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Agent-based modelling of pedestrian movements: the questions that need to be asked and answered

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Abstract. Vulnerable road users have steadily attracted increased importance in transport and planning. The behaviour of pedestrian movements (especially in the areas off but adjacent to roads) requires improved tools to address the issues now being raised. Such behaviour and interactions can now be modelled by using a combination of massively parallel processes simulating individual pedestrians, and a series of behaviours of these simulated pedestrians in the interactions with each other and their environment. The PEDFLOW model has been implemented in the parallel processing language Occam as an agent-based evolutionary system, which allows extensive modelling of detailed pedestrian behaviour with minimal complication. The principles and methodology of its development and application are specified.

1 Introduction: why worry about pedestrians?

Pedestrians are a very important component in any representation of transport movements that seeks to include the constraints and behaviours at all stages in the trips that go to make up a complete journey. Pedestrian movement generally terminates or initiates a chain of linked activities, and, if treated in detail, a single pedestrian movement is found to include a considerable number of subjourneys from one location to another. In general, these subjourneys are unaccounted for within a single pedestrian movement from one location to another.

The pedestrian flows that determine sidewalk capacity have been studied for many years through a level of service approach (Fruin, 1971). This approach has the major flaw that it ignores the individual movements and the connections between different stages of an individual's trip. The ability to rest with this aggregate form of model has become less viable as understanding of the importance of the intermediate stops and pedestrian movement stages in journeys has become more widely appreciated.

There has been a move towards microsimulation in road traffic movement to address the complexities of vehicle interactions on complex road systems, for example, the model PARAMICS (SIAS Ltd, 2000). Similarly, in the present paper we address a complementary approach to representing people walking as autonomous agents interacting in a microsimulation.

The complexity and computer requirements of such microsimulation models have in the past been daunting, but as the elegance and power of the languages [such as Occam (Inmos Ltd, 1987) and the Java package JCSP (1999)] and the computing frameworks, such as parallel computing systems, have improved, there are new opportunities to develop such modelling approaches. Microsimulation has slowly come to be regarded as a 'simple' rather than a 'complex' approach. Memory and computational power constraints are no longer barriers to large-scale handling of many detailed interacting elements. The key aspects are now the clarity of specification and careful design and operational validation of microsimulation frameworks.

Multiagent models have been used to simulate several different aspects of pedestrian movement. The StarLogo language (Resnick, 1994) has been used to examine the influence of the detailed structure of urban networks on pedestrian movements. STREETS, which uses pedestrian walking speed, visual range to determine items (such as buildings) in the environment that will be interacted with, and degree of fixation on the sequence of activities that the pedestrians plan to meet, aims to integrate route choice and pedestrian behaviour over a wide area, and makes a series of design decisions to make this workable (Schelhorn et al, 1999).

In this paper we describe a detailed multiagent microsimulation system (PEDFLOW) designed to represent conflicting pedestrian flows at a detailed level on a section of sidewalk, or in an open or enclosed space with obstructions. Individual pedestrians respond to each other and the barriers in their environment through two key characteristics: preferred gap size, and awareness. The processes and concepts associated with the representation of pedestrian environments and behaviours are specified. The study, analysis, and representation of pedestrians have become important as policymakers and urban designers need to understand more about the nature of pedestrian movement and behaviour in a variety of settings and given circumstances. Microsimulation methods have become practicable at a time when there has been a growing concern over the adequacy of current methods used to assess the impact of infrastructural change on pedestrian activity and behaviour. The decline in walking experienced in the United Kingdom needs to be stemmed and reversed to encourage interchange with other modes on a seamless journey (DETR, 1998; LINK, 1997; OST, 1995). Little is known about the determinants of pedestrian behaviour and trip-making activity, or which measures are more effective in encouraging walking (Department of Transport, 1997). Tools are therefore needed which can aid in the design of pedestrian facilities. Microscopic modelling is one approach that can simulate interventions aimed at improving the pedestrian environment. The representation of street environments and pedestrian behaviours, within the microsimulation model, can help to assess the effectiveness of new layout and street designs in promoting pedestrian activity or in reducing congestion at particular locations in a pedestrian area. Following an overview of the PEDFLOW model, a conceptual approach to represent pedestrian environments and the behaviours involved is given. The research issues addressed are:
(1) How can the behaviours in a given environmental setting be represented?
(2) What are the measurement issues?
(3) How can the environment and behaviours exhibited be operationalised and replicated?

2 Background

Models of pedestrian-flow and movement patterns have been designed for a variety of reasons (Hine, 1995; Timms and Cavalho, 1991). Models have been developed which seek to identify pedestrian movement at a strategic level and they are analogous to a combined set of generation, distribution, and assignment models for motorised vehicles. There are a number of problems associated with these types of model (TEST, 1976; Timms, 1992). Generally these models are only able to represent an approximate route and will not distinguish between, for example, which side of a street a pedestrian is located. This is not necessarily a constraint of this general family of approaches, and generalised network models can now handle this finer level of detail and can even include movement paths through buildings. However, there are other issues where network models fail to represent pedestrian behaviour adequately, and more attention needs to be paid to the mechanisms of movement and interaction on a single link.

Pedestrian trips are less homogenous than vehicle trips in terms of journey purpose and hence route choice is less well determined. The pedestrian mode is usually a minor mode in a larger trip or tour of connected trips. For example, the part of a trip spent walking to or from a bus stop depends on other modes, so that an independent pedestrian model is inadequate. A pedestrian network is much harder to define than a vehicular network as there are numerous paths available to pedestrians that are not available to vehicles, and pedestrians are not limited to crossing roads at intersections. Movements through and within buildings are a feasible option, and many unrecorded intermediate stops or pauses may be made when passing a series of shops. Nevertheless, given appropriate simplified assumptions, fine-detail network models of this extended pedestrian environment can be built, and the multiple stops and linked purposes which include pedestrian movements can be modelled by using activity chain and GIS techniques, given suitable data. The extensive developments in disaggregate models of linked journeys, activities, and multiple mode trips have allowed large-scale modelling of pedestrian route and location choice to be refined. Major models such as the Netherlands National Transport model include walking and cycling as intrinsic modes with significant success (Snellen et al, 1998). However, these are still essentially strategic models. Productive fine-scale pedestrian modelling is at present best achieved by focusing on specific locations and behaviours of interest at the local scale, as in PEDFLOW. Larger scale models are still best constructed to deal with different aspects of pedestrian behaviour, as in the SWARM-based models at University College London (Schelhorn et al, 1999).

Other models have been developed which seek to represent aspects of pedestrian behaviour at an individual level. This work has generally concentrated on one element of pedestrian movement: the delays experienced by pedestrians when crossing the road, once a crossing location has been selected (Goldschmidt, 1977; Griffiths et al, 1984a; 1984b; 1985; Hunt and Williams, 1982). More recently, it has been extended through the development of a crossing criteria – random crossing model (Hunt and Griffiths, 1991) and an index of crossing difficulty by using gap acceptance and rejection criteria (Hunt and Abduljabbar, 1993). Although important for planning and operating instantaneous demand-responsive policies, in relation to traffic signal measures, they may well prove too cumbersome in terms of input data and the amount of time required.

Further models that have been developed, and which represent pedestrians as continuous flows rather than as individuals, are not concerned with full trips and are limited enough spatially to represent the positions of pedestrian flow and pedestrian facilities that exist (Helbing and Molnar, 1997; Timms, 1992). These types of model have been used to: estimate pedestrian routes and congestion in situations which are free from motor vehicles [for example, models have been developed for the London Underground (Annesley et al, 1989; Daly et al, 1991; Harris, 1991), and for a bridge used by pilgrims to Mecca (Selim and Al-Rubeh, 1991)]; and to simulate flows of pedestrians over a length of street which is significantly greater than the area around a single junction or crossing facility (Timms, 1992; Timms and Cavalho, 1991). These models tend to employ an analogy with particle and fluid flow equations because the movement tends to be in predetermined directions and everybody has the same limited set of goals. We argue that such models are too limited when trying to simulate the microscopic effect of infrastructural changes resulting from geometric modifications to the pedestrian space, especially where there is conflicted flow.

In reality, the urban environment is totally different from this somewhat simplified model environment. Each individual has a different goal or set of goals. Individuals have different reasons for being in the urban environments, which will influence the ways in which they move and behave. Most urban spaces allow people to move in all directions at the same time and thus there is a high degree of freedom. The models previously developed are able to restrict these degrees of freedom because they can assume that the goal-set of all the people is much more limited. There is, however, still a choice between modelling the manner in which different forms of activities and constraints are resolved by people over a whole tour or a day, which will yield broad results applicable to specific categories of people, and microsimulations which allow all the people in a specific set of locations to interact and resolve their movement and destination goals. The two approaches are complementary.

PEDFLOW models individuals and has the ability to represent the fine detail that occurs in urban pedestrian areas. Individuals are modelled as a separate entity and thus the model is able to produce a more realistic representation of what occurs in reality. In the model, an individual pedestrian cannot see the complete scene and thus has to make a decision based on incomplete information. In such processing, the result is a behaviour in which local decisions affect the overall global behaviour that emerges from the system. Effectively, each person occupies a small area of the available space for a time related to the speed at which they are walking. It is also presumed that two people cannot occupy the same space at the same time. At the end of this time period, the person looks around to decide into which space he or she is going to move, taking into account obstructions, edges, and barriers and any other people moving in the vicinity. Each person is therefore moving in parallel with all the other people but acts individually as an autonomous agent, in that the rules that govern a person's behaviour are local to that person.

Other research has indicated that our understanding of pedestrian level of service is lacking in relation to how people respond to the influence of other people in different situations and different densities (May et al, 1987). PEDFLOW, owing to its microscopic modelling, provides a means whereby service quality factors can be extracted directly from the model. For example, we can extract variance from desired walking speed either for each individual or for all people; we can determine the number of times people have to come to a halt because their passage is blocked; similarly, the number of times people move without making forward progress can be calculated. Such measures are not available in a statistically based model. However, PEDFLOW is also able to provide such measures as flows, densities, and other averaged measures which can then be related to level of service measures (Fruin, 1971).

One of the driving factors for such a model is the desired walking speed of the pedestrians simulated. This is considered in more detail later, but there are some important broad findings about preferred travel speeds that are invaluable and need to be fed into this process. There are substantial differences in desired speeds displayed by walkers of different ages and genders and in cities of different sizes (Walmesley and Lewis, 1989; Wigan, 1995).

3 PEDFLOW: a behavioural and operational model

The PEDFLOW model uses agent-based technology in that each pedestrian, whether a single person or a group of people, is represented by a single process which has the capability to make decisions concerning the movement the pedestrian will make without recourse to the data associated with any other pedestrian process. A shared data structure is used to record the current position of every pedestrian, blockage, edge, and kerb in the scene being modelled. A blockage is an object around which a pedestrian has to move, an edge represents the edge of a building through which a pedestrian cannot pass, and a kerb represents the edge that separates pedestrian and vehicular space. The rules governing the actions a pedestrian will take in a specific circumstance are captured in a decision table. In theory, every pedestrian in the model could have a different rule set. In practice, the tables have been parameterised to reduce the number of variations.

PEDFLOW uses a hybrid simulation technique in that it has a fixed time step (the current model has a time gap of one tenth of a second), but only those pedestrian processes that can contribute to the result at a given time step are actually processed. This is achieved by special process structures and direct manipulation of the process run queue in the underlying parallel system implementation to optimise the processing of time (Kerridge and McNair, 1999; Kerridge et al, 1999). The space being modelled is mapped onto a grid. A pedestrian enters a grid element and occupies that element for a time that corresponds to his or her actual walking speed. To represent this, the reference to the agent (pedestrian process) is placed in a data structure which holds other references for agents waiting for the same time. In due course, the data structure becomes current and all the agents are processed in parallel. The order in which they are processed is not determined.

An initial phase is used to set up the structure of the space being modelled which loads data concerning blockages, edges, and kerbs into the shared grid-based structure. Because of the operation of the model this information can be changed dynamically during the simulation process. That is, further obstructions can be added dynamically during simulation. This can be driven either by elapsed simulation time or by direct intervention by the modeller. For example, in this way a group of market researchers or a busker can be modelled as a set of obstructions.

3.1 The underlying model

The following diagram (figure 1) shows the basic structure of the model from the point of view of a single pedestrian that is about to be processed. The space is subdivided into a regular grid the size of which depends upon the scenario being modelled. For normal urban situations, a grid size of 750 mm is appropriate. Hankin and Wright (1958) investigated unidirectional speed-flow curves for pedestrians in subways. They found that the maximum flow rate was 27 persons per ft width per minute at a concentration of 0.13 persons per ft^2. Although interaction between opposing flow streams was not considered, the results were used as the basis for subway design standards (Department of Environment, 1966; Ministry of Transport, 1965). Navin and Wheeler (1969) had similar results to those of Hankin and Wright. From studies of Columbia University students, the maximum flow rate was 26.4 persons per ft width per minute at a concentration of 0.11 persons per ft^2. From their studies they recommended that a pedestrian lane should be 2.5 ft wide. This is just 10 mm less than the 750 mm which PEDFLOW uses and a difference that can be ignored. A pedestrian can move into any adjacent grid element giving eight degrees of freedom. In normal forward movement this is usually limited to the three 'forward' grid elements. In slightly more congested situations a pedestrian may choose to move directly to his or her side without making

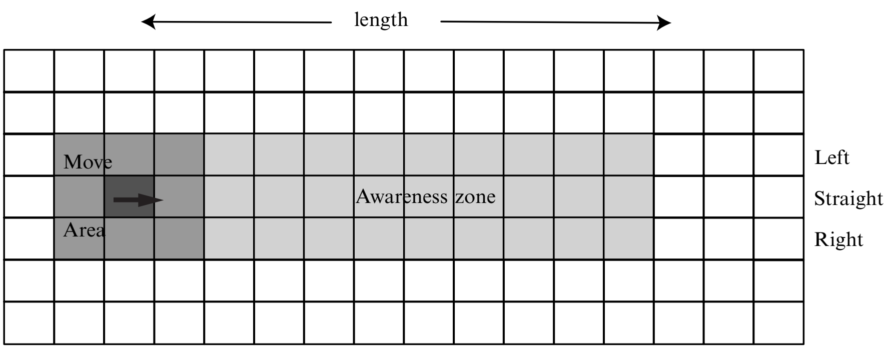

Figure 1

forward progress. A pedestrian is unlikely to move backwards when the desire is to move forwards, but in more complex behavioural modelling this case will have to be considered. The diagram represents the view of a single person but the model is capable of simulating a number of people walking together in some form of cohesive group. For example, a family group walking as a single unit that tends not to allow other pedestrians to move through the group can be modelled, as can a more diverse group of people moving through a space such as a group of tourists being guided by a tour guide.

The PEDFLOW model is not constrained to simulate a single-dimension grid size. As the grid size is reduced, to model more congested situations, then the rule set used will also reflect the fact that people have more constrained movement possibilities. In some situations, a loading of 6 people per m^2 can result where there is a large crowd moving towards and observing a spectacle such as occurs during the fireworks display at the Hogmanay Party in Edinburgh each New Year.

In figure 1, if a pedestrian is occupying the square with the arrow moving in the direction indicated, then the movement of the pedestrian can be determined in the following manner.

Step 1 Determine the type of *entity* in the grid element that is closest to the pedestrian in each of the rows left, straight, and right starting from the grid elements adjacent to the pedestrian and then moving into the awareness zone. An entity can be one of the following.

(a) Another moving pedestrian: If it is another moving pedestrian then we further determine the direction in which that pedestrian is moving relative to the pedestrian we are currently considering. The rules capture different behaviours for pedestrians that are moving relatively in the same, opposite, or a different direction. *Same* means that the pedestrians being considered are moving in exactly the same direction and in this case we identify whether the pedestrian in front is moving relatively *faster* or *slower.* *Opposite* means the pedestrians are moving directly towards each other. *Different* means that the path of one is crossing the other at some angle, other than precisely opposite. Pedestrians can move diagonally between grid elements.

(b) A possible goal point in the simulation.

(c) A stationary object or blockage into which a pedestrian cannot move.

(d) The edge of a building through which a pedestrian cannot pass.

(e) The kerb between a road and pavement.

Step 2 The distance, in terms of grid elements, between the pedestrian being considered and the nearest entity in each of the three rows is also determined.

Step 3 The rules governing the movement decision for a pedestrian are couched in terms of the entity that has been found and its *distance* from the pedestrian. A pedestrian can make one of four decisions:

(a) move to the grid element immediately in front in the row labelled *straight* (the normal movement);

(b) move to the diagonally adjacent grid element in either the *left* or the *right* row (this choice can also be made as a result of random choice selection);

(c) move to the side, either left or right, without making forward progress because the pedestrian is too close to an entity (known as entity *avoidance*);

(d) remain in the grid element because he or she cannot move (known as *pausing*).

Step 4 Having determined the required movement, the pedestrian then occupies the grid element for a period of time that is directionally proportional to the actual walking speed of that pedestrian after which the process is repeated again. The speed a person walks at is either the full desired walking speed or a reduced speed to match that of the person in front and whom they are following.

3.2 Parameterisation of the behaviour

In order to create different categories of behaviour more easily we have identified five underlying parameters that contribute to the decisionmaking process of the person. These parameters were determined both by video observation and by direct observation of a busy street. The first is called static awareness (SA) and is a measure of how far in front the pedestrian perceives changes in the environment. It is represented by *length* in figure 1. The second factor is called preferred gap size (PGS) and represents the smallest space into which the pedestrian is willing to move. The third factor is the desired walking speed (DWS) of the pedestrian. Thus by changing the values of DWS, SA, and PGS we can easily alter the behaviour of each pedestrian in the simulation. The value of PGS must be less than or equal to that of SA. In reality, many pedestrians will be given the same values of DWS, SA, and PGS. The parameter PSM (personal space measure) represents the amount of space that a pedestrian wishes to maintain around his or her person. In some situations the pedestrian is given a choice as to the direction he or she will move because the rule cannot fully determine the outcome. For some pedestrians this CHOICE parameter is predetermined as left or right, whereas for others a random choice is made. These parameters are used to interpret the data retrieved from the environment in which the person is moving. The environment is captured in the grid referred to previously and shown in figure 1.

In making a journey a pedestrian may have a number of subgoals. On each leg of the journey, as he or she moves between the subgoals, the pedestrian may have different parameter values. For example, the first subgoal may be to go to a cash machine to get some money and this will be undertaken with a parameter set that reflects a well-focused purpose, for example high DWS, small PGS, large SA, and always moves to the favoured right if given a choice. Thereafter the person may proceed to a shopping mode where the parameters are modified, say, to lower DWS, larger PGS, much smaller SA, and makes random choices.

3.3 Formulating the rules

When it is the pedestrian's time to move, the grid is accessed to determine the entities that are found in each of the rows as described earlier in section 3.1. Values are returned for each of the predicates DISTANCE and ENTITY for each of the rows left, straight, and right, that is, a total of six values. These returned values are compared with the values stored in the rule table and the rule with the corresponding combination of values is activated. The result of the rule activation is two values that indicate the DIRECTION in which the pedestrian is to move and the SPEED of movement. The distinct values associated with these rule table elements are given below.

$$\text{DISTANCE} = \{\text{Close, Gap, Aware, Far}\} \ .$$

If d is the number of grid elements between the person and the entity, then

$$\text{Close implies } 0 \leqslant d \leqslant \text{PSM} \ ,$$

$$\text{Gap implies PSM} < d \leqslant \text{PGS} \ ,$$

$$\text{Aware implies PGS} < d \leqslant \text{SA} \ , \quad \text{and}$$

$$\text{Far implies } d > \text{SA} \ .$$

It should therefore be noted that the interpretation of these values depends upon the parameters associated with the person during this stage of their journey.

ENTITY = {Faster, Slower, Different, Opposite, Edge, Blockage, Kerb, Goal, Vacant} .

Relative to the person being considered:

Faster implies a person moving in front in the same direction at a speed greater than or equal to the DWS,

Slower implies a person moving in front in the same direction at a speed less than the DWS,

Different means a person moving across the path,

Opposite means a person moving directly towards,

Edge is a physical boundary in the environment through which a person cannot move,

Blockage is an obstruction around which a person can move,

Kerb is the transition from pedestrian to vehicular space, and

Vacant means no entity was found and will occur with distance value Far.

ACTION-DIRECTION = {Straight, Left, Right, Choice, Pause, Avoid} .

The action directions have the following meanings:

Straight means the person moves forward in the straight row,

Left means the person moves diagonally forward into the left row,

Right means the person moves diagonally forward into the right row,

Choice means the person makes a decision based upon the value of the CHOICE parameter,

Pause means the person waits because he or she cannot make forward progress,

Avoid means the person moves into either the left or right row without making forward progress.

ACTION-SPEED = {Match, Desired-walking-speed} .

The action speeds have the following meanings:

Match means reduce speed to that of person directly in front,

Desired-walking-speed means the person maintains the value of the DWS parameter.

3.4 Evaluating the rules

When a person is about to move, the system creates a set of three pairs of values, one pair for each of the rows left, straight, and right. The pairs give the respective values for DISTANCE and ENTITY. Thus the set [(F,V), (A,F), (C,B)]—with each value described by the initial capital letter—would indicate that left row was Vacant and contained no entity; the straight row contained a person moving in the same direction at a Faster speed than the person being considered at an Aware distance; and the right row contained a Blockage at Close distance. Thus we can now consider the action to be associated with a particular set of rule values. Perhaps the simplest rule occurs when there is no entity in front of the individual and he or she can thus walk Straight at their DWS: [(F,V), (F,V), (F,V)] →(S,D). We will consider the rules associated with a person when he or she observes three people moving in front, where the left row is moving in a Different direction, the straight row is moving in the Opposite direction, and the right row is moving in the same direction at Slower speed. This can be represented by the wild card rule, given by [(?,D), (?,O), (?,S)] → (?,?), of which the following are some possible combinations and action outcomes. In all cases we presume that the person is to keep moving forward if possible, reducing his or her speed as necessary.

[(F,D), (C,O), (C,S)] → (L,D) ,

move to left because this gives the best chance of maintaining DWS.

[(C,D), (F,O), (C,S)] → (S,D) ,

move straight at DWS to overtake the person on the right.

[(C,D), (C,O), (G,S)] → (R,M) ,

move right and reduce speed to match that of the person going in the same direction in front; the other rows have a person within the PSM.

[(C,D), (C,O), (C,S)] → (P,D) ,

pause because everybody in front is within the person's PSM.

It is obvious that the number of rules that can be created is large but the number to be searched can be reduced by introducing wild cards into the rules that result in the same action pair. Access is further optimised by having an index into the rule set that identifies major categories of rule depending on the ENTITY value. It is pointless searching rules that contain the entity value B if there is no B in the set of values to be evaluated.

4 Relating the model to the real world

The development of PEDFLOW, as described above, requires careful consideration if pedestrian behaviour is to be represented in a meaningful way. The requirement is not only to represent adequately the physical street environment that an individual pedestrian is engaging with or moving through on a particular journey, but also the *whole* of pedestrian behaviour, which includes both objective and subjective aspects. Objective behaviour of the pedestrian is that which is directly observable and measurable by visual means, for example, through the use of video cameras or time-lapse photography. Subjective aspects of behaviour include perceptions, past experiences, and attitudes, that is, those factors which are unobservable and can help to determine and influence observable pedestrian behaviour. It is important that when modelling pedestrian behaviour both of these aspects are included in any validation and developmental work which lays claim to being a *true* representation of pedestrian behaviour. Lastly, there is a requirement for the model to represent the properties associated with the physical street environment itself. The architecture within the model allows scaleable environmental features to represent those that currently exist and those that are planned for the future. As a design tool, PEDFLOW explicitly separates out behaviour and environment, and recognises that environment can influence behaviour, that is in addition to the existence of other pedestrians in a given environment. Previous work has raised a number of issues surrounding the adequacy of current evaluation and monitoring techniques where the emphasis is placed solely on objective behaviour (Hine, 1996; Hine and Russell, 1996). Microsimulation of pedestrian behaviour demands that both observable (objective) and unobservable (subjective) realms are incorporated and represented in the modelling processes.

A valuable contribution of the microsimulation approach is that emergent behaviours resulting from minimal assumptions can be checked. We do not have to assume that the complexities of human behaviour need to be replicated in the model in order to produce a large amount of the behaviour, and such minimal assumptions can become testable. This is an important requirement. Research has demonstrated that, in certain types of street environment, an evaluation strategy based solely on observable methods will favour fit, young adults. Older pedestrians and children whose observable behaviour is constrained for a variety of reasons may therefore not feature in these evaluations. Older people, for example, may be deterred from using a particular section of street because of the traffic or environmental conditions experienced (Hine, 1996; Hine and Russell, 1996). Subjective methods of assessment such as in-depth interviews and questionnaires are necessary to understand decisionmaking processes and behaviour that may not have been observed on-street. This is where microsimulation models allow a mix of individual characteristics and decision rules for the detailed analysis of movement. It allows us to explore the degree to which individual characteristics influence individual observable behaviours that are detectable from microsimulation runs.

It might be assumed initially that pedestrians of different ages and characteristics populating a given environment do experience deterrence effects in street environments containing a myriad of physical characteristics (traffic, lighting, pedestrian street activity levels). However, we now have an opportunity to test this assumption and thereby understand both objective and subjective aspects of pedestrian behaviour in a consistent framework. Levels of service have been found to be a practical measure associated with the design of pedestrian environments, particularly pavements. This model allows us to determine what practical uses can be made of pavement or general pedestrian spaces and the individual differences that have an effect on behaviour and the levels of service that might otherwise be used for planning purposes. Examples of issues we cannot readily handle at present include the impact on pedestrian movement patterns of a street café where part of the pavement is used, vehicles parking on pavements, buskers, and even the effects of market researchers, where pedestrian avoidance strategies are so often witnessed!

4.1 The objective world

In the objective world, there are numerous measures of pedestrian behaviour, and many studies have been conducted by using a variety of observable measures. For the representation of walking behaviour in the PEDFLOW model, as distinct from road crossing behaviour, a number of measures relating to the development of the behavioural rules initially and then output from the emergent behaviours encapsulated in the model are used. The microscopic modelling approach also facilitates the provision of individual as well as aggregate measures of behaviour. This represents a development of the levels of service concept used in studies of pedestrian movement and will have important implications for the way in which pedestrian facilities are provided. May et al (1987, page 86) have pointed out over ten years ago that: "What appears to be lacking in our understanding of pedestrian level of service is clear empirical evidence of how people respond to the influence of other people in different situations and at different densities". The significance for pedestrian behaviour of level of service and space standards has been thoroughly researched by several authors. Copley and Maher (1973) along with others have identified walking speed and the relationships between walking speed and the numbers of people walking (flow) as being important in relation to the functioning and design of walkways. Earlier work tended to suggest rigid design standards whereas the pioneering work of Fruin (1971), Oeding (1963), and Pushkarev and Zupan (1975) suggests more flexible levels of service. With PEDFLOW we intend to extend model capabilities to the microsimulation of pedestrian crossing behaviour. From previous studies Hine (1995) has identified a wide range of measures that will need to be incorporated into these simulations at both aggregate and individual levels.

These include pedestrian delay, acceptance gap, crossing angle, delay in carriageway, mode of crossing, and traffic speed and flow at the time of the crossing activity being undertaken.

The microscopic modelling approach and emergent behaviour within the model will allow not only the representation of walking speed and flow but also the disaggregation of these variables by a number of attributes (for example, gender and age). This disaggregation is important because it increases our understanding of a number of factors that influence speed and flow. Previous studies have highlighted the complexity and interrelationships of numerous factors with walking speed and flow. This work has to date not addressed the nature of street environment in which behaviours are exhibited and they have tended to weaken the link between environment and behaviour as the focus has solely been on observed behaviour rather than the context in which that behaviour is to be observed. Moreover, levels of service should be suggested that pay attention to the movement requirements of the elderly and shoppers carrying goods and to levels of accompaniment. Morall (1985) concluded that, although level of service is important in the planning of pedestrian facilities, walking speed, flow, and density may not be the best measure of quality of service. Morall suggested that perceptions are important and these will depend on noise, levels of congestion, safety, and ease of crossing. The subjective aspects of pedestrian behaviour and their contribution to the agent-based model are discussed later. PEDFLOW, which is an agent-based model, has an important contribution to make to the development of theory as it relates to pedestrian use of space, architectural and design theory, and the further development of the computing application itself.

4.2 The subjective world

The representation of pedestrian behaviour in a microsimulation model environment demands recognition of the importance of feedback or perceptions mediating behavioural outcomes as an important consideration in the derivation of behavioural rules (Downs and Stea, 1973; Eiser and van der Pilgt, 1988). The centrality of the environmental context within which behaviour is observed is also recognised (Krupat, 1985; Lewin, 1951). In other words, there is a recognition of the link between observed behavioural response, perceptions, and the perceived environmental quality and context.

A wide range of studies have been conducted which have sought to investigate pedestrian perceptions and attitudes towards particular street environments. On the whole, this body of work does not seek to develop links between attitudes, perceptions, and behavioural outcomes. Hine (1995; 1996) has developed an in-depth interview technique which will be used to aid the development of PEDFLOW behavioural rules. This approach involved the use of an in-depth interview guide combined with an edited videotape that was shown to respondents to elicit responses relating to particular street environments. The interviews were designed to gain data on health, age, mobility, and travel patterns. The edited videotape was used to depict five different traffic conditions, and respondents were asked questions on crossing behaviour and perceptions of safety after each video excerpt. This approach was successful in exploring the links between perceived traffic levels, perceptions of safety and risk, and behavioural response. We propose to develop this approach to supplement video data of pedestrian movements on pavements so that information on awareness, aggression and strategies for negotiating pavements under different flow regimes. Studies to date have focused on the impact of motor traffic on pedestrian perceptions and street use. This information, whilst providing a basic grounding to our work on the analysis of pedestrian behaviour, will be supplemented by our detailed assessment of pedestrian perceptions and behavioural outcomes on specific street sections under particular sets of conditions.

5 Conclusions

At the start of the paper we raised a number of questions pertinent to the development of PEDFLOW and we have attempted to address them.

How can the behaviours in a given environmental setting be represented?

PEDFLOW is aimed at the lowest level of microsimulation, with the capacity to simulate flows and movements along sections of sidewalk (which may vary in width), across areas, and around varied obstructions and shopfronts. The key behavioural attributes for the pedestrian agents are the use of preferred gap acceptance and awareness, and a slightly different pair of behavioural aspects as used in motorway and general traffic flow microsimulation work. The detailed implementation structure allows a dynamic representation of boundaries, allowing moving of blockages and continually varying shopfront and kerbside delineation without significantly altering the processing speed. The decision table block structure of the modelling system also allows rule sets to vary as the simulation proceeds, and flexible use to be made of substantial attribute lists associated with each pedestrian agent.

Rule development for PEDFLOW encompasses both the objective and the subjective realms associated with pedestrian behaviour. The PEDFLOW approach will therefore be able to cater for those pedestrian groups, for example, the elderly and children, who may be underrepresented in terms of their observable behaviour on the street. This approach combining both objective and subjective aspects of pedestrian behaviour will aid the rule design by allowing a more detailed analysis of the observed behaviour in a given setting. This approach to the representation of pedestrian behaviour seeks to represent the 'whole' of pedestrian behaviour rather than relying on observable proxies such as pedestrian delay—a behavioural measure that has historically been viewed as a proxy for environmental quality.

What are the measurement issues?

The model has the ability to deal with a number of factors including walking speed, pedestrian density, and levels of service at objective (quantitative) levels. At the subjective or perceptual level (qualitative) the model has the capability to represent and simulate subjective aspects of pedestrian behaviour which influence both movement behaviour (walking) and static behaviour. The nature of the physical environment is also represented in the model as it helps to define the types of behaviour and decisions made and replicated by pedestrians. PEDFLOW has an important contribution to make to the development of theory as it relates to pedestrian use of space, architectural and design theory, and the further development of the computing application itself. We have mentioned previously that the development of the rules for the model will encompass subjective and objective elements. A measurement issue that still needs to be further investigated in PEDFLOW is how to define the nature and attractiveness or unattractiveness of features of the built environment for pedestrians. The literature on pedestrian behaviour and attitudes towards certain environmental features is extensive but we need to increase our understanding of their impact on pedestrian behavioural response. This is achievable if we develop our understanding of pedestrian behaviour and the behavioural rules that will form the basis of the model by using measurement techniques which draw on both the qualitative and the quantitative social science traditions. A strength of the PEDFLOW model is that it will be able to provide urban designers and planners with estimates of the level of service and of measures of pedestrian behaviour at individual and aggregate levels. The model will also provide a systematic and consistent framework through which we will be able to assess the efficacy of street designs and traffic management measures for pedestrians. To date, the focus of much of the work on pedestrian behaviour has been on street environments where high levels of activity are guaranteed, for example, shopping streets and public transport terminals and subways. This may have been for a number of reasons but it raises the problem associated with high survey costs at locations where low levels of pedestrian activity exist. PEDFLOW will provide a means for the analysis of pedestrian behaviour in other street environment types where levels of activity may be lower and may offer a way around high survey costs in such environments.

How can the environment and behaviours exhibited be operationalised and replicated?
PEDFLOW complements the higher level network and decision structure representations in the STREETS model and uses broadly similar agent decision factors. PEDFLOW and STREETS represent an alternative approach to pedestrian modelling increasingly in step with vehicle flow microsimulations such as Stims, PARAMICS, Cluster3, and Transims. Consistent microsimulation of both vehicle and pedestrian behaviours and their interactions are likely to become possible in the reasonably near future.

The benefit of the implementation strategy identified above is that, should subsequent research indicate that the factors we have included are insufficient, then we just have to change the underlying decision table that captures the behavioural rules. The number of factors and the number of different rules can be varied without having to change the rest of the PEDFLOW simulation system. Similarly, behaviours corresponding to different scenarios can be captured by just changing the decision table. In particular, if the grid size is reduced then the set of rules will be radically different, as will the values of the basic parameters SA, PGS, PSM, and DWS to reflect the fact that a much higher loading of pedestrians within the space is being modelled.

The decision table is input at the start of processing and incorporated into the pedestrian agent before the pedestrian commences processing. This offers a number of subsequent processing options that we have yet to exploit. First, the modeller could change the rules associated with some of the pedestrians to reflect a specific change of behaviour, in order to model some external effect that dramatically changes pedestrians' behaviour. Second, it offers the opportunity for pedestrians to 'learn' about their environment and modify the rules they are processing accordingly, by changing the order of rules and the values associated with action determination.

The model is in the category of algorithms known as emergent algorithms. Fisher and Lipson (1999) state that "An emergent algorithm is any computation that achieves formally or stochastically predictable global effects by communicating with only a bounded number of immediate neighbours and without the use of central control or global visibility". In PEDFLOW an agent sees only those pedestrians that are within its awareness zone and, based on that limited subset of information, makes a movement decision. The resulting emergent behaviour of all the pedestrians leads to the obtaining of a number of measures such as average speeds, flow rate, and density which are observable in the real environment. Additionally, PEDFLOW also makes available other measures that cannot be observed but which give a real measure of the level of service provided by a space. These measures include the number of times a pedestrian agent had to undertake the pause action, the percentage of time that a modelled pedestrian was able to maintain his or her desired walking speed, and the number of times a pedestrian had to deviate from his or her desired direction.

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