DEVELOPING THE BEHAVIOURAL RULES FOR AN AGENT-BASED MODEL OF PEDESTRIAN MOVEMENT

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1. BACKGROUND

The recent shift in emphasis towards walking as a safe, healthy and sustainable mode of transport presents a number of practical problems for the urban planner. Until recently, urban planning has largely placed the road user at the centre of infra-structural design, with significant implications for the perceived attractiveness of pedestrian environments (see the National Consumer Council Survey, 1987). This, together with more generalised changes in the pace of urban life and the dispersal of towns and cities, has played a significant role in the decreasing modal share of walking observed over the last quarter of the twentieth century. Our governments' recent commitments to reversing this decline is evidenced by their decision to charge local authorities with developing local Walking Strategies (DETR, 1998; Scottish Executive, 1998).

Encouraging people to walk, however, is not trivial. In order to increase the number of pedestrian journeys within a given area, walking (either as a mode of transport, or as a leisure activity) must be made more attractive. However, remarkably few empirical studies have addressed the issue of how this might be achieved. Effective 'planning for pedestrians' requires a satisfactory understanding of two broad issues: first, what *factors* are most important in individual decisions to walk; and second, which *measures* are successful in encouraging walking. Nonetheless, even as late as 1996, the Department of Transport admitted that these issues remain poorly understood, stating that: "*little is known about the determinants of pedestrian behaviour and trip-making activity and which measures are more effective in encouraging walking*". This picture remains little changed today.

This paper describes the development of a microscopic model of pedestrian movement (PEDFLOW) that can simulate the effects of environmental layout on how pedestrians negotiate the walking environment. Its approach is novel in two important regards: first, unlike most current models of pedestrian movement, PEDFLOW takes an agent-based approach, allowing the characteristics of individual 'virtual' pedestrians to be assigned and varied as required; second, the development of the model will be informed by empirical studies of how pedestrians behave 'in real life'. On their own, these studies will enhance current understanding of which factors influence individuals' decisions to walk a certain route and also, through 'before-and-after' studies, which measures are successful in achieving desired changes in pedestrian mobility and walking behaviour.

Following a brief overview of the prototype PEDFLOW model (section 2), the paper will outline how behavioural research can be applied to yield important insights into naturalistic pedestrian behaviour: section 3 describes the development of a novel methodological protocol, using both observational and interview techniques, aimed at deriving realistic behavioural 'rules' for subsequent inclusion in the model.

2. THE PROTOTYPE MODEL

Unlike many existing models of pedestrian flow, PEDFLOW uses an agent-based approach to simulate the movement of individual pedestrians as they negotiate the walking environment. This approach allows for great flexibility in terms of being able to vary the characteristics of both the individual agents and the layout of the environmental space in which they operate.

Broadly, each pedestrian, represented by an autonomous agent, moves between the elements of a grid in virtual space to a predetermined goal location, avoiding obstacles on the way. Its gross movement patterns are underpinned by the assumptions that agents walk along a straight trajectory, and choose the shortest route to their goal.

Agents negotiate their walking environment through a step-wise process of '*observing*' the space around them, *evaluating* that observation in terms of the presence and nature of any entities in their path, and then *reacting* to these entities according to a simple set of behavioural rules and a set of individual parameters. Currently, the rule and parameter sets are based on a simplistic account of pedestrian behaviour determined through 'common sense' assumptions of how people might behave in a given circumstance.

This process can be represented schematically as an input / output regime. The model acts essentially by taking two sets of input – one describing the structure of the urban space (**environmental context**) and the other certain characteristics of the individual pedestrian (**agent parameters**) – and generating an output, or **action** according to a set of **behavioural rules**. Each of these is considered in turn below.

2.1 Environmental Context (Input 1)

The virtual pedestrian environment is modelled as a two-dimensional grid. Each grid element, which occupies a space of 0.75m length and 0.75m width, can be assigned one of a number of 'entities'. Currently, the entities include edges or kerbs, blockages (stationary obstacles such as items of 'street furniture'), and pedestrians (which may be stationary, or moving – in a defined direction and at a certain speed). Pedestrian movement patterns can thus be simulated within a complex virtual environment constructed according to the operator's own preferences.

2.2 Agent Parameters (Input 2)

Each agent is assigned a set of parameters, or 'personal characteristics' which, together with the environmental characteristics, govern which behavioural rule to execute in performing a movement. Currently, these parameters are: *static awareness* (how far in front the pedestrian perceives changes in the environment), *preferred gap size* (the smallest space into which the person is willing to move), *personal space preference* (the amount of space a pedestrian wishes to maintain around him- or herself), *desired walking speed* (the speed at which a person is most comfortable walking) and *side choice* (preferred choice of direction when overtaking or avoiding). The values of each parameter are currently assigned to each agent 'by hand': the operator decides, for example, that a certain agent should be ascribed a desired walking speed of 1.6 m sec^{-1} and a personal space measure of 0.75 m.

2.3 Behavioural Rules

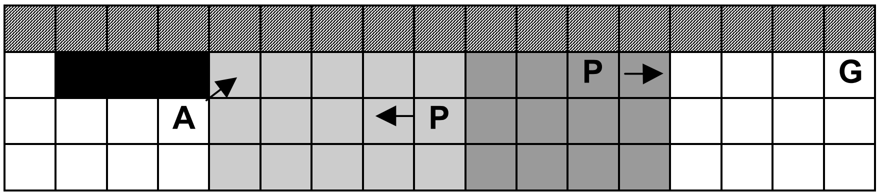
The prototype model is underpinned by a simple set of behavioural rules that determines the action an agent will take when confronted with an entity in its virtual environment. These rules can be conceptualised according to a 'rule table' that describes a number of feasible input - output combinations.

Agents act by scanning the environment for upcoming 'entities' in a step-wise fashion. Once an entity (see input 1) is identified as falling within an agent's preferred gap size (see input 2), some kind of action must be taken. The rules governing what action will be taken are currently based on 'common sense' judgements of what is likely to happen in a given circumstance. For example, if a blockage appears within an agent's preferred gap size on the left, a pedestrian approaching head-on appears straight ahead, and another pedestrian, walking at a slower speed, appears on the right, the current rule set dictates that the agent will deflect its path to the right, and reduce its speed to match that of the person in front (see figure 1).

2.4 Actions (Output)

Each agent starts by walking along a straight trajectory towards its goal location at its desired walking speed. It reacts to obstacles in the environment (input 1) according to its own agent parameters (input 2) and the relevant behavioural rule. The output of the process (the **action**) is a change in either direction (from its original trajectory), speed (from its desired walking speed), or both (or none).

Figure 1: Example of a rule-based action by an autonomous agent



Here, the agent of interest (**A**) must move to a predetermined goal location (**G**), while avoiding other entities in its path such as kerbs (striped cells), static obstructions (black cells), and other agents (**P**), moving at certain speeds and in certain directions (as indicated by arrows). On each step, **A** evaluates the environment in front for possible obstructions. In this scenario, entities in the *static awareness* zone (dark grey cells) are noted, but effectively ignored. The arrival of an entity (**P**) within **A**'s *preferred gap size* zone (light grey cells) triggers an action. The type of action will be determined by the behavioural rule applied: in this case, **A** maintains the same speed but moves *left* to avoid an approaching pedestrian in order to avoid a collision, and maintain the shortest route to the goal.

3. THE BEHAVIOURAL RESEARCH

The PEDFLOW model represents an exciting possibility for the development of a powerful tool for use in the planning and design of urban space for pedestrians. Its agent-based approach yields the potential to model a range of urban environments (which typically differ in the make-up of their pedestrian population) and of individual pedestrians that move within it.

In order to be of value as a planning tool, the model must be able to simulate realistic pedestrian behaviour. Of course, the validity of the model does not depend on the *processes* that drive individual movement decisions in the model being identical to those that underpin the decisions of 'real' pedestrians: what is important is that the model is able to predict the final actions of individual agents with a reasonable degree of accuracy. Remarkably little evidence, however, is available to suggest what 'realistic behaviour', in the context of negotiating a complex environment, may be. Some research effort has been directed at characterising single 'features' of pedestrian behaviour (such as walking speed, personal space, or simple 'yielding' behaviours), and perhaps how these may vary according to factors such as age, gender, or pedestrian density. However, no study has examined the *relationships* between these 'features' and 'influencing factors' within a consistent comparative framework. The aim of the behavioural research outlined in the following sections is to do just this, in the context of informing the development of the PEDFLOW model.

3.1 Aims and Scope

The broad aim of the research, then, is to discover how pedestrians negotiate the urban walking environment. Of course, the potential scale of this task is enormous. First, the pedestrian population is not homogeneous. Individuals vary along a number of dimensions (such as age, gender, mobility, level of awareness, or aggression). They may decide to walk a journey for a variety of different reasons (e.g. to exercise, socialise, or as a mode of transport in its own right – see Wigan, 1995), and walk either alone, or with others.

Second, there are many different kinds of urban environment. Pedestrian environments may be classified according to a number of different criteria. At a macroscopic level, for example, they may differ in terms of their predominant 'function' (e.g. shopping, 'route to school', transport interchange), or their physical layout (e.g. pedestrianized street, pavement skirting a road). At a microscopic level, pedestrians' immediate surroundings differ according to the nature, location and density of other entities (such as street furniture and other pedestrians), which in turn may be influenced by factors such as time (of day, week or year) and weather.

All these variables may affect how individual pedestrians behave within their environment and interact with other entities within it. This presents a considerable challenge for the behavioural scientist: the empirical study of pedestrian behaviour must aim to capture the important aspects of this complexity without severely compromising the simplicity and the flexibility of the model. The research programme outlined in the following sections represents an attempt to do so: its approach is framed in terms of the questions raised by the current PEDFLOW model, and what is already known from the literature about how pedestrians negotiate urban space.

3.2 Questions

In order to 'unpack' this complexity, the behavioural research should initially seek to determine the extent to which the prototype model is likely to represent 'real' behaviour, given what is already known about how pedestrians behave in urban space. A number of research questions may be formulated according to this scheme:

First, agents in the model act according to a step-by-step **process** of 'observing', 'evaluating' and 'acting' (see section 2). As soon as an action is completed and a 'step' is advanced, the agent effectively 'forgets' the previous action, and begins a new observation-evaluation-action sequence. At any point in time, then, an agent has no 'memory' for what action has just been executed, and has no long-term 'plan' for how to negotiate future obstructions.

It is unlikely that human decision-making follows such a scheme: however, the model may still offer a viable means of simulating human behaviour – as long as the process yields an accurate representation of the final *outcome*, or action. This raises several important questions which lend themselves to empirical examination:

Q1. Can pedestrian movement be reliably approximated by such a step-wise process, or is it generally better described in terms of various subroutines, or sequences of manoeuvres? For example, if people move to avoid another pedestrian moving more slowly in front of them, do they continue walking along their new path, as the model would predict, or re-join their original trajectory (i.e. perform an 'overtaking' manoeuvre)?

Second, the model assumes that agents classify the various entities they encounter in their **environment** into several broad categories – including, for example, other agents (moving either in the same or opposite direction as themselves, and either at least as fast as, or slower than themselves), or various obstructions.

Q2. Do these categories capture enough complexity?

- Are all *obstructions* treated similarly by pedestrians? There is some evidence, for example, that the clearance distance left around large, or sharp-edged objects may be greater than that given to smaller, or more rounded items of street furniture. However, whether or not such differences are significant remains unknown.
- Are all *agents* (other pedestrians) treated the same way? The available literature, albeit scant, provides some evidence to the contrary: whether or not individuals 'yield' to oncoming pedestrians, for example, may depend on factors such as age and group size of both parties; younger people / individuals in the smaller group seem more likely to yield to older people / larger groups (e.g. Willis *et al.,* 1979).

Third, the current model relies on the operator to assign, 'by hand', values of each individual **parameter** (such as desired walking speed, personal space measure) to each agent.

Q3. What are *realistic values* for each of these parameters, and how do they inter-relate? How much space does a 'typical' pedestrian like to maintain around him or herself? Is this related to how quickly he or she likes to walk?

Q4. What are the *most important factors* that influence the values of each individual parameter? Can age, for example, account for most of the variance in the walking speed data in the population as a whole, or is trip purpose of greater significance?

- This information is of critical importance for developing a paradigm that assigns parameter values to each agent automatically. The make-up of the pedestrian population varies to a large extent according to the type of environment: as such, the viability of the model will depend in part on ensuring a realistic distribution of 'virtual pedestrians'.

Q5. Do the parameters capture enough *complexity*? The suggestion that agents may incorporate information about other agents' characteristics (such as age, or level of mobility) in their movement decisions may indicate that the current parameter set needs to be expanded to take this into account (see Q2).

Finally, the current set of **behavioural rules** is based on 'common sense' assumptions about how people behave in certain situations, based partly on preliminary observations of pedestrians walking along a busy city centre pavement. Clearly, however, these behavioural rules must have some empirical basis if the model hopes to simulate realistic pedestrian behaviour.

3.3 Approach

The broad approach underpinning the empirical study of pedestrian behaviour is framed by the context of the PEDFLOW model: as such, the research will focus on characterising, for a range of different environments:

- the **input** variables – i.e. the microscopic environmental context, and characteristics of the pedestrians themselves;
- the **output** (or action) that emerges in each situation, such as a change of speed or direction.

Once these parameters have been explored in more detail, some generalised mechanism describing how the input relates to the output must be developed: these **behavioural rules** will be formulated according to probabilistic estimates that a certain 'type' of agent will act in a certain way in a given environmental context.

In order to capture realistic behaviour, the research must aim to examine the behaviour of pedestrians in a naturalistic setting. A laboratory-based approach would confer many advantages – not least the ability to control the microscopic features of the environment under investigation. However, such studies cannot be used to explore the real effects of factors such as walking with others on various aspects of pedestrian movement (such as walking speed, or reactions to certain environmental situations) – yet these factors may prove critical in shaping these outcomes.

Three theoretical issues are immediately evident. First, a clear distinction must be drawn between desired and expressed characteristics when studying naturalistic movement in the context of the PEDFLOW model. Agents in the model act according to parameters such as desired walking speed, and preferred gap size. Observing pedestrians unobtrusively, however, yields only expressed values for these characteristics: a measurement of walking speed, for example, reflects the outcome of an interplay between the desire to walk at a certain speed, the motivation to maintain this pace, and ability to do so.

As suggested earlier (see 3.2), the decision-making process underpinning the model (observation, evaluation, and action) need not represent those of 'real' pedestrians in order to yield reliable predictions of how agents will behave in a given situation. As such, it is not necessary to derive values for desired parameters. Nonetheless, some attempt must be made to ensure that the outcome of pedestrian interactions (such as how close people allow themselves to come to each other, reflecting 'personal space' or 'gap size' measures) are characterised realistically.

Second, pedestrian behaviour is to a great extent dependent on context (see 3.1). In order to address this issue, and to provide a manageable framework for the analysis of pedestrian movement patterns, the behavioural research will initially focus on three or four city-centre sites (Edinburgh and York), incorporating pedestrianized areas and more typical roadside pavements. Later studies will consider behaviour before and after the implementation of measures designed to improve the walking experience – such as the introduction of traffic-calming measures or the installation of road-crossing facilities.

Finally, in order to ensure that all the relevant 'input' and 'output' information can be recorded, the methodology employed must include a combination of *observational* techniques (for accurate measurements of characteristics such as walking speed or personal space), and *questionnaires* (to gather information not discernible from observation alone, and to survey the typical 'makeup' of the pedestrian environment under study: see 3.4). Methodology is considered in more detail in the following section.

3.4 Methods

First, an interesting environmental situation, at a microscopic level, is selected for study. Figure 1 represents a schematic example of one such situation: here, the agent of interest (**A**) is faced with another agent (P) walking towards him or her on a potential collision course. Another simple 'scenario' might include an agent approaching another agent walking in the same direction, but more slowly (see 3.2, Q1).

3.4.1 Data Collection

Next, a combination of observational and interview techniques is used to characterise the 'output' or action taken by the pedestrian in this situation, and the associated ‘inputs’ that could have shaped his or her decision to act in that way:

- the ‘output’ (or action) is characterised in both *qualitative* (did the pedestrian yield to the oncoming person or maintain the same trajectory?) and in *quantitative* terms (how close did the pedestrian get to the approaching person before changing direction? how fast did they walk?);
- the ‘input’ comprises an array of personal details of the pedestrian under study, such as age, gender, group size, and trip purpose, and situational details, such as the equivalent information about the person being approached, the time (of day, or day of week), and the microscopic pedestrian density within the sampling area.

Observation

All observational analysis will be carried out using custom-recorded video data. Recordings will be made using our own hand-held, digital camcorders and city centre CCTV cameras in accordance with formal ethical Codes of Conduct. Cameras will be mounted discretely as high above, and as directly overhead the site of interest as possible to maximise the field of view, and minimize the likelihood that individuals can be identified from the resulting footage: the current settings typically allow a viewing area of approximately 10-15 metres’ length. The footage will be used to derive accurate measurements of individual pedestrians’ trajectories and walking speeds, together with information about their gender, group size and approximate age. The video footage will also be used to calculate aggregate measures of pedestrian activity such as flow and density, and to help characterise the wider pedestrian population associated with the site under study as a whole.

Interviews

Initially, short, on-street interviews will be conducted to collect information not reliably obtainable using observational methods alone (such as trip purpose), for the purposes of characterising the makeup of the pedestrian population in the area of study. Later, interviews will be used to probe attitudinal aspects of pedestrian activity in conjunction with observational methods for ‘before and after’ studies of infra-structural change.

3.4.2 Data Analysis

Observational studies are notoriously prone to subjective analysis. The first consideration in the present study, therefore, must be to ensure that each variable assessed is valid, and as objective as possible. This can, in part, be achieved by establishing rigorous criteria for defining each variable. In terms of the current scheme, for example, both the situational ‘input’ variables (such as group size), and the ‘action’ variables (such as how much distance, or ‘gap’ a pedestrian leaves before ‘yielding’ to an oncoming entity), require careful definition. These two interesting examples are outlined in more detail here:

(a) *Group size*: unless members of a group happen to be involved in some kind of exchange with one another as they pass across the recording field, it may be difficult to determine objectively whether or not individuals in a cluster are walking together. A judgement that two people are walking together might require that, across the sampling frame, they keep within a certain distance, a certain angular trajectory, and a certain speed with respect to each other (see, for example, McPhail & Wohlstein, 1982).

(b) *Gap size*: in our example scenario of two pedestrians on a collision course, some kind of criterion would need to be established for judging the distance at which one (or both) of the pedestrians yielded, or began to deflect from the original trajectory. This would involve establishing some value of angular deflection which, when exceeded, would indicate the point at which the pedestrian had significantly deviated from his or her original trajectory.

In order to achieve accurate measures of distance, and thus also speed, the video image must first be calibrated with respect to 'real world' co-ordinates. The calibration process is considerably more complicated when the camera is not positioned 90° laterally and horizontally above the observation area (as is the case in our study): the perspective foreshortening introduced into the image as a result of off-angle camera positioning means that simple, linear algorithms cannot be used in the calibration sequence, and the two dimensions must be calibrated separately.

The final set of problems centres around the feasibility of tracking the location of individual pedestrians over time – particularly in numbers large enough to represent a statistically viable sample. Until recently, pedestrians' trajectories had to be charted by hand; needless to say, the laborious and time-consuming nature of the task meant that very little research of this kind has been carried out. Recent developments in image analysis, however, have at last yielded a viable alternative: commercially-available motion analysis software, capable of plotting the trajectory of up to ten objects simultaneously, is now available at a reasonably competitive price. This software acts by recognising the changing x or y position of selected object boundaries from frame to frame. The data are output in 'real world' co-ordinates according to a sophisticated calibration protocol which can correct for deformations in the image arising from perspective foreshortening.

The data analysis procedure proposed for the current study may be summarised as follows:

1. Video recordings are captured to a PC via a frame-grabber (video capture) card. The resulting movie files, each of 20-30 minutes' duration, are converted into .avi format.

2. An environmental 'scenario' is defined (such as the situation of an 'agent' facing an oncoming pedestrian on a collision course: see figure 1). All instances of this scenario in the formatted movies are selected, copied and saved as short clips, typically a few seconds long, for subsequent analysis.

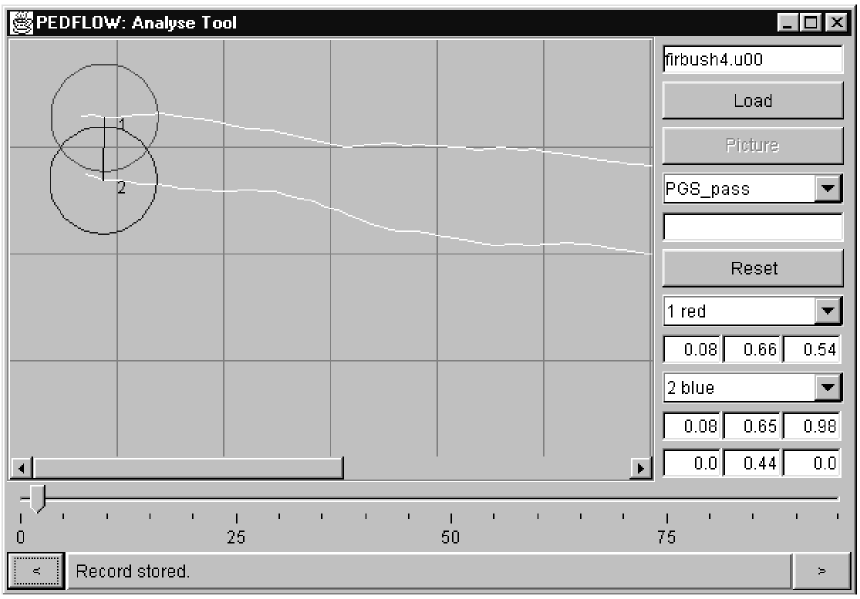
3. Short clips are imported into the motion analysis software The video image is calibrated according to the known 'real world' dimensions of the environment under analysis.

4. The motion analysis software plots the frame-by-frame movement of selected objects (in this case, the two pedestrians approaching each other) for the duration of the clip. 'Real world' *x* and *y* co-ordinates are plotted separately as a function of time (*t*, in frames) for each pedestrian.

5. The data are imported into custom-written software, which plots the *x* / *y* location of all pedestrians on each frame. This software can be used to measure distances between any two specified points, angular differences, and speed (see figure 2).

   The resulting measures are recorded, along with all the other 'personal' and 'situational' details of the case, in a spreadsheet for subsequent statistical analysis.

Figure 2: PEDFLOW Analyze Tool



This custom-developed software plots the trajectories of each pedestrian as they move across the filming area. The position of each pedestrian at any particular frame is shown as a coloured dot along his or her trajectory: the circles around each dot represent the diameter of the grid element in the model (currently set at 0.75m). Any distance can be measured accurately by selecting two points, each representing the 'mid-point' of a pedestrian or static entity (such as an item of street furniture). In this example, points 1 and 2 represent the mid-points of two pedestrians who are walking together; the black line joining these points thus represents the 'personal space distance' between them. Speed can also be calculated, if the two points represent the same pedestrian at two different points in time.

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6. The potentially large number of variables considered here precludes a complex, multi-way statistical analysis that considers all the variables together in determining the microscopic movement behaviours of individual pedestrians. Instead, statistical analyses will be carried out to determine:

(a) which 'personal' factors (such as gender, group size) have a significant effect on movement characteristics (such as walking speed, or gap size), taking into account the large variance anticipated to be associated with pedestrian density (analysis of covariance: ANCOVA);

(b) which of these important factors are related, and how (correlation);

(c) the distribution of values for each movement characteristic (including means and standard deviations) according to the 'significant' personal factors: this information will be useful in assigning parameter values to each agent automatically before each simulation;

(d) whether the final outcome (such as whether or not a pedestrian 'yields' to an oncoming person) depends on the 'personal' factors of both the pedestrian under consideration, and of others present in the environment (Chi-square tests). This will help address whether or not agents act according to the same set of rules, or whether the rules depend on the circumstance according to some kind of implicit social 'hierarchy'.

4. SUMMARY

The PEDFLOW project aims to develop a realistic and flexible planning tool capable of simulating the effects of microscopic environmental layout on various aspects of pedestrian movement. Behavioural research can help establish realistic values for such variables as walking speed and personal space, and, by comparing the 'input' and 'output' from a range of different, naturalistic scenarios, develop realistic behavioural 'rules' that underpin the movement decisions of individual pedestrians.

5. REFERENCES

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