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# Safety in Numbers? Modelling Crowds and Designing Control for the Notting Hill Carnival

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**Summary. Events such as carnivals, parades, rock concerts, football matches, some types of shopping—indeed, any situation involving rapid exit or entrance from or to high-capacity buildings and vehicles—pose significant problems of public safety. Models designed to predict crowding at such events are in their infancy and the best so far simulate panic situations and evacuation possibilities within buildings and similarly confined spaces. In carnivals and street parades, movement is over a much wider area and crowds form as much through competition between attractions as through confinement in small spaces. A model is proposed in which the event space is first explored by agents using 'swarm intelligence'. Armed with information about the space, agents then move in an unobstructed fashion to the event. Congestion is slowly reduced by introducing controls until a 'safe solution' is reached. The latter stages of the simulation require intervention by those who manage the event, the police. The model has been developed to simulate the effect of changing the route of the Notting Hill Carnival, an annual event held over two days in August each year in a 3 sq km area of west central London. The event attracts over 1 million visitors and is widely regarded as posing a major threat to public safety.**

## 1. The Problem

The Notting Hill Carnival has grown from a small West Indian street celebration first held in 1964 to a two-day international event which at its peak attracted some 1.2 million visitors in 1999. It began in the wake of the 1958 race riots when Notting Hill was fast becoming one of the first of the new inner-city areas attracting immigrants from the old Commonwealth. Both the Carnival and the area in which it is held have changed substantially over the past 40 years. Many of the original immigrants have moved out and the area has gentrified with more wealthy, younger residents replacing them. Yet the Carnival has evolved to become a national, indeed international, focal point for the celebration of West Indian culture and music but with the majority of its visitors no longer belonging to the ethnic communities which continue to organise and support it. Tensions between the residents, those who manage the Carnival—namely, the police and local authorities—and even amongst different types of visitor have grown. Crime associated with

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the event has dramatically increased and there are now considerable problems of public safety due to crowding along the parade route itself, at fixed sound systems and at subway (tube) stations which the majority of visitors coming to the Carnival use.

Against this background, there is substantial momentum to address these problems not only through more intensive crowd management on each day of the event but also through altering the route of the parade and perhaps the location of the sound systems. The Carnival Review Group (CRG) set up by the Greater London Authority has initiated an intense process of stakeholder involvement which involves all relevant interests in the technical design activities (CRG, 2001). As part of these activities, the present authors have built various simulation models of the current situation which are being used in the evaluation of new routes (Intelligent Space Partnership, 2002). What will be reported here is only one aspect of these simulations. The paper will introduce and apply an experimental model which enables the assessment of local movement to, from and between the various events that comprise the Carnival, illustrating how crowds build up and generate problems of public safety. The models presented deal with how spatial phenomena emerge through interactions between individuals. The theories of systemic complexity associated with these developments represent the analytical cutting edge of urban and transport science at the present time, where the focus has shifted away from aggregative, static conceptions of how cities are structured to the more detailed dynamics which determine the heterogeneity that cities display at much finer scales. In short, such models are based on the idea that unusual and important behaviours emerge when interactions between the individuals that are engaged in those events accumulate to a point where distinct changes occur in how people react (Batten, 2000). Crowding is one such phenomenon. It generates panic, flight, sometimes mass hysteria, which is clearly applicable to highly concentrated spatial events such as carnivals, street parades, some types of shopping and, indeed, any situation involving rapid exit or entrance from or to high-capacity buildings and vehicles (Canetti, 1962).

Mathematical models of these kinds of event are in their infancy. Most are based on analogies with fine-scale traffic models but where the focus is on walkers or pedestrians, often called ‘agents’. Nevertheless, very different approaches to simulating pedestrian movement have been adopted at different geographical scales. In confined spaces of no more than tens of square metres, models based on analogies with social force and fluid flow have been used (Still, 2001; Helbing, 1991; Henderson, 1971) to predict panic situations in focused events such as football matches and rock concerts (Helbing *et al.*, 2000). For events associated with long narrow spaces where the order of the flow is important, queuing theories have been adopted (Lovas, 1994). For buildings and urban spaces such as shopping malls, event simulation based on task scheduling, often using cellular automata, has been applied (Baer, 1974; Dijkstra *et al.*, 2002; Burstedde *et al.*, 2001; Kirchner and Schadschneider, 2002). For larger areas measured in square kilometres, accessibility models which simulate decisions between competing attractions have been developed (Borgers and Timmermans, 1986). Recently, methods which embody properties of self-organisation characterising how crowds form and disperse have become significant (Vicsek *et al.*, 1995; Helbing *et al.*, 1997). In all these examples, there is an emphasis on the density of flows to measure crowding and vulnerability to accidents.

The model proposed here is based on a mixture of these ideas. First, the relative accessibility is inferred of the different attractions which make up the entire event and then a simulation is made of how visitors walk to the event from locations at which they enter. In events such as these, it is never possible to observe the flow of pedestrians in an unobstructed manner because the events are always highly controlled. Moreover, although good data on densities are available, data on the actual paths taken are rare and are unlikely ever to be available, due to privacy considerations, despite advances in laser scanning and closed circuit TV. Thus the model has been designed in two stages. First, accessibility surfaces are built from information inferred about how walkers reach their entry points (origins) relative to their ultimate destinations at the event. Secondly, these surfaces are used to direct how walkers reach the event from their entry points and then to assess the crowding that occurs. If appropriate, controls are then introduced to reduce crowding, changing the street geometry and volume of walkers entering the event, operating this process iteratively until an acceptable solution is reached. These stages loosely correspond to exploration, simulation and optimisation.

First, an outline of the mathematical structure of the model is presented, emphasising the unique way in which the modelling problem is conceived, where control is an integral part of the events that are observed. The available data are discussed and how it is possible to fit the model to these data. The paper then returns to the nature of the problem, outlining how the model has been used to evaluate different routes for the Carnival but also arguing that to exploit fully these kinds of model, the stakeholders in the process must be intimately involved. The paper concludes with directions for further research and an assessment of work in progress.

## 2. An Outline of the Model

### *2.1 Simulating Highly Controlled Systems*

In most forms of simulation, it is assumed that the structure of the system of interest has evolved as a consequence of behaviour which is stable. Such behaviour is assumed to be independent of any extraneous control of the system from the top–down or, if the system intrinsically depends on explicit forms of control or policy, this is taken to be minimal and/or benign, subsumed in some way within such stable behaviour. These assumptions are made so that the model can be used to test new and different interventions in the system. Although unstated, models assume that their systems have evolved in some 'natural' or unconstrained manner which implies that when used predictively, control or policy can be tested directly without such policy being part of the system that is being simulated in the first place. There is invariably no link between control and model/system behaviour; in short, although control might change the behaviour of elements that comprise the system, this behaviour does not affect that control.

It is known that this is rarely the case although, in many situations, it might form a useful first approximation. However, with discrete spatial events such as parades, concerts and the like, it is impossible to make such assumptions (Batty, 2002). In cases such as the Notting Hill Carnival, control is and has always been an intrinsic part of the events. It is impossible to consider these events as being other than controlled in the first place for their very existence implies some form of management. Where the data on behaviour are conditioned by existing control, it cannot be assumed that the predictive process is one of modelling an unconstrained set of behaviours which will respond independently to new measures of control. Such behaviour has already been affected by similar controls in the past. In one sense, this perversity is no other than the circle of cause and effect which needs to be broken to begin analysis. In this context, it is necessary to be particularly careful how the simulation is developed, in order to be completely clear how control influences the behaviour of the actors or agents who make up the event.

Accordingly, a multistage simulation procedure is developed, based on slowly introducing more and more control into an on-going simulation and simply taking subsequent predictions as additional stages of the same process. In fact, in events dominated by local movement, there are never enough detailed data to develop a one-off simulation and, in this case, the early stages of the modelling process are dominated by the search for data about the event itself.

Thus the simulation begins with a process where walkers are allowed to move to the events comprising the Carnival in a completely unobstructed manner. The initial simulation only assumes knowledge of where walkers come from and end up in terms of the Carnival events and they are allowed to discover for themselves the best way to move through the local street system. This process of discovery thus produces a picture of the geometry of the place. It enables a second stage of simulation to be based on uncontrolled movement from origins where they enter, to destinations which are the attractors of the Carnival itself.

After this second stage, some idea has been gained of the controls necessary for reducing problems posed by crowding, and these are then introduced one at a time, rerunning the model until such problems are resolved. In these stages, the model effectively simulates controls that are adopted to manage the existing event, although the controls that are introduced may be different from those actually used. In this way, the simulation is diagnostic in that it is possible to assess, albeit indirectly, both the effects of and necessity for existing controls. It is thus possible to comment on whether existing controls are adequate, too few, or too heavy-handed. In this way, introducing new controls for future events can be regarded as simply a process of extending the simulation. Prediction is a natural consequence of the existing simulation and extends easily into prescription. For these types of event, the entire process can be seen as one in which the relationships between visitors and attractions is a systemic manipulation of the geometry of movement through control involving policing crowds, closing streets, introducing barriers and every other related action which can change the way both visitors and entertainers interact through the Carnival.

### *2.2 An Informal Description of the Model*

Before these processes are presented algebraically, it is useful to provide a verbal summary of the way the model works. In the first stage, it begins with the visitors to the Carnival located at their ultimate destinations—the Carnival attractions—along the parade and around the sound systems. These locations are known from various density data and it is also known where the visitors enter the Carnival from traffic counts. What is not known are the paths that visitors take between the points from which they enter—their *origins*—and the locations where they reach the Carnival—their *destinations*. In this first stage, the shortest routes from destinations back to origins are predicted using an algorithm based on 'swarm intelligence' which mirrors how insects in the animal world seek out food by foraging away from their nests. These algorithms are being widely developed to deal with many kinds of traffic problem such as congestion in telecommunications networks and travelling salesmen problems (Bonabeau *et al.*, 1999). In essence, agents move randomly from the destinations in search of origins. When they discover an origin—in this case an entry point—they head back to their destinations. To tell others about their discovery, they lay a trail: they drop 'pheromone' in analogy to the way ants react to the discovery of food sources. Other agents who have not yet discovered any entry points on the trip out from their destination, react to such trails, sense this scent and move more quickly and directly to the entry points to which they lead. Then they return to their destinations, dropping more pheromone and thus reinforcing the trails. The entry points which are closest to the destinations are discovered first and this process turns out to be one of finding the hierarchy of shortest routes between destinations and entry points. Once an agent has returned to the destination after such a discovery, it begins again but this time reacting to the pheromone surface where it exists. In this way, the shortest routes are reinforced.

The first stage of this process is illustrated in the flow chart presented in Figure 1.[1] Once an agent discovers an entry point from a random walk through the street system, a check is made to see how much of the acces-

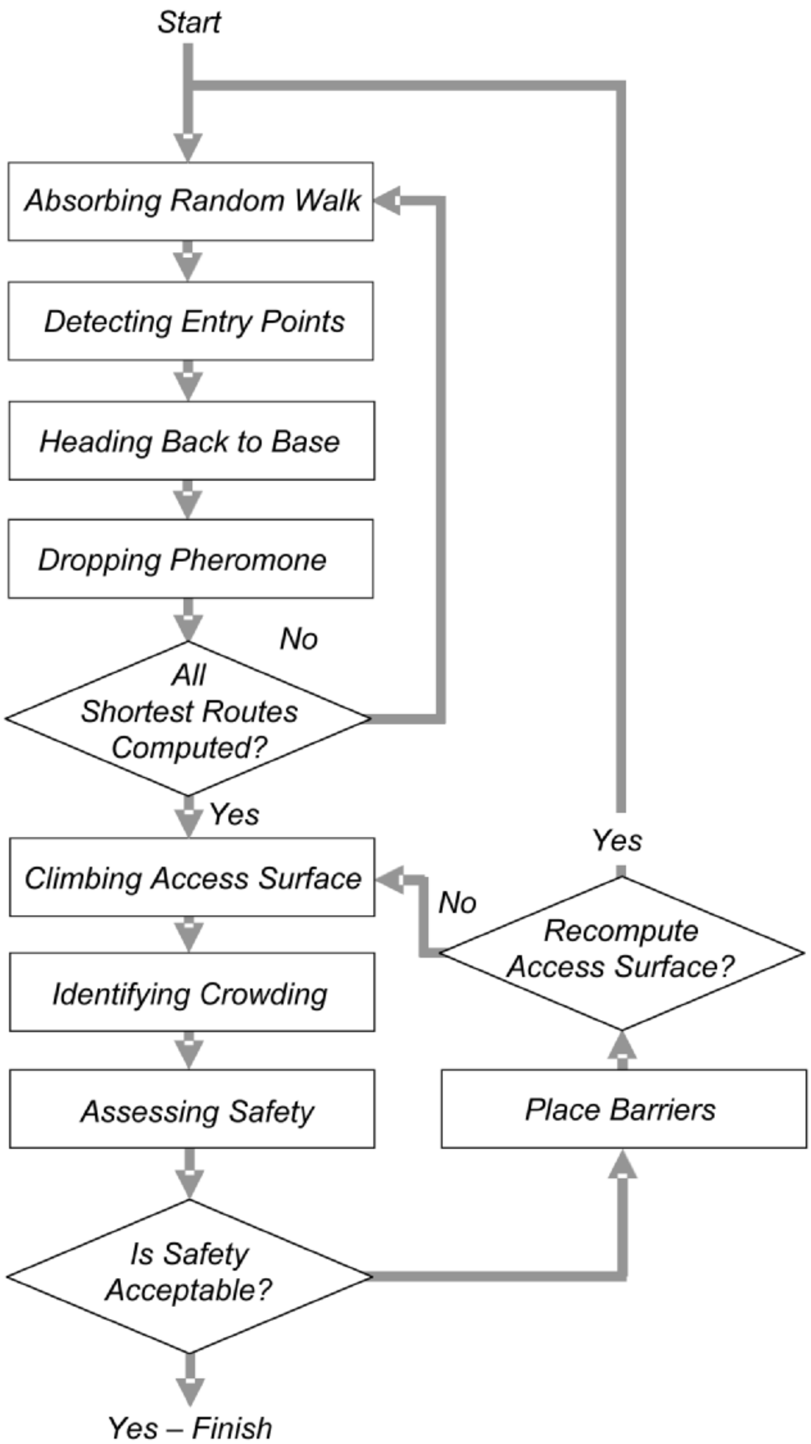


**Figure 1.** The structure of the model. The model is operated in two main stages. First, the hierarchy of shortest routes is computed using the swarm algorithm and this constitutes the first inner loop. Secondly, agents use these shortest routes to reach the event and, if safety levels are breached, this second stage is reiterated with changes to the street system in the inner second loop. The outer loop is activated if these changes lead to radical changes in the shortest routes within the area.

sibility surface encoding the hierarchy of shortest routes has been discovered, and only when each agent has made such a discovery, does the process converge to the point where a complete surface is obtained. This is used in the second stage to launch agents from their entry points, letting them walk towards the attractions of the Carnival which are implied in the gradients associated with the accessibility surface. This time, constraints associated with crowding are also introduced. If crowds build up, they are allowed to dissipate at certain congestion thresholds. Moreover, as more and more agents begin to move along streets, a positive feedback akin to flocking is introduced that concentrates this movement. In this way, a pattern of unconstrained movement to the Carnival is generated and it is thus possible to assess the overall crowding and the public safety problems that emerge. These constitute the output from this second stage which is reached in Figure 1 when the process is checked to see whether or not an acceptable level of public safety has been attained.

If public safety is compromised in some way, barriers or controls are introduced into the geometry of the street system at points where crowding occurs in an effort to minimise congestion. At this point, there are two options: the simpler one is simply to reiterate the second stage in step-by-step fashion, rerunning the model each time, launching the walkers from entry points and then assessing the crowding that takes place. Thus the control needed in order to reduce congestion to acceptable levels is gradually increased. This reiteration ends when a safe solution emerges. The second option assumes that, when new controls are introduced, the accessibility surface which encodes the shortest routes will be sufficiently different that it should be recomputed. Thus the entire procedure is reiterated with the swarm algorithm being rerun from scratch. There are alternative possibilities to this with the algorithm being exercised on the basis of the existing set of shortest routes but this implies that existing routes have some priority and, although this may be the case, it is considered that the most 'objective' way is to assume no prior routing. In any case, whichever method is used, the algorithm will eventually produce the appropriate accessibility surface. There are various intermediate positions for rerunning the entire model with the inner loop in Figure 1 being run several times for every iteration of the outer loop. Various possibilities have been tested and these are reported in the next section.

### 2.3 The Formal Structure of the Model

The model that is used comprises an event space represented by square cells $i, j = 1, 2, \dots, N$, and walkers $k = 1, 2, \dots, K$ whose existence is defined by a binary variable $w_{it}^k$ at a time $t = 1, 2, \dots, T$. The first stage begins with walkers located at their destinations $w_{D1}^k$ where $w_{D1} = \Sigma_k \ w_{D1}^k$. Walkers move from cell $i$ to $j$ in each time-period $[t \rightarrow t+1]$ where $j \in \Omega_i$ and $\Omega_i$ is the eight-cell neighbourhood around $i$. In general, some of these cells will not be accessible because of obstacles such as buildings and barriers; thus a block mask is defined as $b_j = 1$ if cell $j$ is accessible and $b_j = 0$ otherwise. Movement from $i$ to $j$ in search of an origin $O$ is then determined by the probability

$$p_{ijt+1} = \frac{\tau_{jt} b_j}{\sum\limits_{j \in \Omega_i} \tau_{jt} \, b_j} \tag{1}$$

where, $\tau_{jt}$ is the route accessibility to origins.

A move from $i$ to $j$ is determined randomly according to the schedule of probabilities in equation (1). If $w_{it}^k = 1$ and $w_{jt+1}^k = 1$, the accessibility surface to destinations is updated as

$$\eta_{jt+1} = \eta_{jt} + \sum_k (d_{Djt+1}^k)^{-\beta} \tag{2}$$

where, $d_{Djt+1}^k$ is the distance of walker $k$ who starts at $D$ and is now at cell $j$; and $\beta$ is a tunable parameter. The density of walkers at $j$ is then computed as $w_{jt+1} = \Sigma_k \, w_{jt+1}^k$.

The process implied by equations (1) and (2) continues until a walker discovers an origin $O$. For each walker $w_{jt+1}^k$, if $j \in \Omega_O$, the walker switches from exploratory to discovery mode $\bar{w}_{jt+1}^k$ and returns to the destination $D$ with knowledge of the discovery. The probability of returning is

$$q_{ijt+1}^k = \frac{\pi_{jt}^k b_j}{\sum_{j \in \Omega_i} \pi_{jt}^k b_j} \quad (3)$$

where, $\pi_{jt}^k$ is the difference between headings in the direction from $i$ to $j$ and from $i$ to the position defined by $w_{D1}^k$. This move is also chosen randomly and when $\bar{w}_{it}^k$ moves to $\bar{w}_{jt+1}^k$, the walker marks the move by updating $\tau_{jt}$ as

$$\tau_{jt+1} = \tau_{jt} + \sum_k \bar{w}_{jt+1}^k \quad (4)$$

This process is akin to the walker laying a pheromone trail when a discovery has been made: $\tau_{jt+1}$ measures the density of pheromone and this is ultimately the density of routes, the highest densities of which are shortest routes. When the walker comes within the neighbourhood of the destination $j \in \Omega_D$, the walker switches back to exploration mode and the search begins over again. Note that $i$ and $j$ are not unique to origins and destinations respectively but are used as generic indices of location.

It takes some time before agents discover an origin. Before this, the search is a random walk with the route accessibility surface set as a uniform distribution. If a walker crosses the edge of the event space, it is absorbed, regenerates at its destination and begins its search again. In its early stages, this is a random walk with absorbing barriers with the variance of its lengths proportional to $t^{0.4}$, a little less than for the unconstrained random walk where $\sigma = t^{1/2}$ (Sornette, 2000). As the process continues, more and more origins are discovered while, during exploration, walkers 'learn' to direct their search at routes to origins already discovered. Those origins closest to destinations are discovered first and a hierarchy of 'shortest routes' is thus built up, continually reinforced by this positive feedback. This is the process implied by the first inner loop in Figure 1.

This is a variant of a generic algorithm predicting trail formation and collective foraging behaviour amongst animal populations such as ants (Helbing *et al.*, 1997; Camazine *et al.*, 2001). The swarms created are extremely efficient in discovering shortest routes in geometrically constrained systems (Bonabeau *et al.*, 1999). Here, the pheromone trail $\tau_{jt}$ is not allowed to decay, while the accessibility surface $\eta_{jt}$ gives the relative attraction of destinations to different street locations. Figure 2 illustrates this for the accessibility to various destinations and shortest routes to the tube (subway) stations in Notting Hill. To impress its efficiency, the simulation is first shown without obstacles to movement $b_j = 1, \ \forall_j$ in Figures 2c and 2d where this is akin to operating the model in free space without the street pattern. This gives clear and direct shortest routes to the Carnival events—parade and sound systems—which are the destinations $D$ from which the walkers begin the process of discovering entry points $\{j\}$. With the real street pattern imposed in Figures 2e and 2f, the pattern reflects the street systems from the entry points which in this case, for illustrative purposes only, are the subway (tube) stations.

The exploratory stage finishes when the percentage difference in path densities falls below a 1 per cent threshold defined as $\sum_j \lfloor |\tau_{jt+1} - \tau_{jt}| / \tau_{jt} \rfloor \leq 0.01$. In the second stage, walkers are launched from their entry points and these walkers move towards the event using the surfaces $\tau_{jT}$ and $\eta_{jT}$ as indicators of accessibility. These are normalised as $\tau_j$ and $\eta_j$ and combined as $\tau_j^\alpha \ \eta_j^{1-\alpha}$. There are of course many ways in which these two surfaces could be combined and there is inevitably an element of double counting in their joint usage. However, this definition and parameterisation are provided so that different types of accessibility can be merged, the best combination of which will reflect the best fit of the model to the observed situation. The basic probability of movement is now defined as

$$q_{ij} = \frac{\tau_j^\alpha \ \eta_j^{1-\alpha} \ b_j}{\sum_{j \in \Omega_i} \tau_j^\alpha \ \eta_j^{1-\alpha} \ b_j} \quad (5)$$

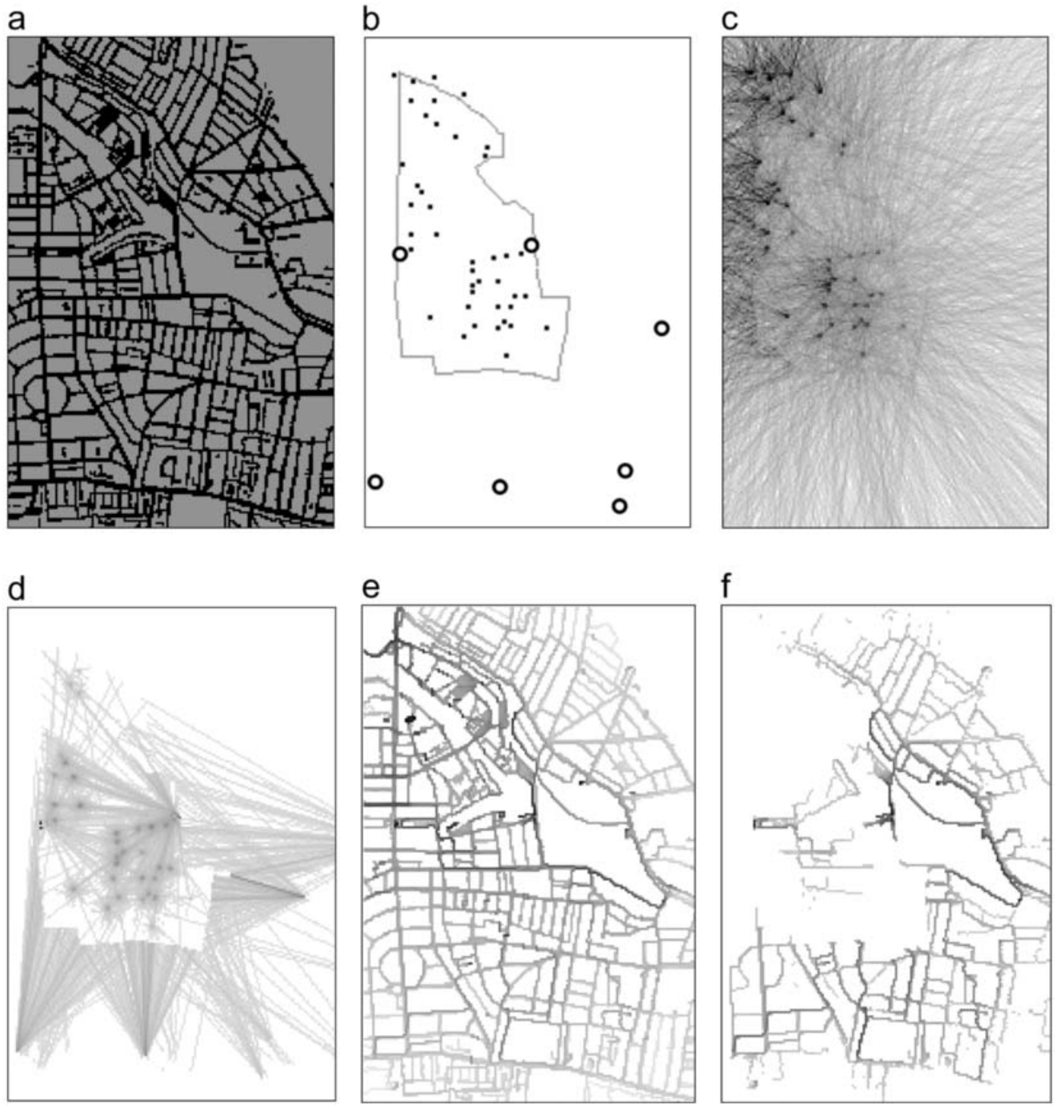


**Figure 2.** Exploration of the geometric space and discovery of entry points illustrated by the tube stations in Notting Hill. In Figure 2a, the street geometry is shown; in Figure 2b, the parade route is shown in light grey, the sound systems as black dots and the tube stations as open circles; in Figure 2c, the accessibility from the parade and sound systems without streets is shown; in Figure 2d, the hierarchy of shortest routes to tubes is shown without streets; in Figure 2e, the accessibility with streets is shown; and in Figure 2f, the hierarchy of shortest routes with streets is shown. Relative intensities (of accessibility in Figures 2c–2f) are shown on a scale from high (dark) to low (light) for the best-fit parameterisation of the swarm model. The horizontal width of each map is 1.7 km.

where, $\alpha$ is a tunable parameter which plays a role similar to homogeneous production functions of degree 1 such as the Cobb–Douglas, widely used in micro-economics for their scaling properties (Henderson and Quandt, 1980).

Equation (5) is used to select directions of movement from $i$ to $j$, using each probability $q_{ij}$ in the neighbourhood $\Omega_i$ to determine the direction $j$ in which the walker moves. This is done randomly with new headings in the direction $j$ computed as $\bar{\theta}^k_{it+1}$ and then used to update the existing heading as $\hat{\theta}^k_{it+1} = \lambda\bar{\theta}^k_{it+1} + (1-\lambda)\theta^k_{it}$ where $\lambda$ reflects a lag in response.

There are two effects that complicate this movement. The first is herding or flocking (Reynolds, 1987; Vicsek *et al.*, 1995). This directs movement as an average of all movement in the immediate neighbourhood where $\theta^k_{it+1} = \Sigma_{k\in j}\Sigma_{j\in\Omega_i}\hat{\theta}^k_{jt+1}w^k_{jt}/\Sigma_{k\in j}\Sigma_{j\in\Omega_i}w^k_{jt}$. However, a move by walker $w^k_{it}$ to $w^k_{jt+1}$ only takes place if the density of walkers in cell $j$ is less than some threshold $\Psi$ based on the accepted standard of two persons per square metre (ppm$^2$) (Fruin, 1971; Still, 2001). If this is exceeded, the walker evaluates the next best direction and, if no movement is possible, remains stationary until the algorithm frees up space on subsequent iterations. These rules are ordered to ensure reasonable walking behaviour. This second stage is terminated when the change in the density of walkers in each cell $\Sigma_k|w^k_{it+1} - w^k_{it}|/\Sigma_k w^k_{it}$ converges to within some threshold where it is assumed a steady state has emerged.

It is now possible to assess how good the model is at predicting the observed distribution of crowds. The predicted density $w_{it}$ is compared with average neighbourhood density $\tilde{w}_{it} = \Sigma_{k\in j}\Sigma_{j\in\Omega_i}w^k_{jt}/\Sigma_{j\in\Omega_i}b_j$ in cells where observed densities are available. These are then related to the number of occupied cells $\Sigma_i n_i = M$ (where $n_i = 1$ if $w^k_{it} > 0$, otherwise $n_i = 0$) and the number of available cells $\Sigma_i b_i = N$ defining system averages as $\rho(t) = \Sigma_i w_{it}/\Sigma_i n_i$, $\sigma(t) = \Sigma_i\tilde{w}_{it}/\Sigma_i n_i$ and $\vartheta(t) = \Sigma_i n_i/\Sigma_i b_i$. For different threshold values $\Psi$, if $w_{it} > \Psi$, then $c_{it}(\Psi) = w_{it}$ otherwise $c_{it}(\Psi) = 0$, and the proportion of the population at risk is thus $Z_t(\Psi) = \Sigma_i c_{it}(\Psi)/M$. Average distance travelled in each time-period $[t \rightarrow t+1]$ is $U_{t+1} = \Sigma_{ijk}d^k_{ijt+1}/M$ with the percentage actually moving $V_{t+1} = \Sigma_{ijk}w^k_{it}w^k_{jt+1}/M$.

These two stages define the entire model with subsequent stages being generated through reiteration either of the second stage or the first, then second again. These additional stages are activated if the statistics generated at the end of the second stage suggest that public safety is being compromised. It consists of examining the statistics from the second stage and gradually making changes to reduce the population at risk by introducing barriers, capacitating entry points and closing streets. This is achieved by changing the mask $b_j$ to $b'_j$. As the repercussions of this are not immediately obvious, these changes are made one by one forming $b'_j$, $b''_j$, $b'''_j$, … , rerunning the model each time until an acceptable solution emerges. These reiterations may keep the accessibility surfaces fixed—the second inner loop reiteration in Figure 1—or assume that these surfaces need to be updated—the entire sequence in Figure 1. In estimation, these subsequent stages can also be used to assess the efficacy of existing controls. In a sense, these latter stages of the model move it from prediction to prescription although it is not possible to develop a formal optimisation procedure as so many additional factors such as resources for policing, etc. cannot be quantified. Nevertheless, this interactive method of introducing control is considered to be the best approach so far for assessing alternative route change, road closures and the imposition of barriers.

## 3. Applications: Predictions and Control

### *3.1 The Problem and Its Data*

The Carnival which began life as the Notting Hill Festival in 1964 had attracted some 150 000 visitors by 1974. This had grown to half a million by 1990 and estimates for 1999 by the police and transport agencies suggested over 1.2 million but the authors' count in 2001 revealed that this number had fallen to 710 000. Bad publicity due to rising crime and safety issues may be the cause of the fall although the estimates in all previous years have probably been inflated. The Carnival, which is held in the late summer over 2 days, usually the last Sunday and Monday in August, consists of a continuous parade along a circular route of nearly 5 km in which 90 floats and 60 support vehicles move from noon until dusk each day. Within the 3 sq km parade area, there are 40 static sound systems and 250 street stalls selling food. The peak crowds occur on the second day between 4 pm and 5 pm when, in 2001, there were some 260 000 visitors in the area. There were 500 accidents, 100 requiring hospital treatment with 30 per cent related to wounding, and 430 crimes committed over the 2 days with 130 arrests (Intelligent Space Partnership, 2002). Some 3500 officials, mainly police, were required each day to manage the event. The parade area is bounded by a traffic exclusion zone which makes the area inaccessible to everything other than emergency vehicles and, with this disruption to residents and the scale of the police operation, considerable resources are expended on the event.

Rising resources and concerns for public safety are the two key issues that dominate future planning for the Carnival. In 2000, three murders took place which drove authorities to set up a wide ranging inquiry into all aspects of its management and organisation. The present authors' involvement in this inquiry consisted in exploring all aspects of public safety concerned with the routing of the parade but set in a much wider context of review involving a large number of different stakeholders. The safety problems posed by the event are considerable (CRG, 2001). There are many routing conflicts due to crossing movements between the parade and sound systems while access to the Carnival area from public transport is uneven with 4 roads into the area taking over 50 per cent of the traffic. A vehicle exclusion zone rings the area and thus all visitors walk to the Carnival. Crowd densities are high for such events in the UK with an overall average of about 0.25 ppm$^2$ of whom 0.47 ppm$^2$ line the Carnival route and 0.83 ppm$^2$ lie inside.

Good data exist for crowd densities from the authors' own cordon survey which involved surveys throughout the 2 days of all those entering and leaving the Carnival area (at 38 entry points), surveys by London Underground Ltd of entry/exit volumes at subway stations and 1022 images of the parade taken by Metropolitan Police helicopters in the early afternoon of the second day (Intelligent Space Partnership, 2002). The accident data from the St John's Ambulance Service, which is the only data source that has been collected systematically for the past 20 years, provides an excellent cross-check on overall volumes at key locations. However, the central problem in building an agent-based model in which a sample of individuals is simulated is the lack of data on personal profiles and preferences with respect to intentions at the Carnival and the lack of data on the paths that each visitor actually takes during their time at the event. Aggregate traffic densities exist, but not actual movements—a typical problem in many kinds of traffic modelling. As argued earlier, one the reasons for developing the model in two main stages is to generate the most likely such paths using swarm intelligence.

One of the critical issues in public safety involves the circularity and continuity of the parade. Most such parades have fixed start and end points in time and space but, in Notting Hill, the parade begins around noon on each of the two days and finishes at dusk. Thus the volume of vehicles builds up and there is considerable lack of control over where and when vehicles enter and leave the route. The fact that all 40 sound systems and most of the food stalls are inside the parade area means that there is considerable crossing of the parade route, leading to many potential accident 'hot spots'. Moreover, there are critical pinch points on the parade route which lead to severe vehicle–pedestrian conflicts and congestion, particularly at points along Ladbroke Grove south, the southern section of Westbourne Park Road around the judging area and in its northern section where the road bends at right angles, in All Saints Road, the Great Western Road and the upper Portobello Road. In these places, densities can exceed those recommended in the Health and Safety guidelines (Intelligent Space Partnership, 2002).

The model involves launching agents from the points at which they enter the Carnival area, and volumes at the 38 entry points defining the traffic exclusion zone must thus be known. In fact, if the route of the parade is changed, then the traffic exclusion zone will also change, and thus before the agent-based model is executed, the numbers of visitors must be predicted at each of the new entry points determined in any new traffic exclusion zone. Thus, a prior model has been developed for such predictions based on computing total numbers entering or exiting each of these points. Relationships to observed entry and exit volumes have been fitted as a linear function of various characteristics such as accessibility to tube stations, the visibility of street lengths, block sizes and related geometric features. For these more aggregate models, it is possible to predict at least 84 per cent of the variance. These models are essential to testing alternative routes as they provide the input data for the agent-based models, although these are not explored further here (details are given in Intelligent Space Partnership, 2002).

The model has been applied to simulate the peak flow of visitors between the hours of 4pm and 5pm on the second day of the Carnival using 2001 data. The temporal simulation is simplified by launching all visitors at once from entry points and, when they reach their ultimate destinations, a steady state distribution emerges; it is this that is used to detect problems of public safety. In fact, the software that is used only enables handling of up to 15 000 agents and thus a 5 per cent sample is taken of the 260 000 visitors (13 000) observed at this peak time. The raster or cellular space on which the simulation takes place is also limited in resolution with the typical cell size used here being about 7 sq metres. This means that all the critical limits and thresholds, such as the 2 ppm$^2$ density limit, must be scaled accordingly. The temporal dynamics are also a radical approximation in that the simulation is not matched to actual speeds of movement. Thus it is not possible to introduce changes in speed due to congestion, flocking and related phenomena, although in principle it would be possible to synchronise the dynamics with real time. The problems posed by these assumptions in terms of the impact of such aggregations are explored elsewhere (Batty *et al.*, 2002) but suffice it to say that this does not distort the conclusions drawn from this application.

### *3.2 Calibration and Prediction: Dimensioning to Real and Future Events*

In equations (1)–(5), there are three parameters $\beta$, $\alpha$ and $\lambda$ that must be tuned in order to calibrate the model. The parameter $\beta$ is a decay parameter which measures the friction of distance with respect to the accessibility surface $\{\eta_{jt}\}$ and this reflects the traditional way in which distance from the ultimate destinations affects the response to entry points in swarm behaviour. The parameter $\alpha$ is a weight which balances the intensity of the shortest route surface against the distance accessibility surface: both would appear to have some importance in directing movement from the entry points to ultimate destinations although exactly what this balance is, is hard to say in advance. Hence this is left to be determined by the calibration. The last parameter is the lag coefficient $\lambda$ which fixes the extent to which changes in direction of movement reflect previous directions, this being the only behavioural parameter governing the randomness of movement. The parameter $\Psi$ is the upper limit on pedestrian density before the congestion dispersion mechanism becomes operable and this has been set at 2 ppm$^2$ following Fruin (1971). Note, however, that this parameter is a norm and may not be the actual value which governs observed crowding. However, as this calibration is as much about dimensioning the problem to correct orders of magnitude, this particular parameter has not been tuned.

To find the best parameter values, it is necessary to explore the phase space defined by $\beta$, $\alpha$ and $\lambda$ and, although this is straightforward, to keep the problem manageable it is necessary to fix the loop structure of the model as illustrated in Figure 1. The model is not run through multiple iterations of the inner second and outer loops but, having run the swarm algorithm, the second stage of the model is then run to assess crowding, place barriers and close streets, rerunning this

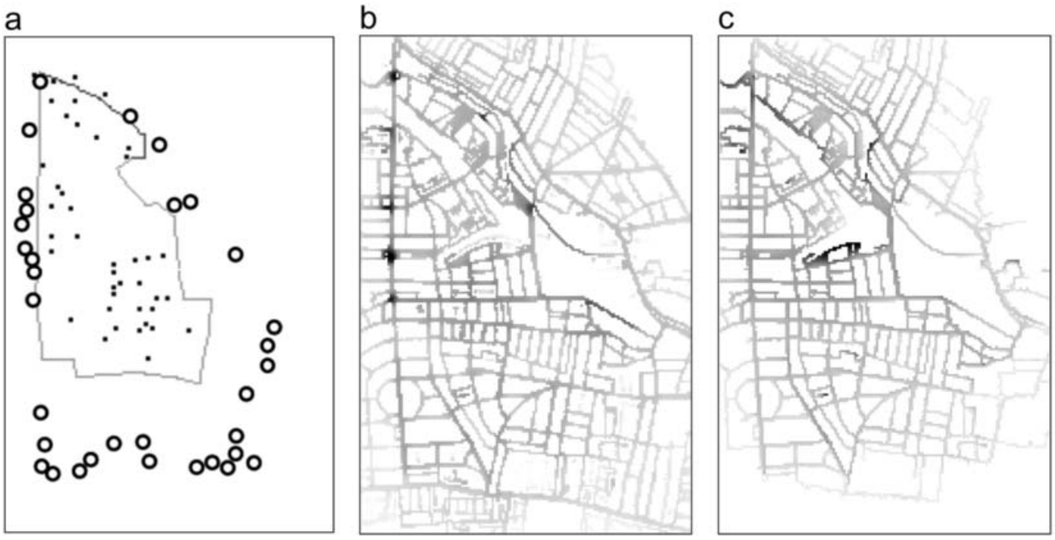


**Figure 3.** Swarm and crowd densities predicted from the two stages of the model. In Figure 3a, the proposed 2002 parade route is shown in light grey with the additional route in 2001 in dark grey, the sound systems as black dots and the entry points as open circles. The composite accessibility surface from the swarms in the first stage is shown in Figure 3b and the traffic density from the second stage in Figure 3c.

second stage only once more. It is found that crowding is reduced in this way, although it is candidly admitted that this limited calibration needs to be explored more thoroughly. The problem being faced is that there are so many potential iterations of the model all requiring new controls to be introduced and/or reduced at each iteration, that there has not been enough time to generate a fixed sequence of controls. Even if this were possible, there is no guarantee that these would be appropriate. The outputs thus produced reflect a minimalist solution.

The best parameter values were found to be $\beta = 0.65$, $\alpha = 0.35$ and $\lambda = 0.4$. Using these values, a start is made by finding the shortest routes from the parade and static sound systems to the 38 entry points located on the edge of the traffic exclusion zone which are now shown in Figure 3a. The swarm algorithm predicts the numbers of walkers who 'find' each entry point and this uncontrolled prediction is compared with the cordon survey, explaining 64 per cent of this variance. The composite accessibility surface $\{\tau_j^{\alpha}\eta_j^{1-\alpha}\}$ which results from the swarm is shown in Figure 3b and this surface is used to direct the movement of walkers in subsequent stages of the model. The observed volumes of visitors at entry points are used to launch agents who then climb the accessibility surface indicated by equation (5). The predicted traffic density of pedestrians $\Sigma_k w_{iT}^k$ in its steady state is shown in Figure 3c and from this, significant points of crowding are identified. Seventy-two per cent of the variance of the observed densities is predicted for 120 locations where good observed data are available. The model is now rerun with the official street closures and barriers imposed, as shown in Figure 4a. This stage increases the variance explained to 78 per cent, but not all the points of extreme crowding have been removed. This suggests that, even in estimating the model, it can be used in a diagnostic manner to identify vulnerable locations. In Figure 4b, walkers are shown as they appear in the simulation in its steady state and this gives some idea of the distribution along streets. Figure 4c presents a smoothed map of the final traffic density which identifies points of crowding critical to the calibration. This can be compared with the observed points in Figure 4d and these show the limitations in the simulation. Crowding is considerably more of a problem

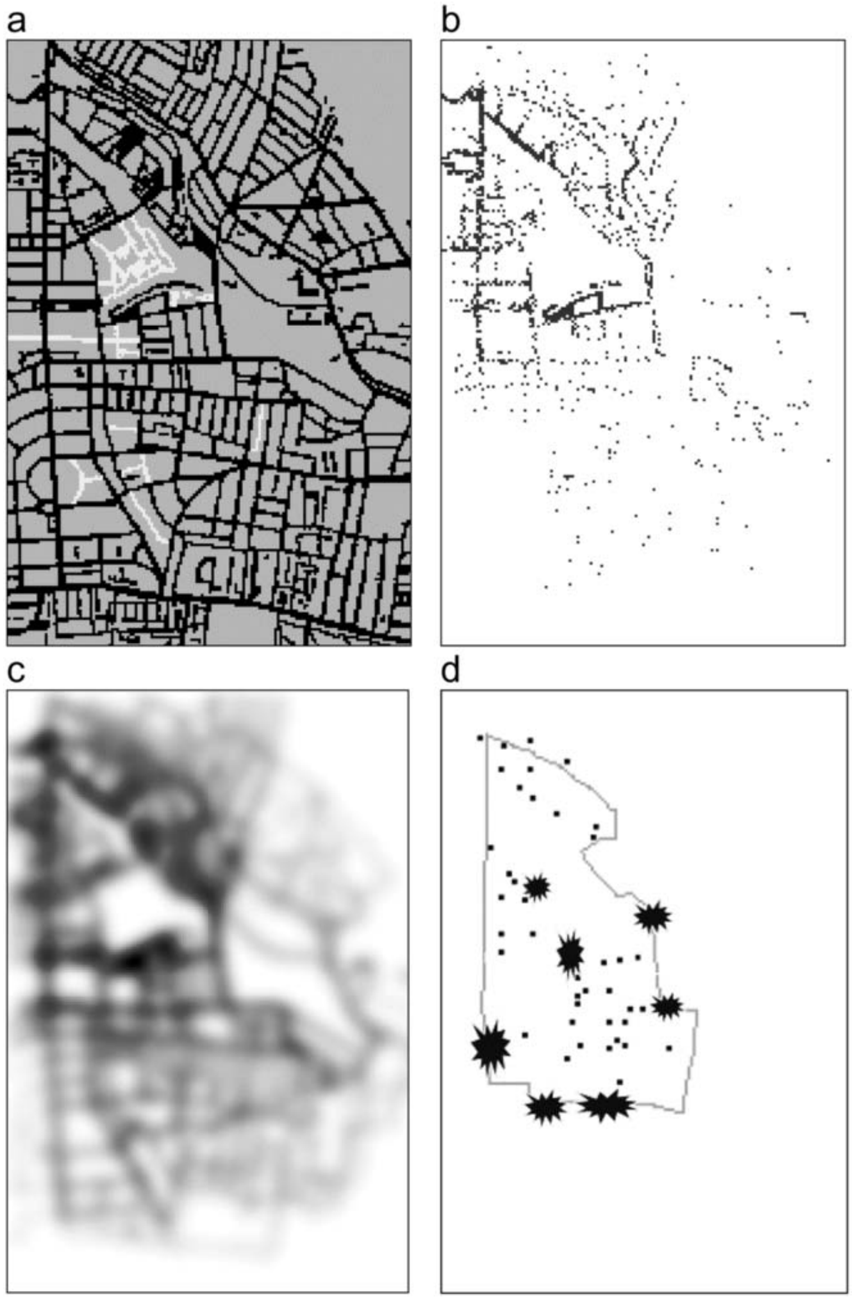


**Figure 4.** Control of crowds and the identification of vulnerable locations. Areas closed by the police used in stage 3 are shown in white in Figure 4a. The locations of walkers in the second stage after controls have been introduced are shown in their steady state in Figure 4b. The vulnerability of locations is shown in Figure 4c on a grey scale with the darkest set at $\Psi \geq 1$ ppm$^2$, the most vulnerable points. The critical observed crowding is shown by hazard symbols in Figure 4d. Best parameter values are set at $\beta = 0.65$, $\alpha = 0.5$ and $\lambda = 0.4$.

than is actually observed in the northern part of the Carnival area while it does not reach the critical levels observed in Ladbroke Grove and Westbourne Park Road along the judging points.

A more focused analysis can be achieved

through examination of average density values for cells and neighbourhoods, pedestrian space occupied, average distance travelled and visitors at risk for different levels of crowding. These statistics illustrate the key differences between each of the two stages of the model—first, the swarm algorithm and, secondly, the unobstructed simulation of movements from entry points to the Carnival events—as well as the effect of introducing controls to reduce congestion in the second pass through the model's second stage. All density statistics fall dramatically at first in each stage of the model because the walkers are launched simultaneously from their ultimate destinations. At the start, these densities are not meaningful in that this mode of operation is purely a device to begin movement towards the ultimate steady state. In short, the initial distribution of walkers and hence all statistical values are arbitrary to begin with. What happens is that the model generates distributions which are statistically extreme at first but then quickly change to 'normal' levels, eventually converging to stable values. In the case of cell and neighbourhood densities $\rho(t)/3$ and $\sigma(t)/3$, these behave as expected with the average cell density higher than the neighbourhood. These values fall slightly between the first and second passes of the second stage where barriers and controls are introduced to reduce first stage crowding.

Average distance travelled $U_t/4$ is fairly stable with a slight increase as walkers converge on the steady state and have less room to manoeuvre. The volatility of this statistic increases quite rapidly for the second stage runs indicating that dissipation of congestion is at work as specified in the model. The percentage population at risk falls dramatically and then rises to a threshold. There is distinct fall in population at risk for $\Psi \geq 0.5$ ppm$^2$ when barriers are introduced, from about 25 per cent of the population to 20 per cent, while this value falls only slightly from 6 per cent to 5 per cent when the threshold is set as $\Psi \geq 1$ ppm$^2$. Finally, the occupancy of the streets with pedestrians in comparison with the total possible cells comprising the streets $\vartheta(t)$ is a little higher for the constrained run through the second stage of the model in comparison with the first and this too indicates that congestion is being dissipated when controls are introduced. These graphs and their relevant values are shown for each of the three runs of the model reported above in Figure 5. On balance, the calibration of the model is acceptable enough, in the present authors' judgement, for use in exploring different solutions. But it requires considerable further development if it is to become the centrepiece of any process in which this is the only model. The model as it stands has been supported by considerable analysis of a more conventional kind and it has only been used to complement this analysis, not to replace it.

A sketch will now be presented of the way in which the model has been used to test alternative routes which meet greater standards of public safety. Alternative routes were initially suggested and refined over a period of two or more years by the Carnival Review Group in liaison with many of the stakeholders such as the Carnival Trust, the police, transport services and community groups. The focus so far has simply been on breaking the circularity of the parade route so that it can be better controlled and limited to fixed start and end points. In this application, six alternatives were tested, ranging from a simple L-shaped route along the main roads to a more convoluted compromise which lengthened the route but broke its circularity. All the routes tested reduced the crowding levels with the biggest reductions being routes which spread pedestrians over a wider area. In each case, a new traffic exclusion zone needs to be drawn, new entry points located and the regression-based model run to determine entry and exit volumes. These entry volumes were then used as inputs to the agent-based model reported here. These routes will not be described as they add little to the insights already communicated in this paper although it is worth saying that the distribution of problem points tended to focus more on the static sound locations than along the parade route in all options tested.

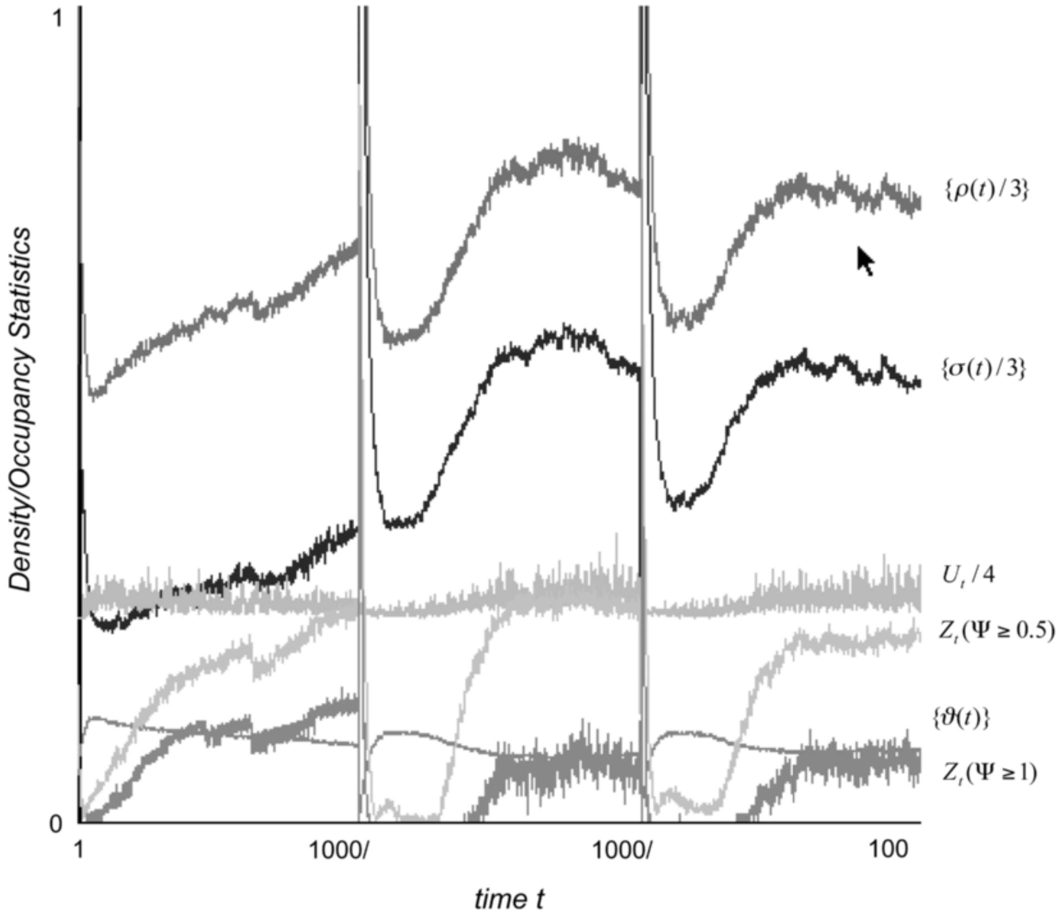


**Figure 5.** Variations in average density, occupancy, distance travelled and population at risk at each stage of the modelling process. *Key*: average cell density in dark grey, neighbourhood density in black, distance travelled in mid grey, percentage of population at risk $> 0.5$ ppm$^2$ and $> 1$ ppm$^2$ both in light grey, and percentage occupancy in mid grey.

At the time of writing, after much debate and given the logistics of the planning for the 2002 Carnival, an interim solution has been proposed. This involves breaking the circularity of the existing route along its northern stretch. The line shown in dark grey in Figure 3a shows the section of the existing parade (light grey) which will be cut out from this year's event. It was felt that the considerable problems posed by a more radical rerouting with all the issues that are involved in educating the paraders in a new protocol of fixed start and end locations, would be too problematic if the entire route were to be switched at once. Nevertheless, it is now widely recognised in the Carnival Review Group and amongst several stakeholders that sound systems as well as the parade route itself will have to be relocated if the Carnival is to be satisfactorily managed in the future. It is intended to improve the model in line with suggestions made below and insights into its behaviour already outlined as the exploration begins of these more radical options.

## 4. Conclusions: Next Steps

Models such as these are so intertwined with the control and management of crowds and streets which are an essential feature of these kinds of event, that stakeholders who manage the Carnival should be intimately involved in the process of using the model to generate appropriate levels of control and policing. In short, they should be involved in working with the model, especially in its later stages when controls are introduced and safety levels assessed. This kind of interaction is largely absent from most kinds of predictive modelling largely because there is an implicit assumption that prediction is always prior to control and design. The model has not yet been used in this way, but there is potential for such extension. It is echoed in the fact that the entire process of redesigning routes for the Carnival is dominated by stakeholder involvement at every stage and the possibilities of using the model in this way will be exploited as the process matures. The redesign of the parade route is an unfinished process at present with only an interim solution implemented in 2002.

A generation ago, the notion that social systems might be simulated from the bottom–up, where every object or agent could be represented explicitly, seemed fanciful. Changes in the way that systems are conceptualised as decentralised rather than centralised structures combined with advances in fine-scale data acquisition and fast computation have made agent-based modelling possible. It is, however, early days yet and the purpose of this paper has been as much to introduce the idea that this type of simulation is possible as to provide a complete methodology for modelling and predicting fine-scale spatial events. Agent-based models do, however, enable the horizon as to what might be modelled to be pushed a little further while, at the same time, articulating important causal effects leading to emergence in social systems—something that has rarely been possible hitherto.

These models also illustrate the key interaction of agents with their environment. In the Notting Hill model, the environment is coded in terms of attractivities—accessibilities—which are embodied in the cells that define the spatial system. Objects interact with each other and with the cells, having the potential to change themselves and their cells. In this case, the cells remain constant from iteration to iteration in that it is conceived that the environment will influence agents, but the ways in which agents influence their environment are not defined. In short, the model is not unlike a cellular automata model with the environment composed of static cells and agents acting as mobile cells. The same kind of logic has been applied to other fine-scale events such as crime patterns (Liu *et al.*, 2002), all the way up to urban regions (Batty, 2001) and even entire societies where there can be interaction both ways between agents and their environment (Epstein and Axtel, 1996).

Besides introducing a more decentralised approach to thinking about urban systems which has wide applicability to cities at all scales, this approach also blurs the distinction between simulation of real systems and their control. In the past, there has been an unwitting assumption that cities can be modelled as quasi-natural systems in which control is something that is applied after the fact. Cities have been modelled and understood as if there were no controls affecting the existing situation, although their entire structure can be viewed as a product of controls based on various decision-making. When the focus changes to discrete spatial events at a very fine scale, then it is no longer possible to maintain this fiction and our models must adapt to take this into account; hence the requirement here to merge simulation with control through a process of gradually introducing constraints on a comparatively unconstrained situation.

Simulation of the existing situation thus becomes a series of diagnostics in which existing controls are also evaluated and this turns the process of prediction into one that is infused with prescription. In one sense, this meets the oft-quoted objection to technocratic, top–down-style planning in which plan and planner take a privileged position. Planning and design conceived here as control and management are thus woven into the very process of simulation itself. Alternative scenarios, in this case alternative routes for the Carnival, are simply different realities to be simulated. This kind of modelling can and should be extended to other kinds of urban system where the comparative realism of the process implies that control, planning and management cannot be separated from the simulation itself. This is the challenge and next steps will involve simulating crowd situations of a less volatile nature where convoluted geometries and competing attractions are important—as in malls, supermarkets and airports. This approach also has relevance to other human or animal circulation patterns and ultimately to development processes of many kinds.

## Note

1. All the figures are reproduced in colour at: http://www.casa.ucl.ac.uk/urbanstudies/.

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