Pedestrian modelling: Current methods and future directions

Daniel Harney

Abstract
People are the foundation of the economic and social processes that drive the urban system. The need to understand the way in which people move through areas leads to the desire to predict pedestrian movements. By predicting pedestrian flows, the effect of changes to the spatial environment and transportation network can be determined.

Pedestrian models are an important tool in assessing the efficiency and safety of pedestrian facilities and are an integral part in the planning and design of modern facilities. Pedestrian movement is complex and various methods have been implemented to attempt to represent this sometimes chaotic behaviour. The focus of this study is on providing a state-of-the-art review of current methods of modelling pedestrian movements and detailing emerging technologies in pedestrian modelling that hold great potential and are rapidly expanding.
INTRODUCTION

Although an important component of a multi-modal transportation system, there are still relatively few studies concerning pedestrian behaviour and modelling. In developing and developed countries alike, the demand for travel is increasing, straining the existing transport systems. As the dynamics of our communities change, greater emphasis will be placed on providing safe and efficient pedestrian facilities.

Pedestrian movement is complex and there have been various methods implemented to represent this sometimes chaotic behaviour. Unlike vehicular movements, more detail is required than just the origin, destination and route taken to model flows. Pedestrians interact continuously with other pedestrians and their environment, changing direction and speed frequently. With the rapid increase in computational power and rich data sets, there are now methods available to represent these chaotic movements and use the results in the planning and design of new structures so that the needs of pedestrians and other users are balanced.

BACKGROUND TO PEDESTRIAN BEHAVIOUR

Pedestrians are the most vulnerable element in a mixed traffic system and also form the largest single road user group. Unlike the rules that govern vehicular traffic, there are few formal procedures or rules that govern pedestrian movement, resulting in often complex and chaotic movements. Pedestrians are not restricted to lanes or specific routes; they are only restricted by the physical boundaries around them such as the width of doorways or presence of walkways.

The modelling of pedestrian movements presents some specific problems not encountered in other forms of transport modelling. In open spaces, flows of pedestrian conflict from a number of directions. Unidirectional flow requires less perceptual energy from the pedestrian, relative to bi- or multi-directional flows, and is also associated with lower collision probabilities (Lovas 1994). Opposing flows may use the same 'lanes' and cross traffic can present itself at any time in open spaces. Pedestrians also have a tendency to walk in groups or clusters, unlike vehicular flows.

Physical features of pedestrian movements

The decisions and interaction between pedestrians is an extremely flexible and intelligent process. To accurately model pedestrian behaviour, the physical features of pedestrian movements such as walking speeds, acceleration, headway, overtaking and queuing must be accurately reproduced. The first three of these features are briefly considered below.

The walking capabilities of pedestrians vary widely. As a percentage of mean speed, pedestrians have a much wider range of desired speeds when compared to drivers (Blue and Adler 1998). Several studies have been conducted to describe the characteristics of the walking speed of pedestrians. Studies by Fruin (1971), Treganza (1976) and Carstens and Ring (1970) reason that walking speed depends on age, sex, physical ability, social position (in groups), trip purpose, weather, amount of baggage, gradient of walkway, mixture of flow directions and the density of pedestrians. Table 1 gives examples of mean free speeds and standard deviations.

Walking speed has also been shown to vary between cities. Table 2 presents a comparison of free flow walking speeds for various cities around the world.

Acceleration is another area in which pedestrian behaviour varies greatly from that of vehicles. Pedestrians can accelerate from standstill very quickly and change speed quickly when gaps arrive, manoeuvring through flows more frequently and casually than can vehicles. A range of accelerations must therefore be accounted for in a representative model.

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<table>
<thead>
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<th>Table 1</th>
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<td>Walking speed in uncongested corridors (Lovas 1994)</td>
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<table>
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<tr>
<th>Source</th>
<th>Mean speed (m/s)</th>
<th>Standard deviation (m/s)</th>
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<tr>
<td>Fruin (1971)</td>
<td>1.35</td>
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<td>Henderson (1971)</td>
<td>1.44</td>
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<td>Hoel (1968)</td>
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<td>Treganza (1976)</td>
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Headway between pedestrians is also an area of considerable variation with respect to vehicular flows. Headway, the time separation between individuals, has been studied previously in various studies including that of Fruin (1971). Due to the multidirectional behaviour of pedestrians both headway distributions and resulting queuing are extremely complex. Other studies have noted that headway depends on a variety of factors including the width of passage and crowd density.

**METHODS USED TO MODEL PEDESTRIAN MOVEMENTS**

A number of models for pedestrian movement have been developed over the years in a variety of disciplines. There are two distinct groups of models: macroscopic and microscopic. Macroscopic models focus on the system as a whole, while microscopic models study the behaviour and decisions of individual pedestrians, their effect on other pedestrians around them, and the system as a whole. Some modelling techniques are a combination of both models and cannot be defined as either solely macroscopic or microscopic.

The following section briefly reviews several ‘classical’ techniques which have been used in practice and then three ‘emerging’ techniques are considered to indicate the advances which they appear to offer.

**Classical modelling techniques**

There are basically four distinct approaches to modelling the system wide or macroscopic effects of pedestrian movements; regression models, spatial interactions / entropy maximising models, Markov models and simulation models (Timmermans, van der Hagen, and Borgers 1992). Each approach will be discussed separately.

**Regression models**

Regression models may be useful in assessing the need for specialist pedestrian facilities and pedestrian safety. The model developed by Sandahl and Percivall (1972) is a typical example of a regression model, based on the assumption that pedestrian flows are characterised by the accumulation of flows around interesting objects. Their model can be expressed as follows:

\[ T_i = a_0 + \sum_{k=1}^{8} a_k X_{ik} \]

where \( T_i \) = the number of pedestrians in zone \( i \);
\( X_{i1} \) = the effective floorspace for retail facilities in zone \( i \);
\( X_{i2} \) = the number of long-term parking lots in zone \( i \);
\( X_{i3} \) = the number of bus routes that stop in zone \( i \);
\( X_{i4} \) = the centrality of zone \( i \);
\( X_{i5} \) = the number of pedestrians that cross the city centre at zone \( i \);
\( X_{i6} \) = the number of bookstalls in zone \( i \);
\( X_{i7} \) = the number of public places in zone \( i \);
\( X_{i8} \) = the number of short-term parking lots in zone \( i \);
\( a_k \) = parameters to be estimated;
\( a_0 \) = the intercept of the regression equation.

This particular model was used to provide a reasonable description of the observed numbers of pedestrians in various parts of the centre of Orebo, Sweden (Timmermans et al. 1992). Another example of the use of a regression model is by Pushkarev and Zupan (1971) for the Manhattan area.

Regression models have many serious limitations. Timmermans et al. (1992) reasons that they do not provide any insight into the factors influencing route choice behaviour, the sequencing of visits, complementary relationships, the strength of functional relationships between streets and products and the influence of the locational pattern of shops on pedestrian movements.
Spatial interactions/entropy maximising models

These are the most popular modelling form currently in use. They can be applied to model many types of interactions and form the basis of classical transportation models. Butler (1978) presents a typical example of a spatial interactions/entropy maximising model. Her model consisted of three submodels: a trip-attraction submodel, a trip-distribution submodel and an allocation submodel. The trip-attraction submodel predicts the total number of stages that start or end in a particular zone. The distribution submodel predicts the distribution of trips across the various districts and the allocation submodel assigns the predicted flows between the origins and destinations to the transportation network using an all-or-nothing assignment procedure.

The spatial interactions/entropy maximising model forms the basis for many computer applications used to model pedestrian and vehicular movements and their goodness-of-fit has increased dramatically over the years. An example of a current package in use throughout the world is PEDROUTE (Buckman and Leather 1994), a simulation model developed by Halcrow Fox and London Underground Ltd.. This model has been used for station design throughout the world, including for the Olympic Railway Station, Sydney, which is designed to be capable of handling 50,000 passengers per hour. PEDROUTE has also been applied to peak post-event demand facility design, such as the redevelopment of the Lang Park Stadium in Brisbane.

PEDROUTE is a suite of pedestrian modelling software that produces a detailed simulation of the movement of passengers around a station and provides statistics of their journey times, the delay, congestion and the level of service (LOS) for each segment. Passengers are assigned along routes through the station using an integral dynamic assignment taking into account bottlenecks and congestion effects. Stations are broken down into different blocks representing stairs, escalators, platforms, ticket halls etc., with each of these blocks having different speed or flow curves associated with the movement of pedestrians through them.

Although providing powerful graphics and computational ability, the underlying assumptions and principles used in PEDROUTE and other similar computer programs are the same as other spatial interactions/entropy maximising models and fail to incorporate the individual basic mechanisms underlying pedestrian movements. These programs cannot represent the interaction of each pedestrian with other pedestrians and the external environment, only the overall or system-wide behaviour.

Markov models

Markov models are based on the assumption that only the last state occupied by the process is relevant to its future behaviour. They have typically been used for analysing the kind and intensity of functional relations in multi-purpose trips. The main advantage of these models lies in their ability to derive some general aspects of trip chaining behaviour by some easy manipulations (Timmermans et al. 1992).

Examples of Markov models can be found in Wheeler (1972), and Horton and Schuldiner (1967). Like the previously discussed models, Markov models have serious limitations. They do not include a preference structure or a choice rule, their theoretical underpinning is relatively weak and not easily applied to changes in variables or conditions. Over the years there have been various changes proposed to the model structure to overcome these limitations but they have mostly served to complicate the model, resulting in only slight improvements in the applicability of these models to a universal pedestrian environment.

Simulation models

Simulation models have the potential to overcome the major limitations of the previously discussed models by incorporating a variety of rules to simulate movements rather than being based on rigorous assumptions and complex theory. Researchers in various fields, depending on the objectives of the study, have created simulation models for their needs. Simulation models have the advantage of being applicable to a greater variety of situations once the appropriate calibration has been conducted. The model produced by Borgers and Timmermans (1986) is an example of a simulation model. The rapid increase in computational speeds and rich data sets has led to the increased accuracy of applications of this modelling technique.

Summary of models

The approaches of regression models, spatial interactions/entropy maximising models and Markov models introduced in this section have been applied to large-scale problems. However, their effectiveness has been limited partly by the absence of adequate...
detailed data and the fact that the underlying assumptions of these models are more suited to modelling general patterns of movement and cannot be used to model the movement of individuals.

OTHER APPROACHES TO PEDESTRIAN MODELLING

More recently, pedestrian modelling efforts have undertaken diverse approaches that cannot be placed in the preceding categories. Lovas (1994) created a mesoscopic simulation for evacuations. Using a stochastic model based on the assumption that any pedestrian facility can be modelled as a set of walkway sections, each pedestrian was modelled as a separate individual queueing network customer. The simulation tool EVACSIM (Lovas 1994), an evacuation simulation program was utilised in this research. Another evacuation or emergency pedestrian simulation model under development is CROSSES (Crowd Simulation System for Emergency Situations (CROSSES 2002). CROSSES aims to provide a virtual reality tool for training people to effectively respond to urban emergency situations through a model for generating and simulation of a virtual crowd.

Algodhi and Mahmassani (1991) developed a macrosimulation of pedestrian traffic at a large religious gathering, consisting of a set of partial differential equations that are solved numerically following a discretisation of time and space. Hoogendoorn and Bovy (2000) develop a new gas- kinetic pedestrian flow model, a paradigm widely applied for modelling vehicle flows. Mesoscopic equations describe the pedestrian phase-space density relationships, essentially two-dimensional dynamics generalisations of convection, acceleration and non-continuum transition terms.

Helbing and Molnar (1995) take a different approach to pedestrian modelling, examining pedestrian movements as either positive or negative social fields, in which a pedestrian behaves as if acted upon by external forces. This approach has similarities with both cellular automata and agent-based models, which are discussed in the following section.

EMERGING TECHNOLOGIES IN PEDESTRIAN MODELLING

Around the world various new techniques are being developed in the field of pedestrian modelling. The following sections outline some of these technologies.

Cellular automata

Cellular automata is an artificial intelligence approach to simulation modelling, defined as:

mathematical idealisations of physical systems in which space and time are discrete, and physical quantities take on a finite set of discrete values. A cellular automaton consists of a regular uniform array of cells, usually infinite in extent, with a discrete variable at each site (‘cell’). The state of a cellular automaton is completely specified by the values of the variables at each site. A cellular automaton evolves in discrete time steps, with the value of the variable at one site being affected by the values of variables at sites in its ‘neighbourhood’ on the previous time step. The neighbourhood of a site is typically taken to be the site itself and all immediately adjacent sites. The variables at each site are updated simultaneously (‘synchronously’), based on the values of the variables in their neighbourhood at the preceding time step, and according to a definite set of local rules.

Cellular automata local rules are used to describe the intelligent decision-making behaviour of the automata, creating an emulation of actual behaviour. Global properties of systems ‘emerge’ from simple behavioural rules instead of formulas. As a result, cellular automata has emerged as a tool for simulating flows and modelling transportation networks. Nagel and Schreckenberg (1992) have analysed vehicular movements using a cellular automata simulation of a lane of traffic. Their simulation has since been extended to a multi-lane model by Richert et al. (1996) and is being used in the traffic-modelling component of the TRANSIMS planning project.

Cellular automata has been extended to pedestrian simulation by Blue and Adler (1998), who first generated fundamental pedestrian flows using a cellular automata microsimulation of a pedestrian walkway with unidirectional flow. Each pedestrian in this study was allocated individual walking speeds and other characteristics, and their movements were governed by local rules. These local rules govern when cells are occupied, when pedestrians overtake, when they can ‘change lanes’ and direct basic forward movement. This simple model replicated both the system-wide effects and individual behaviour of the pedestrian effectively as measured by various performance indicators. A simple representation of
the grid lattice used in this model is shown below in Figure 1.

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 behaviour is a result of the net interactions of the local rules as each pedestrian searches the available neighbourhood of cells (Blue and Adler 2000).

This study is significant to future pedestrian modelling as it provides a good starting point for replicating the complex behaviour of pedestrians. Although simplistic, more local rules can be added to this model to improve its accuracy, for example random effects and behavioural characteristics.

Blue and Adler (1999) expand on their previous work by presenting a cellular automata microsimulation model and emergent fundamental flows for a bidirectional pedestrian walkway. Proceeding in time steps, this cellular automata simulation consists of four parallel updates, applying local rules to lane assignment, lane movement, assigning travel speeds and forward movement. Three sets of experiments were conducted:

- uni-directional flow with varied lattice widths and lengths,
- bidirectional flow assigned to directional lanes with no directional crossover, and
- bidirectional flow, randomly assigned.

The first experiment was conducted to examine sensitivity to the size of the lattice. It was found that changing the dimensions of the lattice did not provide significant changes in system performance. The second experiment examined the distinctions that arise when directionality is added to the pedestrian stream, with no crossover between lanes. Six directional splits were investigated with almost identical speed versus density curves for all. These results confer with field observations that bidirectional flows do not have different characteristics from single-direction flows (Blue and Adler 1999). The third experiment represents walkways where opposing traffic mingles and directional lanes are not set up. The results of this experiment illustrates the modelling power of the cellular automata method and that complex and reasonable group behaviour can emerge from a simple set of behaviourally based rules.

Blue and Adler (2000) further extended their seminal research in this area by developing a cellular automata microsimulation model for four-directional pedestrian flows. By extending the rule set previously developed by the authors for the bi-directional model, cross-directional capabilities were included in the model. As per previous experiments, a simple grid lattice was used in this model to represent a pedestrian environment as shown below in Figure 2.

The cellular automata pedestrian model presented shows speed-flow density and fundamental flow characteristics that are acceptable, based on previous work, but which require verification with cross-four directional field experiments.

Although cellular automata modelling is a 'grainy', discretised approach, complex movements are accommodated with a manageable set of parameters, resulting in viable directional pedestrian models. Although the range of cellular automata movements are not perfect reproductions of pedestrian movements, the range of emergent behaviours realised using this modelling technique shows that cellular automata modelling of pedestrians is a potentially powerful tool for traffic engineers, planners and facility designers.

VISIBILITY GRAPH ANALYSIS

Visibility graph analysis (VGA) is a potential tool for evaluating the impact of development decisions on...
movement patterns and assists in balancing the needs of pedestrians and vehicles.

VGA, pioneered by the Space Syntax Group, England, is a spatial-regression analysis technique useful in the design of urban spaces and buildings. This technique examines how visually accessible points are within an area. Pedestrian movement and flows are heavily reliant on line of sights and visibility when navigating through an area. VGA works on the principle that the design of space, above all else, determines the movement and interaction of people in a built environment.

By demonstrating a relationship between the characteristics of a layout and the way in which people use a space, regression-based statistical models can be used to predict the likely effects of changes to the layout. The methodology by which this tool can be applied to live development projects has been largely through the platform of a Geographic Information System (GIS). This allows economic and social data (such as pedestrian movement) to be linked to the spatial analysis of visual fields created by VGA (Desyllas 1999).

Using VGA techniques, the Space Syntax Laboratory claim to forecast patterns of movement with at least 75% accuracy, whether that movement is of passengers, shoppers or everyday pedestrians (Space Syntax 2002). This relationship between observed and predicted flows using VGA is demonstrated in the results of an analysis of the Tate Gallery in London shown below in Figure 3 and Figure 4.

In Figure 3, the propensity for pedestrians to travel through an area based on visual fields is illustrated by using a colour scale where hot colours (red, orange when shown in colour) indicate high flows and cool colours (green, blue when shown in colour) indicate lower flows.

The prediction of pedestrian movements using VGA shown in this example demonstrates a good replication of actual observed movements. Similarly, Space Syntax Group claims comparable results for other studies they have conducted, including urban sites and analyses of entire CBD areas.

The principles and results of VGA can also potentially be applied to other areas. The Space Syntax Group has also used VGA to study crime patterns in existing housing layouts and public places such as hospitals to identify problem areas and understand the factors which increase vulnerability. Customer movement patterns and shopping behaviour have also been analysed using VGA to forecast the likely effects of redesign proposals on customers in retail environments.

Visibility graph analysis potentially provides a simple and effective tool for predicting pedestrian movements and patterns. Further research in this area will improve the accuracy of the forecasts of pedestrian movements. This technology has good operability with other techniques used to predict pedestrian movements, and its integration with other methods such as agent-based modelling seems a natural progression.

Agent-based models

Agent-based models are an emerging and promising approach to pedestrian modelling. An agent is an identifiable unit of computer program code that is autonomous and goal-directed. This means that the agent is capable of effective independent action and goal-directed in that its autonomous actions are directed towards the achievement of defined tasks. Agents may also possess other capabilities such as intelligence and adaptability. An agent-based model is one in which the basic unit of activity is the agent. Usually a model will contain many agents and its outcomes are determined by the interactions of the agents (Schelhorn et al. 1999).

Agent-based models have been applied to various problems in different disciplines. A good starting point for applications of agent-based models is O'Sullivan and Haklay (2000), with references to other review articles and edited volumes. Agent-based models have been successfully applied to many fields of study including:

- the flocking behaviour of birds,
- simulation of vehicular traffic,
- human movement patterns,
- economic agent-based models, and
- sociological agent-based models.

In this paper only agent-based human movement applications will be examined.

An agent-based model specifically aimed at modelling pedestrian behaviour is the STREETS model (Schelhorn et al. 1999). The STREETS model uses a two-stage process:
1. a ‘premodel’, which populates the urban centre with a population of pedestrians using rich socio-economic data sets in a GIS setting, and

2. an agent-based model, which simulates movement around the urban district, taking into consideration spatial interactions, pre-determined activity schedules, and the distribution of land-uses. The SWARM simulation environment developed by the Santa Fe Institute is used in this dynamic stage of the model (see the SWARM website at www.swarm.org for further details on the SWARM model).

The STREETS model demonstrates the potential of agent-based pedestrian models, with every agent having detailed socio-economic characteristics and behavioural characteristics including factors such as speed, visual range and fixation. The area being modelled utilises detailed GIS data to classify areas according to land-use, walkability and accessibility to assess its attractiveness to the individual agents.

Essentially a mesoscopic agent-based model, the agents use their programmed behaviour to navigate and find their way in the system. However they do not simply proceed from point to point, along the way they interact with other agents and enter shops or buildings that are attractive to their socio-economic details, in much the same way as a real shopper does.

Further development of the STREETS model and the SWARM program are currently being undertaken. Increasing the range of measures of performance as well as enhancing the agent’s navigational behaviour are areas where further development is continuing.

Another agent-based pedestrian model under development is PEDFLOW (Kukla et al. 2001). PEDFLOW is a microscopic model that aims to model the movement of pedestrians as they make each step towards a predefined destination. The behaviour of the autonomous agents in this model is controlled by a set of rules in combination with parameters that are specific to a type of person in a type of situation. Rules capture the general concepts of the simulation; the parameters modify or adjust the rules according to the individual agent’s profile.

Agents in the PEDFLOW model move towards their goal/destination through the modelling environment represented by a grid, where grid elements can be occupied by pedestrians or structures such as street furniture. Each pedestrian takes into account only the part of the urban space that it can observe locally. Agents also maintain a list of sub goals that can be modified through the presence of attracting entities (e.g. window displays). An interesting component of this model is the possibility of actively influencing other agents’ behaviour. Agents can respond to messages sent from other agents and entities and adjust their behaviour.

PEDFLOW is currently only in prototype form with further development continuing. Additionally, utilities for PEDFLOW under further development include a graphical environment editor and Fruin level of service extraction tools.

Further developments in the area of agent-based pedestrian models will expand the application of agent-based models to an increased range of situations with the goal of being applicable to the universal pedestrian environment.

Agent-based modelling provides a convenient and potentially accurate method of modelling the complexity of pedestrian movements. Using detailed socio-economic and behavioural details to populate such models promises to provide a useful tool to planners and designers of infrastructure sensitive to pedestrian traffic.

DISCUSSION

The aim of this paper is to present existing models of pedestrian movements and compare their theoretical underpinnings and performance. This discussion was restricted only to modelling approaches that have been successfully applied to pedestrian behaviour, within the limits of the available data.

The review undertaken illustrates that, over the years, pedestrian models have been developed in a variety of disciplines. However, the analysis of the classical methods discussed suggests the need for substantial improvements in both data and analysis procedures. The majority of these models have been developed by combining models that have been applied to other choice contexts and, as a result, are not suited to pedestrian modelling, lacking the mechanisms that are typical of dynamic pedestrian behaviour.

The emerging technologies of cellular automata, visibility graph analysis and agent-based models,
although still under development, represent a new frontier in pedestrian modelling. In comparison with classical methods, these techniques incorporate a greater degree of fundamental pedestrian behaviour that is not based solely on rigorous assumptions. By assessing the individual movements of pedestrians, these models will provide a realistic and representative image of the microscopic and macroscopic effects of changes to facilities and provide potentially powerful planning and analysis tools. There is a definite need for pedestrian models for accurate multi-modal transport planning, and hopefully after further development, these emerging technologies will enhance the capability for providing such models.

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Daniel Harney

received his Bachelor of Civil Engineering (Honours I) from the University of Queensland, Brisbane, in December 2000. Daniel currently works in the Traffic Engineering and Transport Planning section of Sinclair Knight Merz in Brisbane.

Contact

Daniel Harney,
Sinclair Knight Merz,
369 Ann Street,
BRISBANE, QLD, 4000.
Tel: 07 3244 7227
Fax: 07 3244 7306
Email: Dharney@skm.com.au

Acknowledgements

Elements of the work reported in this paper were conducted as a research project undertaken as a component of an undergraduate subject in transportation engineering at the University of Queensland in 2000.