Modeling Occupant Evacuation using Cellular Automata – Effect of Human Behavior and Building Characteristics on Evacuation

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ABSTRACT: This paper presents a microdiscrete evacuation model which emphasizes the human behavior and is focused on studying the generic properties of occupant evacuation from crowded large, open spaces after a fixed premovement stage. By using Cellular Automata (CA) in developing the rules, the model achieves the advantages of effectively capturing the behavior of occupants at the individual-level while attaining realistic collective level activity. The lively demonstration of the evacuation process offers an easy examination of occupant movement on computer. The studies on some important characteristics in evacuation such as the existence of different velocities of people and the different structure of building offer some key factors affecting evacuation efficiency. By studying on evacuation from a corridor, with and without widen part, we found disordered moving states will badly decrease the evacuation efficiency. It enables us to understand the special phenomena in evacuation and is helpful in performance-based building design.

KEY WORDS: cellular automata, fire, occupant evacuation, human behavior.

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INTRODUCTION

RESEARCH INTO QUANTIFYING and modeling human movement and behavior in fire has been underway for many years. Since the first computer based evacuation model, which concerns the modeling of emergency egress during fires, appeared in 1982, great advances have been made both in the understanding of human response to emergency evacuation situations and in the attempts to model this response [1]. As we know, reduction of casualties in fires will not happen through more ''hard fire science'' or prescriptive requirements for more fire protection in buildings, but through the development of knowledge regarding human behavior in fire [2]. And it has become apparent that there is a trend towards models, which include greater behavioral details. Presently, many models have been modified or new models have been proposed to fit the needs, for example, Exit89, which is modified to model the effect of contra flows and the movement of occupants both up and down stairwells [3], building EXODUS model, into which adaptive behavior is introduced through enabling occupants to make decisions concerning the choice of the most available exit during an evacuation involving a fire hazard [4].

However, irrespective of the behavioral model implemented, no evacuation model to date fully addresses all the identified behavioral aspects of evacuation. Furthermore, not all these behavioral aspects are fully understood or quantified. So, although the future of human behavior in fire research is indeed more promising today than at anytime in the past with the recognition of the need to determine valid evacuation times in the design of the building under the performance code concept, the application of the computer evacuation models based on human behavior is not very satisfying. At the same time, how to apply human behavior in evacuation model under present condition is a noticeable question.

To answer this question, we should be clear what we expect our models to do. Apparently, we shouldn't count on them to tell us clearly and accurately how long it would take for all the occupants to evacuate when a certain building caught on fire at some time. The answer will be doubtful because even one accident may greatly change the final result. For this reason, our models are developed to try to demonstrate the real evacuation process, interpret the interesting phenomena and even tell us the basic rules behind the phenomena. A good model will grasp the key factors of real events and tell us useful information for directing evacuation training and building design. Then what are the standards for a good model? Generally, a good model should contain such characteristics as fidelity, brevity, clarity, unprejudicedness and easiness in operating [5].

The fidelity means the model should be clear at what it describes and then represents it faithfully. The brevity means the model should be ''small'' in the number of variable, the relation of subsystem parts and the number of assumptive conditions. The clarity means the model should be easily understood by people and be easy to offer the prediction or interpretation of the real world. The unprejudicedness means the model should not contain the maker's preference and the object or intention indicated by the model should be unprejudiced. And last, the easiness in operating means its request for computer resource is not reachless.

At the same time, a good model is strongly dependent upon the methods employed by the model. While the key factors in occupant evacuation are the complex interactions including people–people, people–structure and people–environment, the micro-discrete simulation, for example CA model, is a good choice. CA is discrete, decentralized, and spatially extended systems consisting of large numbers of simple identical components with local connectivity. The rational of CA is not to try to describe a complex system from a global point of view as it is described using for instance differential equations, but modeling this system starting from the elementary dynamics of its interacting parts. The original concept of CA was introduced in the late 1940s by John von Neumann and Stanislaw Ulam to model biological reproduction and crystal growth respectively [6]. Since then it has been applied to model a wide variety of (complex) systems, in particular physical systems containing many discrete elements with local interactions such as in fluid flow, galaxy formation, biological pattern formation, avalanches, traffic jams, parallel computers, earthquakes, and many more [7,8].

The work of simulating occupant evacuation using micro-discrete models includes Helbing's ''social force'' models [9,10] and some other CA models [11,12]. In this paper a CA model is presented and by using several simple local rules it can easily grasp the emphases and represent the real world approvingly, so that we are able to spend most time on what we specially care.

MODEL DESCRIPTION

Usually speaking, an evacuation model considering human behavior should contain several key factors including the route choice, the interactions among people and the effect on people by the environment such as smoke and scorching air.

Basically, our model is developed to study the crowded large, open spaces such as bushy shops or theatres. In these situations evacuation time depends mainly upon the movement times of the first occupants to respond and the movement times of the whole occupant population [13]. For the reason that our model is focused on studying the phenomena after all the people start evacuating but not the whole evacuation time, we let premovement time to be studied elsewhere. Thus, we assume that all the people begin to evacuate at the same time after a fixed premovement stage and the evacuation time presented in this paper excludes the premovement time.

In the model, the base structure of the building is represented by a two-dimensional grid. Each cell can either be empty, occupied by obstacle/wall or occupied by exactly one occupant. For each occupant, only those empty cells can be moved into. Each cell has four states: 0 for not being occupied, 1 for occupant whose velocity is 1, i.e., move once each two time-steps, 2 for occupant whose velocity is 2, i.e., move at every time-step and 3 for being occupied by obstacle/wall. The size of a cell corresponds to approximately $0.4 \times 0.4\,\mathrm{m}^2$ [11]. The synchronous update is supposed for all occupants. And empirically the average velocity of the normal man in nervous state can reach $1.50\,\mathrm{m\,s}^{-1}$ [14]. Thus one time-step in our model is approximately 0.27 s, which is of the order of the reaction time, and consistent with our microscopic rules.

In order to determine each occupant's moving direction, *danger grade* is introduced to describe each occupant's knowledge for danger in the room. It can be viewed as one of the properties of the cell. Generally, the danger grade is determined by the distance from the safety exit, i.e. the nearer to the exit, the less the danger grade of the cell. In the model, if we do not want to define the room danger grade beforehand, an optional stage can be used to describe more realistic evacuation, that is, the familiarization stage which is before the actual evacuation stage. In the familiarization stage, occupants are introduced into the room to get familiar with the building and the danger grades of cells are determined in this stage. The process is that occupants are introduced from one of the exits and then walk in the room randomly. When one walks into a cell, he compares the cell's danger grade with those of four adjacent cells. If the danger grade of the cell he occupied is not the least or if the cell has never been walked into by him, it will be changed to 1 more than the least value of the four adjacent danger grades. For example, if the danger grade of the cell he occupied is 5 and the least danger grade of the four adjacent cells is 3, then the danger grade of the cell he occupied will be changed to 4. Thus, different occupants may have different views of cells' danger grades which are dependent of the walking route and the total time steps of the familiarization stage. In the evacuation stage, each occupant's route choice is based on his view of the cells' danger grades.

In CA a rule defines the state of a cell in dependence of the neighborhood of the cell. Figure 1(a) illustrates the basic definition of Von Neumann neighborhood of the cell including the cell above and below, right and left from the core cell; the radius of this definition is 1. In this model we extend Von Neumann neighborhood by considering more layers. The radius of the neighborhood defined in Figure 1(b) is 2, including the 12 cells without shadow except the core cell. And the radius in Figure 1(c) is 3, including the 24 cells without shadow except the core cell, and so on.

In the model, in order to imitate human's intelligence, the term *premeditation* is introduced. Realistically, it means the occupant can consider the later route choice in advance. In this model, the premeditation scope is connected with the radius of the cell's neighborhood with the greater radius meaning the larger scope of premeditation. In Figure 1, the cells without shadow are those that can be considered by the occupant in the core cell (cell-C) when he decides which adjacent cell to move into. In Figure 1(a), for example, if the cell-D has the least danger grade, then he will select to move down. In Figure 1(b), if the cell-U has the least danger grade, then he will select to move up. In Figure 1(c), if the cell-R has the least danger grade, then he will select to move right. In the case when more than one direction, for example moving left or down, has the same advantage, each direction has the same chance. We may mention that, this is a very simple treatment and more realistic one should be studied in the future work.

There are three-stage parallel updates of the set of occupants in this model. Since there are two kinds of velocities in the model, the occupant with the velocity of 1 can only move once each two time-step whether the occupant with the velocity of 2 can move at every time-step. For each time-step, only part of those whose velocity is 1 can move. The parallel update rules of the model are presented in detail.

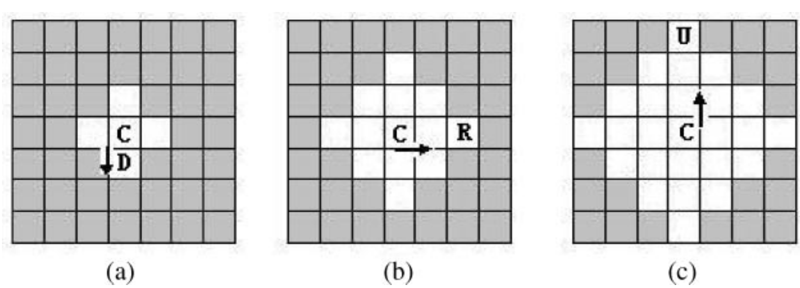

Figure 1. The definition of neighborhood; the white cells except cell-C is the neighborhood of the core cell.

Stage 1: Select those whose velocity is 1 and were not selected to move at last time-step, or randomly select part of them if this is the first time-step; they are selected to move at this time-step with all whose velocity is 2. For each cell occupied by occupant who is selected to move, check the neighboring cells, then select a proper cell and assign the cell to be occupied one more occupant. After all the selected cells are checked, go to Stage 2;

Stage 2: For each cell more than one occupant vying, it is randomly assigned to be occupied by one of the viers with each one having same chance; other occupants have to stay where they were last time-step. After all the cells are checked, go to Stage 3;

Stage 3: Given each occupant, who has decided to move, the probability p_{stay} to stay.

In this model, we assume that the cell with the least danger grade in the neighborhood has the definitive attraction to the occupant. This assumption will provide optimal results and should be studied in detail in the future work. Here, the possibility p_{stay} is introduced to simulate occupant's unexpected behaviors such as suddenly stop for physical and other reasons. It may be different for different people in different situations. In the simulations presented in this paper, an experimental value, 0.05, is used, just to make the model more stochastic. It can be changed according to the real situations.

SIMULATION RESULTS

Firstly, the model is used to simulate the evacuation from a large classroom with two exits.

In the familiarization stage, each occupant is introduced to get familiar with the room for 5000 time-steps. There are two kinds of occupants in this simulation: the slow man, whose velocity is 1, and the fast man, whose velocity is 2. In the evacuation stage, all the 150 occupants start evacuating at the time-step of 1 and the whole evacuation costs 131 time-steps. Typical results of different dynamic stages using the basic model are shown in Figure 2. Figure 2(a)–(c) are the stages at the time-step of 0, 20 and 70, respectively; the radius of neighborhood is 2 and the value of p_{stay} is 0.05. The results show that by introducing the familiarization stage all the occupants can easily find the way out in the building full of obstacles. The method is feasible for that in smoke filled room, if the visibility is limited, the occupants usually used the building signs such as obstacles and structures (the corners, railing, etc) to help orient.

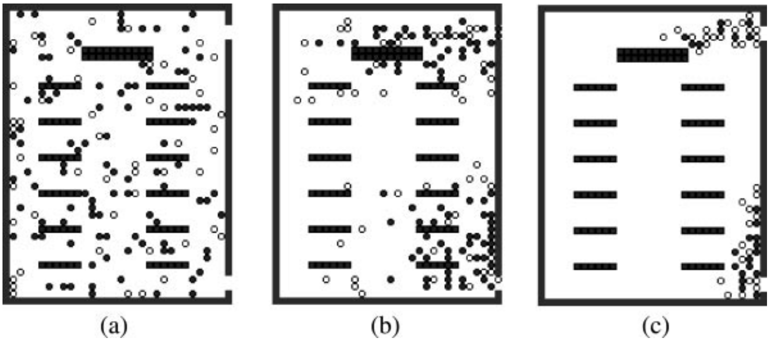

Figure 2. *Simulations of occupants evacuating from a large classroom; the black rectangle represents obstacles, a full circle represents a fast man, an open circle indicates a slow man.*

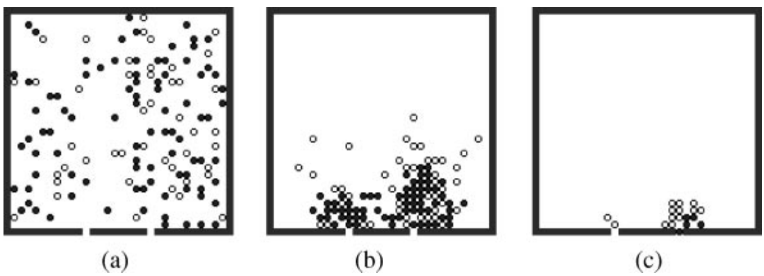

Figure 3. *Simulation of occupants evacuating from a room with asymmetric occupant density.*

Another simulation is introduced to study the effect of *premeditation* by simulating the occupants evacuating from a room with two exits.

In this simulation, at the beginning of evacuation, there are about 45 occupants in the left part of the room and 90 occupants in the right part. All the occupants begin to move at the same time-step of 1. Typical results of different dynamic stages are shown in Figure 3. Figure 3(a)–(c) are the stages at the time-step of 0, 30 and 155, respectively; the radius of neighborhood is 3 and the value of p_{stay} is 0.05. According to our model's rules, at first, each occupant will move to the nearest exit, but because the right part has more occupants, once the occupants of the right part find they may evacuate from the left exit earlier, they will move to the left part. In the simulation, about 15 occupants from the right part evacuate through the left exit. From the results, we find the term *premeditation* can model the human's intelligence in some degree.

Further, as an example of application in building design, the model is used to study on evacuation from a corridor. Two scenarios are comparatively studied here; one is 2 cells wide, 60 cells long common corridor, the other corridor has a 6 cells widening part in the middle (see Figure 5). Again, there are two kinds of occupants in this simulation: the slow and the fast.

Suppose that 500 occupants evacuate through the corridor from a large packed room, in the simulations the percent of slow persons varies from 0 to 100%. For each percentage, the simulation is performed in the respective scenarios with the same initial conditions and the same boundary conditions. Here we simulate in many different initial and boundary conditions and get the common results.

The total time cost with different percentage of slow man is showed in Figure 4. From Figure 4, we can find several interesting phenomena. First, the total time cost increases with the increase of the slow man, but when the percentage of the slow man is greater than about 85% (about 80% for widened corridor) the total time begins to decrease. This means when there is only one velocity, the evacuation efficiency is greater than when there are two velocities coexistent. According to the study of Helbing et al. on cars and lorries traveling along a two-lane highway with different velocities, there is a highly coherent state when the traffic flow is high and stable characterized by all vehicles having the same average velocity and a very small dispersion around this value [15]. They also observe the effect in real Dutch traffic data. In our simulation when there is only one velocity, the overtaking is scarcely, the evacuation can be viewed as reaching a stable coherent moving state.

However, different kinds of people coexisting in real evacuation are inevasible. The existence of little percentage of slow man (or fast man) will cost many more time-steps than the situation of having only fast

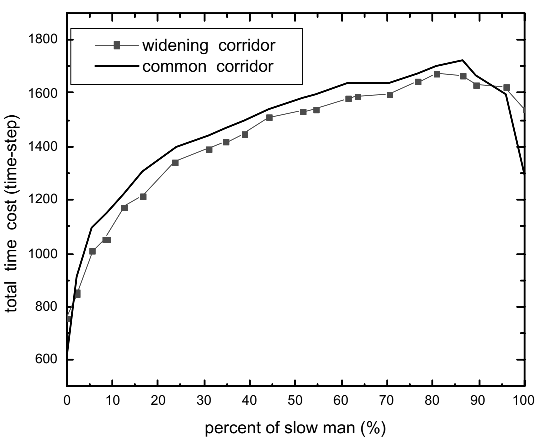

Figure 4. *Total time cost with different percent of slow man.*

(a)
(b)
(c)
(d)

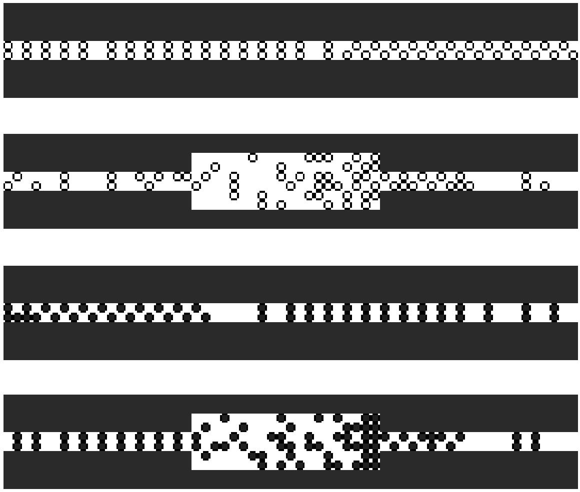

Figure 5. *Simulations of occupants evacuating through two different corridors from left to right; (b), (d) have a widening part in the middle. (a), (b) percent of slow man is 100%; (c), (d) percent of slow man is 0%.*

men (or slow men). From Figure 4, when the percentage of slow man is 0 the total time is 624 time-steps (754 for widened corridor), but when the percentage of slow man reaches 5%, the total time is 1094 time-steps (1010 for widened corridor). When the percentage of slow man is 100% the total time is 1290 time-steps (1540 for widened corridor), but when the percent of slow man is 95% the total time is 1596 time-steps (1622 for widened corridor). By studying the dynamic demonstration of the evacuating process, we find the existence of slow man prevents the fast man go ahead smoothly, the fast man has to switch from one ''lane'' to another frequently, this greatly increases the total time cost. Here we view occupants evacuating along the assumed ''lane''. Also, when the percentage of fast man is little, the switch of the fast man frequently from one ''lane'' to another affects the stable process of slow man. From above analysis, one can find it is very important for the evacuating occupant to maintain a coherent moving state. So if we do not consider the great effect of coexisting different kinds of people, we can not get the reasonable evacuation time for building design.

Second, let us study the effect of building characteristics, when the percent of slow man is near 0 or 100%, the existence of widening part will decrease the efficiency of evacuation. The similar results were obtained by Helbing et al. in his another article when simulating an escape with a wider area [10]. The reason is that the widening leads to disturbances of

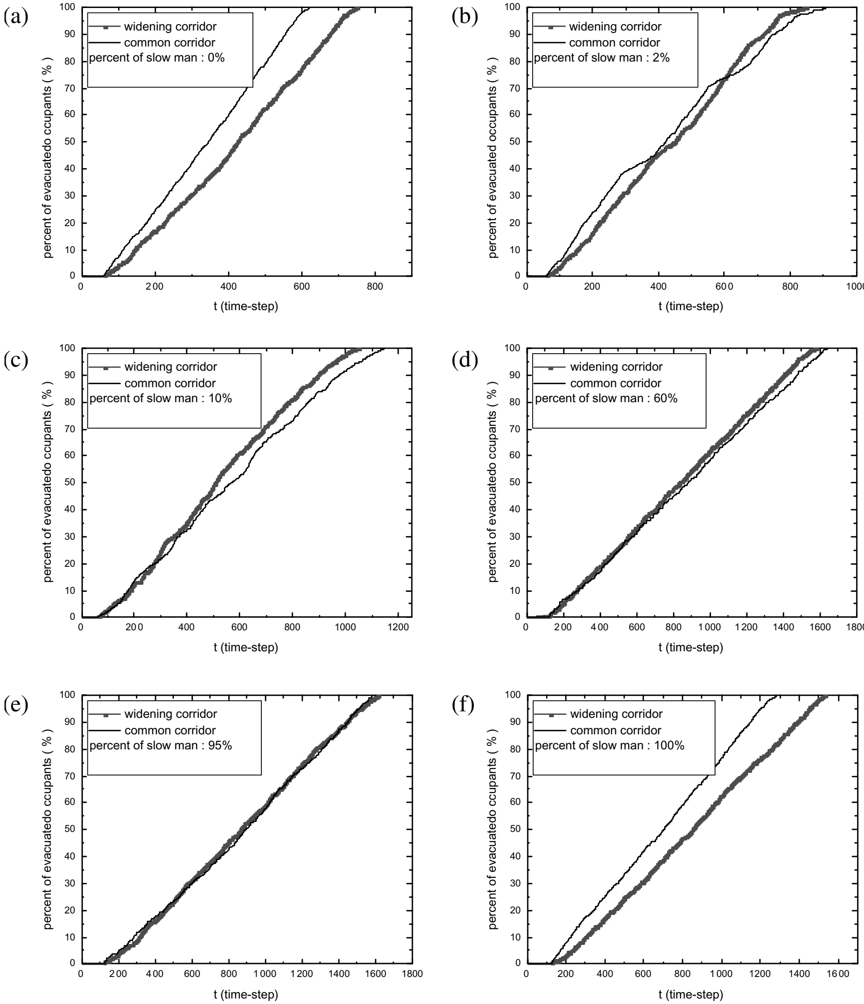

Figure 6. *Efficiency of occupants evacuating through two kinds of corridors with the percent of slow man: (a) 0; (b) 2%; (c) 10%; (d) 60%; (e) 95% and (f) 100%.*

pedestrians; they try to overtake each other in the wide area and squeeze into the main stream again at the end of the widening. Hence the end of widening part acts like a bottleneck, and leads to jamming (Figure 5(b),(d)). Figure 5(a) and (c) are corresponding stages for the common corridor and the movement is more coherent and stable. More detailed comparison of efficiency when the percentage of slow man is 0 and 100% are shown in Figure 6(a) and (f). However, when the

(a)

(b)

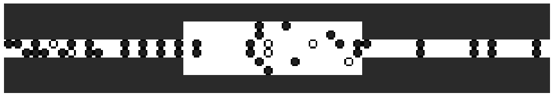

Figure 7. Simulations of occupants evacuating through two different corridors from left to right with the percent of slow man is 20%: (a) common corridor; (b) widening corridor.

percentage of slow man is between about 2 and 95%, occupants evacuating through the widening corridor use less time-steps than through the common corridor. More detailed comparison of efficiency is shown in Figure 6(c),(d). Figure 6(b) and (e) are two stages near the critical condition. Actually, the slow men are often in the way of the fast men, so the widening part provides a place for the fast man to overtake the slow men, thus in this situation the widening part acts like a reducer valve (Figure 7). Figure 7(a) shows a stage when the slow men are in the way of the fast men the blocks form behind the slow men. Figure 7(b) shows how the widening part provides the space for the fast men to overtake. Figure 7(b) shows the fast men (full black circles) begin to disperse and overtake the slow men. From the above analysis, it is not easy to judge whether the introduction of widening part will benefit for evacuation or not. Its advantage is related to the distribution of different kinds of occupants in the buildings.

CONCLUSIONS AND REMARKS

In this paper, a stochastic cellular automaton model is proposed to simulate occupant evacuation from fire room. The model is focused on studying the effect of the evacuee's principal behavior and building structures on evacuation efficiency. Here are some advantages of this model.

The model is set up based on describing the principal individual behavior in evacuation as well as the effect of environment on evacuee such as smoke and scorching air. Thus, by adjusting the human behavior according to the development of fire we are able to study the different results of different behavior characteristics. In addition, the lively demonstration of the evacuation process offers an easy examination of occupant movement on computer, which enables us to study the effect of building structure on evacuation and is helpful in performance-based building design. Also, the introduction of familiarization and evacuation stages makes the evacuation closer to real condition and the determination of escape route easier. The concept *premeditation* is useful in simulating human intelligence and can also be used to describe the condition in smoke-filled building.

Basically, the model is set up to study the special phenomena in evacuation. And an accurate knowledge of the collective behavior of evacuee is valuable for it can provide new insights in the formulation of more effective strategies of managing crowd escape as well as the design of efficient exits. In this paper we found disordered moving states will badly decrease the evacuation efficiency. The coexistence of different kinds of people may cause such disorder. The widening part of corridor at some degree resolves the problem but when there is only one kind of velocity it will destroy the stability and increase the evacuation time. So its application should be studied practically and carefully. In addition, the set of special pass for the slow man may be a good means to solve the problem and the feasibility needs further studies.

Orderly and stable movement is a very efficient state but can not be easily attained. It is very important for the occupants to take part in evacuation training so that they can do better in the evacuation. Also, a good design of building should be able to resolve the conflict in evacuation effectively.

Besides the simulations presented above, some other special phenomena in occupant evacuation can also be described. For example, in our further work, we will introduce the effect of smoke on occupants through slowing their speeds and other human characteristics. It can be safely predicted that after introducing more parameters, the model will be more reasonable and useful.

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