Emergent Fundamental Pedestrian Flows From Cellular Automata Microsimulation

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ABSTRACT

In recent years cellular automata (CA) have been successfully applied to modeling traffic flow. This paper examines the use of a cellular automaton for modeling pedestrian flows. A particle hopping model for a single directional pedestrian flow over a multi-lane walkway is presented. This model offers the advantage of effectively capturing the behaviors of pedestrians at the micro-level while attaining realistic macro-level activity. The emergent group behavior is an outgrowth of the interaction of the rule set in simulation. The results show that a heuristically derived minimal rule set produces flow patterns that closely resemble the accepted fundamental diagrams. Important parameters for determining the shape of the fundamental diagrams are examined. Key rules used in a vehicular traffic CA are tested for their applicability to the pedestrian CA-model.

INTRODUCTION

Cellular Automata (CA) is an artificial life approach to simulation modeling. It is named after the principle of *automata* (entities) occupying *cells* according to localized neighborhood rules of occupancy (*1*). The CA local rules prescribe the behavior of automata creating an emulation of actual behavior. Since many of the rules are used to describe intelligent decision making behavior of the automata, CA models appear to exhibit artificial intelligence (AI) and therefore are often termed artificial life (A-Life) models.

In recent years, CA models have been used to model transportation systems. Nagel and Schreckenberg (N-S) have analyzed vehicular movements with a CA car-following model (*2*). They have demonstrated, through local rule sets for vehicles, the emergent macroscopic behavior as appropriate speed-flow-density relationships. The CA automobile models exhibit non-linear speed transitions and self-organized criticality that is present in actual shock waves (*3-5*). Most promising for CA traffic modeling is that high-density chaotic traffic phenomena are difficult to capture with equation-based models and that the short-term inter-vehicular reactions of drivers can be approximated by a limited rule set. The N-S rule set has been extended to a two lane CA traffic model (*6*). The N-S CA car-following model is being used in the traffic modeling component of the TRANSIMS planning package (*7*).

Although pedestrian flows are an important consideration in the transportation arena and guidelines for level of service analyses are defined in the Highway Capacity Manual (HCM) (*8*), there are few microscopic models for studying the movement of pedestrians. The few that have been applied in practice have been based on applying statistically derived speed-flow-density relations to individuals, rather than on a behavioral basis. The complexity of the task of modeling the conflicting and flexible movements of pedestrians has been daunting to a lower level of microsimulation development.

Pedestrian movement is a highly complex and often chaotic process. While pedestrians appear to follow heuristic conventions, such as a tendency for forward-moving pedestrians staying toward the right, there are no formal procedures, such as speed limits or passing rules designed to control vehicular traffic, that govern pedestrian movements. Whereas vehicle flows are restricted to channelized lanes, pedestrian flow is only restricted to a general width of walkway without well-defined channelization. It is not assured that pedestrians will follow a specific lane. The Highway Capacity Manual goes as far as stating that the concept of "lanes" for pedestrian movements is only useful to determine the number of pedestrians that can walk abreast on a given walkway width. In addition, unlike vehicular movements, there is a tendency for pairs or groups of pedestrians to walk side-by-side or in clusters. On pedestrian walkways, traffic progresses in both directions and avoidance of head-on collisions must be considered. In open spaces flows may conflict from a number of directions.

CA presents the possibility of using individual behavioral rules to recreate the chaotic behavior of pedestrians. In drawing from the example of car-following CA, it would be expected that the emergent aggregate behavior be realistic. As discrete entities that move with short-term step choices, pedestrian movements are a logical candidate for CA modeling. Furthermore, the interaction of walkers is intelligent in the respect that decisions are made individually, according to actual conditions on a case-by-case basis. These decisions result in pedestrian movements that are extremely flexible and walking speeds and accelerations that are frequently adjusted.

This paper explores the use of cellular automata for modeling pedestrian walkways. A pedestrian rule set that is necessarily different from car-following behavior in some important respects is presented. The pedestrian rules developed here are intuitively based, since pedestrian path negotiation and inter-pedestrian actions at the micro level are less understood and less constrained than auto movements. As is the case with CA, many rule sets are possible. Since the development effort is largely heuristic, it is difficult to determine which rules are essential. The rule set applied in this research was constructed to contain minimal essential factors for pedestrian decision making that would result in realistic emergent group behavior. The performance of the model is evaluated based on widely accepted fundamental pedestrian flows as described in the Highway Capacity Manual and other sources.

BACKGROUND

In recent years there has been a growing interest in understanding traveler behavior, including that of pedestrians. The costs of facility design, where people movement is an important factor, is a driving force in the effort to better attend to pedestrian needs. The growing world population especially in dense clusters, is also driving interest. Intermodal and transit facilities, pedestrian walkways, sidewalks, traffic intersections, office building lobbies, markets and malls, all have pedestrian flow requirements under normal, high demand, and emergency demand (evacuation) conditions. There also arise high density outdoor activities such as at sporting events, concerts, and religious gatherings that might be better and more safely planned after using a microsimulator of pedestrian actions. It is thought that a microsimulator that can capture the generalized effects of pedestrian movements, while beyond the scope of this paper, would be a welcome addition to the toolbox of professional facility planners, designers, and operators. This paper aims at establishing the cornerstone of larger multi-purpose models by developing a minimal set of rules that result in accurate fundamental relationships of speed-flow-density.

Classical work in describing the fundamentals of pedestrian flows is presented in the HCM (*8*). The HCM provides a record of essential research on pedestrian behavior and diagrams of the accepted fundamental speed-flow-density relationships. Various researchers have studied pedestrian flows statistically. It is not intended to reexamine that material in detail here. Notable in recent times is a study by Virkler and Elayadath (*9*) that examines the speed-flow-density relationships. They used seven well-established curve fitting methods in examining experimental data from unidirectional peak demand in a pedestrian tunnel.

Pedestrian microsimulation models suited for various purposes have been developed. Pedestrian traffic in building evacuation has been examined by Lovas (*10*) using a discrete event queuing network. Pedestrians with individually assigned characteristics are “moved” through a network (the building) consisting of rooms and doorways (modeled as nodes and links respectively) with the goal of reaching an exit as quickly as possible. Capacity constraints placed on corridors and doorways serve to cause queuing and congestion. Walking speeds within rooms are generated from an established speed-density relationship. As a behavioral tool this model stopped at the route choice level and its time effects, and did not go into inter-pedestrian negotiations. A CA model of evacuation would attempt a rule-based approach to exiting through bottlenecks, perhaps similar to Blue, et al. where bumping rules are employed to capture jostling effects of a crowded 4-directional lattice of pedestrians (*11*).

Simulation of crowding behavior at a large, highly concentrated religious gathering has been modeled by AlGadhi and Mahmassani (*12*). A set of simultaneous partial differential equations are solved numerically by discretizing time and space. Several classifications of users, depending on direction of movement, are used in conservation of mass flow equations between cells of participants. The model uses an empirically derived speed-concentration relation in determining speeds. Though similar to a CA model in that cells and time slices are used, this model is not based on rules of behavior of individuals, but rather aggregates behaviors of individuals based on equations.

In pointing out the differences between these simulation models and the CA approach presented here, the intention is to clarify the fundamental break with previous simulation methods that CA makes. There is no comparison intended with the goals and methods of the above two simulation models which are well conceived. The main point of contrast is that the CA model is based on behavioral rules, and thus, the emergent group behavior comes from the dynamics of the pedestrians in motion across the cellular lattice of possible pedestrian positions. Most simulation models apply equations and not behavioral rules. The CA behaviorially-based cellular changes of state determine the emergent results. CA has the possibility of giving rise to very lifelike phenomena, and to new possibilities of modeling based on behavioral rules.

CA MODEL FORMULATION

Transferring logic to a pedestrian CA model is more than a scaling problem of other CA models, such as the N-S vehicular traffic rule set. Pedestrians are self-propelled and their walking capabilities can vary greatly. As a percentage of mean speed, pedestrians have a much wider range of desired speeds, unlike drivers who are more aligned with a speed limit. Since pedestrians generally do not experience fatal crashes with one another, their behavior is different from drivers. Pedestrians do not use rear view mirrors and do not have much concern about those behind them. They do not have the same acceleration problems as cars, since pedestrians are capable of changing speed more quickly when gaps arise to do so. They may change lanes more often and more casually. They are accustomed to roadways many lanes wider than auto roadways (if a lane width is considered one traveler wide). Though not treated in this paper, opposing flows may use the same lanes and cross traffic may present itself at any time in open spaces.

The pedestrian walkway is modeled as a closed loop system as described by Nagel and Rasmussen (*3*) in their single-lane traffic flow model. The pedestrian walkway is represented as a circular lattice of width W, length G, and lattice of class L = W*G. Each cell is given the notation L(i, j) where $1 \leq i \leq W$ and $1 \leq j \leq G$.

At the start of the simulation, a density d, where $0.05 \leq d \leq 1.0$, is generated and N = INT(d*W*G) pedestrians are created and assigned randomly to the lattice. This set of N pedestrians $P = \{p_1, p_2, \ldots, p_N\}$ remains constant throughout the simulation as conservation of walkers is maintained. Having a circular lattice allows the set of pedestrians to interact at constant density D = N/L and constant space allowance S = L/N.

Pedestrian behaviors are varied by assigning each pedestrian p_n a maximum desirable walking speed, denoted $v_{max}(p_n)$. In each time step T_i for i := 1 to maximum number of time steps, the pedestrians are moved through the lattice according to a set of local rules. Movement includes both lane-changing and cell hopping.

During each time step, cell L (i, j) can take on one of 2 states, unoccupied or occupied, and is assigned the value:

$$L(i,j) = \begin{cases} 0 & \text{If cell } (i,j) \text{ is unoccupied} \\ p_n & \text{If cell } (i,j) \text{ is occupied by pedestrian } p_n \end{cases}$$

In the CA model, a pedestrian p_n moves at velocity $v(p_n)$ with a maximum desired speed, $v_{max}(p_n)$. The range of allowable movements is equal to minimum of {$v_{max}(p_n)$, gap (p_n)} where gap (p_n) is the number of empty cells ahead and $v_{max}(p_n)$ is the predefined velocity parameter for pedestrian p_n. Pedestrians change lanes on row i and then move forward in column j.

Statement of Local Rules

Each iteration of the simulation is based on a two-stage parallel update of the set of pedestrians. During the first stage, a set of lane changing rules are applied in parallel to determine if pedestrians will change lanes within the lattice. During the second stage, all of the pedestrians are assigned a current speed based on the available gap and are advanced forward by this speed. This section presents a descriptive account of the rule base.

Four rules are used to prescribe lane assignment. The first two rules are applied to determine if there is an adjacent cell which could be a candidate for lane switching. If the adjacent cells are occupied or perceived to be unavailable for switching, the latter rules are bypassed. The latter two rules assign each pedestrian to the lane, current or adjacent, having the maximum gap available.

Rules 1 and 2 are used to determine if either or both adjacent lanes, immediately to the left or right of a pedestrian p_n, are free (unoccupied and within the defined lattice). Rule 1a checks if the cell immediately to the left of the pedestrian's current cell is free; rule 1b checks the cell immediately to the right. Rule 2 prohibits a collision with a pedestrian two lanes over who might want to switch lanes and occupy the same adjacent lane. Though pedestrians may not be concerned with pedestrians behind themselves, they generally don't wish to collide with someone a lane away who might also switch to the same adjacent lane at the same time.

(Rule 1a) **IF** the lane immediately to the left is beyond the lattice boundary

OR the cell immediately to the left is occupied by another pedestrian

OR the cell immediately to the left is free but the cell two lanes over to the left is within the lattice and occupied by a pedestrian

THEN assign the cell to the left to be occupied

(Rule 1b) **IF** the lane immediately to the right is beyond the lattice boundary

OR the cell immediately to the right is occupied by another pedestrian

OR the cell immediately to the right is free but the cell two lanes over to the right is within the lattice and occupied by a pedestrian

THEN assign the cell to the right to be occupied

(Rule 2) **IF** the lane immediately to the right is assigned to be occupied
AND the cell immediately to the left is assigned to be occupied
THEN assign pedestrian p_n to his current lane
ELSE goto rule 3

Once it has been established that either or both adjacent cells are free, rules 3 and 4 are used to assign pedestrian p_n to a lane. Begin by computing the existing gaps in the current lane i and for the unoccupied adjacent lanes i+1 and/or i-1.

(Rule 3) **IF** there exists a gap that is uniquely maximal
THEN assign p_n to that lane

(Rule 4) **IF** there exists equal maximum gaps in two or more lanes, apply one of the three tie-breaking rules to determine assignment for p_n:

(***4a - 3-way tie***): Randomly determine lane assignment using 80/10/10 split between current lane and two adjacent lanes.

(***4b - 2-way tie between the adjacent lanes***): Randomly determine lane assignment using 50/50 split .

(***4c - 2-way tie between current lane and single adjacent lane***): Randomly determine lane assignment using 50/50 split .

In rule 4a, it is assumed that pedestrians usually remain in the current lane but sometimes drift out of it.. For rule 4b, a 50/50 split is the most reasonable assumption for unidirectional flow. For rule 4c, a 50/50 split assumes pedestrians have as much interest in maintaining a cell-width of separation from an adjacent person (in the occupied adjacent lane) as they have in remaining in the current lane.

The probabilities specified in rules 4a, 4b, and 4c are those that were chosen for our simulation experiments as they were found to work best. It is certainly possible to experiment with other values.

The second parallel update of the pedestrian stream is movement forward in the newly assigned lane. Rule 5 determines how many cells the pedestrian is advanced. The maximum possible number of cells that a pedestrian can be advanced is the minimum of his personal maximum velocity compared with the current gap. $v(p_n)$ is the assigned velocity for the current time step equivalent to the number of cells that walker p_n in L(i,j) will be advanced during the current time step. The gap value may be different from that used in the lane changing decision, because pedestrians may have moved in front, based on their lane changing decisions.

(Rule 5) **IF** the current gap is less than or equal to the maximum speed for the pedestrian

THEN set the current speed of the pedestrian to the gap size [$v(p_n) = gap(p_n)$]

ELSE set the current speed of the pedestrian to the maximum speed [$v(p_n) = v_{max}(p_n)$]

Advance each pedestrian p_n, $v(p_n)$ cells forward in the lattice

SIMULATION EXPERIMENTS

This CA model is run with pedestrians distributed randomly on a lattice 40 cells long and 10 cells wide. Each cell is considered square, 0.457 m (18 inches) per side. This cell size is scaled according to minimal requirements for personal space as described in the HCM and to meet the speed-flow-density requirements that emerge. The lattice is connected as a loop where pedestrians circulate on a walking track at a given density. Conservation of pedestrians is strictly maintained. There are no curvature effects with the loop, since it is an artifice of the computer allowing the same pedestrians to walk long distances together. This resolves the difficulty of trying to feed more pedestrians into the network than capacity will allow. The average performance of all pedestrians over 10,000 time steps is used in the performance analysis. In the experiments a time step of one second was adopted.

The fundamental diagram of pedestrian flow is the target for determining the effectiveness of the CA model to adequately portray macroscopic behavior. Level of service criteria for pedestrian flows are defined in the HCM and are based on the relationship of three variables: *space, flow rate,* and*, walking speed.* ***Space*** is the inverse of density and relates area of walkway to number of pedestrians. Space is typically measured in square feet per pedestrian. ***Flow rate***, measured in pedestrians per minute per foot of width, is analogous to volume. ***Average speed*** is the rate of movement given in ft/min. The fundamental relationship is given as:

Flow Rate = Average Speed / Space = Average Speed * Density

For the CA model, the prevailing flow rate was determined by counting the number of "laps" that each entity makes (i.e., the number passing a counting station at the end of the lattice L(N, j) over 10,000 seconds (2.78 hours). Speed is the total number of steps taken by each entity over the time period, which in each case is 10,000 seconds. Density for the system is predefined for any simulation run and its reciprocal is used as the space parameter. Each performance measure is scaled against the cell size.

A parallel updating procedure, as described earlier and similar to that defined by the multi-lane N-S rules [6] was employed. In the parallel procedure, each pedestrian bases its behavior in the current time step on the perceived conditions in the neighborhood during the previous time step. In car-following behavior terms, pedestrians make lane-changes and adjust their velocities based on the speeds and positions of pedestrians immediately in front of them and in adjacent lanes. The parallel updating process involves an iteration in four stages applied during each time step. First, lane changes are examined for all entities. Second, the lane changes are made. Third, the allowable forward movements are determined for each entity. Fourth, all entities are advanced by the determined speed. Parallel updates are preferred to sequential updates because the latter would give results that are dependent on which pedestrians move first. A sequential update would reflect instantaneous reaction to the behavior of the pedestrians in the neighborhood. This is an unrealistic and problematic method for this type of CA model.

The model was run for 11,000 time steps with the first 1,000 time steps used to initialize the walkway with movement. The statistics for this start-up period are discarded. A set of twenty replications were done at each density examined. A total of nineteen sets of runs were simulated with densities ranging from 0.05 to 0.95 in increments of 0.05. The values of the parameters of fundamental flow are generated as the average of the 20 replications per set.

Density is a predefined parameter in each run. This density, specified as a percentage of occupied cells, is applied to allocate the pedestrians to the walkway. At a density of 1.0, total gridlock is experienced and average speed and volume have a value of zero. At a density of approximately zero (i.e., only 1 pedestrian in the system) the mean free speed is the system speed.

Multiple Walking Classes

It has been shown that pedestrians move at different rates and it would be simplistic to model pedestrian flows with a single class. Mean free speeds are quoted by Lovas (*10*) with a mid range value of 1.35m/s (4.43 fps) and 0.15 m/s standard deviation (from Fruin (*13*)). If only speeds of 1 m/s, 1.5 m/s, and 2 m/s are allowed, 95 percent would walk at 1.5 m/s and 5 percent of pedestrians would travel at the other rates to create the same standard deviation. Others have cited higher standard deviations on the order of 0.30 m/s (*14*) that indicate 20 percent would have uncongested speeds of 1.0 m/s or 2.0 m/s in creating a standard deviation of 0.30 m/s.

Three walker classes were adopted for the experiments: ***Class A,*** those assigned with maximum rate of 3 cells per time step (about 1.3 m or 4.5 ft per time step), ***Class B,*** those moving with a maximum rate of 2 cells/time step (about 0.85 m or 3 ft per time step), and ***Class C,*** those moving with a maximum rate of 4 cells/time step (about 1.8 m or 6 ft per time step). It was found that a *90% distribution of walkers* (meaning 90%- Class A, 5%- Class B and 5%- Class C) produced the best realization of the fundamental diagram for pedestrian flows.

Using multiple classes is necessary because under a single class all entities want to move at the same speed and it is possible, that at some densities, the entities self-organize into lock step, marching in rows separated by 3 cells and columns separated by 1 cell without opportunity for lane changing. This unrealistic behavior allows for speed at or near maximum flow. Even when the runs where no lane changing occurs are ignored, the speeds and flows are uncharacteristically high at a density of 0.2 P/ft^2 at which lock-stepping tends to occur to some extent with a single user class. In the N-S traffic flow model, this problem is avoided by adding a randomization step to decrease the speed of some traffic and introduce perturbation into the flow at each time step.

Figure Sets 1 and 2 illustrate the resulting fundamental diagrams for the 90% distribution case as compared with a single regime linear speed-density model as shown in the HCM (referenced from Pushkarev and Zuppan (*15)*) and a bell-curve hypothesis. In the field data curves fit by Virkler and Elayadath, the speed-density model that most closely describes the shape found with the CA rules is May's bell-shaped model (*9)*. For this experiment the equation for the bell curve that was used is given as:

$$V = \alpha e^{-\beta D^2}$$

where the values α = -270 and β = 24.5 were used.

Figures 1 and 2 illustrate that the pedestrian CA model is a realistic representation of macroscopic flows. The maximum flow of 24.5 Ped/min/ft-of-width is very close to the maximum capacity of 25 Ped/min/ft-of-width shown in the HCM. The model seems to fit the bell shaped hypothesis extremely closely. Though a detailed comparison with speed-flow-density models is beyond the scope of this paper, it is clear that the CA simulations faithfully produce a reasonable representation of pedestrian activity as demonstrated by the curves shown.

Experiments were also conducted for distributions of 80%, 75%, and 50%. At low densities, there are a greater number of empty cells and as a result more freedom for walkers to change lanes and accelerate to their maximum desired values. At low densities the curves were almost identical in shape except for a minor decrease in the speed and volume (a 5% difference in capacity between 90% and 50% distributions) due to increased turbulence from the greater number of pedestrians having lower maximum desired speed. At densities above 0.2 P/ft^2 the constraining effects of tightly spaced pedestrians cause average speeds and volumes in the three distributions to be even closer.

Comparison to Traffic Flow CA

The initial single lane CA model of traffic flow proposed by Nagel and Schreckenberg (*2*) (N-S) used two primary steps, vehicle velocity update and movement, performed simultaneously across the vehicle fleet during each iteration. The velocity update had three components:

1. ***Acceleration:*** If a vehicle is moving at a speed less than his maximum allowable speed and the gap is greater than or equal to the vehicle's current speed + 1 then the vehicle's speed is increased by 1.

2. ***Deceleration:*** If the current gap is less than or equal to the vehicle's current speed - 1 then the vehicle's speed is reduced to the size of the gap.
3. ***Randomization:*** Each vehicle's speed is reduced by 1 with a probability of 50%.

In this N-S model, vehicle speeds are allowed to vary between 0 and a predefined V_{max} which was tested at between 2 and 5 cells per iteration.

In rule 5 of the pedestrian flow CA model stated above, we assume pedestrians can easily and quickly adjust their speed. Therefore, we allow pedestrians speeds to increase more than one cell per iteration. We also do not introduce any randomization effects to reduce speeds. To test the applicability of the N-S vehicle flow model to our pedestrian flow model we decided to perform some experiments where two additional rules, based on the N-S model were introduced to the base rule set.

(Rule A) ***Randomization***: For pedestrians with speed greater than 1 cell per iteration, reduce each pedestrian's speed by 1 with a probability P_m.

(Rule B) ***Limited Acceleration***: If a pedestrian is moving at a speed less than his maximum allowable speed and the gap is greater than the pedestrian's current speed + 1 then the pedestrian's speed is increased by 1.

CONCLUSIONS

The process of creating a CA model of pedestrian movements provokes in depth thought of pedestrian behavior and how to model probable movements. The CA format allows for treatment of otherwise intractable combinations of movements. The single-direction walkway model presented here appears to be the best known rule set to date, and can be taken considerably further. As universal simulators, CA models appear capable of representing any pedestrian behaviors that are deemed appropriate. The adaptability of the automata to circumstances appears to be a valuable strength in capturing a large range of pedestrian movements.

The rule set presented captures the aggregate behavior of pedestrians for a reasonable distribution of desired walking speeds. By changing this distribution, results follow very closely the variations in the patterns shown in the HCM for fundamental relationships. Further, the speed-density curve's similarity with the bell-shape model is very appealing. The simulation results follow from perfect rule following (with some stochasticity) for relatively long periods and averaged over several runs. Empirical data is harder to produce, especially with the precision and duration of the CA model. If the CA model points to a particular regression model, then perhaps that form has improved validity.

Modification of the rule sets and scaling of cell size may produce closer fit to the behavior of pedestrians which can vary with trip purpose. For example, relaxing Rule 2 so that the separation lane can be used by at least one person would make sense, though preliminary tests, have not shown a substantial improvement in performance. Also, when the cell size is changed to 1.4 feet, there is closer fit with the HCM flow-space curve near peak capacity. However, these refinements are left for further study.

The Nagel-Schreckenberg rules for speed variation and acceleration, though appropriate for vehicular movements, appear less useful or unnecessary for pedestrian activity. It is clear from the simulation experiments that the pedestrian rule set is distinct from that for vehicles, as would intuitively be expected.

The proposed CA model is capable of capturing the mean and variance of speeds for demands that are typical of pedestrian corridors. Expanding the range of speeds of pedestrians could be accomplished by using shorted time steps and smaller cells, though somewhat longer computer processing times might result. Preliminary speed tests performed on a Pentium 150 Mhz computer indicate that the model's computational speed is in the neighborhood of 150,000 updates per second at mid-range corridor densities (without streamlining the C++ code). Further study with this model will examine computational efficiency which is another advantage of CA models.

Sensitivity analyses with other lattice lengths, cell sizes and movement combinations may refine the results found, but the basic finding is that a minimal CA rule set can represent much of the behaviors of pedestrians and results in a reasonable representation of pedestrian flows. Opposing flows are an intriguing aspect of pedestrian movements. Additional perceptual work is required by pedestrians when opposing flows conflict. Both lane changing behavior and forward movement is modified by opposing pedestrians. An obvious advantage of CA is that such a fluid dynamical back pressure can be modeled with rules for opposing flow behavior. This is the next step in our analytical endeavors.

In using pedestrian CA in larger microsimulations, numerous possibilities are apparent. Dynamic demand rates exhibiting peaking from a particular direction (as when passengers depart from a train) are a distinct possibility for future study. Blockages to flow such as an information booth, luggage, and so on can be placed on the floor and pedestrian flows studied. Pedestrians often travel in pairs and small groups that operate with a cohesive rule set when encountering traffic blockages. Intelligence could be added to the pedestrians so that they have more foresight in their next cell choice. Performance of pedestrian CA at bottlenecks such as doors, escalators, elevator banks, and transit vehicles might be modeled. These larger rule sets could be combined into complex and large scale pedestrian facility analysis for normal, high demand, and emergency evacuation studies.

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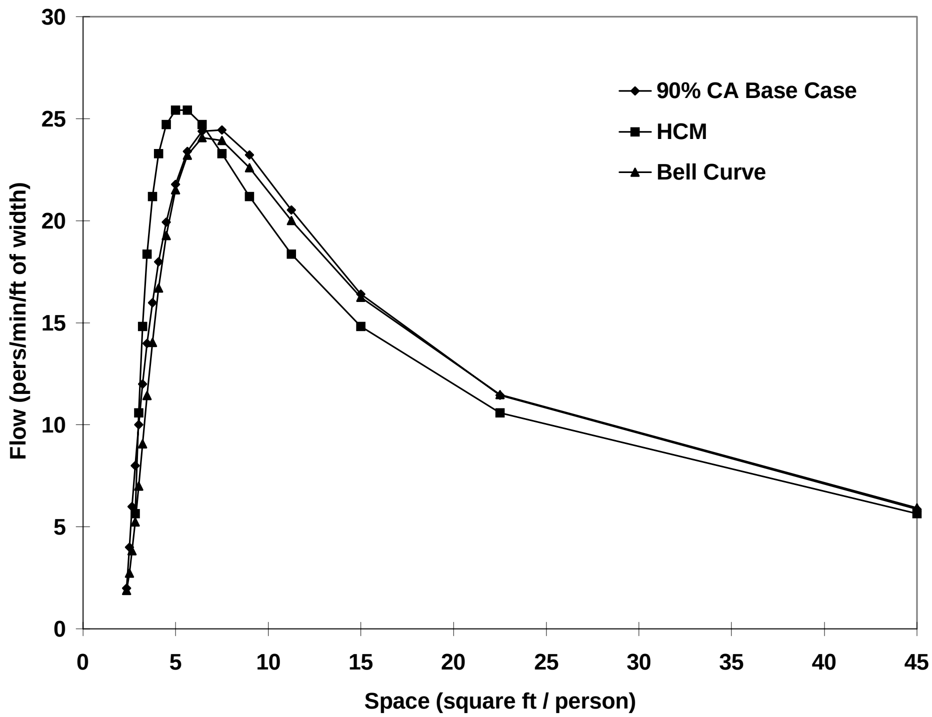
Figure 1: Fundamental Diagram of CA Pedestrian Rule Set
90% Distribution and Base Rule Set
Flow - Speed - Space



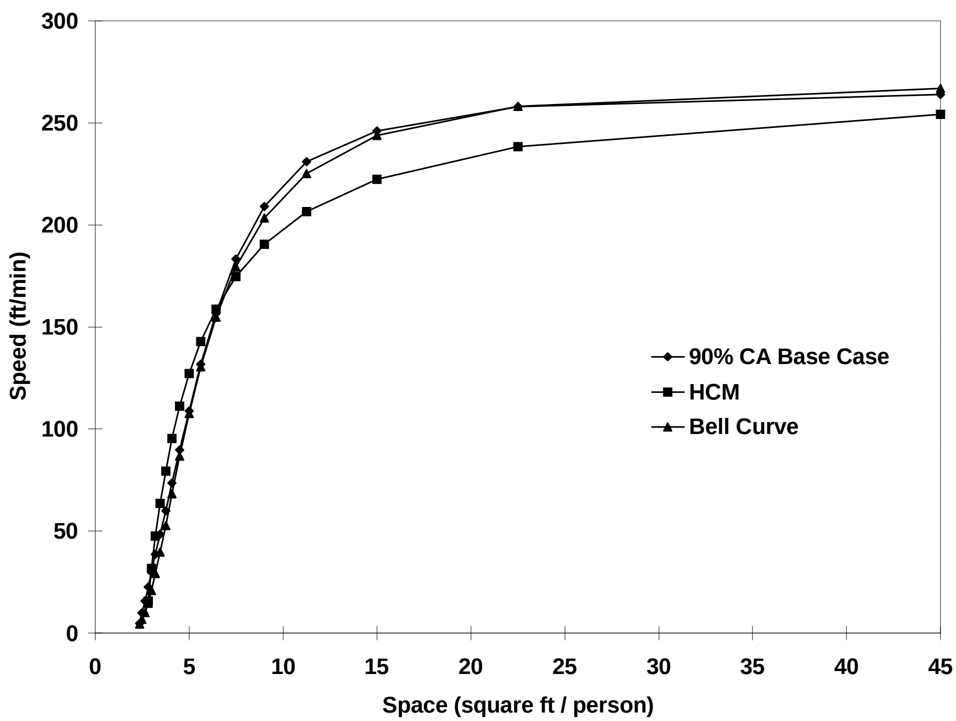
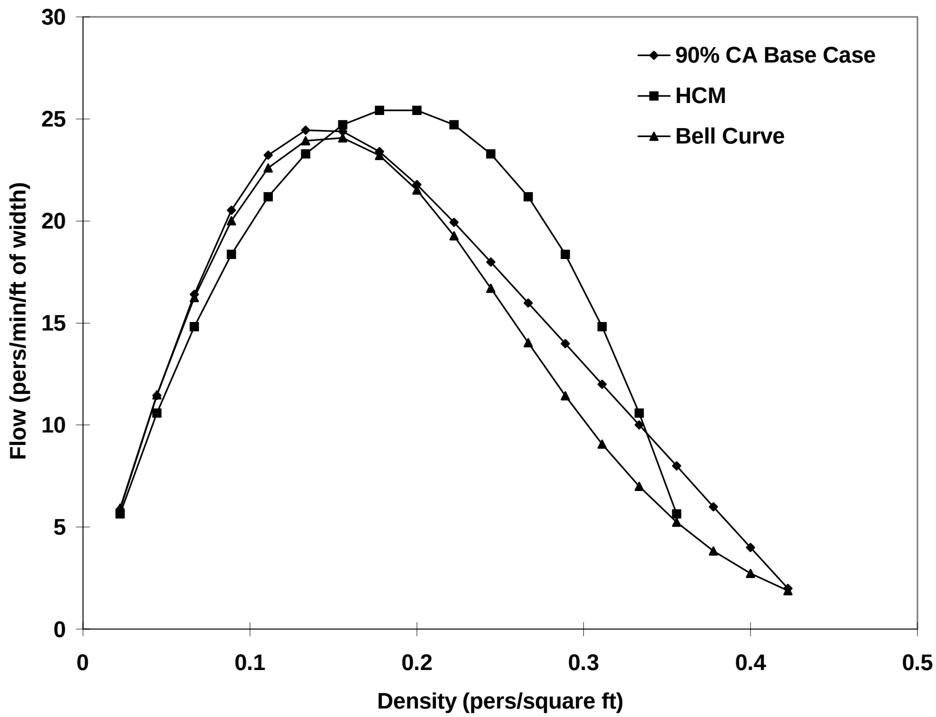


**Figure 2: Fundamental Diagram of CA Pedestrian Rule Set
90% Distribution and Base Rule Set
Flow - Speed - Density**



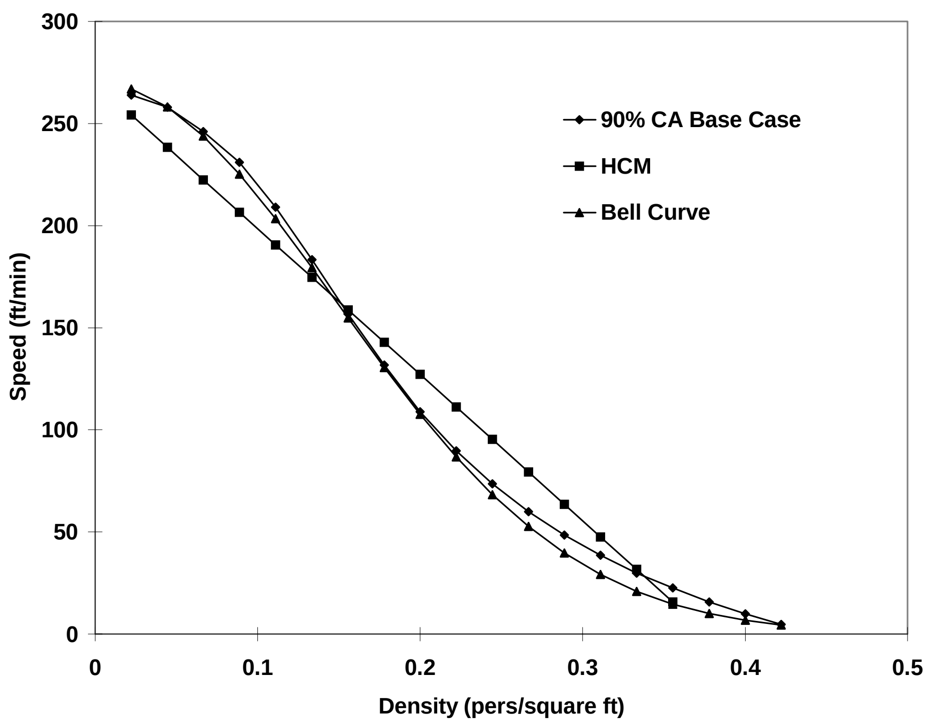
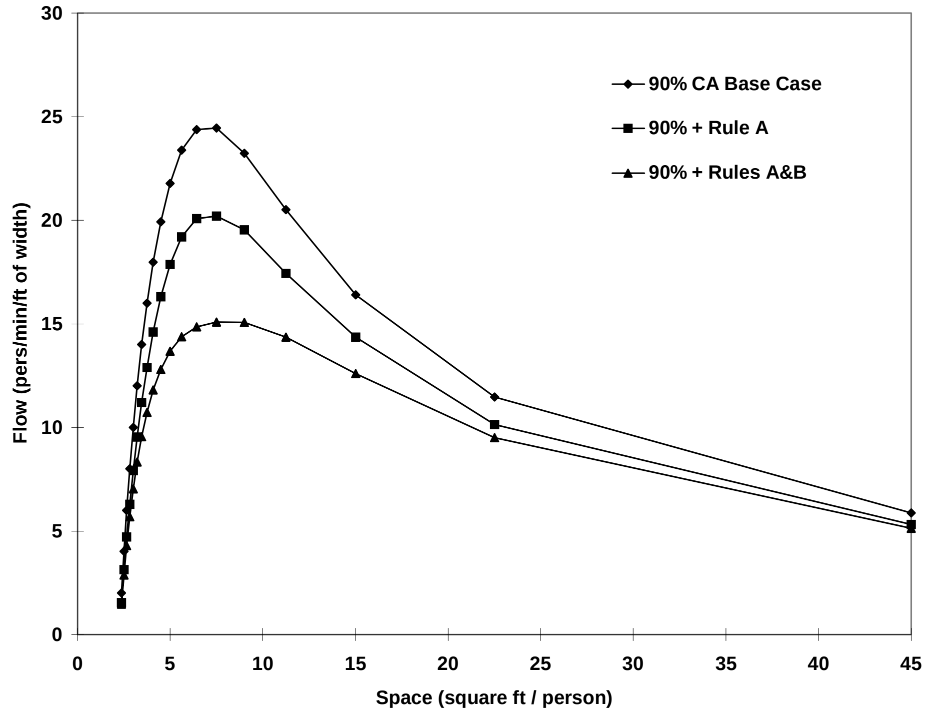


Figure 3: Comparison of Basic CA Pedestrian Rule Set to Nagel- Schreckenberg Rule Set at 90% Distribution Flow - Speed - Space



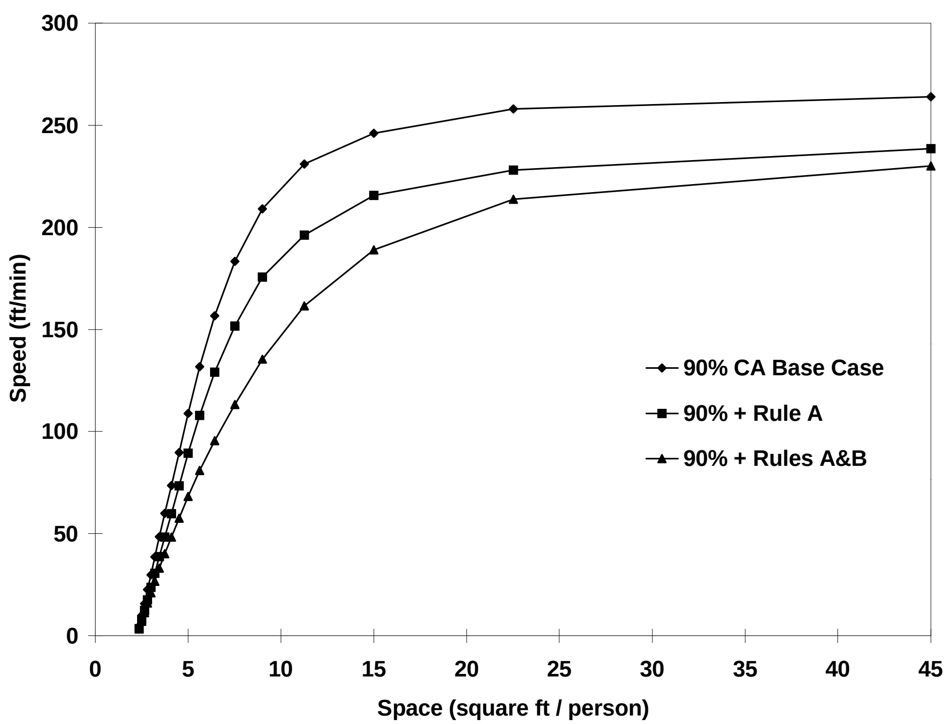


Figure 4: Comparison of Basic CA Pedestrian Rule Set to Nagel- Schreckenberg Rule Set at 90% Distribution Flow - Speed - Density