that the pioneering study offers some promising properties to address the complex interactions between vehicle and pedestrian flows. Our preliminary simulation experiment also reflects that neglecting the conflicts in a mixed-flow environment may result in over-estimate of its network MOEs. Note that this work is exploratory in nature, and we fully recognize that much remains to be done in developing an efficient and operational simulation software that can different modes of traffic and their conflicts as well as interactions. Our model can be specifically applied to the metropolitan downtown area where complex modes exists, and for a detailed level of downtown evacuation planning and operations, e.g., stadium or shopping mall evacuation. Our ongoing research along this line is to integrate the simulation model with the optimization model for planning the optimal multi-modal evacuation process.

References

[1] FHWA, “Development and testing of INTRAS, a microscopic freeway simulation model,” Program Design, Parameter Calibration and Freeway Dynamics Component Development, Volume. 1, 1980, US

Department of Transportation

[2] R. F. Benekoha, J. Treiterer, “CARSIM: Car following model for simulation of traffic in normal and stop-and-go conditions,” in Transportation Research Record 1194, Washington. DC: TRB, Nat. Res. Council, 1988, pp. 99-111

[3] Van Aerde M, Yagar S. (1988) Dynamic integrated freeway/traffic signals networks: a routing-based modeling approach. Transportation Research-A, 22 (6), 445-453

[4] Codelli D. K, Niedringhaus W. P, (1992), The Traffic and Highway Objects for Research, Analysis and Understanding (THOREAU) IVHS model, Volume 1. Technical Report MTR 92W208VI. MITRE, McLean, Virginia

[5] G. I. Duncan, “PARAMICS wide area microscopic simulation of ATT and traffic management” in Proc. 28th ISATA Conf. Stuttgart, Germany, 1995, pp. 475-484

[6] Jayakrishman, R., Mahamassani, H., An evaluation tool for advanced traffic information and management systems in urban networks, Transportation Research-C, 2 (3), 129-147

[7] Yang, Q, H. N. Koutsopoulos (1996), A microscopic traffic simulator for evaluation of dynamic traffic management systems, Transportation Research C 4 (3), 113-129

[8] J. Esser, M. Schreckenberg, Microscopic simulation of urban traffic based on cellular automata, International Journal of Modern Physics C, Vol. 8, No. 5 (1997) pp. 1025-1036

[9] M. F. Aycin, R. F. Benekohal, Linear acceleration car-following model development and validation, in Transportation Research Record 1644, Washington DC. TRB, Nat. Res. Council, 1998, pp. 10-19

[10] A Halati, L. Henry and S. Walker, “CORSIM-Corridor traffic simulation model,” in Proc. Traffic Congestion and Traffic Safety Conf. Chicago, IL: ASCE, 1998, pp. 570-576

[11] J. Barcelo, J. Casas, “Dynamic network simulation with AIMSUM”, in Proc. Int. Symp. Transp., Yokohama, Japan, 2002, pp. 1-25

[12] Sameh EI Hadouaj, Stephane Espie, A generic road traffic simulation model,

[13] Ghulam H. Bham, Rahim F. Benekohal, A high fidelity traffic simulation model based on cellular automata and car following concepts, Transportation Research Part C 12 (2004) 1-32

[14] M.N.Lighthill, G.B.Whitham, On Kinematic Waves. II. A Theory of Traffic Flow on Long-Crowded Roads, Porceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, Vol. 229, No. 1178, pp. 317-345

[15] H. J. Payne, Models of Freeway Traffic and Control, Math. Models Publ. Sys. 28 (1971), 51-61, Simul. Council Proc

[16] L. Henderson, The Statics of Crowd Fluids, Nature, Vol 229, February 5, 1971

[17] Roger Hughes, A Continuum Theory of the Flow of Pedestrians, Transportation Research Part B 36 (2002) 507-535

[18] Robert E. Chandler, Robert Herman, Elliott W. Montroll, Traffic Dynamics: Studies in Car Following, Operations Research, March-April, pp 165-184

[19] Robert Herman, Elliott W. Montroll, Traffic Dynamics: Analysis of Stability in Car Following, Operations Research 7, pp. 86-106

[20] Denos C. Gazis, Robert Herman, Car-following theory of steady-state traffic flow, Operations Research, Vol. 7, No. 4, pp. 499-505

[21] Gipps, P. G. (1986), A model for the structure of lane changing decisions, Transportation Research

20B (5), 403-414
[22] Ahmed, K. I., M. E. Ben-Akiva, H. N. Koutsopoulos, Models of freeway lane changing and gap acceptance behavior. In J. Lesort (Ed.), Transportation and Traffic Theory, pp. 501-515, Pergamon
[23] Dirk Helbing, Peter Molnar, Social Force Model for Pedestrian Dynamics, Physical Review E, Volume 51, May 1995
[24] D.R.Parisi, C.O.Dorso, Microscopic Dynamics of Pedestrian Evacuation, Physica A 354 (2005) 606-618
[25] Gianluca Antonini, Michel Bierlaire, Discrete Choice Models of Pedestrian Walking Behavior, Transportation Research Part B, 40 (2006) 667-687
[26] S.P.Hoogendoorn, P.H.L.Bovy, Pedestrian Route-Choice and Activity Scheduling Theory and Models, Transportation Research Part B 38 (2004) 169-190
[27] I. Prigogine, F.C.Andrews, A Boltzmann-like approach for traffic flow, Operations Research, Volume 8, No. 6, pp. 789-797
[28] S. L Paveri-Fontana, On Boltzmann like treatments for traffic flow, Transportation Research. 9: 225 (1979)
[29] M. Schreckenberg, L. Neubert, Simulation of traffic in large road networks, Future Generation Computer System 17 (2001) 649-657
[30] J. Wahle, L. Neubert, A cellular automaton traffic flow model for online simulation of traffic, Parallel Computing 27 (2001) 719-735
[31] Kai Nagel, Michael Schreckenberg, A cellular automaton model for freeway traffic, J. Phy. I France 2 (1992) 2221-2229
[32] Kai Nagel, Hans J. Herrmann, Deterministic models for traffic jams,
[33] Kai Nagel, Maya Paczuski, Emergent traffic jams, Physical Review E, Volume 51, Number 4, pp. 2909-2918
[34] Henryk Fuks, Nino Boccara, Generalized deterministic traffic rules,
[35] M. Schreckenberg, A. Schadschneider, Discrete stochastic models for traffic flow, Physical Review E, Volume 51, Number 4, pp 2939-2949
[36] Minoru Fukui, Yoshihiro Ishibashi, Traffic flow in 1D Cellular Automaton Model Including Cars Moving with High Speed, Journal of the Physical Society of Japan, Volume 65, No. 6¸June 1996, pp. 1868-1870
[37] Z Csahok, T Vicsek, Traffic models with disorder, J. Phys. A: Math. Gen. 27 (1994) L591-596
[38] Satoshi Yukawa, Dynamical phase transition in one dimensional traffic flow model with blockage, Journal of the Physical Society of Japan, Vol. 63, No. 10, October 1994, pp. 3609-3618
[37] K. H. Chung, P. M. Hui, Traffic flow problems in one-dimensional inhomogeneous media, Journal of the Physical Society of Japan, Vol. 63, No. 12, December 1994, pp. 4338-4341
[40] H. Emmerich, E. Rank, Investigating traffic flow in the presence of hindrance by cellular automata, Physica A 216 (1995) 435-444
[41] Yoshihiro Ishibashi, Minoru Fukui, The bottleneck effect on high-speed car traffic, Journal of the Physical Society of Japan, Vol. 70, No. 5, May 2001, pp. 1237-1239
[42] Takashi Nagatani, Shock formation and traffic jam induced by a crossing in the 1D asymmetric exclusion model, J. Phys. A: Math. Gen: 26 (1993) 6625-6634

[43] Takashi Nagatani, Jamming transition in the traffic-flow model with two-level crossings, Physical Review E, Volume 48, Number 5, pp. 3290-3294
[44] Takashi Nagatani, Bunching of cars in asymmetric exclusion models for freeway traffic, Physical Review E, Volume 51, Number 2, pp. 922-928
[45] Peter Wagner, Kai Nagel, Realistic multi-lane traffic rules for cellular automata, Physica A 234 (1997) 687-698
[46] Chulam H. Bham, Rahim F. Benekohal, A high fidelity traffic simulation model based on cellular automata and car following, Transportation Research Part C 12 (2004) 1-32
[47] Masakuni Muramatsu, Tunemasa Irie, Jamming Transition in Pedestrian Counter Flow, Physica A 267 (1999) 487-498
[48] Fang Weifeng, Yang Lizhong, Simulation of Bi-Direction Pedestrian Movement Using a Cellular Automata Model, Physica A 321 (2003) 633-640
[49] Li Jian, Yang Lizhong, Simulation of Bi-Direction Pedestrian Movement in Corridor, Physica A 354 (2005) 619-628
[50] Yang LiZhong, Li Jian, Simulation of Pedestrian Counter-Flow with Right-Moving Preference, Physica A 387 (2008) 3281-3289
[51] Y. F. Yu, W. G. Song, Cellular Automaton Simulation of Pedestrian Counter Flow Considering the Surrounding Environment, Physical Review E 75, 046112 (2007)
[52] W. G. Weng, T. Chen, Cellular Automaton Simulation of Pedestrian Counter Flow with Different Walk Velocities, Physical Review E 74. 036102 (2006)
[53] W. G. Weng, S. F. Shen, A Behavior-based Model for Pedestrian Counter Flow, Physica A 375 (2007) 668-678
[54] Hao Yue, Hongzhi Guan, Study on Bi-Direction Pedestrian Flow Using Cellular Automata Simulation, Physica A 389 (2010) 527-539
[55] Cellular Automata Micro-simulation for Modeling Bi-Directional Pedestrian Walkways, Victor J. Blue, Transportation Research Part B 35 (2001) 293-312
[56] Yusuke Tajima, Takashi Nagatani, Scaling Behavior of Crowd Flow Outside a Hall, Physica A 292 (2001) 545-554
[57] Kouhei Takimoto, Takashi Nagatani, Spatio-Temporal Distribution of Escape Time in Evacuation Process, Physica A 320 (2003) 611-621
[58] Ryoichi Nagai, Masahiro Fukamachi, Takashi Nagatani, Experiment and Simulation for Counter-flow of People Going on All Fours, Physica A 358 (2005) 516-528
[59] Ryoichi Nagai, Masahiro Fukamachi, Takashi Nagatani, Evacuation of Crawlers and Walkers from Corridor Through an Exit, Physica A 367 (2006) 449-460
[60] Weiguo Song, Xuan Xu, Simulaiton of Evacuation Processes Using a Multi-grid Model for Pedestrian Dynamics, Physica A 363 (2006) 492-500
[61] Xuan Xu, Weiguo Song, Staircase Evacuation Modeling and its Comparison with an Egress Drill, Building and Environment 44 (2009) 1039-1046
[62] W. G. Weng, L. L. Pan, Small-grid Analysis of Discrete Model for Evacuation from a Hall, Physica A 374 (2007) 821-826
[63] Dirk Helbing, Notonari Isobe, Lattice Gas Simulation of Experimentally Studied Evacuation

Dynamics, Physical Review E 67, 067101 (2003)
[64] Motonari Isobe, Dirk Helbing, Experiment, Theory, and Simulation of the Evacuation of a Room Without Visibility, Physical Review E 69, 066132 (2004)
[65] Xiaomeng Li, Tao Chen, Lattice Gas Simulation and Experiment Study of Evacuation Dynamics, Physica A 387 (2008) 5457-5465
[66] Qiu Bing, Tan HuiLi, Lattice-gas Simulation of Escaping Pedestrian Flow in Corridor, Volume 13, No. 7, July 2004, 990
[67] Bing Qiu, Huili Tan, Cellular Automaton Simulation of the Escaping Pedestrian Flow in Corridor, International Journal of Modern Physics C, Volume 16, No. 2 (2005) 225-235
[68] Hao Yue, Herui Hao, Simulation of Pedestrian Flow on Square Lattice Based on Cellular Automata Model, Physica A 384 (2007) 567-588
[69] Masahiro Fukamachi, Takashi Nagatani, Sidle Effect on Pedestrian Counter Flow, Physica A 377 (2007) 269-278
[70] Satoru Ito, Takashi Nagatani, Volatile Jam and Flow Fluctuation in Counter Flow of Slender Particles, Physica A 373 (2007) 672-682
[71] S. Maniccam, Traffic Jamming on Hexagonal Lattice, Physica A 321 (2003) 653-664
[72] C. Burstedde, K. Klauck, A. Schadschneider, Simulation of Pedestrian Dynamics Using a Two-Dimensional Cellular Automaton, Physica A 295 (2001) 507-525
[73] Ansgar Kirchner, Andreas Schadschneider, Simulation of Evacuation Processes Using a Bionics-Inspired Cellular Automaton Model for Pedestrian Dynamics, Physica A 312 (2002) 260-276
[74] Katsuhiro Nishinari, Ken Sugawara, Modeling of Self-Driven Particles: Foraging Ants and Pedestrians, Physica A 372 (2006) 132-141
[75] Ansgar Kirchner, Hubert Klupfel, Simulation of Competitive Egress Behavior: Comparison with Aircraft Evacuation Data, Physica A 324 (2003) 689-697
[76] Ansgar Kirchner, Katsuhiro Nishinari, Friction Effects and Clogging in a Cellular Automaton Model for Pedestrian Dynamics, Physical Review E 67, 056122 (2003)
[77] Colin M Henein, Tony White, Macroscopic Effects of Microscopic Forces between Agents in Crowd Models, Physica A 373 (2007) 694-712
[78] Kazuhiro Yamamoto, Satoshi Kokubo, Simulation for Pedestrian Dynamics by Real-Coded Cellular Automata (RCA), Physica A 379 (2007) pp. 654-660
[79] Dirk Helbing, Rui Jiang, Analytical Investigation of Oscillations in Intersecting Flows of Pedestrian and Vehicle Traffic, Physical Review E 72, 046130 (2005)
[80] Rui jiang, Qingsong Wu, Interaction between Vehicle and Pedestrians in a Narrow Channel, Physica A, 368 (2006) 239-246
[81] Rui jiang, Qingsong Wu, The Moving Behavior of A Large Object in the Crowds in a Narrow Channel, Physica A 364 (2006) 457-463
[82] Muhammad Moazzam Ishaque, Robert B. Noland, Trade-offs between vehicular and pedestrian traffic using micro-simulation methods, Transport Policy 14 (2007) 124-138