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Title: **Modeling Four Directional Pedestrian Movements**

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Modeling Four-Directional Pedestrian Movements

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Abstract: The objective of this paper is to explore the modeling of multi-directional pedestrian flows. The complex interactions between flow entities within m-directional space present challenges that cannot be readily handled by existing bi-directional flow models. A cellular automata microsimulation model for 4-directional flow is prescribed. This model, built upon previous bi-directional models developed by the authors, additionally seeks to manage cross-directional conflicts. Performance of this model and potential extensions to the more general m-dimensional case are presented. The applications extend to m-directional terminal facility design and to 4-directional street corners, a vital component in any network model of pedestrians.

Key Words: Pedestrian, traffic flow, simulation, cellular automata

INTRODUCTION

Pedestrians are an integral component of the transportation system. Their movements influence the design and operation of transportation terminals and timing of traffic signals. In recent years there have been several attempts to model pedestrian flows. Chapter 13 of the Highway Capacity Manual *(1)* is dedicated to modeling pedestrian flows and describing macroscopic techniques for capacity analysis. For the most part, the HCM focuses almost exclusively on uni- and bi-directional movements occurring within walkways or along sidewalks. Blue and Adler *(2-5)* have applied cellular automata (CA) microsimulation to model uni and bi-pedestrian directional walkways and demonstrated that these models produce acceptable fundamental flow patterns. Hoogendoorn and Bovy have developed a model of pedestrian flows based on a gas-kinetic modeling paradigm widely applied for modeling vehicle flows (*6)*, Lovas (*7*), AlGahdi and Mahmassani (*8*), Gipps (*9*), and Helbing and Molnar (*10*) are among others who have worked toward developing pedestrian flow models. In general, most of these efforts have focused on uni- and/or bi-directional pedestrian flows.

Models of multi-directional pedestrian movements are needed to analyze more complex transportation terminals and network flows. There has been almost no work on assessing multi-directional pedestrian movements. The HCM *(1)* provides a brief treatment of multi-directional flows by presenting a procedure for analyzing directional flows at a macroscopic level as a prelude to designing signal timings at street corners.

The general multi-directional pedestrian flow problem can be understood by considering pedestrian movements through an open concourse having several access and egress points. As the number of access-egress point pairs increase and the orientation of these points spread around the concourse, there will be an increase in the paths the pedestrians will follow. This, in turn, will lead to an increase in the number of conflicts between individual pedestrians. As the flow rate increases, the intensity of the set of conflicts will multiply further. The complexity of m-directional flows represents a daunting data collection task. The use of a simulation model extends the range of knowledge and can help to create an approach by which empirical measurements may be gathered and used effectively.

This paper focuses on the problem of modeling a four-leg concourse that supports pedestrian movements in four directions. In this paper we refer to this problem as ***4-Ped***. While it is true that the cellular automata microsimulation approach described in this paper is an extension of previous work by the authors focused on bi-directional flows, the work represents a significant departure. The objective of the research is to provide insight into both modeling complex pedestrian flow movements and the applicability of using CA microsimulation. Although CA microsimulation has proven worthwhile for modeling uni and bi-directional flows, it is not readily apparent that it would be equally useful for modeling more complex pedestrian concourses. In particular, the need to expand the rule set and make additional passes through the set of entities to handle more complex interactions within a m-directional space may prove to be computationally inefficient. Figure 1 is a representation of the bi-directional, multi-directional, and 4-directional cases. The multi-directional case would be an extension of the 4-directional model presented here to include methods of seeking particular destination cells and resolving the conflicts that arise.

Cellular automata models or particle hopping models, as they are sometimes referred to, are accepted in transportation science, having been transferred from the physics and mathematical computing communities. Models of auto traffic have been advancing rapidly in the past few years *(11-19)*. Cellular automata models are artificial intelligence models. Each automaton is an intelligent agent, or pedestrian in this model, capable of evaluating its opportunities on a case-by-case basis. The emergent group behavior is the result of the net interactions of the local rules as each pedestrian searches the available neighborhood of cells. The movements are not in any way hard-coded beforehand, but rather the local rules for each pedestrian are applied in each situation in each time step. The term, emergent, refers to the macroscopic patterns that arise from the local interaction of agents *(20, 21)*. As such, CA models represent a discrete surrogate for the partial differential equations that would describe 4-directional pedestrian flow *(21)*. The goal in this paper is to arrive at a 4-Ped model rule set that effectively reproduces macroscopic speed-flow-density characteristics.

THE 4-PED MODEL

The 4-direction pedestrian flow model must account for three types of movements: pedestrian following behavior, head-on conflicts, and cross-directional conflicts.

Pedestrian Following Behavior: As the name suggests, pedestrian following behavior provides a way to model forward movements of pedestrians. Similar to car-following models, changes in speed in each time step depend on whether the pedestrian is a leader (no other pedestrian moving in the same direction is directly ahead) or a follower (a pedestrian moving in the same direction is ahead within range). Passing (lane-changing or sidestepping) movements are also important parts of pedestrian following behavior, but are also somewhat different from autos *(2-5)*.

Head-on Conflicts: In bi-directional pedestrian flows a mechanism is needed to resolve head-on deadlocks that do not occur in car-following models (Figure 2, Case 1). Avoiding oncoming pedestrians and exchanging positions when necessary are added to the unidirectional pedestrian flow model. In avoiding oncoming pedestrians, stepping behind a same direction pedestrian is helpful in producing lanes. In addition, in 4-directional flows, a bi-directional diagonal exchange is allowable (Figure 2, Case 2), though these bi-diagonal exchanges hinder purely bi-directional flows, since it is counterproductive to lane formation.

Cross-Directional Conflicts: When pedestrians moving at right angles to each other vie for the same cell, only one pedestrian can use it and the other must adjust, say, by backing off a step. If a pedestrian backing off a cell has another competitor, the process is reiterated. Also, cross-directional exchanges are needed to resolve deadlocks (Figure 2(b)). These exchanges should first favor forward movement for each member of the exchanging pair (Figure 2, Case 3), and secondarily favor forward movement for one and sidestepping for the other member of the exchanging pair (Figure 2, Case 4).

The basic rules for pedestrian capacity analysis, as defined in the HCM *(1)*, focus exclusively on uni- and bi-directional movements. In addition, the HCM uses the assumption that bi-directional flows separate into (only) two lanes. Under this condition it is as if a bi-directional walkway is really two adjacent walkways, each handling flows of different directions. However, the authors have observed bi-directional flows that separate into multiple lanes in Grand Central Station in New York City. Further, the multiple lanes form dynamically as demand varies slightly and we term this dynamic multiple lane (DML) formation. DMLs have also been recognized and treated with a social force model *(10)* that is more thoroughly discussed in *4, 5)*. Another bi-directional case exists when lanes do not form at all that we term interspersed flow (ISP). This is usually of short duration, before lanes can form. It is posited that cases like bi-directional DML and ISP flows, without separation into only two lanes, and cross- or 4-directional flow require new methods for generating level of service characteristics than are presently available in the HCM *(1)*. Under such conditions one should expect an increase in conflicts that lead to decreases in walking speeds and volumes. Blue and Adler, in their studies of emergent fundamental properties of ISP *(3)* and DML bi-directional flows *(4, 5)*, demonstrate this phenomenon using CA microsimulation. In the computer program, the base case is ISP flow, and DML lane changing rules are turned on to augment the base-case. In these simulations DMLs are not hard coded but emerge from the rule set's processing. The resulting speed-density and volume-density graphs are shifted downward indicating a lower capacity and lower speeds. This phenomenon is further explored and extended to cross- and 4-directional flows in this paper. This paper focuses on the description of the 4-Ped model and discusses a series of microsimulation experiments performed to examine behaviors emerging from the model.

The 4-Ped CA rule set, shown in Table 1, extends the rule set previously developed by the authors (*4*) for bi-directional pedestrian flows. The CA rule set is applied in each time step and consists of two parallel updates. This is done as described in the procedure for multiple lanes of vehicles in Rickert et al. *(12)* and in Simon and Gutowitz *(14)*. The procedure consists of two independent steps: (a) lane changes and (b) forward movements. In the case of pedestrians, lane changes refer to lateral sidesteps, because walkers do not follow lanes, generally. Though applied on a serial computer, the two updates function as if applied on a parallel computer just as a true CA would. That is, each pedestrian is taken in turn (sequentially) examining its local neighborhood without anticipating what other pedestrians will do. The pedestrians move only after all pedestrians on the lattice have been visited and the allowed moves have been identified, a virtual parallel update. Though the 4-directional rule set is an expansion of those shown previously for unidirectional and bi-directional flows, which remain intact, the entire rule set is shown, in order to present a complete and consistent exposition. The primary additions are to the Step Forward Rules where Rule 2, resolving cross-directional conflicts; Rule 4, bi-directional diagonal exchanges; Rule 5, cross-directional diagonal exchanges; and Rule 6, cross-directional lateral exchanges have been added. One improvement has been made to the Lane Change Rules in that Rule 2aii has been added to help create DML formation. In the case studied here Lane Change Rules 2bii and 2biii have been adjusted to keep pedestrians in lane rather than allow random sidestepping when breaking ties in lane choice.

The 4-directional pedestrian rule set is presented in Table 1 using a nomenclature in which L(i, j) is the Lattice cell (i, j) for pedestrian number p_n where i is the forward direction and j is the lateral direction of pedestrian p_n. Pedestrian p_n has a desired speed *v_max* and moves with velocity $v(p_n)$ determined for each pedestrian in each time step from the gap computation subprocedure shown at the bottom of Table 1.

Beginning with the lane change rules, pedestrians can change lanes only when an adjacent cell is available. If a single lateral cell separates two pedestrians, a random number is drawn to designate the lane as available to only one of them. If an adjacent lane is available, then the lane change is determined by the maximum gap ahead. The base case is bi-directional interspersed (ISP) flow (no lane formation), but dynamic multiple lane (DML) flows will result by assigning a forward gap of 0 if encountering an opposing entity ahead (from Lane Change Rule 2ai). DML formations are further enhanced when a pedestrian steps behind a same direction walker when avoiding an oncoming pedestrian (from Lane Change Rule 2aii). This behavioral adjustment tends to move the pedestrians into same-direction flow lanes. Lane changing in this set of experiments is restricted to the cases where it is clearly advantageous to change lanes. Any unnecessary lane changing results in slowing aggregate speed, and this should be expected in actual populations of walkers. More lane changing is easily added to the model by adding a stochastic factor into the tie-breaking rules (see references 2-5). In addition the flows can be separated into (only) two lanes by skipping Lane Change Rule 2a and breaking two-lane ties between the adjacent to center lanes (Lane Change Rule 2bi) by always giving the right lane to the walker. This separates the flows nicely without excessively causing the flows to move towards the corridor boundaries.

A pivotal concern encountered in programming the CA model is assuring conservation of entities, that none are destroyed (or created) in the processing. If two entities vie for the same cell, only one can use it. The second entity assigned to a cell will annihilate the first. This difficulty is resolved for cross-directional pedestrians in this model by giving one entity the cell by even random choice and causing the other to back off one cell. If the backing-off entity is then engaged in another conflict for the new cell, the procedure is iterated recursively until at worst one entity winds up remaining in its original cell. Three-way conflicts do not occur in the model. Bi-directional entities vying for the same cell go only *up to* halfway to the cell (or exchange places), as shown in the Gap Computation Step 2. Because bi-directional pedestrians can not collide, three-way conflicts do not occur and only two cross-directional pedestrians can vie for the same cell.

For pedestrians that do not move in the Step Forward Parallel Update in Rules 1-2, Rules 3-6 allow for a variety of position exchanges to safely take place. Such exchanges are necessary otherwise jams will deadlock as density increases. Rule 3 for bi-directional exchanges is discussed at length elsewhere *(3-5)*. Rules 4-6 are added to deal with concourse-type flows. In fact Rule 4, bi-directional diagonal exchange, is counterproductive in the formation of DML flows under purely bi-directional flows, since bi-directional diagonal exchanges counter formation of lanes. Thus, Rule 4 is turned off when only bi-directional flows are present. Cross-directional exchange rules (5-6) would not be applicable under purely bi-directional flows. For 4-directional flow, all the exchange rules (Rules 3-6) are scanned in succession (while still maintaining parallelism) under the assumption that an exchange decision hierarchy exists. We assume a preference of exchange exists, in order of desirability, between pairs of:

(1) directly oncoming pedestrians,

(2) bi-directional diagonal pedestrians,

(3) cross-directional pedestrians where both exchanging positions move forward, and

(4) cross-directional pedestrians where one moves forward and the other moves laterally (lateral exchange).

Only one of these four choices may be used by pedestrian p_n and then only if it and its exchanging counterpart have not yet moved. These exchanges are shown in the same order in Figure 2.

The probability of exchanging position, *p_exchg*, is applied to each pedestrian for each applicable scenario on the grid. Pair exchange helps the model to resolve conflicts and has its physical counterpart as well. Pedestrians vying for the same space will twist their bodies slightly to step by one another, effectively exchanging places. Once an exchanging pair is identified, each member of the pair is eliminated from further consideration. If only one of the above exchanges is applicable for a given pedestrian then *p_exchg* would be used once. If two cases above are applicable to a pedestrian, the choice hierarchy would apply *p_exchg* to the first case, since a pedestrian would find that most desirable. If the exchange is rejected, then the routine would apply *p_exchg* to the second case, making the total probability of an exchange greater than *p_exchg* (i.e., *p_exchg + (1 - p_exchg)* p_exchg*. Thus, in this analysis *p_exchg* is applied as a conditional probability that is empirically reasonable, since some exchanges are more desirable than other exchanges and also since there is a greater necessity and possibility that neighbors would exchange places when more are in a jam. Other methods of applying the probability of exchanging position are possible of course. P*_exchg* may change with density, though its values have not been studied empirically. The modeling requirement is that a flexible mechanism allows pedestrians to percolate though a crowd without jams that deadlock permanently. The approach taken allows the modeler to use a random variable *p_exchg* to emulate, study, and calibrate the movements involved in pedestrian bi- and cross-directional flows, especially, at high density. The authors' experience is that concourses generally do not pack to high density except perhaps briefly, since people will avoid large jams. However, pedestrian jams do occur and a useful model must be capable of processing them.

When only cross-directional flow is considered, a bias may result since cross-directional exchanges will tend to move the walkers toward the direction the cross-directional flow comes from. Bias in cross-directional exchanges is countered by flagging each such exchange and aiming to return to the lane when a tie results between the same lane and the adjacent lane in the direction of the cross-directional flow. This amounts to applying a special cross-directional correction factor to Rule 2bii.

SIMULATION EXPERIMENTS

The unidirectional and bi-directional experiments *(2-5)* allowed pedestrians to walk on a grid that wrapped around for walking in a continuous loop. Similarly, this set of experiments allows wrapping around for both bi-directional flows, effectively forming a toroidal grid for studying flows. In 4-directional flow, walkers proceed in two bi-directional loops that intersect over a 50 x 50 grid of cells. To begin, the grid is filled randomly at a given density, introducing some noise to the problem, since the number of pedestrians is not precisely constant for replications done at a given density. The model returns results at each density for number of steps taken, number of laps completed, number of sidesteps, and number of exchanges. These are converted to speed, volume, rate of sidestepping, and rate of place exchange at each density.

The model was run for unidirectional, bi-directional, cross-directional, and 4-directional flows. It can be run under different parametric tests such as directional flow splits, exchange probability, adjacent lane change probability, and separated, interspersed or multilane flows. These are factors that can be varied in the model and the sensitivities of these factors are primarily the subject of this analysis. There are a large number of possible parametric combinations, some of which have been analyzed before for unidirectional and bi-directional flows *(2-5)*. Since exchange probabilities of 0 and 1.0 are certainly extreme cases, a more representative value of 0.5 exchange probability is used. This examination focuses on unidirectional flow, 90-10 and 50-50 bi-directional and cross-directional flows, and 25-25-25-25 (balanced) 4-directional flows. In this way a wide range of representative and important upper and lower bounds on fundamental flows can be examined for a mid-range exchange probability on a single set of charts.

The model was run for 1000 time steps for which the first 100 time steps were discarded as potential transient data, yielding 900 time steps of useful data. Using one second per time step, the final 900 seconds amounts to a simulated 15-minute sample period. Ten such replications of 900 seconds were run at each density to get statistical samples, the modeling equivalent of collecting data on 10 samples of 15 minutes of very carefully analyzed videotaped pedestrian flows. This size statistical sample is justified, since long-term steady state conditions are not the rule in pedestrian environments. Also, fundamental flows in the HCM *(1)* were determined from data sets that were generally short, of 15 minutes or less. The results for the ten replications at each density were averaged for analysis and presentation. Samples of the flows shown below are available for viewing at www.ulster.net/~vjblue.

ANALYSIS OF RESULTS

We examine in Figures 3-6 the simulation results with respect to the sensitivity of speed, volume, sidestepping, and place exchange with density.

Unidirectional Flows

Though unidirectional flows have been treated before *(2)*, this investigation focuses on more restricted sidestepping that improves speeds and volumes at low density. Figures 3-6 show the unidirectional curves for speed, volume, sidestepping, and place exchange with density, creating a baseline for comparison with the bi-, cross-, and 4-directional flows. We note the standard speed-density and volume-density curves that are similar in shape to auto fundamental flows.

There is a low rate of sidestepping shown in Figure 5 and only at densities between 0.05 and 0.4. In past experiments *(2)* we included more lane changing in the rules (20 percent lane change with tied choices versus staying in lane here). Somewhat surprisingly, as the proclivity for lane changing increases, aggregate speed decreases from that shown in past studies. In simulation tests of tie-breaking rules, it was noted that speed and volume decrease as lane changing increases, even though the adjacent lane was just as desirable as the center lane. Evidently, pedestrians who need to sidestep in order to improve speed are slowed by others making optional lane changes. Optional lane changing also breaks up the mode-locking or marching effects that create efficient movement. Of course there are no exchanges in unidirectional flow.

Bi-directional Flows

It has been shown in previous work that there are three types of bi-directional flow: (a) directionally separated flows, (b) dynamic multi-lane flows (DML), and (c) interspersed flows (ISP). The first, separated flows amount to two unidirectional flows. Since most environments do not formally channel flows and leave pedestrians to form their own lanes, bi-directional flows may not form clearly defined lanes which we call Dynamic Multi-Lane flows (DML). The third type, where no lanes form at all, is termed here Interspersed flows (ISP). Indeed ISP flows may be more effective at moving people at high density than separated flows or DML flows, since ISP place exchanges may improve speed and volume, because people step forward into the opposing pedestrians and are not as jammed by those ahead. The primary interest in this paper is with DML flows since separated flows are effectively unidirectional and ISP flows are considered transient.

DML bi-directional flows at directional splits of 50-50 and 90-10 are shown in Figures 3-6 (DML 50-50 and DML 90-10). The 50-50 speeds and volumes are greater than 90-10, due to the better lane formation with evenly divided flows. A graphic representation of the pedestrians in simulation shows the formation of flexible lanes. At the unbalanced 90-10 directional split the minor direction does not form lanes well. The peak volume of 77 Ped/min/m-of-width is 88 percent of the unidirectional capacity, which is the one special case noted in the HCM *(1)* as about 85 percent.

The sidestepping pattern shows for both cases a similar peak at density of 0.2 and a steady drop off as density increases. There is an inverse pattern with respect to exchanges.

Cross-Directional Flows

Again we examine flows at directional splits of 50-50 and 90-10 but this time we focus on cross-directional flows (C-dir 50-50 and C-dir 90-10 in Figures 3-6). A reversed pattern emerges from DML bi-directional flow. Here the 90-10 speeds and volumes fare better than 50-50. There is a considerable increase in sidestepping for both splits, and at the peak the 50-50 split has almost double that of the 90-10 split (17.9 versus 9.9 sidesteps/min). Both splits show a "plateau" curve in exchange rate but the 50-50 split is considerably more pronounced.

Cross-directional flows allow for different types of exchanges than bi-directional flows, and sidesteps are evidently also very important. There is nothing particularly surprising about this, since the basic pattern is consistent with intuition and experience. As one tries to negotiate walking through cross-directional traffic, more sidestepping and exchanges would be necessary than in a bi-directional flow.

However, the cross-directional 90-10 speed and volume curves do better in midrange densities (0.35 to 0.6) than the bi-directional flow. It seems that lane changing and exchanging for the minor direction are more effective for cross-directional flow.

We also note that at density of 0.7 or above the speed and volume curves for all the scenarios thus far examined are very close and that the speed curves have the same basic reversed S-shape. The volume curves are similar, except that the 50-50 cross-directional flow has a fairly level slope between 0.35 and 0.6 density that is above the 90-10 bi-directional flow volume between 0.5 and 0.7 density, where the cross-directional speed is also greater.

4-Directional Flows

The results for 4-directional flows show changes in the shapes of the curves. The speed curve shows a steep decent at low density, losing the characteristic S-shape, and a flattening out at high density that results in higher speeds than all the other scenarios thus far examined. From 0.36 to 0.6 density the curve crosses over the previously examined curves.

Corresponding to the speed curve, the volume is lower at low density and is rather high at high volume. Though this flow may look unreasonable, it is correct for the assumptions used. Where volume = speed x density, if the speed is 8 times what separated flows would produce (11.9 instead of 1.5 m/min at density of 0.95), the volume will be 8 times larger (54 instead of 6.8 P/min/m-of-width).

It is not clear that these high-density volumes occur in practice, since maintaining the exchange rate may be implausible. As shown in the exchange rate curve the rate climbs to almost 30 per minute at 0.95 density. This is about the maximum attainable at 0.5 *p_exchg* and, of course corresponds to a totally jammed 4-directional environment. Also note that the sidestep rate curve is similar to that of the 50-50 cross-directional rate, except that it is shifted to the left (toward lower density) and does not fall off as fast at high density. It should be noted that the sixth rule of the Forward Step Parallel Update allows for a lateral exchange by one of the exchanging pair and this lateral step is counted as a side step. At high density sidestepping laterally is more pronounced than for 50-50 cross-directional flow. The 4-directional model reaches the sixth forward step more often because of the variety of directional jam combinations. The effects appear reasonable given the model's assumptions of the use of a single *p_exchg* that may be too high in practice. Certainly, safety considerations may make such practice dangerous at high density, though in theory efficient.

All Flows Examined Together

At a density of 0.55 all the alternatives cluster closely around a speed of 20.0 ± 3.0 m/min despite the variety of lane change and exchange rules applied. All the curves begin to transition between a fast vertical drop and a gentler drop at this density. This is evidently due to the restrictive character of the entities upon one another to forward movement, though why all the scenarios should have a common intersection point at this particular density is unclear.

The largest range of speeds among scenarios at any density is between 0.1 and 0.4. At densities of 0.20 and 0.25, the range of speeds is about 30 m/min. This region may be where the most non-linear, unstable performance occurs.

For many scenarios at density of 0.35 to 0.4, speeds are about half of the free flow speeds. Speeds at low-density decrease with directional complexity, but at mid-to-high-density speeds converge, until above 0.7 density, 4-directional, basically ISP movements, flows improve. Peak volumes decrease as the directionality becomes more complex. The side step and exchange rates generally increase as the directionality becomes more complex.

Computational Speed

CA models perform many simple calculations that require integer arithmetic for counting cells. This means the models generally run faster than those requiring more involved floating point calculations. Running the 4-directional model at a mid-range density of 0.5 on a 233 MHz Pentium processor, the unidirectional runs ran at 120,00 updates/sec, bi-directional DML and cross-directional runs ran at about 80,000 updates/sec, and the 4-directional run ran at about 55,000 updates/sec. The processing rate improves at higher density since there is relatively less counting per pedestrian, because the entities are more closely packed together.

DISCUSSION AND CONCLUSIONS

The microscopic CA pedestrian model presented is capable of capturing the movements of pedestrians in four directions through the enhancement of adding cross-directional capability to the previously published bi-directional model *(3-5)*. The model results show speed-flow-density fundamental flows that are consistent and explicable in the aggregate from the microscopic rules that are applied. The model suggests that bi-directional flows that do not separate into only two lanes, cross-directional flows, and 4-directional flows result in a lowering of speed and capacity that is yet to be reflected in the Highway Capacity Manual *(1)*. The model evidently has sufficient flexibility and robustness to capture the critical minimal movements to result in reasonable fundamental pedestrian flows.

Although CA modeling is a “grainy,” discretized approach, the major movements are accommodated and conservation of entities is assured, resulting in a viable 4-directional pedestrian model. As simulations, the microscopic CA movements are not perfect reproductions of pedestrian movements, but effectively result in pedestrians being in appropriate locations at the end of each time step. CA automobile simulations have shown faithful reproductions of traffic jams, for instance, by representing vehicles with analogous particle hopping models *(18, 19)*. The very slight difference in distance traveled from diagonal movements is not considered a problem. In measuring speed in these experiments we are only interested in the forward movement. We assume pedestrians take lane changing in stride (as it were) without loosing forward motion. Pair exchange helps the model to resolve conflicts and has its physical counterpart as well. Pedestrians vying for the same space can twist their bodies slightly to step by one another, effectively exchanging places. This kind of place exchange behavior has been noted on crowded subway platforms as people push past one another entering and leaving a subway car. Macroscopically, the model exhibits fundamental flow characteristics that are acceptable based on published bi-directional field data, though not verified with cross- or 4-directional field experiments. The model sets the stage for 4-directional flow studies that can be used to modify the model as needed. The CA 4-directional model here illustrates a viable method to solve a formerly intractable analytical and simulation problem that yields reasonable results.

The biggest hurdle to applying the model at this point is that actual microscopic pedestrian behaviors have not been studied in depth. The model has been developed from personal perspectives, study of peak flows at Grand Central Station in New York City, and from analytical inference based on the outputs of trial runs. Factors such as exchange probabilities for bi-directional, diagonal, and cross-directional flows are not sufficiently documented and study of these parameters is warranted if the model is to be applied as a fully functional design tool. For example, exchange probabilities may have a probability distribution. Also, that distribution may change with density or the frequency of need for exchanges. Lane changing behaviors of pedestrians also need to be studied.

Development of the model has identified those critical factors that can be varied to arrive at acceptable aggregate performance. As a proof of concept the model appears to use a set of parameters that appear minimally necessary, though incompletely understood. Such data has not been collected to date and is beyond the scope of the current model building effort. With the extension of the model to the 4-directional case, the need for and justification of collection of such pedestrian data is advancing quickly.

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Table 1: 4-Ped Rule Set

Lane change (parallel update 1):

(1) Eliminate conflicts: walkers that are laterally adjacent may not sidestep into one another. An empty cell between two walkers is available to one of them with 50/50 probability. For an unavailable lane, set gap = ∅ for the lane.

(2) Identify gaps and lane choice: same lane or adjacent (left or right) lane is chosen that best advances forward movement according to MAX (gap_left, gap_center, gap_right) up to *v_max* from the gap computation subprocedure* (following the Step Forward update).
  (a) For dynamic multiple lanes (DML):
    (i) Step out of lane of a walker from opposite direction by assigning gap = 0 if within 8 cells
    (ii) Step behind a same direction walker when avoiding an opposite direction walker by choosing any available lane with gap_same_dir = 0 when gap = 0.

  (b) Ties of equal maximum gaps ahead are resolved according to:
    (i) 2-way tie between the adjacent lanes: 50/50 random assignment
    (ii) 2-way tie between current lane and single adjacent lane: stay in lane
    (iii) 3-way tie: stay in lane.

(3) Move: each pedestrian p_n is moved 0, +1, or –1 laterally to cell L(i , j ± [0, 1]).

Step forward (parallel update 2):

(1) Update velocity: Let $v(p_n)$ = gap where gap is from the gap computation subprocedure*.

(2) Resolve cross-directional conflicts: for a desired cell common to two cross-directional pedestrians A and B, cell L(i + gap_i, j), IF rand() < 0.5 pedestrian A gets cell L(i + gap_A, j) and pedestrian B gets cell at L(i + gap_B – 1, j) ELSE pedestrian B gets cell L(i + gap_B, j) and pedestrian A gets the cell at L(i + gap_A – 1, j). IF a conflict at the new cell L(i + gap_ i – 1, j), reiterate this procedure.

(3) Bi-directional exchanges: IF gap = 0 or 1 AND gap = gap_opp (forward cell occupied by an opposing pedestrian) THEN with probability *p_exchg* $v(p_n)$ = gap + 1 where new cell is L(i + gap, j) ELSE $v(p_n)$ = 0 and gap = 0.

(4) Bi-diagonal exchanges: IF gap = 0 AND L(i + 1, j ± 1) occupied by an opposing direction pedestrian (either diagonally forward left or right cell occupied by an opposing pedestrian) THEN with probability *p_exchg* $v(p_n)$ = 1 ELSE $v(p_n)$ = 0; IF both diagonally forward cells occupied by an opposing pedestrian in diagonally left and right cells; with probability *p_exchg* and rand() < 0.5 $v(p_n)$ = 1 where the new cell is L(i + 1, j ± 1) ELSE $v(p_n)$ = 0.

(5) Cross-diagonal exchanges: IF gap = 0 AND L(i + 1, j ± 1) is occupied by a cross-directional pedestrian moving forward (either diagonally forward left or right cell occupied by a cross-directional pedestrian that is moving forward relative to the pedestrian under evaluation) THEN with probability *p_exchg* $v(p_n)$ = 1 ELSE $v(p_n)$ = 0; IF both diagonally forward cells occupied by a crossing pedestrian in diagonally left and right cells; with probability *p_exchg* and rand() < 0.5 $v(p_n)$ = 1 where the new cell is L(i + 1, j ± 1) ELSE $v(p_n)$ = 0.

(6) Cross-forward-adjacent exchanges: IF gap = 0 AND L(i + 1, j) occupied by a cross-directional pedestrian (forward cell occupied by a crossing pedestrian) THEN with probability *p_exchg* $v(p_n)$ = 1 ELSE $v(p_n)$ = 0. The forward move is to L(i + 1, j) and the adjacent-moving pedestrian exchanges laterally to L(i, j ± 1) from its perspective.

(7) Move: each pedestrian p_n is moved $v(p_n)$ cells forward to the appropriate cell L(i + $v(p_n)$, j ± [0, 1]) on the lattice.

Subprocedure: Gap Computation

(1) Same direction: Look ahead a max of 8 cells (8 = 2 * largest *v_max*) IF occupied cell found with same direction THEN set gap_same to number of cells between entities ELSE gap_same = 8.

(2) Opposite direction: IF occupied cell found with opposite direction THEN set gap_opp to INT (0.5 * number of cells between entities) ELSE gap_opp = 4.

(3) Assign gap = MIN (gap_same, gap_opp, *v_max*).

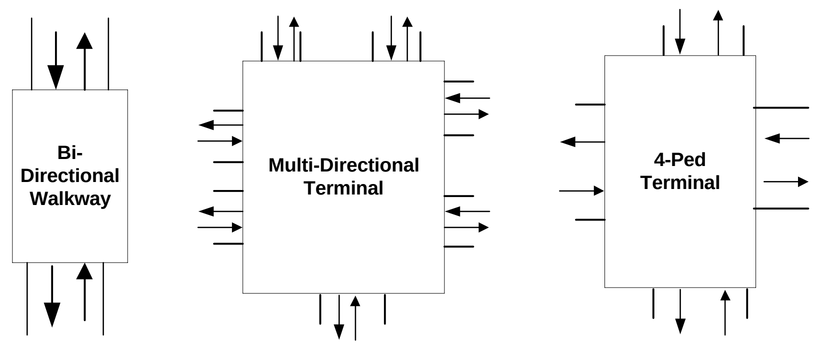

Figure 1. Pedestrian Flow Movements

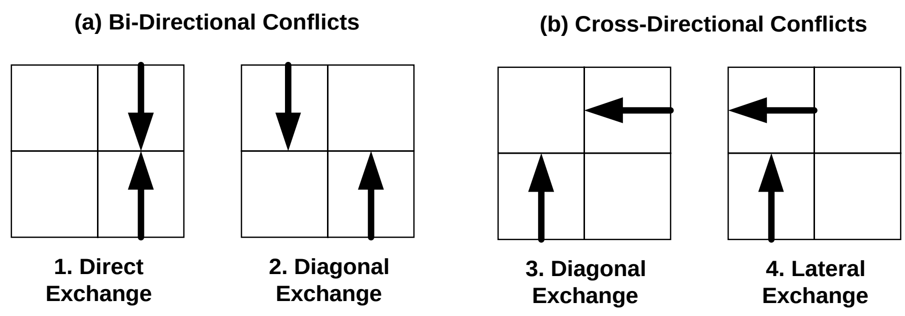

Figure 2. Conflicting Movements.

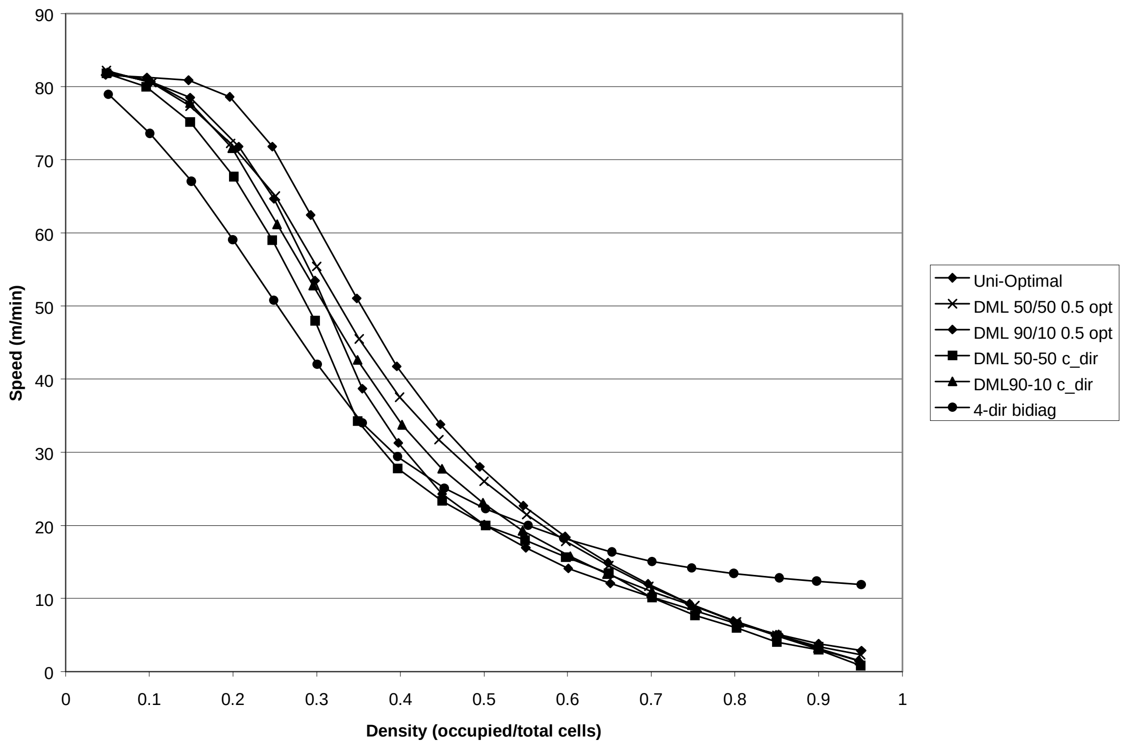

Figure 3. Speed – density curves.

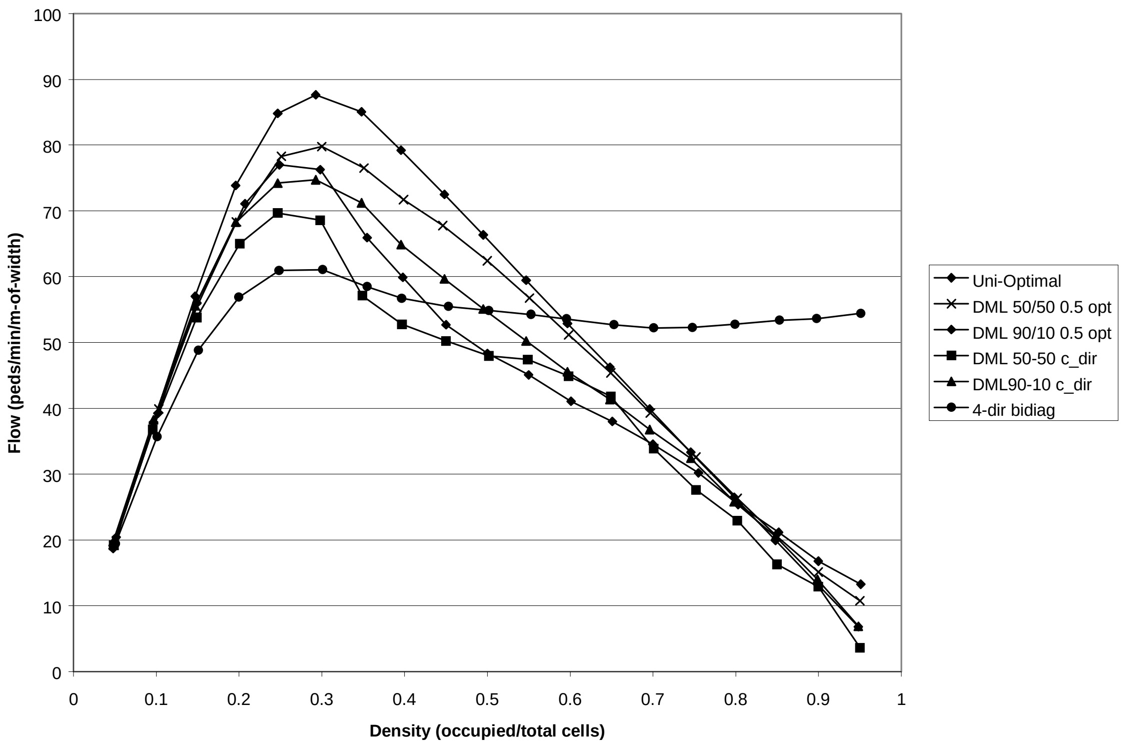

Figure 4. Volume – density curves.

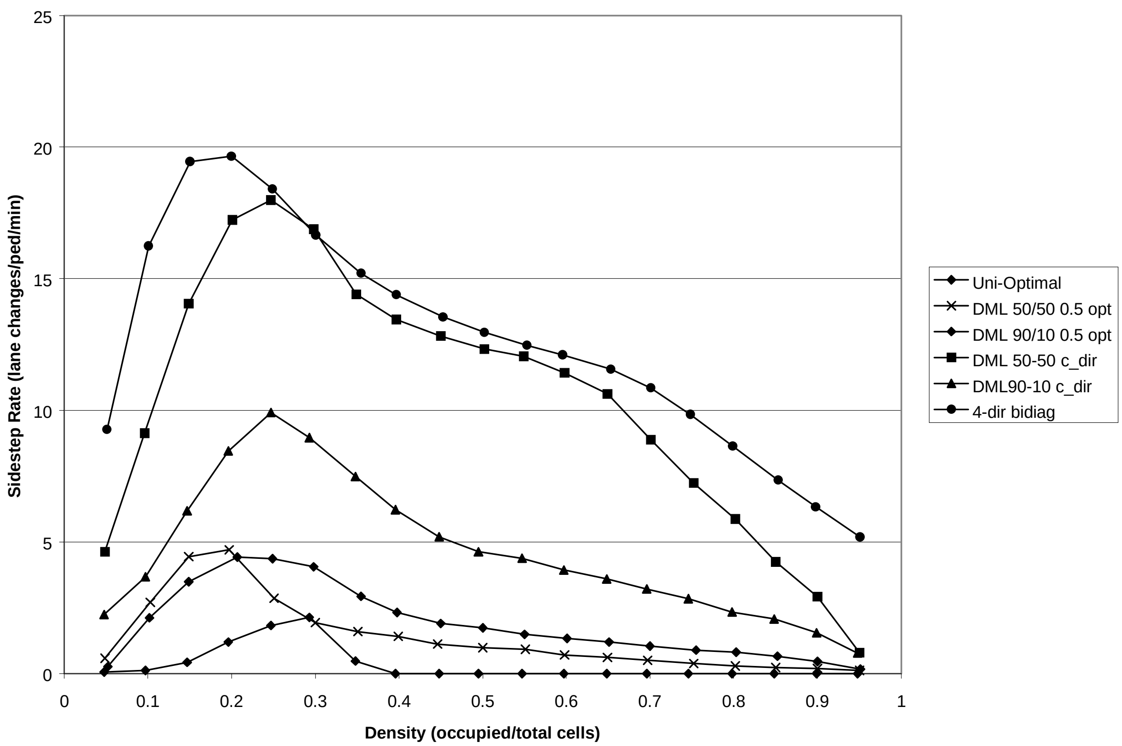

Figure 5. Sidestep rate – density curves.

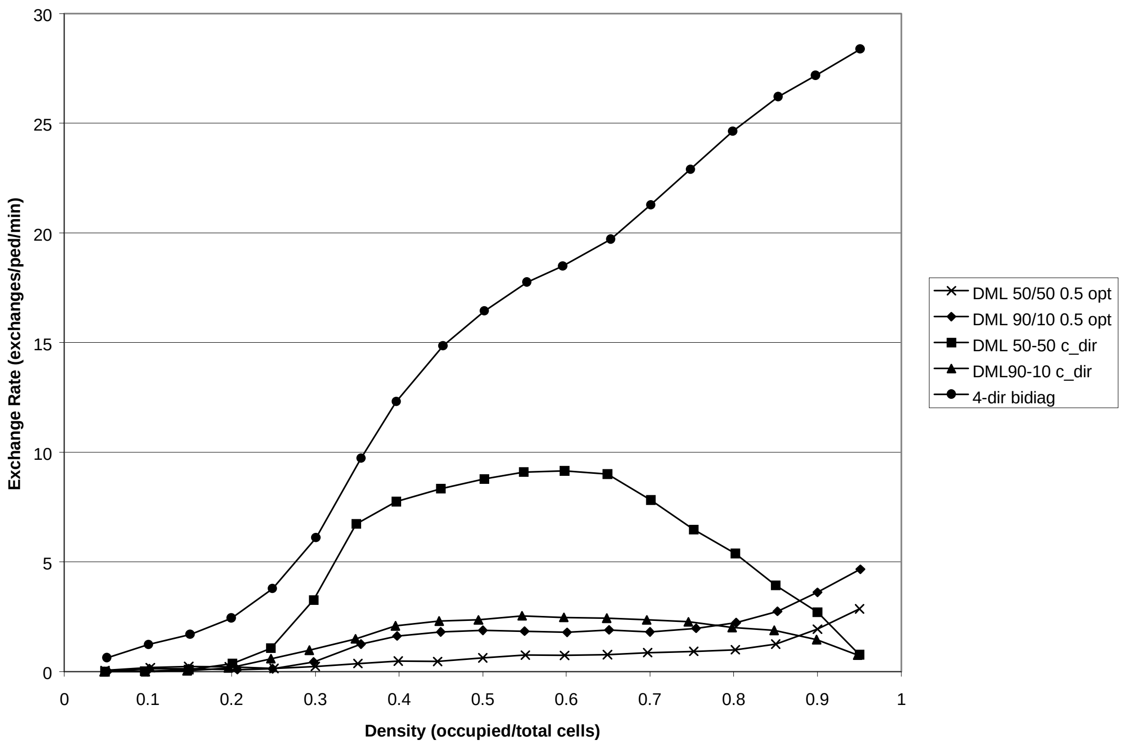

Figure 6. Exchange rate – density curves.