

Cellular automata modeling of pedestrian's crossing dynamics*

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Abstract: Cellular automata modeling techniques and the characteristics of mixed traffic flow were used to derive the 2-dimensional model presented here for simulation of pedestrian's crossing dynamics. A conception of "stop point" is introduced to deal with traffic obstacles and resolve conflicts among pedestrians or between pedestrians and the other vehicles on the crosswalk. The model can be easily extended, is very efficient for simulation of pedestrian's crossing dynamics, can be integrated into traffic simulation software, and has been proved feasible by simulation experiments.

Key words: Cellular automata modeling, Pedestrian's crossing dynamics, Traffic simulation

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INTRODUCTION

Computer simulation of traffic can give insight into a wide variety of phenomena observed in real traffic flow; lead to a greater understanding of its basic principles; and can also help researchers explore the effects of implementing new traffic rules and control systems without doing potentially hazardous experiments with real traffic. Approaches that apply classic differential equation methods to model the nonlinear dynamics of this problem can describe only part of the phenomena due to the fact that traffic flow modeling is a highly complex, nonlinear and stochastic problem.

In recent years, many of the microscopic traffic models developed have been formulated using cellular automata (CA), which is an artificial life approach to simulation modeling and is named after the principle of automata (entities) occupying cells according to localized neighborhood rules of oc-

cupancy. Each cell can have one of a finite number of states. In CA, time and state variables are discrete which makes it ideally suited for efficient computer simulations of complex traffic phenomena. A very simple CA model known as N-S model was introduced (Nagel and Schreckenberg, 1992), which provided a microscopic description of the vehicular motion using a set of update rules. Although it is one of the simplest traffic flow models, it is nevertheless capable of reproducing essential characteristics of real traffic flow. N-S model has offered basic rules for relatively complicated traffic phenomenon such as two-lane traffic (Richert *et al.*, 1996) and bi-directional traffic (Simon and Gutowitz, 1998), etc. Most of the CA models developed are for application to vehicular traffic flow. As an important component of road traffic, especially of mixed traffic, pedestrian motion must necessarily be considered in estimating road transit capacity, designing traffic light, and setting up traffic facilities.

Pedestrian motion exhibits more flexible and unrestricted dynamic path choices. A pedestrian

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movement model was put forward for a large open space such as a rail or bus terminal, shopping mall, or office lobby (Blue *et al.*, 1997). A driven random walk model was presented for pedestrian motion (Muramatsu *et al.*, 1999). A four-directional pedestrian walkway model and a bi-directional one were designed (Blue and Adler, 2000; 2001). All the references above mainly concern the conflicts between pedestrians and rarely include dynamic conflicts about the other vehicles and the surroundings. In the following, a 2-dimensional CA model for simulation of pedestrian's crossing dynamics will be presented in detail. To deal with traffic conflicts among pedestrians or between pedestrians and the other vehicles, a conception of "stop point" is introduced. Simulation experiments will be described to prove the model's validity.

MODELING APPROACHES

Summarizations below are the basic characteristics of a pedestrian's movement in crossing traffic (Zheng and Li, 1998):

1. The common parameters of a pedestrian are average speed 1.2 m/s, maximum speed 1.4 m/s, and average space distribution of dense pedestrian flow $0.4 \times 0.4 \text{ m}^2$ or $0.457 \times 0.457 \text{ m}^2$.
2. Pedestrian's movements on crosswalk are bi-directional. The loss time of a pedestrian bypassing an opposite one is 0.2 s averagely.
3. The conflicts of pedestrians are not only among them but also between them and the other vehicles on the crosswalk. When a pedestrian encounters a vehicle, whether the pedestrian stops or continues depends on the distance and velocity of the conflicting vehicle.
4. Pedestrian's arriving law obeys Poisson arrival distribution when the bi-directional flow of crossing pedestrians is no more than 1000 per hour in general.
5. An impact called throng effect will be exerted when more than three same-direction people gather. A pedestrian will feel safe in the throng and move together with it with little or even no heed of the time interval between vehicles. A pedestrian's judging time is about 1.5–2 s and reduced to 1–1.2 s

in a throng.

The term CA comes from defining discrete squares of space, or cells, each of which has a set of rules that automatically governs its state at each time step. CA models are characterized by four features: a) size of the state space, which regulates the scope of moving objects; b) number of each cell's attributes describing the state of the cell; c) neighborhood of a cell, which define the cell's view about the other cells; d) local rules, which allows translating the interactions between cells into local ones.

Combining with the basic characteristics of pedestrian's crossing dynamics, the CA modeling is analyzed by specifying the four features of CA modeling one by one.

Basic hypothesis of the CA model

The size of the state space is defined as the crosswalk. The pedestrian's updating time has to be consistent with the whole traffic flow including motorized and non-motorized vehicles, so it is determined as 1 sec. Suppose that the pedestrians move on a 2-dimensional rectangular lattice. The size of the cells is $48 \text{ cm} \times 24 \text{ cm}$. The minimum horizontal space between pedestrians is 48 cm and the minimum vertical space length is 48 cm. Therefore, one pedestrian occupies two cells. The pedestrians are allowed to move five cells ahead or two cells sideways per time step at most. That is the vertical velocity of the pedestrian is 1.2 m/sec and the horizontal velocity is 0.96 m/sec. The three possible moving directions of a pedestrian are forward, left side and right side, which are shown in Fig.1.

In order to handle conflicts between pedestrians and the other vehicles, the definition of "stop

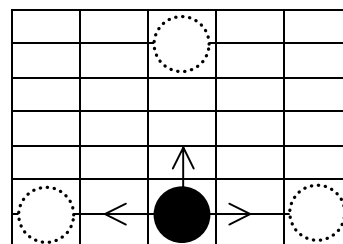


Fig.1 Possible moves of the pedestrians

point” is introduced. Stop points are supposed to be in the middle of where each driveway crosses the crosswalk. The active area of every stop point depends on the shape and velocity of conflicting vehicles. Whether the pedestrian will pass a stop point depends on the state of it.

The visual field of a pedestrian includes its surrounding cells that can arrive during one period. When a pedestrian cannot go forward, the visual field will also include cells nearby right and left boundary. The neighborhood of a cell or a pedestrian is expressed in Fig.2 exactly. The solid line denotes a pedestrian and the two dashed circles express virtual pedestrians. The states of two virtual pedestrians will help the pedestrian to bypass an obstructed or congested area. The stop point’s rule will be described in Section 2.

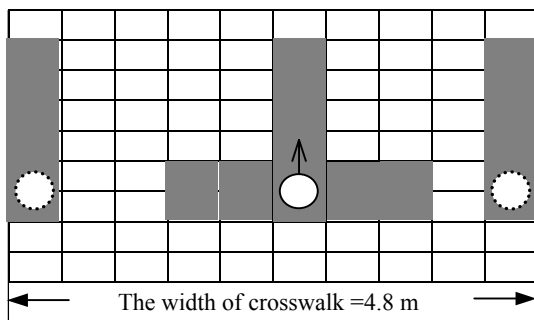


Fig.2 The visual field of a pedestrian

Basic rule of the model

In each updating step for each cell, a desired movement is chosen according to the transition probability, which is divided into two components. One is static component that does not change with time and the other is dynamic component that varies with time.

(1) Static component includes:

1) The priorities of pedestrian’s next direction choice D_{ij} . Forward direction is the first choice and its probability is equal to 0.5. Right and left side’s probabilities are 0.25 respectively.

2) The geometry effects G_{ij} . The probability of being outside the crosswalk and of fixed obstacles is set to zero. For other probabilities, set $G_{ij}=1$.

3) The effect of an opposing pedestrian. An even delay time of 0.2 s will be brought when one

pedestrian bypasses another opposing one. If the delay time is converted into the pedestrian’s forward moving velocity, the displacement will be reduced by one cell length of 0.24 m in the circle as the vertical velocity is 1.2 m/s.

4) The existence of a central refuge CR_{ij} . When a pedestrian reaches a central refuge and pedestrian’s traffic light is red, the pedestrian will wait for the next green period to cross the street. Therefore, CR_{ij} at the edge of the central refuge will take zero in that situation and 1 in the other situations.

(2) Dynamic component includes:

1) The effect of pedestrian traffic light TL_{ij} . When the light turns red and the pedestrian just steps into the lengthways boundary of the crosswalk, TL_{ij} is set to zero, else it is set to one.

2) The occupation number of the target cell n_{ij} . A motion in direction (i, j) is only allowed if the target cells are empty and there are no obstacles between the original position and the target position, otherwise the target is not allowed to occupy. The occupation rule is as follows

$$\text{if } (i, j) \text{ is allowed then } (n_{ij}=1) \text{ else } (n_{ij}=0). \quad (1)$$

3) The stop state of a stop point S_{ij} . $S_{ij}=0$ means that the pedestrian cannot move to this cell and $S_{ij}=1$ means that the pedestrian can move to this cell. Its effect is two-way. One is to decide pass or stop from the original position to another one, which can be defined as S_{ij}^1 . The other is to decide the radial direction via the stop states of cells nearby the right and left boundary, which can be defined as S_{ij}^2 . The stop state of the stop point S_{ij} can be obtained from $S_{ij}^1 \times S_{ij}^2$.

(3) Confirming rule of a Stop Point’ Stop State S_{ij} :

From the above section, the active area of the stop point depends on the distance, shape and velocity of the conflicting vehicle. The acting area may extend to spaces outside the crosswalk because of the large shape and velocity of mobile vehicles. When a moving pedestrian’s visual field overlaps the acting area, the stop state of the cells in the

overlapped area depends on pedestrians' safe crossing space between vehicles.

On condition of no-signal crosswalks, the necessary pedestrians' safe crossing space between vehicles can be calculated using Eq.(2).

$$\tau = D/v + R + L, \quad (2)$$

where τ is the necessary pedestrians' safe crossing time space, D is the width of a driveway, v is crossing velocity of a pedestrian, R is pedestrian's judgment time when estimating the condition of vehicles, and L is the time crossing the length of a vehicle. The even test value of τ is about 4 seconds. Then stop state S_{ij}^1 can be calculated by Eq.(3).

$$\text{if } t \geq \tau \text{ then } S_{ij}^1 = 0 \text{ else } S_{ij}^1 = 1, \quad (3)$$

where t is the actual crossing time space.

On condition of existence of signal crosswalks, when the signal is green, pedestrians may also conflict with turning vehicles or vehicles that have not driven out since the last green signal. According to traffic rules, pedestrians have advantages in this instance, so the even test value of τ is reduced to about 2 seconds.

Suppose a pedestrian (i_0, j_0) cannot go ahead to (i, j) and $S_{1j}^1, S_{i_{\max}j}^1$ of two virtual pedestrians near right and left boundary are known. S_{ij}^2 will be confirmed in succession. All the preliminary values of $S_{i,j}^2 (i=1 \dots i_{\max}, j=1 \dots j_{\max})$ are supposed to be 1.

$$\begin{aligned} &\text{if } S_{1j}^1 = 0 \text{ and } S_{i_{\max}j}^1 = 1 \text{ and } S_{i_0+1j_0}^1 = 1 \text{ then } S_{i_0-1j_0}^2 = 0 \\ &\text{else if } S_{1j}^1 = 1 \text{ and } S_{i_{\max}j}^1 = 0 \text{ and } S_{i_0-1j_0}^2 = 1 \text{ then} \\ &S_{i_0+1j_0}^2 = 0. \end{aligned} \quad (4)$$

Therefore, the second rule of stop state is applicable. When a pedestrian cannot move forward, the radial direction can be chosen based on the stop state S_{ij}^2 of cells nearby the right and left boundary. Thus, the stop state of the cells S_{ij} in the overlapped area

is determined by $S_{ij} = S_{ij}^1 \times S_{ij}^2$.

A simple possibility taking into account all the static and dynamic components is to define the transition probability p_{ij} in direction (i, j) by

$$p_{ij} = N \times (D_{ij} \times G_{ij} \times CR_{ij}) \times (TL_{ij} \times n_{ij} \times S_{ij}), \quad (5)$$

where (i, j) is the possible target positions and N is a normalization factor to ensure $\sum_{i,j} p_{ij} = 1$.

Update procedures

The simulation update procedures of pedestrians and other vehicles are asynchronous, but the simulation update procedures of pedestrians are either synchronous or asynchronous.

There exists a "collision problem" in synchronous automata in multi-dimensions. It means that two or more objects could possibly occupy the same cells at the same time. To avoid such a situation, special complicated procedures are taken to separate the collision automations. A cell that is occupied by more than one pedestrian is drawn under the concerned pedestrians. The losers move back to their old positions. The random sequential update moves the pedestrians in a random order but every pedestrian once only in a time step. There is no problem with multiple occupations of cells because pedestrians move in sequential order.

As mentioned previously, the pedestrian's updating time has to be such a long period as 1 second due to mixed traffic. Random sequential update procedures are selected for simulation of pedestrian's crossing dynamics without consideration of traffic accidents.

Extended models

Extended models are improved by special demand based on the basic model. It may include several aspects as follows.

(1) Consider the effects of the number of pedestrians in the group attempting to cross the roadway. The pedestrian's judgment time may be changed from 1.5–2 s to 1–1.2 s due to a moving throng.

(2) The pedestrian expected waiting time

seems to profoundly influence the number of attempts needed to successfully cross the street. It is said that when waiting time exceeds 40 seconds pedestrians will very likely take a risk in crossing the roads.

(3) There may be a probability of people not following the traffic light.

(4) The differences of pedestrians may be taken into account. Age, gender, socioeconomic characteristics and marital status are pedestrian variables which may influence behaviors of the pedestrian.

This simple scene was chosen as the pedestrian delay was only due to the conflict between pedestrians and the other vehicles, so it was easy to sum up the impact of pedestrians on mixed traffic. The parameters of the simulation are given in Table 1. The arriving of all the vehicles obeys Poisson distribution.

Fig.4 shows the average mean velocity, minimum velocity and maximum velocity of the crossing pedestrians versus the increasing average number of pedestrians. Fig.5 shows the average me-

SIMULATION EXPERIMENTS

The simulation research was based on Urban Mixed Traffic Simulation and Analysis System (UMTSAS), a traffic simulation software developed by ITS Research Center of Zhejiang University in China. Under open boundary conditions, simulations were carried out using random sequential update. The simulation scene was of one road with one no-signal crosswalk, as shown in Fig.3.

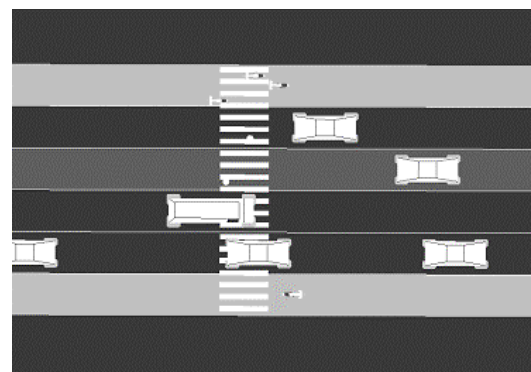


Fig.3 The simulation scene

Table 1 Parameters for the simulations

Road size	Motor vehicle	Bicycle	Pedestrian
Driveway (bi-directional) Length: 600 m Width: 3.5 m	Two driveway of each direction	One driveway of each direction	One crosswalk
One crosswalk (In the middle) Width: 4 m	Flow of bi-direction: 800 per hour	Flow of bi-direction: 500 per hour	Flow of bi-direction: 0, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000 per hour

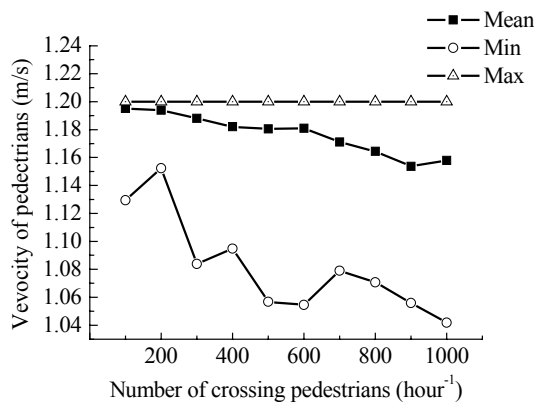


Fig.4 The average mean, minimum and maximum velocity of the crossing pedestrians versus the increasing average number of pedestrians

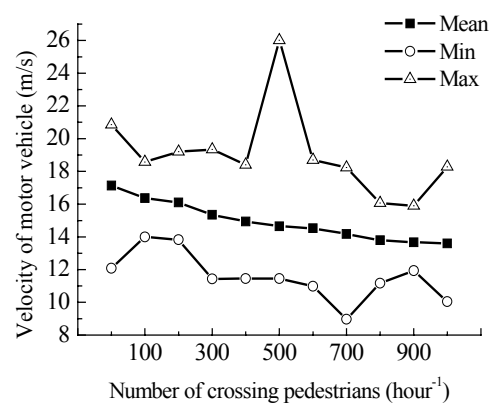


Fig.5 The average mean, minimum and maximum velocity of the motor vehicles versus the increasing average number of pedestrians

an, minimum and maximum velocity of the motor vehicles versus the increasing average number of pedestrians, which reflects the impact of crossing pedestrians on conflicting motor vehicles. All the data in the simulations were the average results of 7200 seconds.

Fig.4 and Fig.5 show that the average mean velocities decreased almost linearly with the increasing number of pedestrians. Few values are out of the linear rule while the pedestrian flow increases. The maximum mean velocity of crossing pedestrians is 1.2 m/s, which is equal to the maximum value prescribed in advance. The minimum velocity of crossing pedestrians, the minimum and the maximum velocity of motor vehicles seem to be in disorder. It can be explained that the transportation system has its own characteristics: complexity and disorder, but the relation of mean velocity and density is linear in the rough. The simulation showed that when the number of crossing pedestrians exceeds one thousand per hour, a traffic jam will occur easily. This reveals that the crosswalk will need a traffic light to control the traffic when the pedestrian flow exceeds one thousand per hour, which is true of traffic rule.

Therefore, the simulation results fit the traffic rule well qualitatively, but the parameters were not validated by field data. No published data are available about the relation of densities between vehicles and crossing pedestrians. Quantitative investigation is still needed for the further research.

CONCLUSION

We have presented a simple example for application of a 2-dimensional model for simulation of pedestrian's crossing dynamics. Moreover, it can be applied to complex mixed traffic conditions. The

transition probability is determined by two separate components: static and dynamic component. The model can be easily extended and is very efficient for simulation of pedestrian's crossing dynamics. The presented pedestrian's crossing model was applied successfully and verified efficient in the Simulation and Analysis System for Urban Mixed Traffic (SASUMT) developed by the ITS Research Center of Zhejiang University of China. The presented pedestrian model can be integrated into other traffic simulation software to determine feasible signal timing strategies at intersections or sections of highway with quite a few of pedestrian traffic.

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