Carleton University
Final Year Project in Computer Science

A Study of Modeling Crowd Dynamics

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Abstract:

The following paper considers the field of Crowd Dynamics, and also the modeling thereof. This discipline has been becoming increasingly important in recent years and concerns itself with the propagation of pedestrian traffic in dense quarters. By considering such traffic flow a number of unique features and patterns can be discerned. Studied will be the current 'state of the art', and a modeling project based on one of the cited papers will be constructed and considered in further depth.

Acknowledgements:
An appreciation of Professor White's time and patience would probably be well deserved at this point.

Also important to give credit for Victor J. Blue and J. L. Adler's *Modeling Four-Directional Pedestrian Movements*, upon which the latter half of this paper is centred.

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Introduction

Crowd Dynamics is an importantly critical study to be both aware of and versed in for people in a host of careers: architecture, civil planning, event management, and others. The proper application and credence of the general principles outlined by its theory is instrumental in not only efficient use of space and flow of traffic during both normal and emergency crowd situations, but in the prevention of injury or even loss of life due to unforeseen events.

What exactly are Crowd Dynamics anyway? It's a discipline which deals with and studies the management and the flow of pedestrians in crowded venues and situations. Keith Still, a noted academic in the area, calls it "the study of the how and where crowds form and move above the critical density of more than one person per square metre."[1] It is a field which today is being given more and more importance in light of recent crowd disasters. Throughout history accidents involving trampling and crushing have occurred in crowded and emergency evacuations. Through the study of human group movement we can hope to design smarter spaces and identify problem areas in those which already exist.

The concern herein will be much the same as outlined above, that is, with the movement, propagation, and interaction of pedestrians in high density situations. Also explored will be the patterns and behaviours we can predict and expect given various areas of space and the destinations of our walkers. All this with an eye to learning the norms we can expect so as to design safer and more efficient buildings, concert areas, and places were people can gather.

"Designers of walking infrastructure such as transfer stations, city centre areas and shopping malls need to assess the quality of the plans."[2] From this springs the impetus to create an interest and an industry to study, model, and specialize in crowd dynamics.

Throughout the following paper we will discuss the field in depth and look at both various techniques of studying and modelling the pedestrian flows and current ideas about execution. Some of the models studied were much more detailed than others and many looked at aspects that were absent or ignored in the rest. A few of those studied were much more specific than the average which tended to present more broad ideas about these pedestrian flows. For example, one such specific topic was evacuations. By looking at the field as a whole we can hope to get a feel for the general standards of the field and what is working for current researchers.

The second half of the paper will consider and discuss an implementation done on Victor J. Blue and J. L. Adler's *Modeling Four-Directional Pedestrian Movements*. Special attention will be given to comparing the findings from the included model (as implemented by *this* author) to those found by Blue and Adler, also considering any possible reasons for discrepancies between the Netlogo program done for this paper and Blue and Adler's own Java implementation (by way of the results given in their own paper as well as those presented here).

Lastly we will make note of the strengths and weaknesses of their approach when compared to the other models studied.

Survey of the Field

Methods

As alluded to briefly in the introduction, not all of the papers researched for this project concentrate on the same aspects of the field and Crowd Dynamics. While most of the papers refer to general modeling of traffic using many various methods, some of them look specifically at validating models (Bierlaire, Antonini, Weber), building evacuation (Siikonen and Hakonen), and others along the way. The following will try to look at all and compare the features that seem common or interesting and also interesting when considering the group together.

The papers studied used a variety of techniques to model and learn from crowd dynamics – these included Cellular Automata (also known as Particle Hopping) as done by Keith Still, Blue and Adler among others, Social Force models as done by Helbing and Molnar, and those simulations based on a gas-kinetic paradigm like Hoogendoorn's.

The Cellular Automata seems both very intuitive and attractive, in that it seems by far the easiest to understand of the models. Some of the papers, especially Helbing's, go on about the mathematical basis, equations, and methods which support the model at great length. The two papers studied from Daamen and Hoogendoorn said surprisingly little about the implementation of their models and mostly focussed on the effects of their experimentation methods and results, though based on the general feeling I've received it seems likely heavily based on equations as well.

Certainly using models that are more easily grasped is a boon to someone uninitiated in that particular technique, but doesn't in and of itself say anything about the quality or success of the system used.

It seems as though it might be worth while to look at the various different techniques employed by the papers studied. In the next section each will be looked at briefly through comments made by the authors themselves in regards to their own justifications and feelings for the choices they made and on the reasons for their rejections of other systems.

Cellular Automata is a system which uses simple 'autonomous' agents based on quite natural, intuitive rules. It is through these we can see the emergence of complex patterns and systems. Blue and Adler have the following comments on their choice:

> "The CA automobile models exhibit non-linear speed transitions and self-organized criticality that is present in actual shock waves. Most promising for CA traffic modelling 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."[3]
>
> "These decisions result in pedestrian movements that are extremely flexible and walking speeds and accelerations that are frequently adjusted."[4]

Schreckenberg and Nagel speak further on it with regards to their traffic simulation models. Nagel in particular seems to be one of the first proponents of Cellular Automata as a method to model traffic.

> "The main advantage is that in CA models one deals exclusively with discrete variables both for time and space (and consequently for the velocity of the cars) with *local* update rules for the internal parameters, i.e. the velocity. These models allow for large scale simulations on (parallel) computers with results comparable to data measured in real traffic."[5]

Though Nagel – at least in some of his models – used a system which was very much like CA superficially, it was set up specifically to run *serially*; choosing random pedestrians to move at a given point.

Bierlaire, Antonini, and Weber used a system unlike any of the others I read. They rejected CA as being too inflexible and as not being conducive to different choices when given similar stimuli. They look at a solution based on individual agents, but one with some unique differences.

> "[There are] two main methodological approaches that we have adopted: *agent-based simulation* and *discrete choice models*. An agent is an entity with its own behavior within the simulator" "It provides a great deal of flexibility, as the behavior of each element in the system can be modeled independently, and complex interactions captured." "Designed to forecast the behavior of individuals in choice situations." Bierlaire, 3-4

They don't get into much greater depth or detail about their complaints here however, so it's hard to judge whether something like the randomization and circumstance based choices implemented in the Blue and Adler model would be enough to satisfy this objection. Cellular Automata remained the a popular choice among those authors studied, however.

Social force models seem a potentially very interesting way of considering traffic flow and the movements and actions observed in crowded areas. Imagining that strangers we encounter exert a true repelling effect against people, and contrarily, our friends or even interesting things in a shop window might attract us, is an intriguing premise.

> "A pedestrian feels a strong aversion to taking detours or moving opposite to the desired walking direction, even if the way is crowded."[6]

Helbing shows that his model also accounts for many other observed features such as 'fingering' effects (having numerous lanes of oppositely moving traffic in a crowd), shockwaves, lane formation and others. Blue and Adler had a few issues with the presented theory though:

> "The pedestrians in their model separate into lanes by direction due to the interactions of the attraction-repulsion forces on pedestrians. However, they only demonstrated a single instance of these abilities and did not publish results at many densities or calibrate them against established fundamental flows."[7]

Helbing calls the gaskinetic approach closely related to his own Social Force model, and Keith Still comments on the extensive work done by Helbing in this area and the pros and cons of such a system (accurate modelling of many observed situations vs. heavy complexity), but the gaskinetic model also seems to be the one preferred by Hoogendoorn. Some of the major problems Still found with fluid-like systems were that they would not reproduce the *edge* effect, that is, having a crowd travel more quickly along the edges than in the centre.

Evacuations

During an emergency evacuation speed can be a critical thing, it can also be a very *dangerous* situation when it comes to crowded venues. An example of this would be the nightclub fire last February (2003) in Rhode Island in which at least 95 died as the fire raced through the building and people scrambled to escape.

In general, at any location it's important to know the egress and ingress capabilities of said location. In buildings this may include evacuation by use of stairs and elevators together or stairs alone. As a general rule, elevators can transport about 1.5 times more passengers in down-peak than up-peak (i.e. egress vs. ingress). Commercial elevators tend to have higher capacities than residential as well. Reasonable values might be 22.5 - 27 % of an office's population for each 5 minutes in down-peak. Elevators are generally shut down during a fire however, and it's critical to consider movement on stairs.

> "In office buildings, the egress time by the stairs is shorter for a building with 50 floors or less, and fewer than 50 persons per floor. For 100 persons per floor, the evacuation time by elevators is faster for 25 floors or more. For higher amounts of population per floor, elevators are faster for even 15-20 floor buildings." [Siikonen and Hakonen]

Elevators do in fact stay operative for some emergencies, though clearly not all. Best times are usually seen when some combination of stairs and elevators are used together. "If elevators are used in mega high-rise buildings during an emergency situation, evacuation times can drop to 15-30 minutes instead of 2-3 hours."[Siikonen and Hakonen, sec. 6]

Both noted by Siikonen and Still is the reaction time and process time during an emergency. They cite that up to two thirds of the total time to evacuate a building is spent just on recognizing the emergency and then reacting to it, before the last third spent actually leaving.

Similarly, crowd movement at outdoor venues needs to be factored carefully. Pedestrian flow rates are given as approximately 40 people per metre of width per minute. [Primrose Guide] And travelling speeds as a whole would of course be effected by bottlenecks, turns, and obstacles in the system, all of which can cause crowding at certain points and slowdowns.

Effects and Patterns

There are several interesting phenomena which are emergent in crowds and pointed out by a variety of authors for study. Keith Still spells out a number of them nicely in his thesis:

- *Edge Effects:* when the edges of a crowd move faster than the centre of the crowd.
- *Finger Effects:* Bi-directional high-density crowds flowing through each other with relative ease.
- *Density Effects:* Crowd compression in local areas can imbalance the crowd flow.
- *The Human Trail:* Pathways can erode with time based on the principle of least effort (i.e. shortcuts).
- *Shockwaves:* propagation of some effects spreading throughout a densely pact crowd.

  [Still, 2000. Largely word for word]

Perhaps it's a stretch to consider this next an 'effect', but a number of statistics give values on the way people react to certain other people, either being more careful to give them berth or less so. Some statistics have women (especially culturally defined attractive ones) being given more space while some disagree and say men are granted the greater leeway. Also pointed to are larger groups of individuals gaining precedence over smaller groups. Lastly, a point on the 'minimum effort' expectations of pedestrians who will often only move enough to avoid contact if the other person also moves similarly (this is more common between members of the same sex, however). [Daamen and Hoogendoorn, 2003]

Verification Methods

Proving that their models work as they theorize gets quite a reasonable amount of text given in certain papers. This issue can be a difficult thing to show as a proof and many authors resort to

hours spent studying the problem first hand through eye witness accounts, among them Blue and Adler and Keith Still. Beyond that, Still however, clearly gives the most conclusive validation of all (though admittedly he has by far the most words of space of those papers studied, so it may be an unfair comparison). The tests are done versus (among other things) all the different effects mentioned previously, as have been observed by people: fingering, the edge effect, density effects, and the human trail. Experiments are setup with the software for each case and both the software and the results between real life observations can be made. This is in line with the validations done by many of the other authors. Still also compares his results versus Fruin and other notable authors and manuals of pedestrian travel.

Bierlaire et al's focus was on using video surveillance to pick out potential problems automatically and to verify their models. Certainly the issue of detecting the potential for crowd disasters, and identifying the patters than occur during buildup all without human intervention would be an incredibly important tool (or even with intervention!)

Route Choice, Conflicts, and Planning

Interactions between pedestrians moving either oppositely or perpendicular to each other create a host of new dynamics and issues.

When navigating crowds some of the models look at the actual size requirements of people, as statistically determined to see where people could *literally* fit (Still for one and others such as the social forces model of Helbing which repel others with varying degrees of strength based on their own personal comfort. Vicsek uses a similar system to this as well). Some others, as Blue and Adler do, look at things a bit more simply, placing each individual in an equal square on a large grid and which only he or she may occupy. To counteract the issues of size they allow 'exchanges' where by people would imaginably twist their bodies to slip past each other.

Some models keep specialty rules similar to the above on how people deal with moving through crowds. Using conceivable line of sight to choose direction is one such method, as is the direction of least negative force. Blue and Adler consider the spacing sizes and speeds of relative objects.

Others take an important step further in modelling by considering specific pedestrian destinations or a series of destinations to be reached by each person. Still takes this issue to the next level and also deals with this in his design by considering the expected congestion caused by crossing streams of traffic. Certainly this is perhaps the most quickly *useful* application looked it by any of the authors, rerouting traffic subtly through model adjustments to create a safer and swifter moving reality. Yet others will have entities take in all manner of context specific information through which to plan flexible routes to set destinations, taking into account levels of congestion visible in their locality.

Results and Conclusions

There are many situations where proper or improper planning can effect all of us in our day to day lives: office and residential buildings, outdoor arenas, and more. While there are many ready places to see the activities described above in real life, an example close to home would certainly be the foyer in Southam Hall during a class change which can quickly fill to capacity and see human snakes of traffic running through it only to be cut off by another (as perhaps demonstrated most ably by Vicsek).

Through the considered application of modelling techniques as well as the more traditional study of literature and guides on the subject (or relatively traditional, this is still somewhat a new field after all), we can choose to make educated decisions about the venue, staff on hand, barrier restrictions, and route planning with an eye to keeping an event safe and swift moving.

Modelling

General Overview:

To explore the world of pedestrian traffic further, delving into the intricacies and dynamics of Crowd Dynamics through modelling is useful. Certainly though, some models are also beyond the scope of an honour's project, even to recreate, such as Keith Still's impressive Legion.

The model implemented and tested for this project was a paper by Blue and Adler looking at four directional, intersecting pedestrian flow. The sort of dynamics and emergent phenomena they seem to study through the research considered here seems largely path fingering and lock stepping (having pedestrians move abreast of each other at the same rate, the authors looked to introduce a *noise* factor to eliminate this to some degree, however).

During the research for this project a number of papers by Blue and Adler were studied, all of them look at pedestrian traffic flow using the same basic model, only expanding upon it each time with both new features and traffic behaviour. This does not mention the implementation improvements added throughout (for instance, the averages produced by running their models for eleven thousand rounds was roughly equivalent to running them for a mere one thousand).

The one which looked at traffic movement from all four directions is the paper which took their model to its furthest point, as it suggests bringing pedestrians from all sides together to work at navigating their way amongst the crowds to secure their goal on the far side. Though not as complex as models that took into account specific location goals and agendas (i.e. Still and Hoogendoorn) it provided an extra dimension of interactions.

While Blue and Adler often give mention to other systems of design in their papers (Queuing theory, or Equation based systems) they chose to use Cellular Automata as the foundation for their models, seeing it as “an intuitively appealing emulation of pedestrian behaviour and reliance on integer arithmetic for fast computation.” [Blue and Adler, 1998]

They also however, suggest that their pedestrian models are repulsed and attracted as are particles in social force models, and beyond that, that they emulate the behaviour associated more realistically.

The objective throughout all their work is a minimal rule set, which is consistent with, and follows from the idea of Cellular Automata.

Problem Specifics

Blue and Adler’s implementation gives us somewhat spacious grid of fifty by fifty of possible turtle (entity) locations to work with. In their models each of these squares is eighteen inches across (this is not listed specifically in Blue and Adler, 2000, but in a former paper, and without information to the contrary it seemed safe to assume it would remain the same).

And based on this pedestrians are granted one of three different speeds which apparently were determined statistically. By default this is traveling three squares maximum per time step (which are each a single second), that group comprises 90% of all modelled pedestrians. Another 5% cover 2 squares each second, and the last 5% 4 squares each time step (4.5, 3, and 6 feet per second respectively). One might wonder if a slightly smoother gradient might produce better results, but this seems like it would be a good approximation and certainly sufficient for a model such as this.

Of the specific emergent phenomena studied by the considered authors in their papers, Blue and Adler refer to the forming of ‘fingers’ of like direction walkers as *Pedestrian Following Behaviour* and observed the leader and follower patterns weaving their way through their simulated crowds. *Head-on Conflicts* too, which saw pedestrians come face to face with one another and if not able to step around, the option is given to the pedestrian to twist their bodies sideways, so that in this way they may slip around each other, an ‘exchange’ in their terms. And lastly, *Cross-Directional Conflicts* which comes into play as pedestrians travelling at perpendiculars come into conflict. These are resolved much the same way as head-on conflicts, though it adds different problems as the people involved are not always moved farther towards their goal, but sideways.

Conflict scenarios:

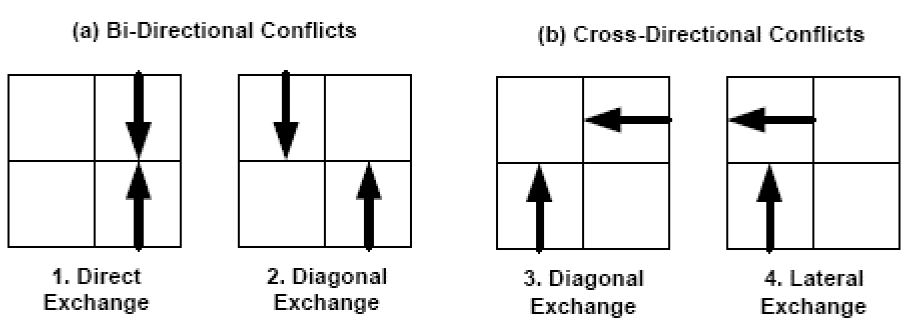


Fig. 1 [Blue and Adler, 2000]

These diagrams outline the four exchange scenarios dealt with by the model. Only the first and the fourth present an impediment from going forward, but all are possibilities for pedestrian exchange (although it should be added, that none of them will take place if the route ahead is clear). And as mentioned above, the second and third will tend to move pedestrians laterally too, the fix Blue and Adler propose for the sort of 'drifting' that this may cause is flagging turtles which have made such a movement, and then moving them back towards their original lane later in the advent of a tie between two choices (where as normally the authors would have it chosen randomly between the two).

When calculating the distance ahead we're able to travel, avoiding opposing pedestrians is done through halving the potential distance travelled between any two such bodies. Checking for cross directional conflicts (that is, a turtle travelling perpendicular to us with the same destination) however enters into one of the major computational hurdles of Blue and Adler's model. Each turtle checks for conflicts and should any be found one of the two of them (as decided randomly) will be backed off one step, and that turtle will recursively be checked to ensure it in turn is not violating anyone else's movement.

Lane changing, though almost an obvious feature (or at least perhaps an expected one) was also one of the steps added over the evolution of Blue and Adler's model. And it's also one that adds an important dynamic to the system. Pedestrians may move to either their right or left – assuming there is space for them – and it's randomly assigned should there be two entities vying for it. When studying the results of this what the author's find is that applying further restrictions to lane changing actually improves the flow of traffic. In this way no one has to deal with any one cutting out in front of them.

Similarly, in terms of the facilitation of traffic flows studied were different 'volume of flow' configurations. That is, they looked at situations where 50% of the total flow was coming from the east and 50% from the west (or north, or south, or whichever), and also situations where it might be 10% from the north, and 90% from another direction. What they found in such cases was that traffic flowed better in opposite directions when the volumes were similar, but that the 90-10 split inhibited the formation of lanes, the resulting minority serving only to get in the way of the other pedestrians. But contrary to that, in cross directional flow (that is, pedestrians walking perpendicular to each other) it's the opposite that's true, a smaller number of one direction leads to better flow and smaller disturbances. And all this doesn't even begin to take in the associated variables with four full directions at once. (25-25-25-25%)

Implementation Differences and Specifics

There were some deviations from and choices made when recreating Blue and Adler's 4-Ped model. The most basic difference perhaps is the language mine and theirs is written in. They wrote in Java (if their online implementations are any cue) and this project was instead done with Netlogo. And there are certainly definite differences between the two, a striking one being that *their* implementation was written on a sequential language while Netlogo allows processes to interrupt each other for processor time. That was certainly an issue which provided some unique difficulties to be overcome.

More trivial, is the grid setting, originally tested on a fifty by fifty space, Netlogo comes with its own grid for Cellular Automata built in, yet only seems to allow odd numbered sizes (two zero axes and an equal number of rows/columns on each side of it). All things considered though changing the model to run on a fifty-one by fifty-one grid is not an issue which should produce any marked differences.

Blue and Adler in their 2000 paper describe a detailed algorithm which they follow during implementation and which was followed here too. But apart from that all the of actual implementation was left up to this author, which along with the language necessarily means real time speed differences for runs.

Also, as done by the original authors, the probability for two pedestrians to exchange with one of their neighbours is set at the fixed rate of 0.5 (50%).

Lastly, a quick note on colour conventions used within this model for clarification. Each of the four major directions of the compass is coded with its own colour (green, red, blue, or yellow). To help the user pick out pedestrians who are travelling at different speeds, slight colour variations have been introduced. Faster pedestrians are a slightly lighter shade of the direction's colour, and slower pedestrians a slightly darker shade. (Recall that most 'people' travel at three squares per second, but some travel at either 2 or 4 squares per second.)

Results

This section considers and compares various statistics between the model completed for this paper and the results listed by Blue and Adler in their paper. Variations and differences are noted.

The statistics of interest to the original authors were four basic measures:

- Speed: the average number of meters covered per minute by pedestrians
- Volume: the average number of pedestrians per minute per metre of width (counted in this implementation every time a turtle crosses the zero axis perpendicular to their heading)
- Sidesteps: the average number of sidesteps (lane changes) per person per minute
- Exchanges: the average number of exchanges made by pedestrians each minute (including all available types: bi-directional, bi-diagonal, cross-diagonal, and cross-forward)

By way of note, because of time considerations (a single densely packed model could take upwards of 30 minutes alone in the Senior Lab, and more on a lesser computer, the recursive methods to avoid conflict in the 4-Ped model is likely the major overhead) there were ten runs (10% density through to 90% density) for each of the six different models, whereas Blue and Adler ran twenty for each (from 5% to 95% density), and in some cases this superficially creates an apparent difference (that is, in some models their graph may start at a value of 20, whereas mine starts at 40, the slope was fairly steep in some places, especially when comparing very low densities.

As mentioned above the model was run with six combinations of direction, all at varying densities.

- Unidirectional: trivially, all pedestrians in the model are travelling in the same direction

- Bidirectional: two groups of pedestrians running in opposing directions. This came in two varieties a 50/50 split (half of the total running in one direction, and half the other) and a 90/10 split
- Cross-directional: two groups of pedestrians running in perpendicular directions. This also came in both 50/50 and 90/10 splits.
- 4-directional flows: this consists of pedestrians travelling in all four of the major directions. As with Blue and Adler's model this was always run with equal numbering among all participants (i.e. a 25/25/25/25 split)

Brief notes on each of those studied are listed below, with an attempt to be salient, and to avoid simply rehashing Blue and Adler's work. Collectively, the paragraphs beneath refer to figures 2 through 5. (I chose not to include them right here because four consecutive pages of figures breaks up the flow of text a little. They will be included immediately after the main body of this text.)

Unidirectional

Some few lanes of 'fast' turtles could be seen to form under medium to lower densities, although this would be a mostly random occurrence, rather than one defined by rules. Pedestrian speed began to drop *very* sharply as compared to the other models when density increased. (Admittedly the probably reason for the speed deviance next to the other tests was because occasionally the model will allow one pedestrian to land on top of another during bidirectional flow. This has some obvious advantages for speed, certainly.)

Bidirectional

As cited by Blue and Adler, the first part of any newly 'introduced' groups of people moving contrary to each other will produce a short lived period they call Interspersed Flow, the first 100 steps of each run will be running through this to get to the more ordered Dynamic Multiple-Lane (DML) flows.

The authors speak of lane formation difficulties during the 90/10 split, and this is certainly the case, though there was some indication of lanes at low densities.

Cross-directional

With this grouping we saw the best overall speed in the 90/10 split, opposite the case of bidirectional flow, where the poorer lane formation hampers overall movement and increases exchanges.

There is quite clearly an increase in sidestepping as lane formation isn't a variable in this case.

4-directional Flows

Four simultaneous directions produced near chaos especially at higher densities. Observable was some tight clustering at seemingly random points on the board which would shift or disperse to other places given time.

Speed in this scenario remains lower than the zenith those others reached, yet at the highest densities it kept better performance than the others.

Exchange levels are seen here to rise to extreme levels, we're given the caution that in practice the exchange probability (50%) may be too high to maintain at the highest densities.

Finally, some quick attention to differences within the results found here from those of Blue and Adler. In terms of speed and flow there is a general tendency to report higher values than those observed by the original authors, though not enough to be overly worrisome, hopefully. (And this is likely tied to the aforementioned possibility of a couple of pedestrians being able share the same spot)

Occasionally when taking the statistics also, one of the four values will produce a grossly different result which can't quite be attributed to anything this author is currently aware of. (And may repeat a similar value, or return to a more standard one with nothing in the range between them.)

Conclusions and Model Expansions

The model presented, when properly applied and provided for, can help with a greater understanding of pedestrian movement, and provides a good approximation for real situations.

However, for real world applications and the planning of true applications a more robust system would probably be required (one such as Still's). There are certain further advancements which could be added to the model to make it more functional however. One would be to implement 'obstacles' within the model world to be navigated around or through: bottlenecks, walls, hallway corners to be navigated around. This would also require certain behavioural updates for the pedestrians involved as they are currently quite single minded about moving forwards.

On that topic however, implementing specific *destinations* for people would be another interesting expansion. It would also certainly more closely mimic actual human travel.

Mentioned above was also a consideration for more dynamic pedestrian speeds instead of three static values. That would be something which would require much more significant model changes than might be first imagined. Currently a person is always in a specific square. Anyone with a traveling distance of 3.5 though will no longer be in that position – determining whether there is room to sidestep (among other things) would certainly be an added complication. Although, it and these could help a more realistic and useful view.

Modeling as an exercise and a tool to further our understanding is and will increasingly be an essential tool during planning. Recurring crowd issues and casualties only underscore this point and need. Blue and Adler provide an important building block in this work to further knowledge on this topic and move towards more sophisticated models and insights.

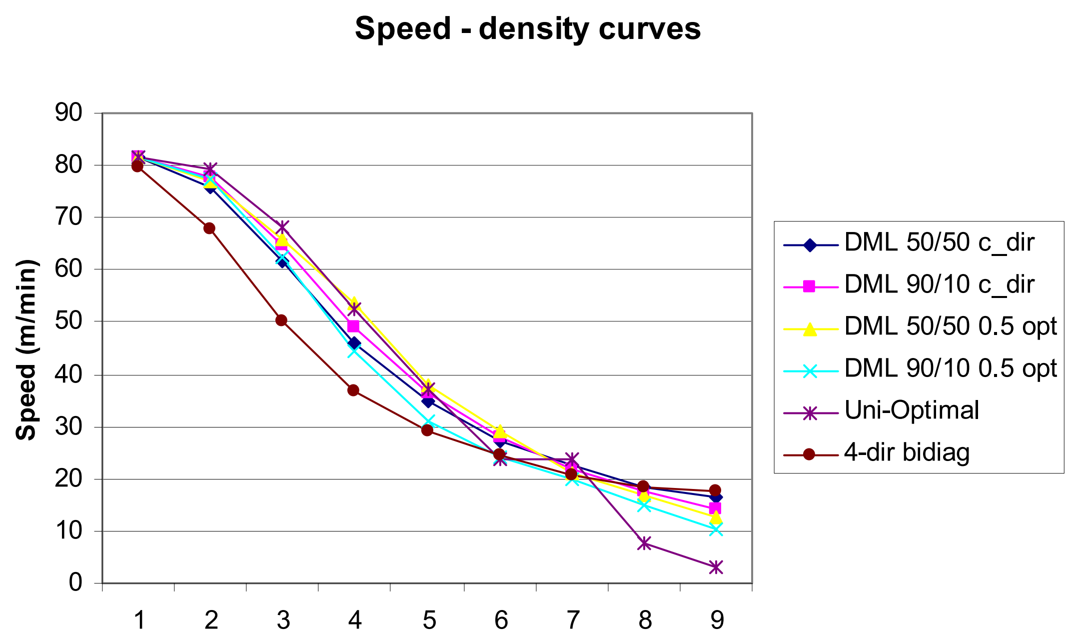
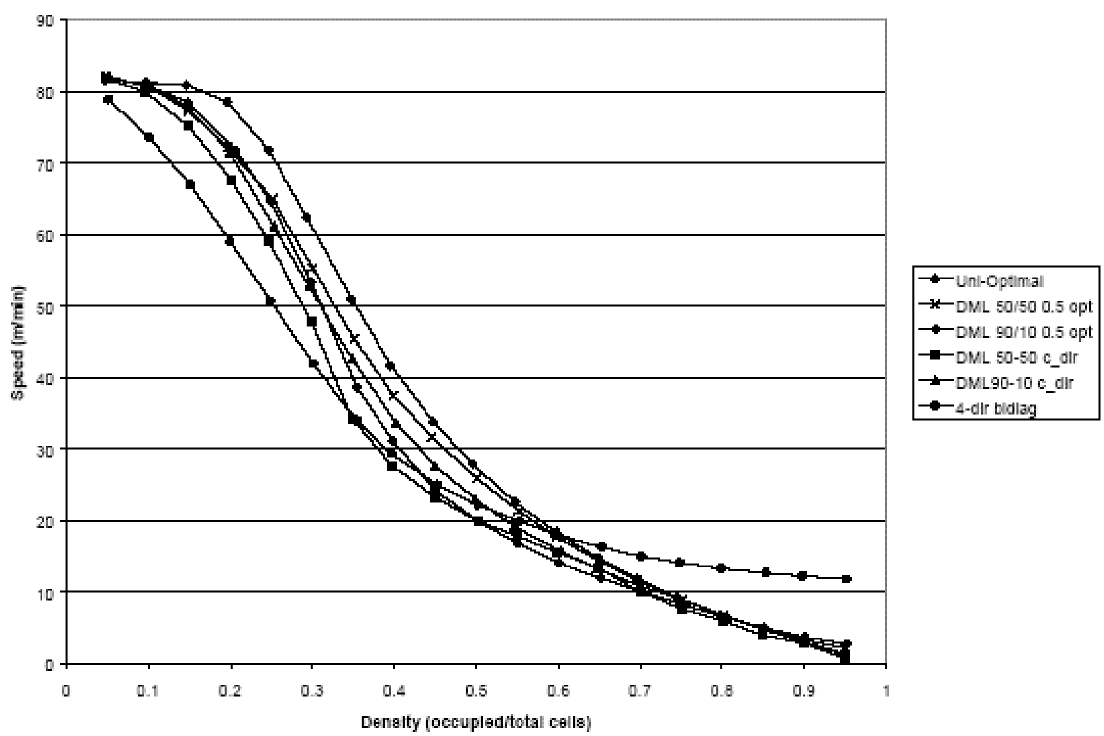


Fig. 2

Above: This model. *Below:* Blue and Adler's model:



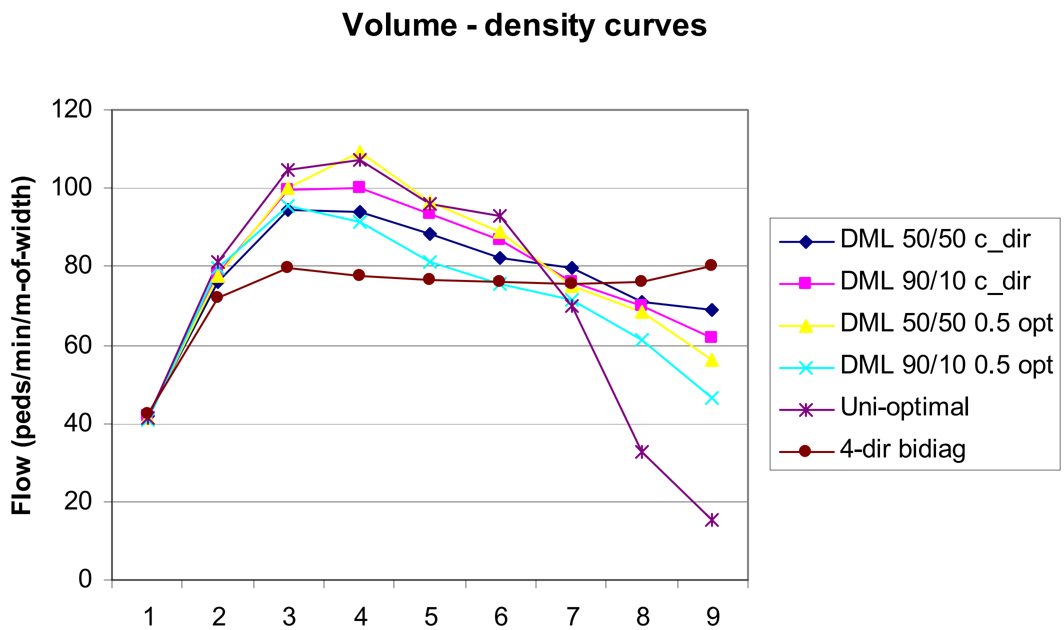
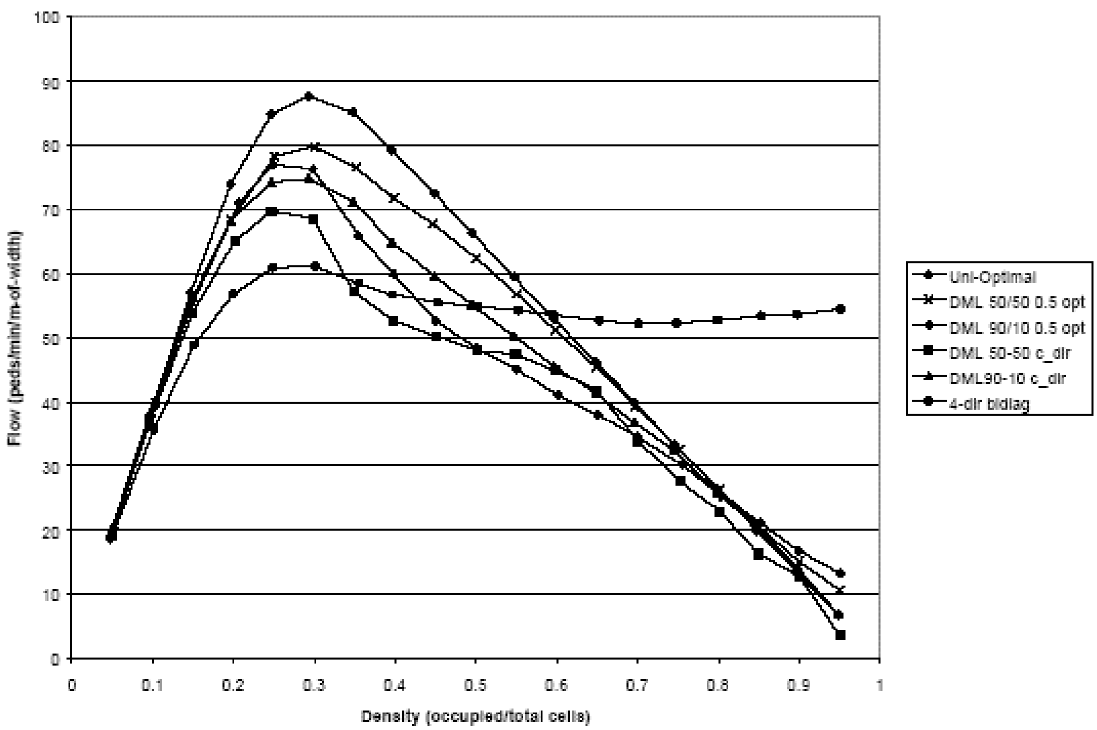


Fig. 3

Above: This model. *Below:* Blue and Adler's model:



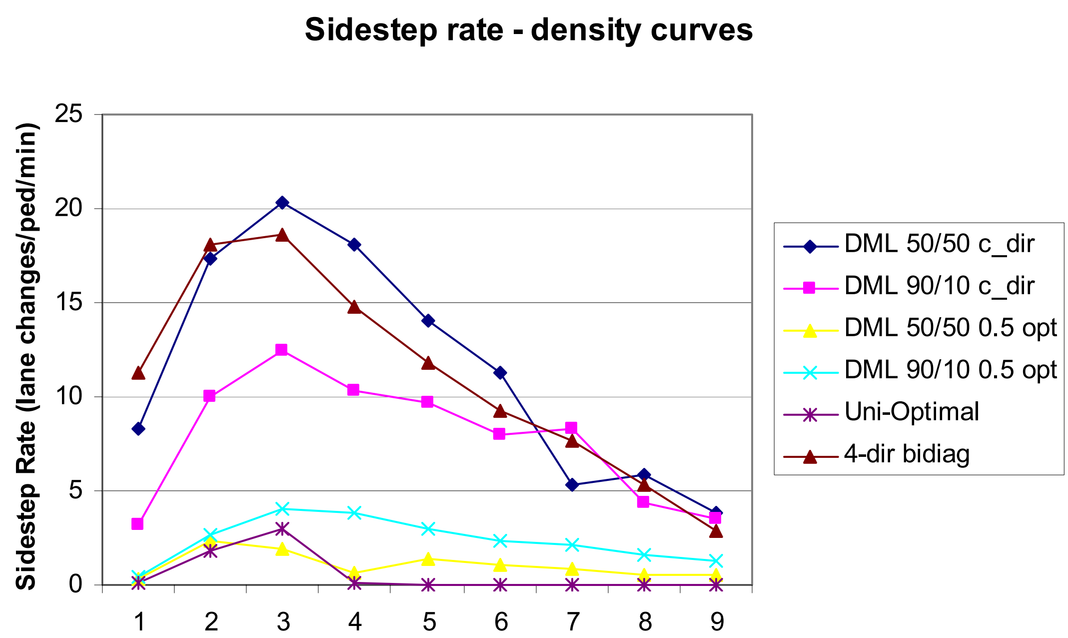
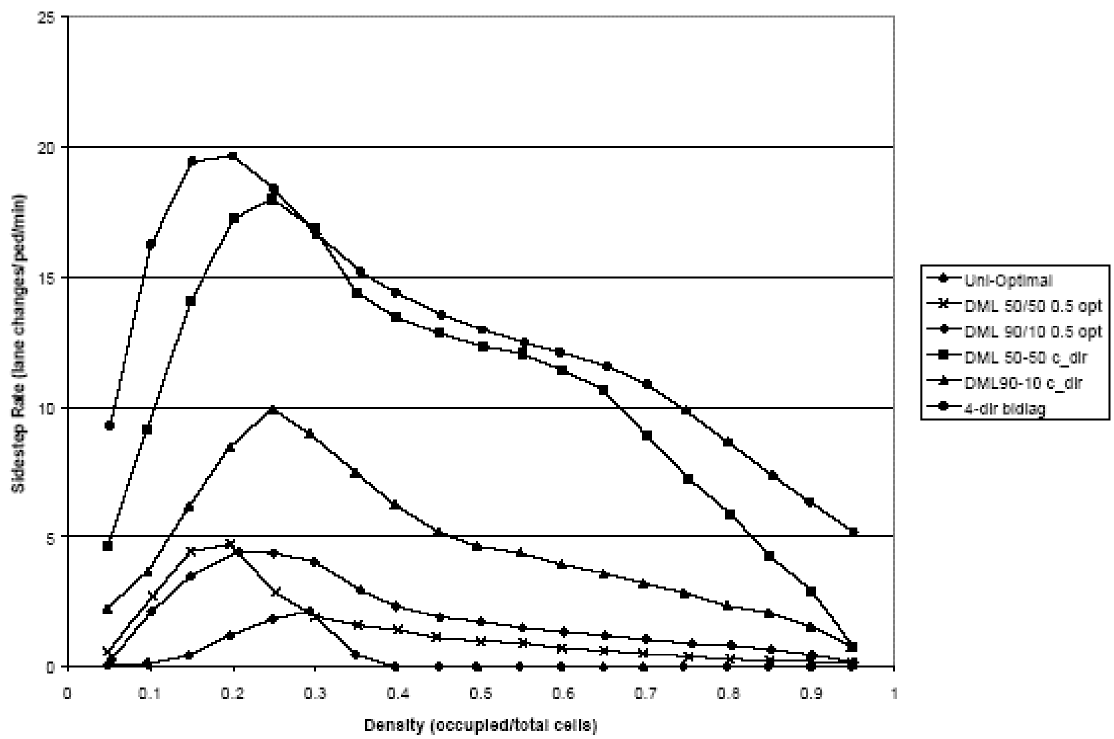


Fig. 4

Above: This model. *Below:* Blue and Adler's model:



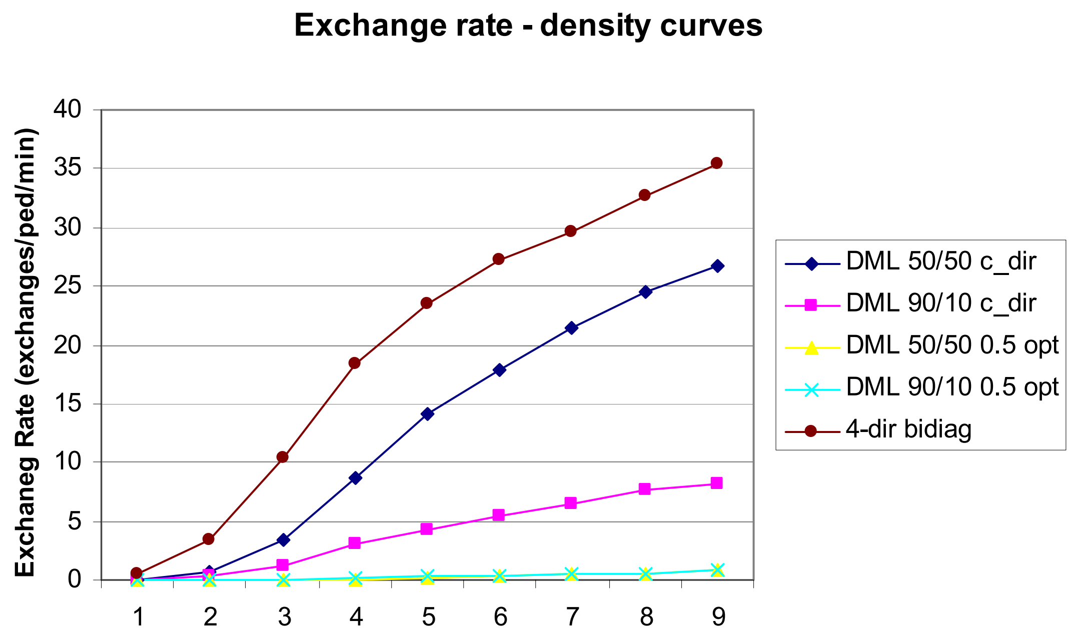
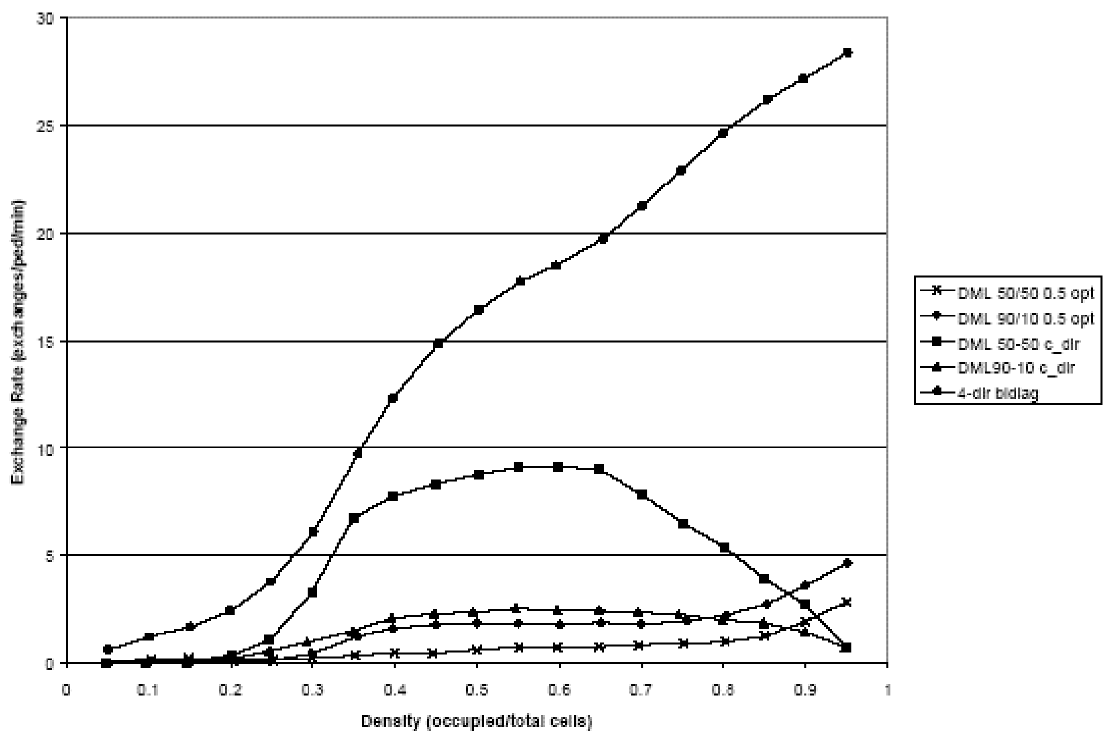


Fig. 5

Above: This model. *Below:* Blue and Adler's model:



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Appendix:

Just some brief words on the included CD.

The “readme.txt” file in the root directory gives all the specifics, but among other things it includes a .PDF format copy of the paper implemented for this project as well as digital copies of all the work submitted and associated files.

And as the program was written in Netlogo, a current copy of it will be included.