Crowd Dynamics

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by

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Special thanks to Ian Stewart for his guidance through all weathers. Without his tireless moral and academic support it would not have happened, or been as much fun.

Declaration

I hereby declare that the dissertation, submitted in partial fulfillment of the requirements for the degree of Doctorate of Philosophy and entitled Crowd Dynamics , represents my own work and has not been previously submitted to this or any other institution for any degree, diploma or other qualification.

G. Keith Still

August 2000

Abstract of thesis entitled Crowd dynamics

Crowd dynamics are complex. This thesis examines the nature of the crowd and its dynamics with specific reference to the issues of crowd safety. A model (Legion) was developed that simulates the crowd as an emergent phenomenon using simulated annealing and mobile cellular automata. We outline the elements of that model based on the interaction of four parameters: Objective, Motility, Constraint and Assimilation. The model treats every entity as an individual and it can simulate how people read and react to their environment in a variety of conditions, this allows the user to study a wide range of crowd dynamics in different geometries and highlights the interactions of the crowd with its environment. We demonstrate that the model runs in polynomial time and can be used to assess the limits of crowd safety during normal and emergency egress.

Over the last 10 years there have been many incidents of crowd related disasters. We outline deficiencies in the existing guidelines relating to crowds and, by comparison and contrast with the model, we highlight specific areas where the guides may be improved. We demonstrate that the model is capable of reproducing crowd dynamics without additional parameters thus satisfying Occam s Razor.

We propose an alternative approach to assessing the dynamics of the crowd through the use of the simulation and analysis of ***least effort*** behaviour. The model is tested against known crowd dynamics from field studies, including Wembley Stadium, Balham Station and the Hong Kong Jockey club. Finally we test the model in a variety of applications where crowd related incidents warrant structural alterations at client sites. We demonstrate that the model explains the variance in a variety of field measurements, that it is robust and that it can be applied to future designs where safety and crowd comfort are criteria for design and cost savings.

To my beloved wife Valerie. None of this would
be possible without your love and support

To my children, Harry and Erin, who are the reason
to try and make the world a safer place.

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Chapter 1 Introduction

Crowd dynamics can be defined as the study of the how and where crowds form and move above the critical density of more than one person per square metre. At this density there is the potential for overcrowding and personal injury.

We examine different approaches used to define crowd safety, in particular the ***Green Guide*** [1, 2] which defines the criteria for sporting grounds, the ***Purple Guide*** [3, 4] which defines the criteria for pop concerts and similar events and the ***Primrose Guide*** [5] which defines the criteria for existing places of entertainment.

We examine the relationships between crowd flow and density, specifically the work of Fruin [6] who has been instrumental in setting the standards for pedestrian planning around the world. We also examine the work of Ando, Aoki and Togawa [7, 8, 9, 10], Henderson [11, 12], Helbing [13, 14, 15, 16, 17, 18, 19, 20], Galea [23, 24], Paulsen [25], Cohen [26, 27] and Penn [28].

In addition to the existing body of literature and guides we perform extensive field studies to examine the nature of crowd dynamics with respect to local geometry, for example, building entrances, turnstiles and corridors. Case studies, Balham Station, Wembley Stadium and the Hong Kong Jockey Club are presented.

1.1 Legion

Legion is the name used to describe the collection of programmes developed to analyse the dynamics of crowds. The heart of this suite there is an algorithm which models the dynamics of the crowd by using a ***least effort*** algorithm. It treats every person (entity) in the crowd as an individual, calculating their positions by scanning their local environment and choosing an appropriate, humanlike, action.

1.1.1 The *least effort* algorithm.

Suppose we have N entities, with an entity i at position (x_i, y_i) inside a region R of the plane R^2, representing the accessible parts of a building. Each entity's path P_i through the building is constrained: first, by the entity's speed distribution, and secondly by the requirement that entity i visit certain places or subregions of the building in some order. Call the set of ***all*** these constraints on the entity i's path C_i.

There are also non-collision constraints K_{ij} which asserts that entities i and j cannot occupy the same position at the same time. There is a ***cost*** function $u(P_i)$ for example, length, total time, effort. For a set P of paths P_i satisfying constraints C_i and K_{ij}, there is a total cost $U(P) = u(P_1) + ... + u(P_n)$. The problem is to minimize U(P) subject to those constraints, thereby finding the set of paths (flow pattern of the crowd) that requires the ***least effort*** (in total). This optimization problem can be solved by a type of simulated annealing, iteratively starting from a set of paths P, randomly varying it, seeing if the cost goes down, and if so choosing the cheaper set of paths; then repeat. The algorithm stops when it fails to improve the solution.

It can be shown that the algorithm solves the problems of calculating the dynamics of a large population (>100,000) in the simulation in polynomial time.

Further detail of the algorithm is subject to a commercial non disclosure agreement. However, we discuss its inputs, outputs and the validation process in this thesis. We also examine the emergent phenomena, unique to crowds, which can be examined using the simulation suite and the ***least effort*** algorithm.

1.1.2 Introduction to the Legion tools

The Legion tools consist of a prototype development suite, a C library, a model builder and simulator (commercial products developed for client projects) and a replayer, which allows the clients to view, review and analyse their models.

With Legion it is possible to alter various parameters and study the effects of, for example, increasing the crowd density. The use of a simulation provides us with two important perspectives. Firstly, the simulation provides us with insights to the nature of crowd dynamics, often it is the insight to the problem that leads us to the solution. Secondly, the simulation can be used to prove or disprove a variety of relationships observed in the crowd, for example, it is presently assumed that doubling the width of an egress route will double the flow of people on that route, but this turns out to be wrong.

Applications include modelling multi-venue events, such as the Olympics Games. Figure 1 shows the screen display from the Legion replayer and Figure 2 shows the plan of the same area of the Sydney Olympic Park.

Figure 1 - Legion replayer model. Stadia and general layout.

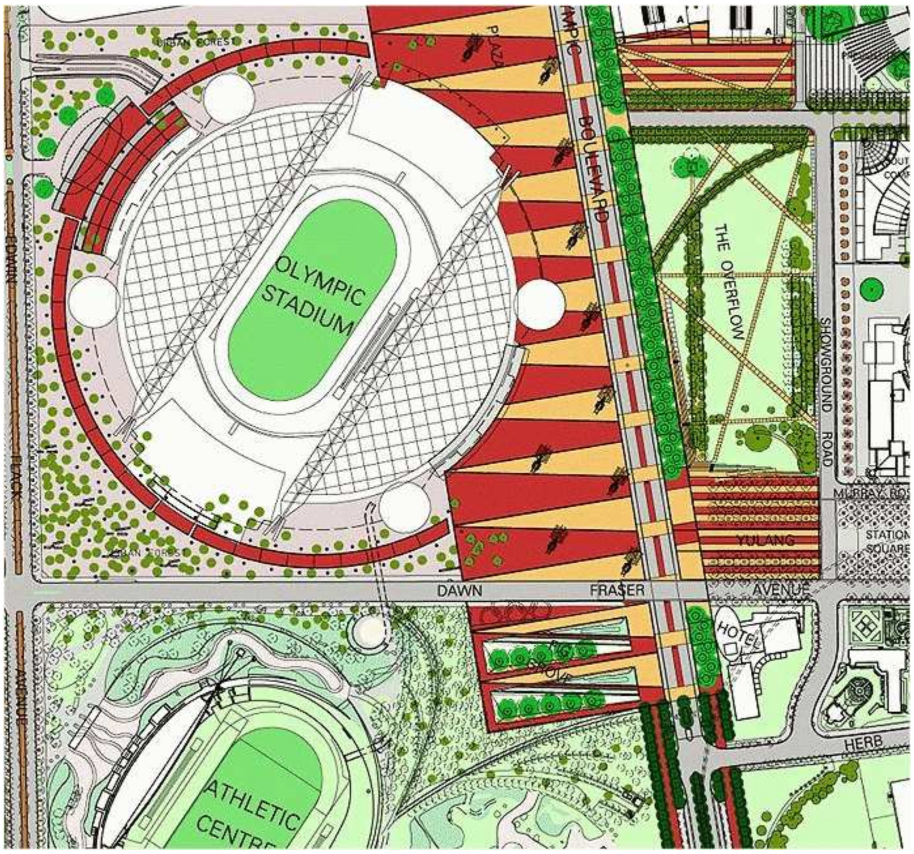

Figure 2 - Sydney Olympic Park. General plan and location of stadia.

The boulevard and rail station are a common domain for all venues. Loading and unloading crowds are simulated using the Legion system (Figure 1).

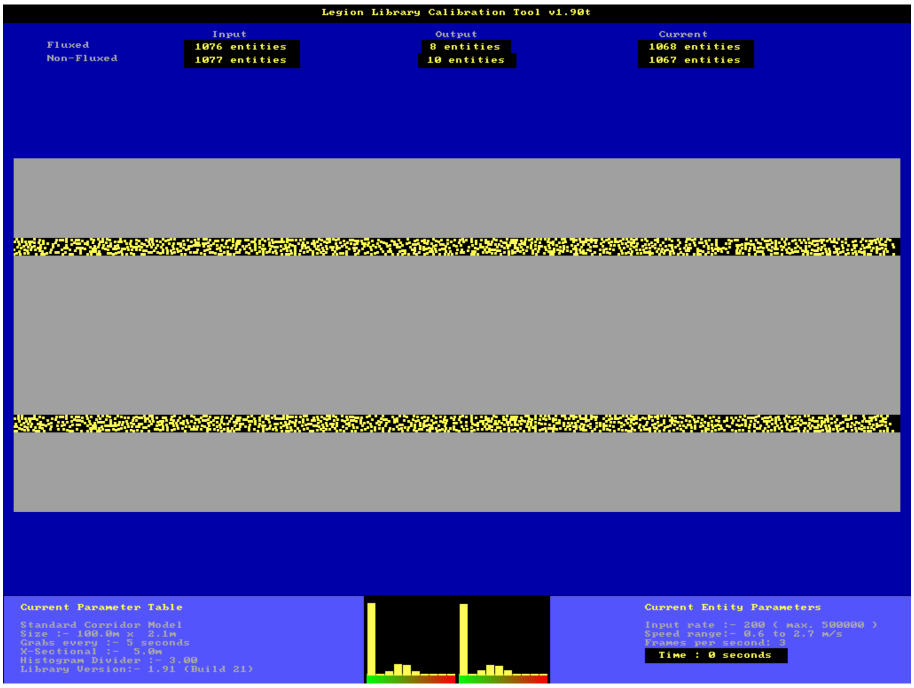

Figure 3 - The display screen of the validation tool (chapter 6)

Figure 3 shows the validation tool displaying the entities (yellow dots) moving along two corridors (grey = walls). During the simulation run the entities move around the screen, avoiding each other and the local geometry.

1.2 Brief synopsis of chapters 2 - 9

In chapters 2 and 3 we discuss the various problems relating to crowd movement and crowd safety. We discuss the problems of applying the present guidelines and review the various methodologies used to assess crowd safety. We also discuss the application of a variety of techniques presently used to model crowds and review the existing literature.

Chapter 4 discusses the principles of computer simulation, the problems of developing a suitable model of crowd dynamics and the parameters required for accurate crowd modelling. We relate the psychological factors of human decisions to a mathematical framework, using the four rules which define the ***least effort*** algorithm: Objective, Motility, Constraint and Assimilation.

In chapter 5 we discuss the various inputs to the Legion simulation suite, why they were chosen and the relevance they have in determining the parameters for assessing crowd risk and crowd safety. The entity behaviour, and its significance to simulating crowd dynamics are also discussed in chapters 5 and 6.

Chapter 6 discusses the validation of the algorithms and compares the results to field observations and historical studies. We examine the qualitative and quantitative data, the results of the Legion analysis and the emergent phenomena which are unique to crowds.

Chapters 7 and 8 discuss case studies using the tools we have developed.

Chapter 9 draws the previous chapters to a conclusion and indicates the scope of the simulation, how and where it should be applied and the potential future developments of the Legion methodology.

It is important to understand the framework for the development of these tools and we need to outline the various guidelines which are used to define crowd safety in places of public assembly.

1.3 The Guides

There are a number of documents which have been produced to advise on crowd safety issues. The relevant documents are the ***Green, Purple*** and ***Primrose Guides***. The guides are advisory documents for use by competent persons. They are the distillation of many years of research and experience of the safe management and design of places of public assembly. The guides have no statutory force but many of their recommendations are given force of law at individual sites by their inclusion in safety certificates issued under the Safety of Sports Grounds Act 1975 or the Fire Safety and Safety of Places of Sport Act 1987. The advice given in the ***Guides*** is without prejudice to the application of the appropriate building regulations, the Health and Safety at Work Act 1974, and any other relevant legislation.

1.4 Crowds and occupant capacity

The maximum size of the audience for a particular event is generally determined by the licensing authority (taking advice from the fire authority) and is known technically as the "occupant capacity". This will include all ticket holders, pass holders and guests. The method for establishing this capacity is calculated by finding the total area available to the public (in square metres) and multiplying by 2, where 2 = two people per square metre. For example: An outdoor site measuring 100 metres x 50 metres with all areas available to the public could accommodate a maximum of 10,000 people (100 x 50 = 5,000 sq. metres x 2 = 10,000 people). We will discuss the naivety of this type of calculation in later chapters.

1.5 Nomenclature

Crowds have certain interactions which are part fluid, part granular and part psychological reaction. The nomenclature we will use as follows.

Unimpeded speed	The individual, free space, walking speed
Least effort	The easiest path or route from A to B that individuals take as they progress through an environment. This can be reduced to two simple algorithmic rules. 1. Individuals will take the shortest available route to get from source to destination. 2. Individuals try to move at their normal speed.
Focal routes	A focal route is the shortest (***least effort***) path an individual would take to reach their destination.
Multiple path interference	When more than two focal routes cross

Crowd speed The emergent speed of a group of individuals. The speed/density relationship is not a constant value but is a function of the local geometry and the interactions within the group/crowd.

Space utilisation The use of space over time (that is the relative proportion of time in which a given region of space is occupied). An area of low space utilisation is rarely used and an area that is in constant use has a high space utilisation.

There are other effects which we introduce during the discussion on validation in chapter 6. These relate to the emergent phenomena unique to crowds, such as the fingering effect seen in areas of high density bidirectional flows, crowd compression effects which alter the dynamics of crowd movement, and edge effects where speeds are distributed within the crowd.

The author has attended and worked alongside many crowd safety engineers, security staff, stadium managers, computer programmers and mathematicians for the last 10 years. The author is a regular visiting speaker at Easingwold, (the Cabinet Office Emergency Planning College) where he runs a three day crowd dynamics workshop to those people responsible for the safety of crowds at public venues. The inclusion of the photographs, illustrations and diagrams, are based on the experience of meeting, talking, lecturing and learning from that audience.

Chapter 2 Crowd problems and crowd safety.

2 Introduction

In this chapter we discuss the problems of crowd dynamics and the fluid analogy using areas of Wembley Stadium to illustrate various crowd safety features.

2.1 Keeping the crowd out of danger: an overview

Designing an effective evacuation (egress) strategy for places of public assembly is a formidable problem. Every building is unique and operational efficiency during emergency egress cannot be fully tested until a real crisis occurs. Therefore the challenge is in anticipating the problems that may occur during an emergency, especially where they relate to the complexity of human behaviour. If the design could be constructed in advance, it would be possible to perform qualitative and quantitative risk assessment by destructive testing. Unfortunately it is not feasible to test every layout for every possible scenario. It is also unethical to expose people to real emergencies in order to analyse their behaviour and reactions.

There is a saying in the industry To ignore the danger is to deserve the disaster. Computer simulations are one method of addressing the problem. A range of network flow, crowd and egress analysis systems are available on the market. They are all useful, but no single system provides a comprehensive range of scenario testing for safety engineering purposes. Many treat human traffic as blocks of uniform individuals moving as one. Some systems use the mathematics of fluid dynamics to predict human flow patterns. Some systems are based on assumptions that are fundamentally flawed.

Furthermore, the present guidelines have inconsistencies which can lead to misinterpretation. These need to be highlighted and an alternative methodology used.

The objective of this research was to develop a model of crowds, specifically aimed at the issues of, and to define numerical standards for, crowd safety.

We chose to study stadia as they have been part of our culture for the last four thousand years. Why we need a tool for assessing crowd safety is highlighted by the following catalogue of disasters from around the world.

2.2 A catalogue of catastrophes

There are inherent dangers associated with every large public gathering. Every year there are reports of overcrowding and crushing incidents from around the world. To put the problem into perspective, the following list highlights just some of the events that have ended in tragedy.

1964 - 300 die in a stampede after goal disallowed, Olympic qualifying match. **Lima, Peru**.

1968 - 74 died when a crowd stampeded after burning paper was thrown onto terraces. Fans head towards a closed exit and are crushed against the doors. **Buenos Aires**.

1971 - 66 died when barriers in Ibrox collapse during football match. **Glasgow, UK.**

1974 - 49 trampled to death as crowds break barriers. **Cairo.**

1979 - 24 died and 27 injured in a stampede as fans stampede during a light failure. **Nigeria**

1981 - 24 died in a stampede as fans rush to leave ground. **Piraeus, Greece**.

1981 - 38 injured during a crowd surge at Hillsborough Stadium. **Sheffield, Great Britain.**

1982 - 340 died at European Cup Match between. Incident occurs when fans, leaving stadium, try to re-enter after last minute goal. **Moscow, Russia**.

1982 - 24 died and 250 injured in a stampede, caused when drunken fans provoke a stampede. **Cali, Columbia**.

1985 - 10 died and 29 injured trying to force their way into a stadium. **Mexico City**.

1985 - 39 died at Heysel Stadium when riots break out and wall collapses. **Brussels**.

1988 - 70 died in stampede towards locked exits in a hailstorm. **Katmandu, Nepal**.

1989 - 95 died when police open gates to alleviate crowding. Hillsborough, **Sheffield, UK.**

1990 - 1,426 died in stampede in overcrowded pedestrian tunnel. **Mecca, Saudi Arabia**.

1991 - 40 died along fences when fans try to escape fighting. **Orkney, South Africa**.

1992 - 50 injured falling from upper tier of Maracana Stadium when part of the fence gave way when 150,000 fans await the Brazilian championship final. **Rio de Janerio**.

1994 - 270 died in a stampede during stoning the Devil ritual. **Mecca, Saudi Arabia.**

1996 - 83 died and 180 injured at a World Cup qualifying match. **Guatemala City**.

1998 - 150 Muslim pilgrims crushed to death in a stampede. **Mecca, Saudi Arabia**.

1999 - Jan 15th - 51 Hindus killed and 100 injured in a stampede after part of a shrine collapsed. Over 1.5 million present at ceremony. **Kerala, India**.

1999 - May 31st - 54 dead, 150 injured, 78 hospitalized (35 still on critical list) when a crowd of 2,500 rushed to get out of the rain at the railway station. **Minsk, Belarus.**

2000 - June 28th - 8 trampled to death at rock festival. **Roskilde, Copenhagan, Denmark.**

2000 - July 12th - 12 die, dozens injured as crowd flees from police tear gas. **Harare, South Africa.**

2.3 Gate C

Crowd behaviour can be anticipated, even when it appears counterintuitive. Figure 4 shows the top of the stairs at gate C of Wembley. There is a gap in the fence where supporters can take a short cut by walking up the embankment and ducking under the hand rail (Figures 5, 6 and 7).

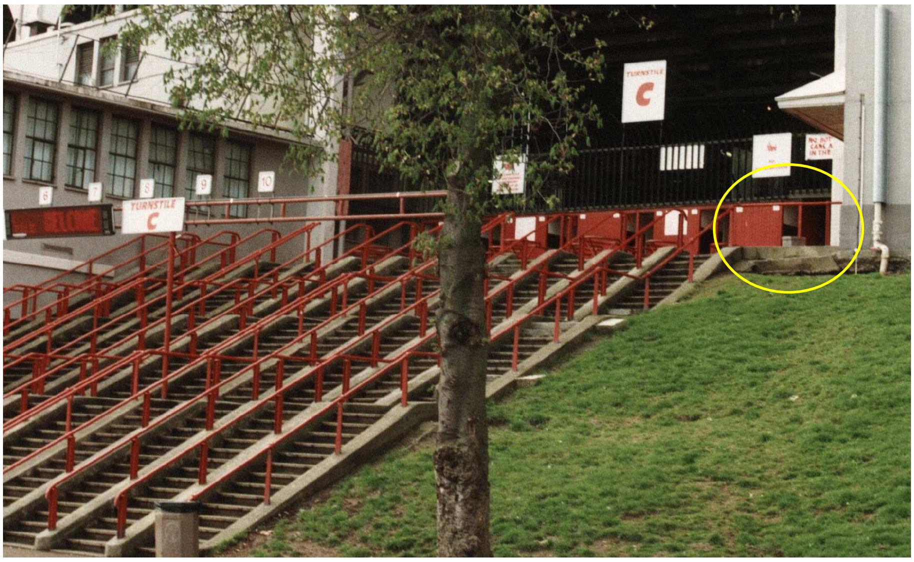

Figure 4 - The gap offers a view of the turnstiles, especially when the stairs are full

The view of the short cut is shown in Figure 4, as seen from the approach to gate C along the main concourse. As the crowd occupies the grass embankment (Figure 6) it is natural for those people simply to use the available gap in the fence as a short-cut (Figure 7). This exploitation of a short cut is a ***least effort*** behaviour.

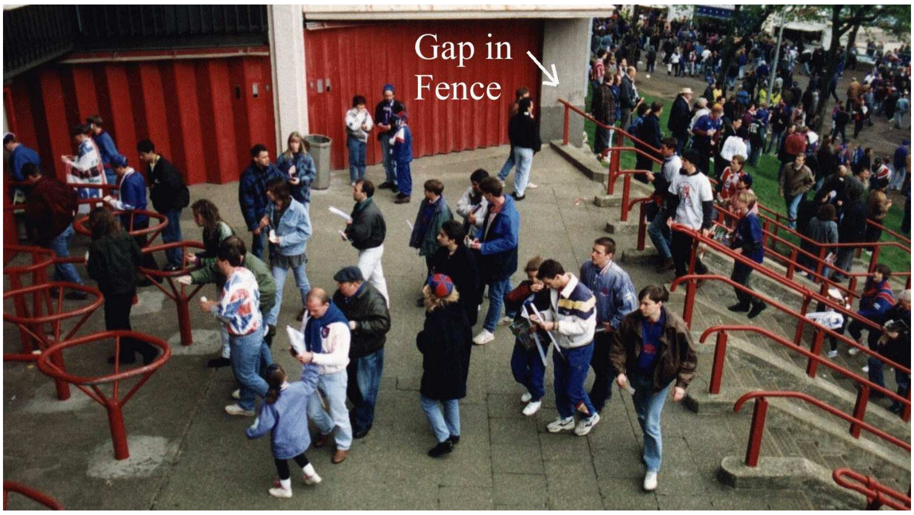

Figure 5 - Gate C with people waiting and coming up the embankment

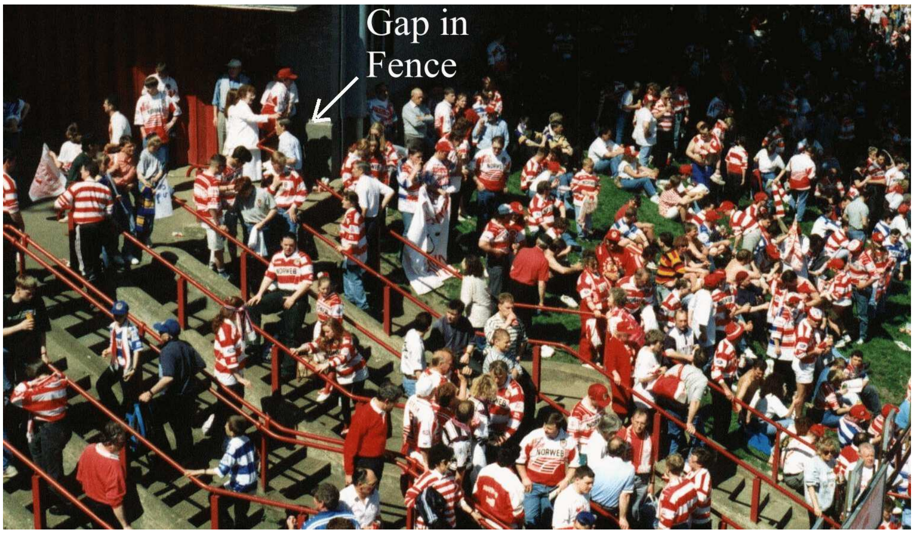

Figure 6 - Gate C - the embankment is used as a seating area prior to entry

It was noted that a few people cutting through this gap can effect the movement of the people on the stairs. In 1992 the author stood in the stair queue for four hours while a stream of people moved up the embankment to gain entry. The area on the upper stairs, in front of the turnstiles, is 15 by 7 metres (105 square metres) and counts of 400 to 500 people can be observed during a typical ingress.

Figure 7 - Using the short cut from the embankment to the turnstiles.

Between 3 and 5 people per square metre are typical of the normal ingress density. When patrons exploit the short cut under the railing, a triangular phalanx forms which pushes toward the turnstiles (Figure 8) this impedes the flow of patrons on the stairs. The phalanx creates a lateral pressure across the top concourse, pinching off the crowd flow up the stairs. The problems are: how to assess the impact of this flow, and how to optimize the crowd dynamics for these turnstiles. The answers lie in understanding the nature of crowd dynamics.

2.4 The players tunnel

Between B and C turnstiles there is a tunnel where the players enter the stadium (bottom left in Figure 8). This area is a focus of attention when the team coaches arrive. The crowd is held clear of the road by police horses. When the coaches pass into the tunnel the horses move aside and the two crowd, to the left and right of the tunnel, flow past by each other. The crowds can be seen in Figures 9 and 10.

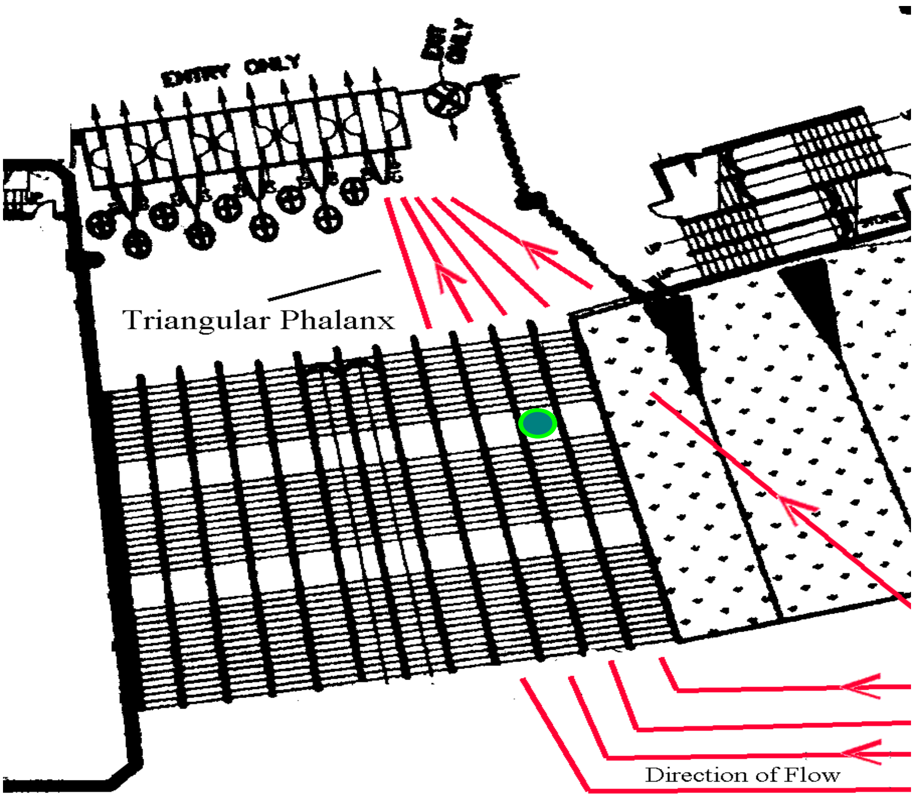

Figure 8 - Plan of gate C showing how people exploit the short cut and it effect on the crowd dynamics on the concourse. The problem is solved by closing the gap.

In this high density crowd movement we observe the phenomenon of self-organized, bidirectional, flow. Where two opposing flows self-organise into long chains of people passing each other, like conga lines at a party, flowing easily through one another - a phenomena unique to interactive systems but not fluids.


Figure 9 - View from top of players tunnel - bidirectional crowd flow.

Figure 10 - Zoom of Figure 9 showing the ***fingering*** patterns forming

Similar patterns are often seen in densely crowded areas. We shall examine how and why this occurs and how they form in crowds in chapter 6.4.7.

2.5 The fluid analogy

After the observations at gate C in 1992 an investigation began into the literature relating to crowd movement and the legislation relating to crowd safety. The literature was sparse, assumptions of average density and average flow were used to indicate safety limits, for example, in the Building Research Establishment document [29]. The papers were inconsistent with the observations!

Crowds are often described in fluid terms, a sea of people , ebbing and flowing like a tide the language rich in fluid analogies. Egress routes and building designed are based on the fluid flow assumption ***Flow volume = Average speed x Average density***. Also, the assumptions that crowds flow like a fluid implies that the fastest flow is down the centre, as in Poiseuille flow [30]. Yet field observations clearly demonstrate that crowds move more quickly at the sides. Clearly there was a need for further research into the phenomena observed at Gate C.

2.5.1 Why is the fluid analogy untenable?

Understanding crowd dynamics is essential for understanding crowd safety. In 1992, at gate C, a small flow of people, coming up along the edge of the queue via a grass embankment, had an effect on the operation of the turnstiles. This small flow effectively blocked the forward motion of the crowd. No such phenomenon occurs in fluids, so there have to be some fundamental differences between crowd and fluid flows. The laws of crowd dynamics have to include the fact that people do not follow the laws of physics, they have a choice in their direction, have no conservation of momentum and can stop and start at will. They cannot be reduced to equations which are appropriate for the movement of ball bearings through viscous fluids [31].

2.5.2 Definition of crowd density

In the ***Guides*** the safety limit for crowd density is defined as 40 people in 10 square metres for a moving crowd and 47 for standing areas. The following problem of a crowd filling an area was highlighted in the Taylor Report [32].

2.5.3 Crowds find their own levels.

It was assumed that people entering an area will distribute evenly across the available space. The conjecture is that a crowd finds its own level is based on a fluid model of a crowd. This assumption implies that the crowd has complete awareness and behaves in a sensible manner for the benefit and safety of all the individuals in that crowd. It also assumes that individuals in the crowd are free to migrate across the available space. This is not the case when an area such as a pen, front of stage or station platform is filling to capacity; there is little room for the individual to manoeuvre to lower density. In those environments people compete for space.

2.6 Two key questions

There are two key questions which arise from the assumptions of crowd behaviour. Firstly, do crowds find their own levels as claimed? Secondly, as previously reported statements indicate, do crowds flow like fluids?

As the initial interest in crowd dynamics occurred at Wembley Stadium, permission was sought, and duly granted allowing the author unlimited access over a two-year period (1994 and 1995). The management team headed by operations director George Wise (now retired) allowed access to available historical video footage, attendance of all the major events for the two year duration of the field study, maps of the local area, plans of the stadium and access to observation points, from which the public are normally excluded, for photographs and observations.

The stadium has a capacity of 82,000 and hosts football, rugby, concerts, greyhound racing and wrestling. All of the approaches to the Wembley area are monitored for a radius of 20 miles (via police cameras situated on motorways) where traffic can be observed and the event can be delayed if necessary.

Although Wembley Stadium has no history of any crowd related disasters, the staff are aware that complacency is the biggest threat to public safety.

2.7 Ingress safety at Wembley

Wembley Stadium (Figure 11) hosts a variety of events. Patrons arrive by a number of means (trains, coaches, cars, and the London Underground system). For sporting events, all of the supporters can arrive in a relatively short space of time (30 - 90 minutes). 30,000 supporters can arrive in the hour prior to kick-off.

Figure 11 - Aerial view of Wembley Stadium showing location of the gates.

To analyze the operating parameters of Wembley it is necessary to study the records of the turnstile computer. This information is recorded. Ingress numbers are printed and a copy is kept as an archive. The computer system also records the flow rates during ingress but those data are available only during the event.

2.7.1 Wembley turnstile data

Every turnstile at Wembley Stadium has a counter which is tripped when a person enters. The final count through each turnstile is recorded.

Some data (stored on floppy computer disk) were recovered from previous system tests. Along with the 1994 FA cup final, which was recorded and video taped. Those data are used to illustrate the problems of late arrivals and the impact of changing flow rates. The ingress distribution for the turnstiles for several football events at gate C is shown in Table 1. The usage is not evenly distributed and Figure 12 shows the graph of this distribution.

Gate C	91/04/14	91/05/18	34057	93/03/31	94/05/14	96/04/11	97/04/09	Total	Average
1	677	646	8	397	385	575	94	2782	397.43
2	612	794	96	605	586	672	166	3531	504.43
3	573	803	80	644	541	508	200	3349	478.43
4	736	915	237	643	810	678	327	4346	620.86
5	902	734	176	752	770	546	263	4143	591.86
6	1004	1157	77	843	875	655	409	5020	717.14
7	924	934	135	743	638	848	384	4606	658
8	1268	920	257	1074	962	979	591	6051	864.43
9	1090	1084	297	1021	699	797	648	5636	805.14
10	1292	1188	496	953	801	800	719	6249	892.71
All	9078	9175	1859	7675	7067	7058	3801	45713	6530.43

Table 1 - Gate C Wembley Stadium ingress over several (football) events showing various event dates (horizontal axis) against turnstile counts (vertical)

It is clear from the histogram that the turnstiles are not being used evenly. In fact turnstile number 10 has an average total ingress double that of turnstile 1.

The crowd approaches the turnstiles along the concourse (Figures 4 and 8) and the nearest turnstile is 10. We examine this uneven usage in chapter 3.4 (Effects of geometry) in more detail.

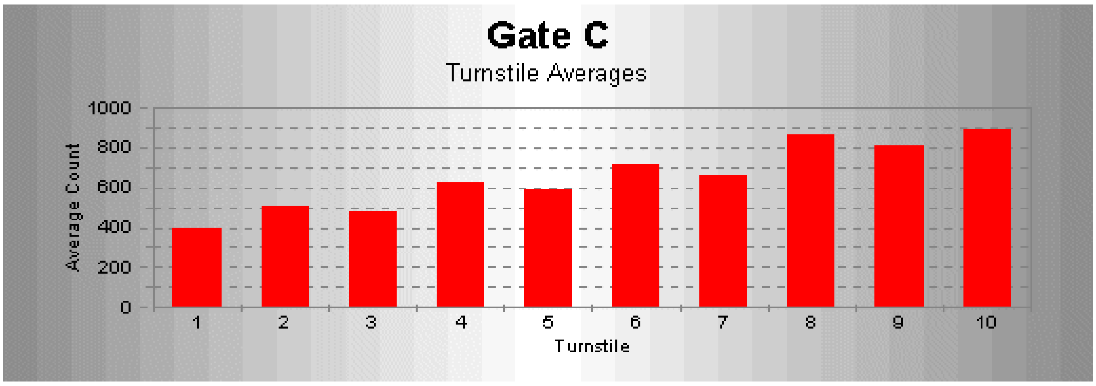

Figure 12 - Histogram of turnstile usage at gate C (averaged over several events)

2.7.2 Wembley ingress capacity

Wembley Stadium has 10 turnstile groups and 2 gallery entrances. The gates are labelled A, B, C, D, F, G, J, K, L and M and are all operated by turnstiles with entry numbers and flow rates shown on the main computer in the control room. The

Olympic gallery entrances are labelled E and H and have a manual ingress count.

Gates A, B, C, D, F, G, J, L have 10 turnstiles each, M has 8, K has 12 but 11 and 12 are not used. The stadium capacity is 82,000, with an ingress capacity of 660 per turnstile per hour, the total capacity is 660 x 98 = 64680 per hour or 1078 per minute. It would therefore take 76 minutes to fill the stadium given an even distribution of patrons to each turnstile. The gates are opened 2 hours prior to kick-off for football matches. It is clear that ample time has been allowed for orderly, safe ingress. The wide concourses and the stairs leading up to the turnstiles act as passive crowd management aides, by design.

The records for four events are summarized in Figures 13 to 20. These show two graphs (side by side for each event) of the entry counts per minute (left hand graph) and the counts per minute (right hand graph). Both graph types have time across the horizontal axis and start when the gates open. The slope of the right hand graph gives an indication of the entry rates. The important feature to note is the shape of the left hand graph (the initial peak is when the gates open and the initial waiting crowd enters). The plateau shows the majority entering. The gap between the peak and plateau indicates the differences in the walk-up (the name given to the mass of fans arriving close to kick-off) and those patrons who arrive in good time for the gates opening. Two other noteworthy features are the slope on the tail end of Figures 13, 15 and 17 compared to the sharp drop for Figure 19. This indicates that there were more fans entering at a higher rate closer to the kick-off time.

This effect distorts the averages and a number of the turnstiles exceed the entry rate limit of 660 people per hour. This indicates that a potential problem exists but is hidden in the data. If we average the peak flow over the duration of the peak flow we find that many turnstiles are operating at a flow rate > 800 people per hour.

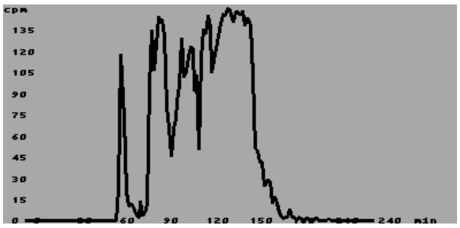

Figure 13 - Counts per minute

14th April 1991
FA Semi-Final
Max. 140 ppm
Total count
76,467

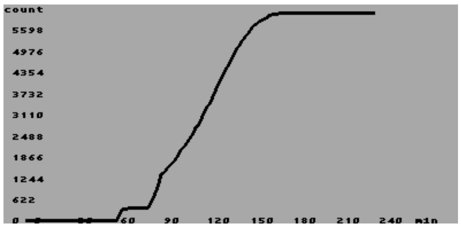

Figure 14 - Entry count per minute

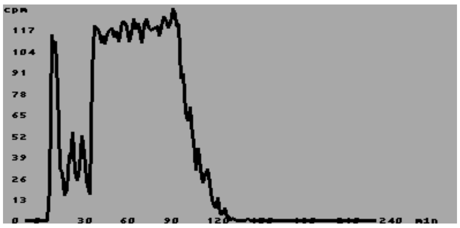

Figure 15 - Counts per minute

18th May 1991
FA Cup Final
Max. 120 ppm
Total Count
79,079

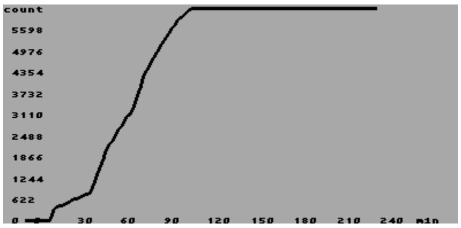

Figure 16 - Entry count per minute

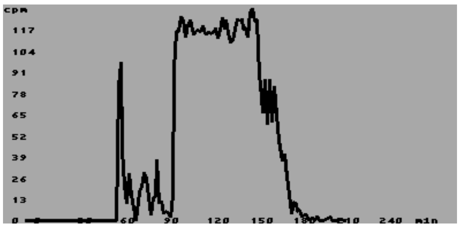

Figure 17 - Counts per minute

31st March 1993
1st Division
Playoffs
Max. 120 ppm
Total Count
72,455

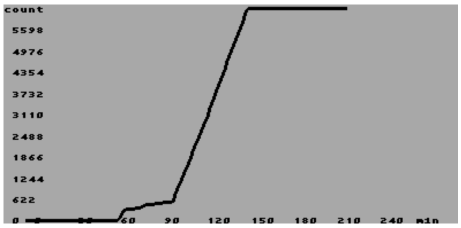

Figure 18 - Entry count per minute

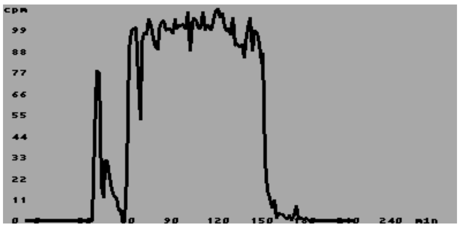

Figure 19 - Counts per minute

14th May 1994
FA Cup Final
Max. 120 ppm
Total Count
78,579

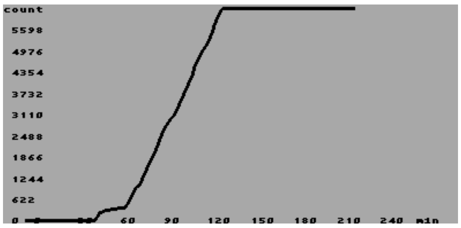

Figure 20 - Entry count per minute

It is worth noting that these graphs were obtained by taking a series of screen grabs from the turnstile computer system. The process involved taking a copy of data from the main computer (not automatically saved) after the event, and running it on a different computer to obtain the graphs. It was not possible to extract this data from the archived materials kept at Wembley Stadium in a single process. The same system is still in operational use and the flow rates are not recorded or analysed for trends in arrival patterns.

2.7.3 G and J turnstiles

When the concourse area is empty, the perception is that the area has ample space for crowd circulation.

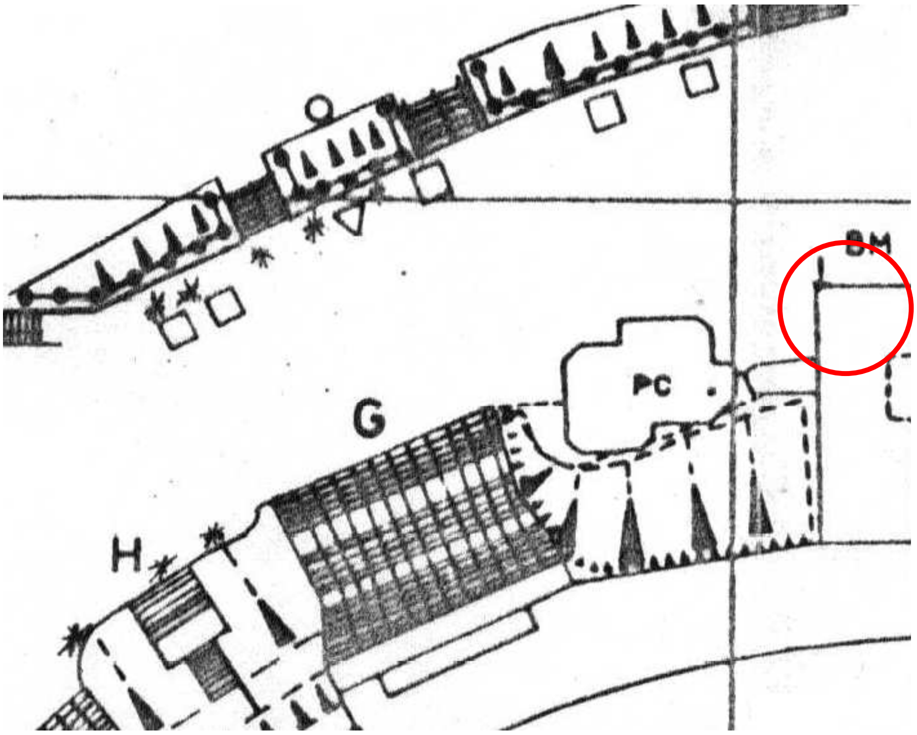

Figure 21 - Plan of G, H and J (far left) turnstiles and concourse area (Wembley Stadium)

The main line railway station is to the left of Figure 21, the car parks are at the top of the plan, and the tube station is to the right of the plan. The area in Figure 21 is the most congested area of the Wembley concourse. It measures some 23 metres in width. From a vantage location, circled in Figure 21, the scene in Figure 22 was found to be typical of a normal crowd ingress to the stadium.

The concourse area by G, H and J turnstiles is multidirectional with crowd flows from both left and right (car parks at either side, underground and main line railways). There are toilets below the walkway (entrance to the Exhibition Hall), and there are a number of concessions (hot dog stands, merchandising, etc.). Concession stands lead to queuing and interferes with the overall crowd flow. G, H and J turnstiles are of concern due to the congestion on the concourse in the illustrated areas. The flow patterns and crowd dynamics in this area appear chaotic.

Figure 22 - The heads and faces show no clear sense of direction in this crowd.

Crowd sway, when a congested crowd moves from side to side, can lead to problems. The edges of the crowd, in a confined space, can reaches high density and supporters are in danger of being injured by being crushed against any solid walls.

As Figure 22 shows, the crowd is very tightly packed. It can be seen from the way that the heads are facing that there is no clear sense of direction. Should there be a need to clear this area there is no identifiable egress route. Yet, at densities of 5 to 8 people per square metre - the crow still flows in a bi-directional manner.

2.8 Wembley Complex Station.

The Fire Services College prepared a guideline for existing rail surface stations [35, 36] which echoes the ***Guide*** recommendations of egress rates:

$$\textbf{No. of Units of Exit Width required (each width = 0.55m)} = \frac{\textbf{Number of Persons (1)}}{\textbf{Flow Rate (2) x Evacuation Time (3)}}$$

Where number of persons (1) means the maximum number of people that could be expected to be on a platform at any time. Flow rate (2) means 40 persons per minute for escape routes incorporating stairs, and 60 persons per minute for level escape routes (without stairs). Passenger walking speeds should be assumed to be 38 metres per minute for horizontal circulation. These figures are based on research by John Fruin [6]. Table 2 indicates the square metres per person related to this Level of Service category. We question these assumptions in chapter 3.2.

Fruin - Level of Service Category

Level of Service	A	B	C	D	E	F
Walk ways	>3.25	3.25 to 2.32	2.32 to 1.39	1.39 to 0.93	0.93 to 0.46	< 0.46
Stairw ays	>1.85	1.85 to 1.39	1.39 to 0.93	0.93 to 0.65	0.65 to 0.37	< 0.37
Queuing Areas	>1.21	1.21 to 0.93	0.93 to 0.65	0.65 to 0.28	0.28 to 0.19	< 0.19

A = Free Flowing	D = Restricted mo vement for most
B = Min or Conflicts	E = Restricted mo vement for all
C = Some Restrictions to Speed	F = Shuffling movemen ts for all

Table 2 - Fruin Level of Service data

Evacuation time (3) is derived from the ***Green Guide***, which takes into account the maximum flow rate figures, the provision of fire safety measures, and emergency exit routes.

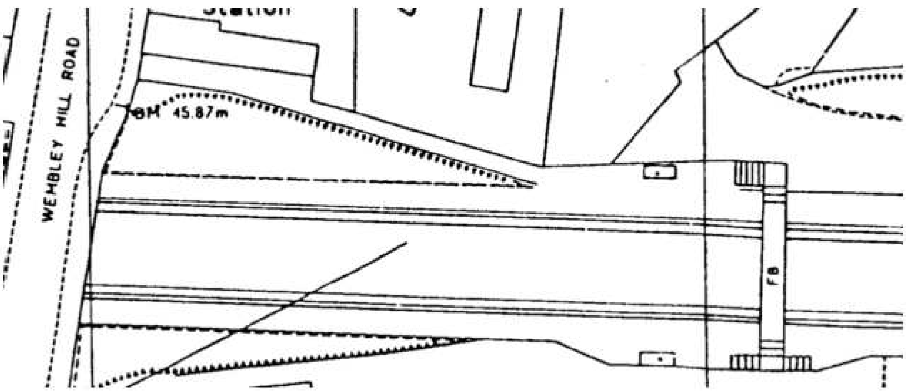

Figure 23 - Enlarged plan of Wembley Complex Station platforms

The maximum capacity of a train coach will not generally exceed 100 persons. The platforms are serviced via two bridges from Wembley Park Road (left and right of Figure 23 and in background of Figure 24). The left-hand bridge (Figure 23) is a pavement/road whereas the bridge (Figure 24) is a footbridge only.

Figure 24 - Station platforms, as seen from Wembley Hill Road

South Way can be seen in Figure 25. It runs from the Wembley Hill Road to the stadium. During egress on 28th May 1994 South Way was full of supporters, jubilant after their resounding victory; spirits were high and a party atmosphere prevailed. Had they lost, the behaviour of this group would have been different.

Figure 25 - The queue on South Way extends several hundred metres

Supporters who do not want to queue on South Way can walk round to the other platform entrance, via Wembley Hill Road. The narrow pavement and lack of crowd management measures, temporary barriers, or police monitoring, mean that queuing supporters spill over the pavement and onto the busy road (Figure 26).

Figure 26 - View of unregulated queue spilling onto Wembley Hill Road

2.9 Why we need something different

From the initial observation of the unusual crowd movements at Wembley Stadium several models of crowds were created. Initially built in a virtual reality environment, these proved to be computationally limited due to the time it took to calculate the collision detection of the virtual objects. This led to an extensive literature search and discussions with the authorities from the local fire officers, architects, design engineers, safety consultants, consulting engineers, the home office, the fire research station, the building research establishment and the construction directive.

These investigations raised further questions about the nature of crowd dynamics, and directed the objectives of the research programme. This initial work was followed by two seasons of crowd study, again at Wembley, in which the nature of crowd safety began to direct the course of development.

The field studies proved the contradictions of the fluid analogy as we can see from the photographs of Wembley Complex Station. On the platform (Figure 24) there are sections of the platform (bottom right) that are empty, where the area in the middle is more densely packed. Yet the crowd outside the station appears to follow the fluid analogy where the crowd is finding its own level.

2.10 Analysis of the Hillsborough disaster (1989)

One of the worst disasters in British football history, where the crowd failed to find its own level, occurred at Hillsborough Stadium on April 15th 1989. Hillsborough had hosted similar FA cup semi-final matches, without incident, many times before. This included the same fixture between the same two teams the previous year. The circumstances that led to 95 deaths and over 400 injuries highlight the lack of understanding of the nature of crowd dynamics in these environments. They also signified a turning point in the attitude of management to safety, for the first time putting greater emphasis on human factors. The Archbishop of York said this at the Hillsborough memorial service.

Events of the magnitude of Hillsborough don t usually happen just for one single reason, nor is it usually possible to pin the blame on one single scapegoat... ...Disasters happen because a whole series of mistakes, misjudgements and mischance happen to come together in a deadly combinations.

It is not difficult to reconstruct what happened at Hillsborough. 24,000 Liverpool fans approached Hillsborough from Leppings Lane. 10,000 of them would make their way to the terraces (behind the goal) which were serviced by seven turnstiles. The late arrival of the fans created a dangerous crowd build-up by the perimeter gates. There was no single factor that led to those late arrivals and within 20 minutes the problems of crowd density, and hence crowd safety, became unmanageable. Approximately 5,000 fans were in danger of physical harm around the perimeter gates and turnstiles in Leppings Lane. In an attempt to relieve the pressure at the turnstiles, the police opened the exit gates (gate C - Figure 27) allowing 2,000 additional fans into the ground and towards pens 3 and 4 which were already full.

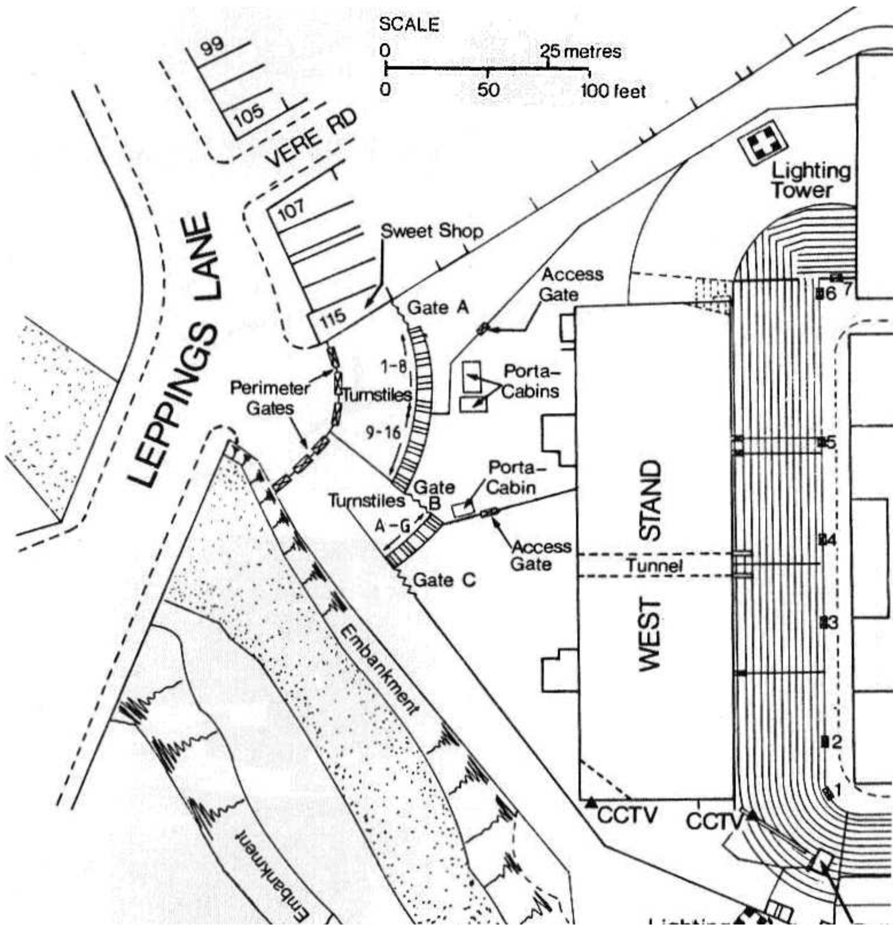

Figure 27 - Plan of the Leppings Lane end of the grounds at Hillsborough (1989)

The crowd approached the perimeter gates from the narrow bottleneck in Leppings Lane and the area was engulfed. In previous years, a line of police horses was used to filter fans at the perimeter gates. This was to ensure that fans without tickets did not enter the area and create a problem at the turnstiles. It was speculated that had this exercise been repeated the disaster might have been averted.

2.11 Conclusion

The disaster at Hillsborough and the observations at Wembley, gate C, J/G turnstile, and Wembley Complex Station, directed the main focus of research toward the safety of the individual in the crowd, for example protecting them from high density crushing. The catalogue of disasters serves as a warning against underestimating the enormous forces at work in high density crowds. The Hillsborough disaster illustrates the problems which can arise through lack of understanding, poor design and bad operational planning and management.

The Taylor final report [32, 33, 34] highlights the need for this research:

... tests can only be carried out by using real spectators. Bank computers and other computer technologies can be tested by putting through figures, data and printout. But the system can only be tested by putting through people. So in the very testing of whether the system may cause danger, danger may be caused.

Observations of how local geometry can affect the crowd can be seen in the movement and packing configurations on any busy station platform. The crowd did not find its own level. So, that respect, it does not behave like a fluid, either in motion or in nature. Yet, a few metres away, the behaviour of the crowd was fluid in nature exploiting the weakness in the management system along South Way and Wembley Hill Road. As a result the crowd appears to exploit the space and the routes which were not appropriately managed. This exploitation can be explained as a collective behaviour emerging from the individuals propensity to expend the ***least effort*** to reach their objective. In this specific example it is less effort to walk a longer distance to reduce the overall time to get home (including queueing for the train).

Density is not evenly distributed across areas of limited space. We shall examine the relationship of local geometry in more details in chapter 3.4 where we will look at the turnstiles around Wembley.

The objective we have set for ourselves is to determine the critical factors involved in crowd dynamics and crowd safety in places of public assembly. Specifically, the objective is to use the simulation tools to provide the user with a flexible what-if system to experiment with, test and educate themselves in the nature and problems associated with crowd dynamics.

Using such a simulation to supplement the existing legislation and building guidelines, to test various crowd parameters in a safe and thorough manner, is the ultimate goal. We can make the environment safer by design and test the limits of safety by using a range of tools including the simulation system.

The goal of the research is to improve all aspects of crowd safety through the use of a computer simulation and an appropriate methodology. To achieve this we have to understand the problems associated with computer modelling of both the dynamics and the behaviour of crowds.

Chapter 3 Crowd dynamics

3 Introduction

In this chapter we examine the present crowd and pedestrian planning tools, the existing body of literature, and the applicability of present techniques. Further references to the ***Guides*** and the work of John J. Fruin are examined in detail. We also highlight the dynamic effects of geometry on the crowd. We introduce how network analysis tools are used in the guidelines, Braess s paradox and the problems with the ***Green Guide*** network analysis are introduced and compared.

3.1 John J. Fruin - Pedestrian planning and design

John Fruin researched crowds in the early 1970's. His book ***Pedestrian Planning and Design*** [6] has been cited in many of the present guidelines for pedestrian planning. This research has become the standard for many subsequent building design and planning operations. References to Fruin have been universally accepted. Fruin states, in his book [6]:

The ideas expressed therin should be tempered by recognized engineering practices, guidelines, codes and standards.

Fruin, more than any other individual, has defined the criteria for safety standards in places of public assembly. He defined the level of service concept where the density and speed relationship are stated as guidelines for comfort and safety. It is important to note that Fruin made his measurements in a pedestrian street environment. Crowd behaviour on a city street with its many distractions is quite different from a stadium behaviour, and very different to emergency egress behaviour. The modem stadium has crowd densities in excess of the Fruin observations and therefore the application of Level of Service needs to be examined.

Fruin Level of Service						
Level of Service	A	B	C	D	E	F
Walk ways	>3.25	3.25 to 2.32	2.32 to 1.39	1.39 to 0.93	0.93 to 0.46	< 0.46
A = Free Flowing		D = Restricted movement for most				
B = Minor Conflicts		E = Restricted movement for all				
C = Some Restrictions to Speed		F = Shuffling movements for all				

Table 3 - Abridged version of Table 2 (Chapter 2.8.2)

3.1.1 Fruin Level of Service (LoS)

The following paragraph is paraphrased from Fruin [6 - page 19].

Body depth and shoulder breadth are the primary human measurements used in considering pedestrian spaces and facilities. Shoulder breadth is the major factor in the design of doorways, stairways etc. Many portals are designed to allow two or more persons to pass through abreast but actually have insufficient width for this purpose.

We examine the Fruin data and find that his measure for a fully clothed male labourer is 22.8 inches by 13 inches (57.9cm by 33cm). The author is 6 feet 3 inches (190 cm) tall, sturdily built (some may say overweight) and is larger than the average individual with a breadth of 53cm and depth of 28cm. Figure 28 shows the comparison of the Fruin body size and the author.

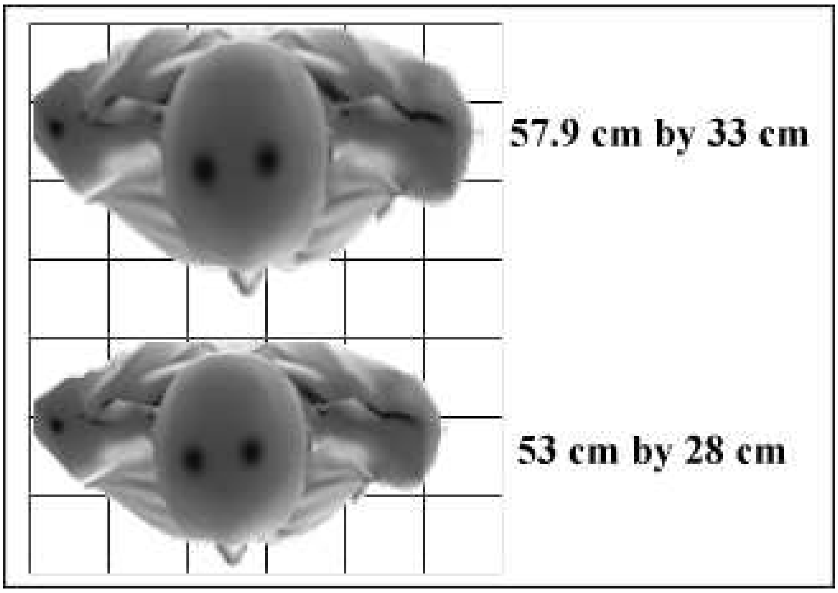

Figure 28 - The Fruin laborer 57.9cm by 33cm (top) profile and the author s 53cm by 28cm (bottom) profile. Note: The author is in the 95 to 99 percentile anthropomorphic size range.

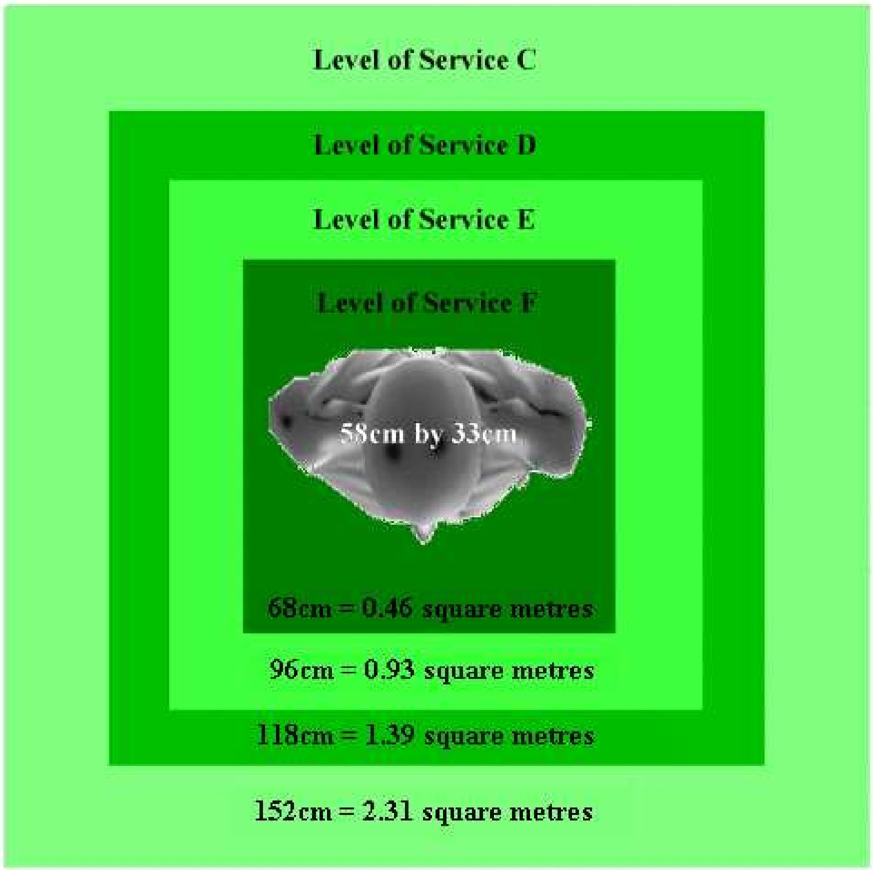

Figure 29 - The Fruin Level of Service area per person (metric scale).

The Fruin data appear to be generous, but we have to remember that the environments Fruin measured, and applied his level of service calculations, were predominantly city streets. There is no doubt that ***if the space is available*** then his guidelines represent ideal conditions. However, in the modern stadium space is a premium and crowds can accumulate beyond the measurements made by Fruin.

Fruin goes to great lengths to describe the applicability of his data and the LoS, but many users take the LoS as a de facto standard without consideration of the local environments. Body sizes differ and this needs to be considered for high density environments, in particular ingress and egress periods.

3.1.2 Anthropomorphic tables

Anthropomorphic sizes for a large cross section of the world s population were obtained from a database used by the US Standards [38] and are shown below:

Population	Breath (cm)	Depth (cm)	Area (m2)
British Males	51.00	32.50	0.26
British Females	43.50	30.50	0.21
Polish Males	47.50	27.50	0.21
Polish Females	41.00	28.50	0.18
Japanese Males	41.00	28.50	0.18
Japanese Females	42.50	23.50	0.16
Hong Kong Males	47.00	23.50	0.17
Hong Kong Females	43.50	27.00	0.18
Elderly Males	48.00	29.00	0.22
Elderly Females	41.50	30.50	0.20
USA Males	51.50	29.00	0.23
USA Females	44.00	30.00	0.21
French Males	51.50	28.00	0.23
French Females	47.00	29.50	0.22
Swedish Males	51.00	25.50	0.20
Swedish Females	42.50	30.00	0.20
Swiss Males	47.50	29.50	0.22
Swiss Females	45.50	32.50	0.23
Indian Males	45.50	23.50	0.17
Indian Females	39.00	25.50	0.16
Average	45.58	28.20	0.20
Maximum	51.50	32.50	0.26

Table 4 - Anthropomorphic sizes of the worlds population

The 95 percentile means that in any given population 95 percent of that population will have dimensions less than or equal to the figures given above. These apply to the unclothed individual. Fruin made the assumption of adding 1½ inches (3.81 cm) to the breath and width, to allow for heavy clothing. This appears to be an overgenerous allowance.

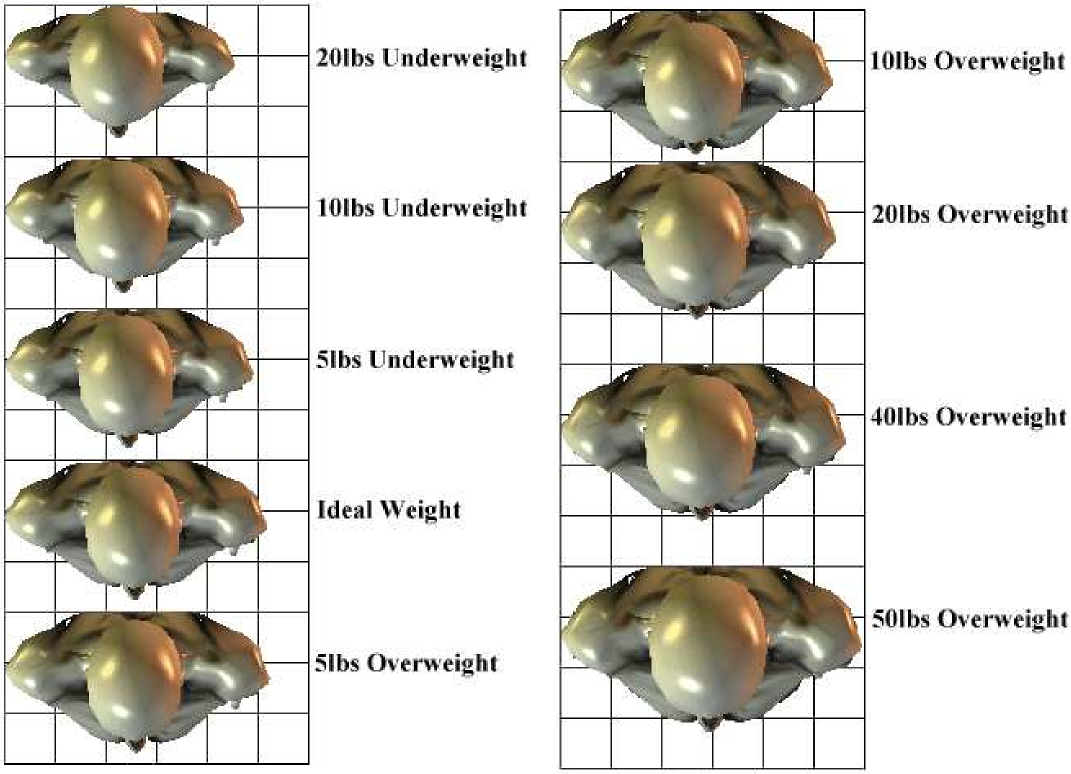

Figure 30 - Population by size

When these dimensions are drawn on a grid, we can determine the average areas, in 10cm squares (Figure 30). Taking a 50cm by 30cm profile, ideal weight, we can illustrate the Fruin LoS-D on a marked grid of 10 cm squares (Figure 31).

Fruin claims this represents restricted movement for most pedestrians. Observations at Wembley Stadium of crowds of much higher density contradicts this observations. The reasons for this apparent contradiction are found in the relationships between the people and the local geometry, and the relationship of the speed distribution, of the individuals in the crowd, to the crowd flow volume. People do not ***all*** move at the same speed and hence complex conflicts arise.

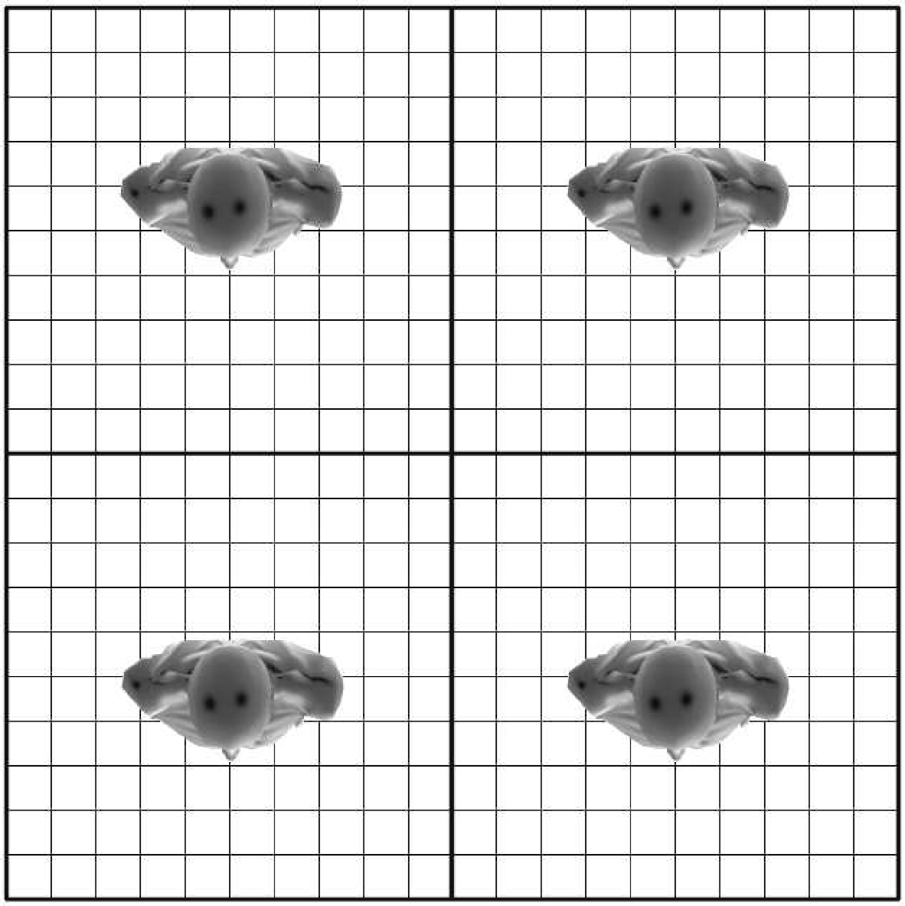

Figure 31 - Fruin Level of Service D (at 1 person per square metre)

The relationship between speed and density is a complex dynamical problem. It includes parameters relating to human decision making in a variety of densities.

3.1.3 Field observations contradict Fruin

The video footage from the Hillsborough disaster [39] shows 2,000 spectators flowing through gate C at a fast steady walk. This is confirmed in the Taylor Report [32, 33, 34]. The width of gate C is 4 metres. This gives the average flow volume of 100 people per metre width per minute. A fast steady walk is approx. 1.3 metres per second the density would be in the order of 1.28 people per square metre or LoS-E.

As this is indicated as Restricted movement for all according to Fruin, there is an inconsistency in the reported and recorded speed density relationship.

Densities of 4.7 people per square metre are typical in and around Wembley Stadium. We can see (Figures 9, 10 and 22) there ***is*** space to manoeuvre at LoS-D. Although such crowds are congested, movement is not, as Fruin suggests, ***virtually impossible*** [15, page 78]. The phenomenon of self-organisation gives the lie to the Fruin assumption. Furthermore the ***Green Guide*** [1, 2] indicates 109 spectators per metre width per minute, and this presents a very different relationship between crowd speed and crowd density.

3.1.4 Fruin Density v Speed

In ***Pedestrian Planning*** Fruin draws the following graph (Figure 32)

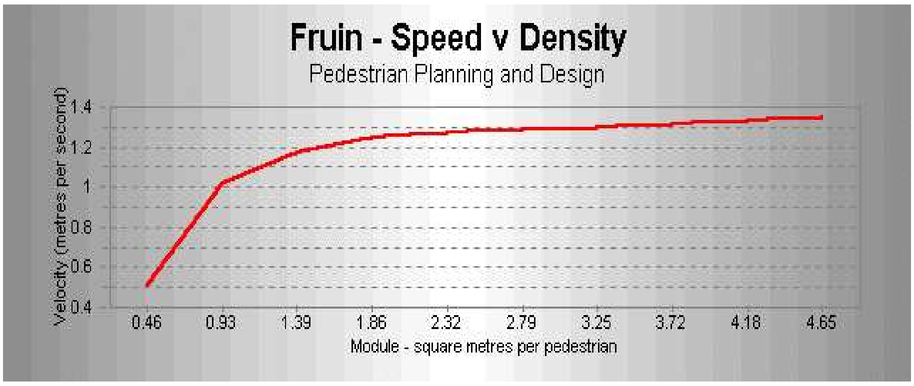

Figure 32 - Fruin speed v density graph from ***Pedestrian Planning and Design***

On the basis of the Fruin LoS, the conclusions are that the crowd exhibits marked speed reduction when space around a person is less than 1 square metre. This is true of a random, nondirectional crowd, such as one would find in a shopping mall or busy city street. Fruin has observed several situations in which his LoS does not apply and explains his findings as follows [15 - page 45].

Reportedly, marching soldiers in precise military formation, each occupying about 6 square feet (0.56 square metres), can attain flows of 48 pedestrians per foot per minute (157 people per metre per minute) for the width of the formation. However, normal pedestrian flows cannot maintain the precise cadence and area occupancy required to attain this flow on a sustained basis.

Where Fruin is correct in his observation there are phenomena of high density crowds which fall outside his reported observations. We illustrated, in chapter 2.4, the phenomenon of self-organization in bidirectional, high density environment. The ***fingering*** effect is spontaneous and high density crowd behaviour has other unique characteristics which we will discuss in chapter 6 - Validation.

3.1.5 Green Guide - density v speed

The ***Green Guide*** states that the ***capacity of an exit system is limited by its narrowest element . . .Where reservoir areas are used as part of an exit system, their capacity should be calculated on the basis of the appropriate rate of passage (109 people per metre width per minute). A density of 40 persons per 10 square metres of the area available for standing within the reservoir area is the maximum permitted for safety. It is the responsibility of management to ensure that this density is not exceeded.***

3.1.6 Fruin v the Green Guide

The ***Green Guide*** states that a maximum flow, for safety, is 109 people per metre width per minute. This figure is used throughout the ***Guides*** [1, 2, 5] worked examples as the base figure for calculation of both the egress capacity and flow rates. If the speed of the individual is been capped at a nominal 1.34 metres per second we can use it as a comparison to the Fruin data.

109 people per minute per unit (metre) width equates to 1.82 people per second per unit (metre) width. Using Flow Volume = Average Speed x Average Density [1, 2, 5] we can derive two tables: density and speed.

Average Speed	Density Density	(Capped at 1.34ms^{-1})	Average Density	Speed Speed
1.30	1.40		0.50	1.34
1.20	1.51		1.00	1.34
1.10	1.65		1.50	1.21
1.00	1.82		2.00	0.91
0.90	2.02		2.50	0.73
0.80	2.27		3.00	0.61
0.70	2.60		3.50	0.52
0.60	3.03		4.00	0.45
0.50	3.63		4.50	0.40
0.40	4.54		5.00	0.36

Table 5 - Calculated densities and speeds from the ***Green Guide*** figures

Togawa, Ando, Aoki and Oto [7, 8, 9, 10] studied the speed density relationship with respect to their development of a simulation system (based on grid matrix analysis) and derived the curve (Figure 84). This is comparable with the ***Green Guide*** calculations. Togawa [3, 26, 27, 28] derived a formula for the speed density relationship (Figure 33):

Walking velocity (V) = V_o $^{-0.8}$

Where is the density in persons per square metre, V_o is a constant 1.34m s^{-1}.

Figure 33 - The Fruin, ***Green Guide*** and Togawa (Japanese) speed density relationships

We compare this to the Fruin LoS and observe that the LoS criteria may be inappropriate at higher densities. We can also see that if we maintain the LoS concept then the safety margin is generous with respect to the ***Guides*** recommended speed versus density relationship. The ***Green Guide*** states.

When applying the guidance and recommendations in the Guide, it should be remembered that the principal objective is to secure reasonable safety at the sports ground when it is in use for the specified activity (as stated in section 2(1) of the Safety of Sports Grounds Act 1975). Absolute safety, however desirable in theory, is, in reality, unattainable.

To establish safety criteria, without a clear understanding of the levels of risk, we are not able to secure ***reasonable safety*** by definition. We need to define the speed versus density relationship more precisely than the LoS indicators.

3.1.7 Is high density unsafe?

We consider normal ingress packing density at Wembley Stadium as typical of a safe ingress. Gate C (Wembley) has 10 turnstiles and these have been measured at 660 people per hour per turnstile - in fact, they were the standards that set the

Green Guide measure. The packing density in that area exceeds the limit of 4.0 people per square metre (Figure 34).

Figure 34 - Gate C packing density exceeding 4 people per square metre.

At this packing density (gate C) Wembley allows 660 people per hour per turnstile (10 turnstiles) therefore 6,600 people per hour flow through these densities in safety. It is clear that we have to define a safety limit of high density exposure with respect to time.

3.1.8 How long can high density be sustained?

The limiting factor is the chest cavity where breathing is restricted. Clearly we cannot test the limits in a crowd as that would endanger lives, however we have several examples with which we can define a working criterion for high density exposure in a moving environment.

From the ***Green Guide*** we have the limit of 4 people per square metre set as a safe density for a moving crowd. This density may be exceeded during ingress and egress situations for limited periods. However, it is an average value and we need to consider the range of densities for risk assessment. We shall take gate C at Wembley Stadium as a measurement to assess a density and time limit for a safety criterion.

The area at gate C can support 500 people (from chapter 2.3.1). We can see from Figure 34 that the density in this area has exceeded the ***Green Guide*** limit of 4 people per square metre. There are 10 turnstiles and each can process 660 people per hour. Given the uneven distribution of usage we shall take a figure of 600 per hour as a basis for calculation. This allows 5,000 people per hour, or 10 times the volume of traffic present in turnstile area. The exposure time is then calculated as the time it would take an individual to navigate high density areas.

It is reasonable to set the time exposure to high density as follows: 5,000 people per hour = 83.333 per minute. 500 / 83.333 = 6 minutes. The time taken to process 500 people is therefore 6 minutes. We shall use this value as our limit for exposure to high density. If an entity is exposed to density above 4 people per square metre for more than 6 minutes then we need a safety alert in the simulation system.

3.1.9 Is the Fruin Level of Service wrong?

It is important to note that we are not stating that the Fruin LoS ideal is incorrect. Clearly there is a margin for increased density and flow in a safe and nonthreatening environment. The LoS standards, as a design criteria, is clearly an ideal guideline to achieve. But flow does not cease at the Fruin LoS-F, therefore we need appropriate measures for risk assessment at high density.

In constrained geometry (where walls or fences are boundary limits), a high density flow constitutes a hazard. The photographs (Figures 9, 10 and 22) were taken prior to the gates opening at Wembley Stadium for a FA championship cup final. Here the crowd (multidirectional flow) is moving in a shuffling manner. The density is approx. 4-6 people per square metre, higher than the Fruin observations. Although the area attracts criticism for being overcrowded, no incident has been recorded where pedestrians have been injured due to congestion.

Within the stadium, in enclosed spaces such as concourses, the circulation of supporters often exceeds the density observed by Fruin. These areas are also observed to be free flowing in multiple directions.

The effects of geometry (dead-ends, barriers, constriction in corridors and changes in corridor widths) create their own dynamic compressions in a moving crowd. We need to know the limits for safety and how close any particular environment is to those limits.

To conclude, the Fruin Level of Service is not wrong! When it is applied as a general rule of the thumb there can be little doubt that there is margin for error. Fruin also states his concerns clearly.

Many designers have been using the maximum flow volume, which occurs at or near the critical pedestrian area occupancy, as a basis for design.

We will see that calculations based on maximum flow rates are dangerously close to the safety limits. We now examine other aspects of stadia ingress and egress design.

3.2 Effects of geometry

When approaching a set of turnstiles or entry gates, the spectators do not distribute evenly across the whole area. With respect to the ***Green Guide***, which quotes 660 people per turnstile per hour, might say that all geometries are equal, but some are more equal than others when flow rates are averaged over time.

The reasons are obvious but the effects on system, and the network performance can be quite pronounced. We shall examine the geometry and approaches at Wembley Stadium with respect to the turnstile gate ingress trip counter totals.

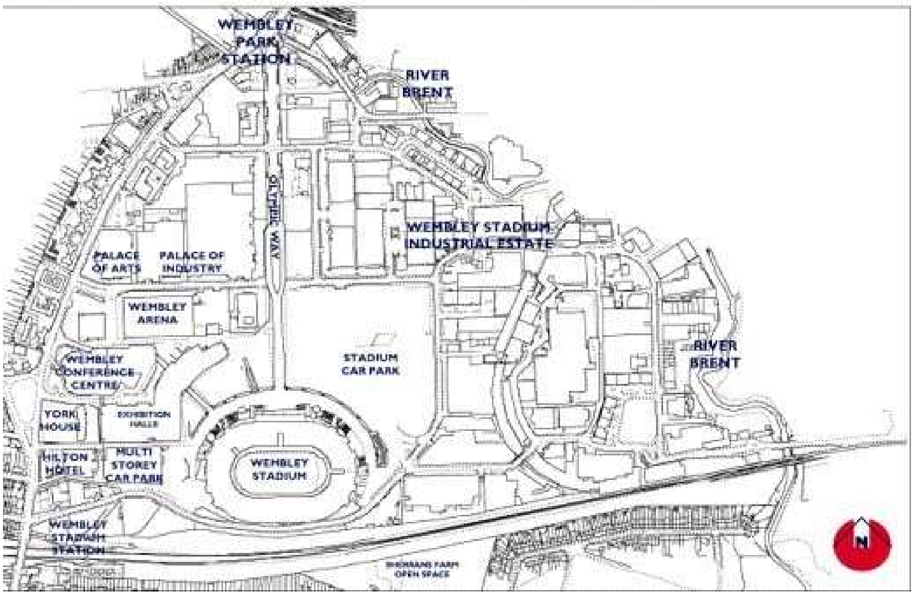

Figure 35 - Stadium approaches and local area

The main approach route to the stadium is via the underground station (Wembley Park Station) which leads to Olympic Way and joins the main concourse in front of the banqueting hall. There are car parks (Figure 35) surrounding the concourse areas. The Chiltern line station is seen on the lower left (Figure 35).

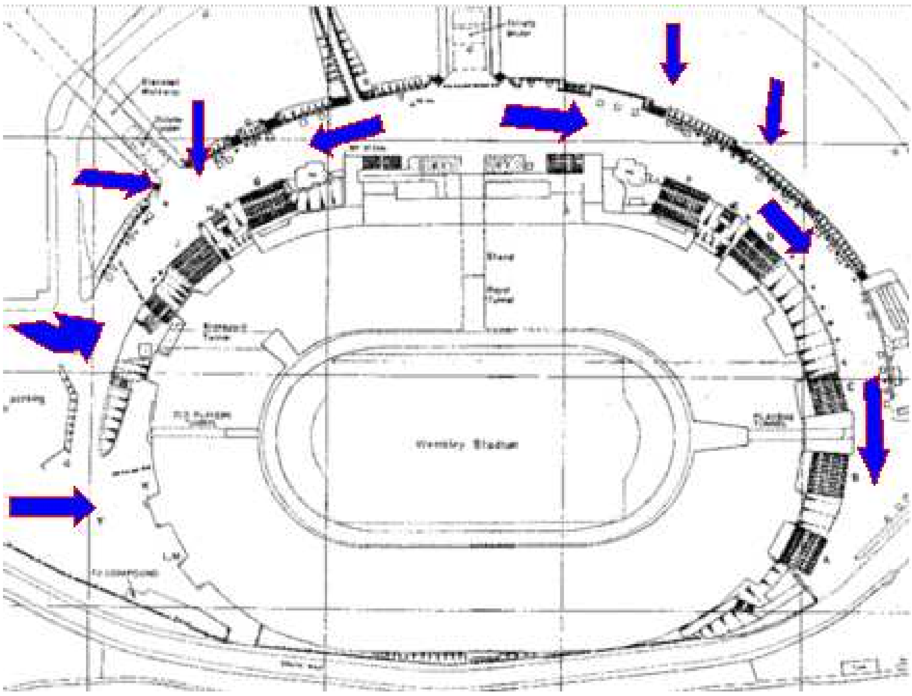

Figure 36 - Wembley plan showing the main routes taken by spectators.

3.2.1 Approach routes to Wembley Stadium

Every stadium ticket has a plan printed on the rear. The ticket indicates the turnstile gate, block, row and seat number. The exceptions to this are concert tickets where only the turnstiles are indicted. The ticket also details transport details including rail (Wembley Complex Station), underground (Wembley Park Station), bus and car. Spectators are well informed of their entry gate and seat locations.

3.2.2 Problems with entry points

It is clear that inappropriate signage inside the stadium can be a problem, where congestion can human traffic can be high. However, the same principles applie to the approach routes. Although emphasis is made in the ***Green Guide - 6.9 Providing clear information,*** which relates to numbering of the turnstiles and gates, there is no account of the problems associated with inappropriately placed signage, or visibility of signs in crowded areas, for normal and emergency egress.

The ***Green Guide*** states:

6.7 <u>Providing a sufficient number of turnstiles or entry points.</u>

Although the entry capacity is determines by the number of spectators who can be admitted within a period of one hour, in practice many grounds admit spectators well in advance of the start of a sporting event. Furthermore, for many events, large numbers of spectators arrive close to the starting time. These variations should be recognised when determining the number of turnstiles or entry points to be provided, or staffed on particular event days.

The ***Green Guide*** goes on to state that:

6.8 <u>Design and management of entrances and entry points</u>

The design and management of entrances and entry routes should take into consideration the following:

a) Entrances to each part of the ground should, wherever practicable, be designed and located so as to allow for the even distribution of spectators and to prevent local pressure building up outside the ground.

What is missing from this design criterion is an explanation of the problems associated with turnstile designs. Looking at the plans of Wembley one could conclude that they look as if they would have an even distribution, at least on one side. However, the approaches do not support even turnstile distribution. This needs to be addressed both in a qualitative and quantitative process during the design phase as ingress routes, circulation routes and egress routes can all have hidden problems.

We can apply some simple geometric rules to analyse the likely problems that might be expected along these routes. But, before we do this, it is important to clearly identify the problems associated with crowd dynamics and how they relate to entry routes. We shall assume that people will use the ***least effort*** to move from their present position to their next position.

As we have seen, from Figures 9, 10 and 22 the concourse is congested in areas where bidirectional flow occurs. We can also see from Figure 11 and 21 that there are a number of concessions stands on the concourse (indicated by the square and triangular blocks in Figure 21). Concession stands create local high density as people queue for food, beverages and merchandise. The crowd dynamics are complex.

During 1994-1995 records of the turnstile counts (chapter 2.7) were obtained. These highlight the problems that geometry and crowd dynamics have on turnstile usage. When we examine the layout of Wembley Stadium (Figures 35 and 36) we can see that the turnstiles are evenly distributed only on the Northern side of the concourse. The Southern side is bounded by a road so the inner concourse (level B) is used as a circulation route.

Supporters who have tickets for the South of the stadium gain entry via turnstiles A, L or M. To understand the problems we examined each of the Wembley turnstile gates in turn to determine the principles of ***least effort*** and the effects of geometry. We illustrate this with a few examples in the following section.

3.2.3 The Wembley turnstiles (A-M)

From the turnstile distribution the queuing behaviour (Figure 37) is typical, and during the two years of observation this phenomenon was noted at the turnstiles.

Figure 37 - Queuing at gate C. Note: all turnstiles are manned

The combinations of a strong visual indicator, local geometry and queuing behaviour are all contributory factors. Once a queue has formed it has a dynamic attraction of its own. We can see how this behaviour can arise. Given a choice of a queue that is moving or an apparently empty turnstile, at the top of a set of stairs, which might be unmanned, you can save yourself a trip up the stairs and simply join the queue. You know that the queue is going somewhere, but you do not know what awaits you on the empty stairs. Therefore it is less effort to join a queue.

The turnstiles around Wembley Stadium, have a large red letters printed on a white sign. At turnstile D there is a moderate central bias - this is a function of the angle of approach and the location of the turnstile indicators. The turnstile bank is not central to the stairs, and we see a significantly lower proportional use of turnstile 10.

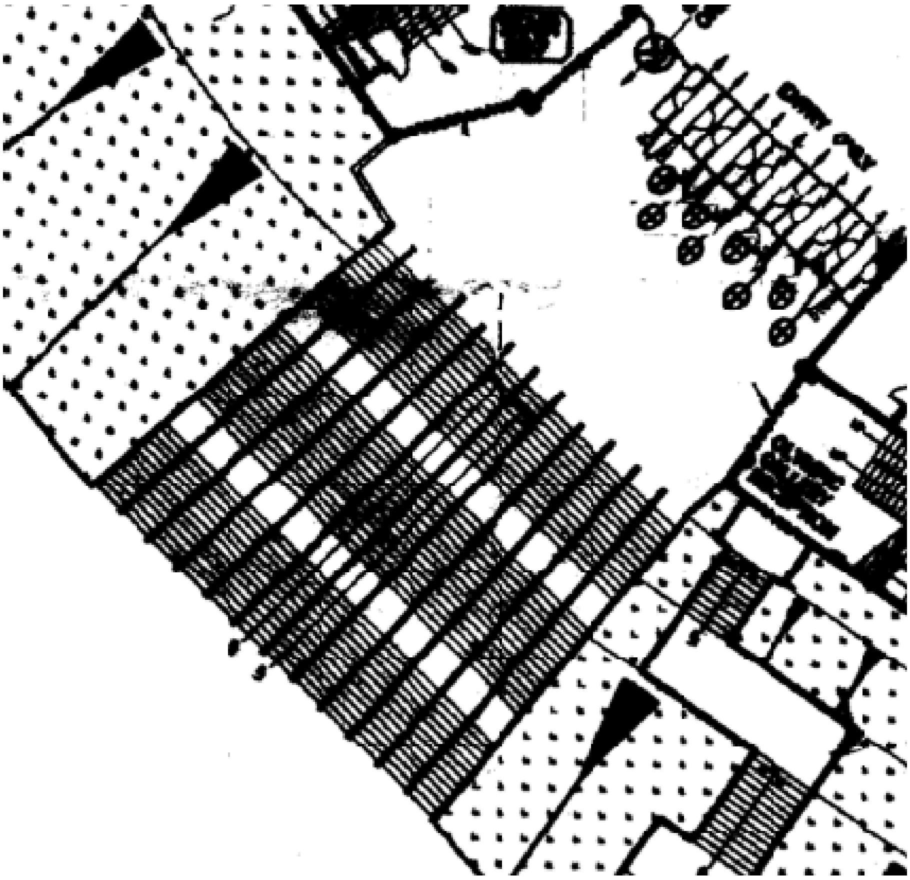

Figure 38 - Plan of gate D and turnstiles (Left = 1, Right = 10)

People prefer a route with a minimum number of angular turns, which gives rise to the uneven distribution, this requires the ***least effort*** to reach a destination.

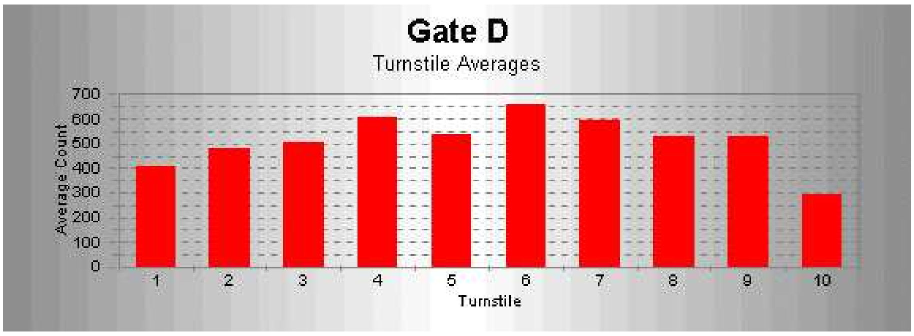

Figure 39 - Graph of D turnstile usage (averaged over several events)

If we compare the distribution of turnstile D to turnstile F we can see how the differences in the geometry can effect the distribution (usage) of the turnstiles.

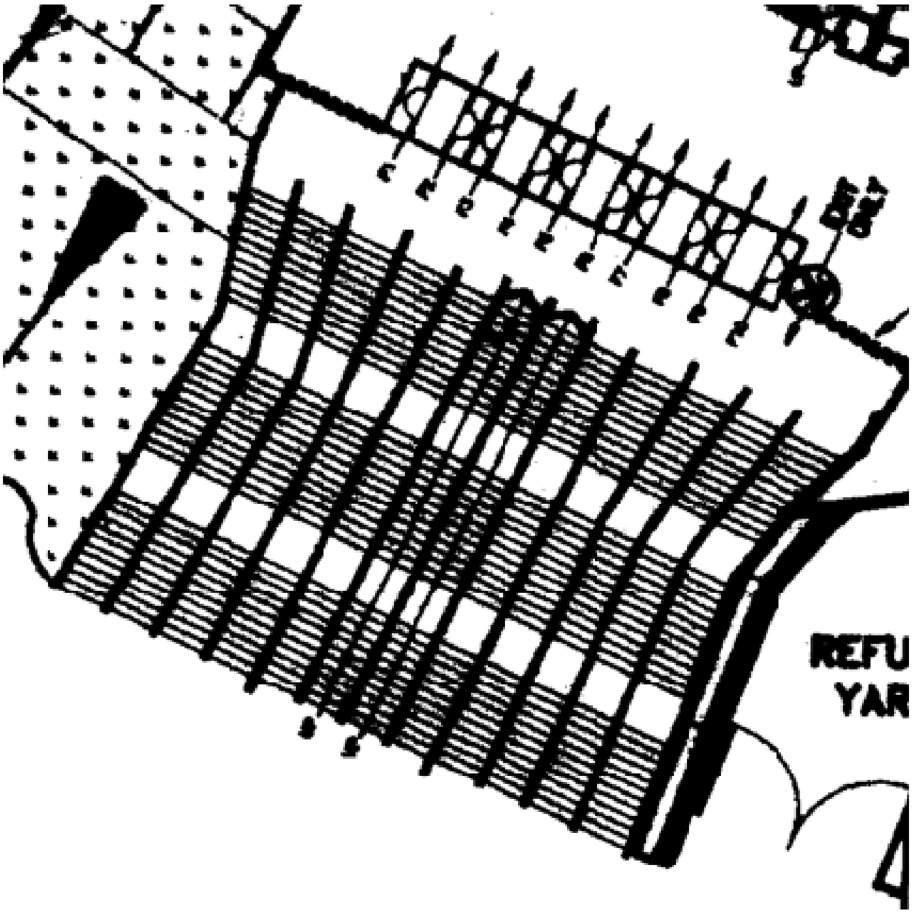

Figure 40 - Plan of gate F and turnstiles (Left = 1, Right = 10)

Gate F (Figure 40) has a stair configuration that spreads out and presents an unusual visual reference to the spectators on their approach. The propensity for the crowd to flow in paths of ***least effort*** leads to the imbalance we see in Figure 41.

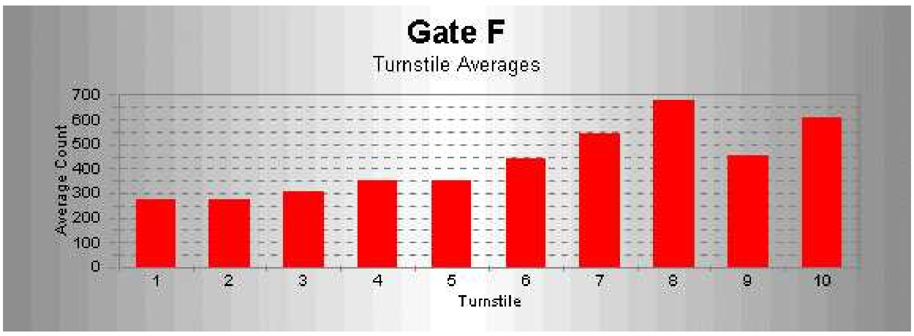

Figure 41 - Graph of F turnstile usage (averaged over several events)

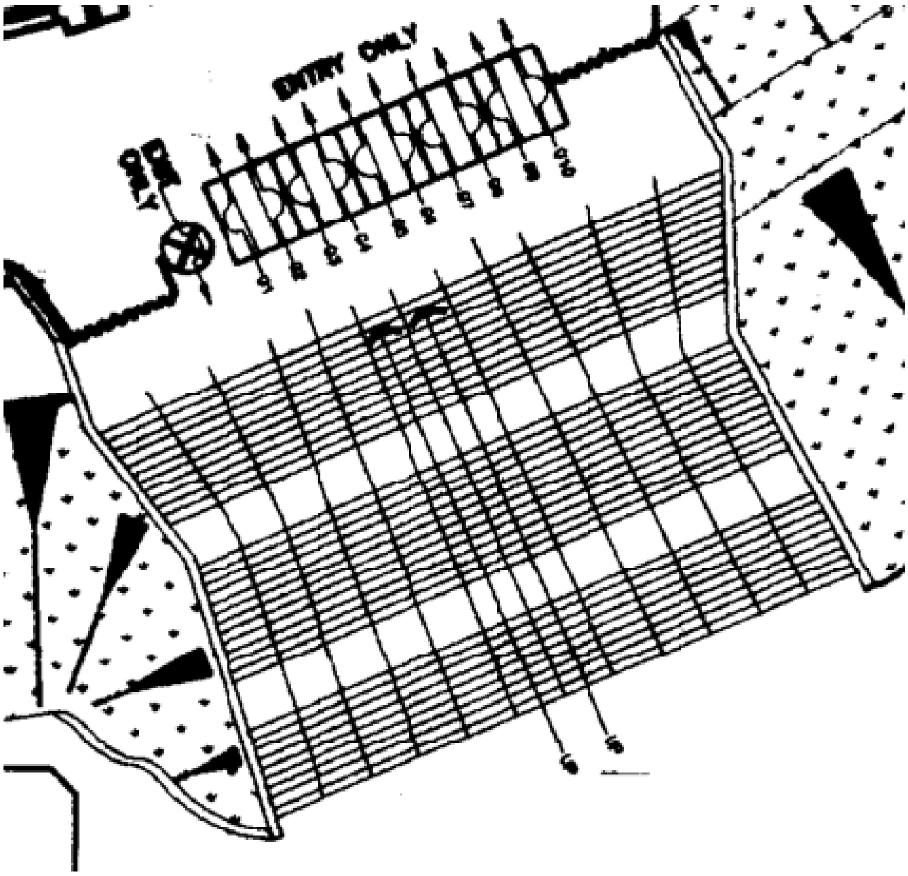

Figure 42 - Plan of gate G and turnstiles (Left = 1, Right = 10)

Gate G is approached from the left (Figure 42) we can see the principles of ***least effort*** can allow us to predict the turnstile usage. The graph (Figure 43) is predictable from the relative interactions of the people with the geometry.

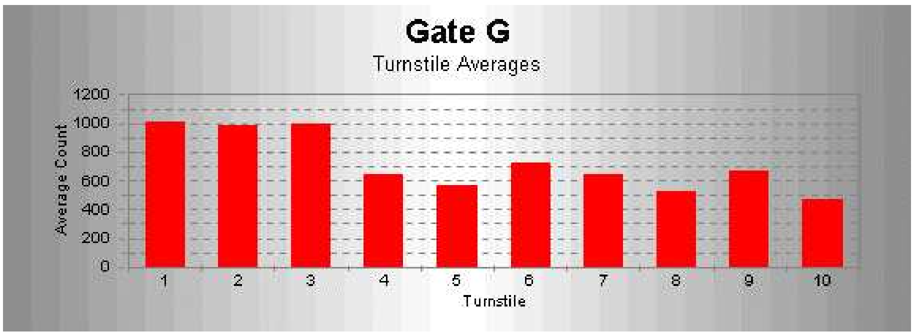

Figure 43 - Graph of G turnstile usage (averaged over several events)

We can see the effect that the shortest route has on turnstile usage. Furthermore we can see that the dynamics of a crowd turning a corner also has an effect on usage and distribution. One could speculate why the figure of 660 people per turnstile per hour is multiplied by the number of turnstiles to provide the ingress capacity figures! Averages can conceal hidden surges and peaks in the data.

Estimating ingress capacity based on numbers of turnstiles may not be the most appropriate method of calculating ingress capacity. However, crowd dynamics and shortest path combine to produce different analysis of the effects of geometry, a ***least effort*** view of turnstile usage.

Post mortem analysis of the Hillsborough turnstile configuration (Figure 27) reveals there were inherent design problems for a large crowd approaching from Leppings Lane. This highlights the need for a different approach to the design of places of public assembly and a more appropriate methodology for risk analysis.

3.3 Network analysis (Green Guide)

A stadium, indeed any place of public assembly, can be a complex system consisting of multiple routes through the geometry and multiple ingress/egress options. To facilitate understanding on these geometries the ***Green Guide*** stipulates that once spectators have passed into the exit system they should be able to keep moving throughout its length. In the event of an incident which renders the usual exit route unusable, spectators should be able to use an alternative exit route or routes. Where there is a simple exit route; that is, a direct passage from the viewing area to the exit gate from the ground, every part of that route should be able to accommodate the flow from the terrace or stand area. For a more complex exit system which combines a number of exit routes and/or offers a choice of alternative routes, the system should be analysed in the form of a network. This is in order to check that the capacity of the exit route from the viewing area is sufficient to ensure a free flow of spectators to the various exits from the ground. Where branching of routes gives spectators a choice of paths, the proportion of the crowd likely to use each part should be assessed; for example, the exit closest to a railway or bus station may be likely to attract a higher proportion of spectators. Grounds which have complex exit systems should have clear, illustrative plans of the network system which serves each section, identifying the capacity of the routes within the system. These plans should be kept with the drawings of the section of the ground to which they relate. Any changes to the ground which affect the entry/exit routes should be identified on the network plan.

A series of worked examples are included to assess both the capacity and the flow calculations for networks. The example (Figure 44) shows an assessment.

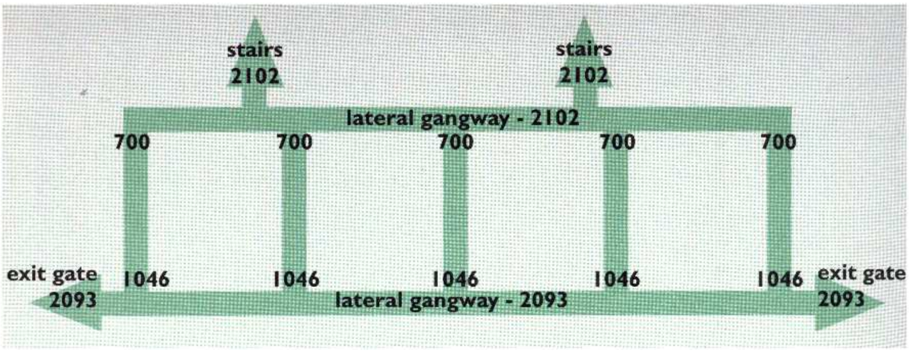

Figure 44 - Network plan to analyse exit systems. From the ***Green Guide*** (page 212)

The ***Green Guide*** states that:

The purpose of the plan is to analyse each part of the exit system to ensure that it has the capacity for all spectators to flow freely through it within eight minutes.

In principle this is a very good idea, assessing the individual routes and taking the aggregate flow as each path converges. The figures relate to the proposed eight minute evacuation time. For example, the exit gates are 2.4 m x 109 ppm x 8 minutes = 2,093. However, this is a naive assumption and the dynamics of crowds are not so easily calculated. The ***Green Guide*** is assuming that the maximum flow is sustainable and homogeneous. As Fruin indicates this assumption is dangerous.

Furthermore, the effects of local geometry are not considered in a network analysis, the relationship between speed and density is not addressed and neither are the interactions of merged flows.

It is important to note that network systems are not behavioural. They demonstrate evacuation capacities based on the assumption that people behave in an ***appropriate*** manner.

3.3.1 The dynamics of crowds in a network

Crowds do not flow like fluids. They do not fill space in an even and regular manner. We call this effect the space utilization function. This effect is often neglected and the following examples illustrate the problem in a simple geometry (Figure 45). Figures 45 and 46 show that the density at the corner is higher than the surrounding area, the inner comer is used more often. The measure of space utilization is a central theme in the simulation of crowd dynamics yet, according to the Building Research Establishment [29]:

..corners and bends have no effect on flow rate.

The corner effect is neither a transient, nor negligible. It relates to the dynamics of crowds and the use of space, it has a relationship to the crowd density and speed. It can be seen (Figures 45 and 46) that there is an effect on flow rate.

Figure 45 - As the crowd turns the corner the space is not used evenly

In confined spaces crowd dynamics is a function of the local geometry and this effect can dominate the crowd flow and behaviour especially during emergency egress. Study of crowds under emergency conditions is clearly too dangerous to investigate. However, with a suitable ***simulation*** we could study a variety of scenarios, potential problems, their consequences, and the outcome and effect of changing the local geometry.

Figure 46 - As density increases the available space is still not fully utilised.

3.3.2 Braess s paradox

Braess s paradox [48] is an important consideration for the analysis of any network system that has alternative routes. To summarise Braess s paradox: you sometimes increase congestion by increasing a choice of route. This is a similar finding to the interaction based paradox, where an increase in the number of interactions can reduce the overall system flow performance. Typically you find examples of the paradox in city traffic design and network analysis.

Mark Wainwright has turned a description of Braess s paradox into an excellent html. The following description is very heavily paraphrased from his website [49].

To illustrate this paradox consider a network of roads between two sites (A and B in Figure 47). These types of networks are typically described in economic terms, associating a cost for travelling on a particular edge of the network. Each edge in this example is labelled with some function of the number of cars on that edge: the more cars the longer the journey time, the more frequent the number of accidents, the longer delays become, hence the greater the fuel consumption will be. The function of cost will in general be complex but for the purposes of illustration we shall assume a simple linear function for each road (Figure 47).

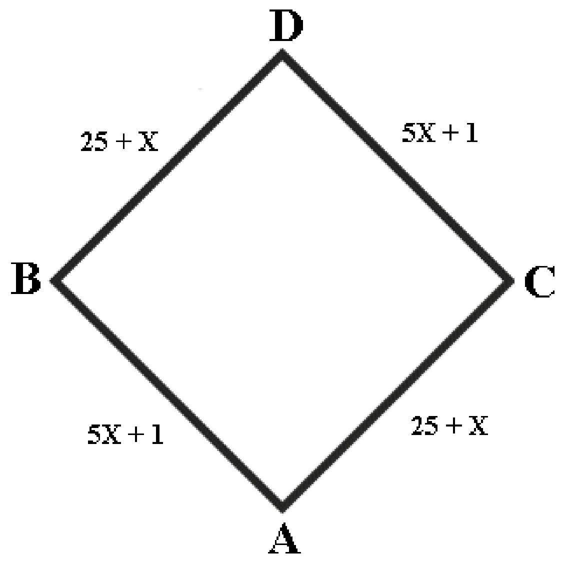

Figure 47 - The four edges (roads) are marked with their associated cost functions. The symbol x indicates the relationship of cost to the number of cars on that road.

Consider each car in turn leaving from A. Every driver can observe the density of traffic ahead of him/her and make a choice of route based on that observation. The first driver is presented with two empty roads, and we shall assume that his probability of going either way is 50%. Successive cars using this network will be influenced by the previous driver s choice assuming free flowing conditions. We shall also assume a small number of cars (say 6) therefore the cost for each car will be 26 + 6x3 = 44.

Braess s paradox is observed when another road is added (Figure 48).

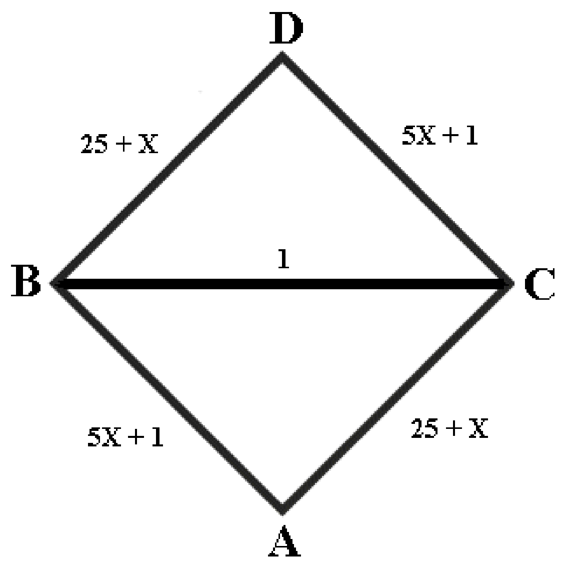

Figure 48 -The addition of a central connecting road would appear to provide a lower overall cost to the network

We can see that the driver of the first car now has several alternative routes through the network: A-B-D (6x + 26), A-B-C-D (10x + 3), A-C-B-D (2x + 51) and A-C-D (6x + 26). He would take A-B-C-D as it has a cost of 13 (10x + 1: x=1). Driver 2 may take A-B-C-D as it is still the lowest cost (10x + 3 = 23: x = 2). Driver 3 may also take A-B-C-D (10x + 3 = 33: x = 3). Driver 4 may take A-B-D but this would cost 42 (5x + 1 = 16: x = 3, 25 + x = 26: x=1) so he takes A-B-C-D, whose cost is only 22 (5x + 1 = 16: x = 4 + 1).

By the time Driver 5 sets out, A-B-D cost 27 is cheapest (5x + 1 + 1 = 27: x = 5). Driver 6 takes A-Y-B with the same cost (52). We can see that as the road usage increases the addition of the X - Y road has increased the overall cost of transport.

We have added an alternative route and the cost to the whole network has increased. This is counterintuitive, and the impact is not easy to perceive, or to calculate unless you are familiar with the nature of these types of problem.

We have to examine the paradox in more detail. First let us consider the assumptions we have made in this model.

Cars enter the system in single file.

We have allowed each driver to enter in turn and make a decision based on their perceived congestion in the network.

The Greedy algorithm is implicit.

We have allowed each driver to take the route with the lowest cost/least density.

These assumptions may be incorrect, so let us first examine the network in more detail. In our original network, the solution we found (three drivers going each way) is stable. This means that once the cars are arranged this way there is no advantage in changing route. Any route changes will cost more (traveling back down the network).

It is also the only stable solution. If we arrange the cars in a different way, say four to the left and two to the right, then one driver will soon notice that he can lower his own journey cost by taking a different route.

So, if we start with any arrangement of cars on roads, but let the cars change to a different route if it is cheaper, they will soon arrive at the stable solution. This is also the one we find by the greedy algorithm.

What is particularly interesting is that these properties apply to the modified network. The solution given by the greedy algorithm, with four cars taking A-X-Y-B, and one each A-X-B and A-Y-B, is stable, and it is the only stable solution. If the six cars start off by using their old route to work - three each to the left and the right -

one driver will soon notice that he can improve his time by cutting across between X and Y, and gradually others will also change until the cars are arranged in the new formation where everyone's journey is more expensive.

We have a solution where every car is careful to take the cheapest available route, and yet the total cost has increased. How can adding a road to a network slow everyone down?

The key is how the cost of using a road varies with the number of cars. Using our linear functions, we can imagine the constant term as representing the road's length, and the term in x an indication of how prone the road is to congestion. Note that this idea supposes that the `cost' of a journey is purely a matter of how long it takes. Then the new road allowed a short cut between the two north westerly roads, which are shorter than the alternatives, but suffer from substantially worse congestion.

The result is that each driver in turn takes this slightly quicker route, at a small saving for himself, but causing substantial extra delay to a number of other drivers. By the time everyone has decided whether to take the short cut, the total congestion gained by the system far outweighs the savings in distance.

The modified network is really a classic example of the Prisoner's Dilemma (PD), a paradox with many applications. Adding the extra road gave the commuters the opportunity to `defect', in PD terms. In this particular case it did not even have any compensating benefits.

When we consider the paradox with respect to egress systems we have many examples of Braess s paradox in building design. Specifically, the assumption that adding addition exit routes it will increase the overall egress capacity. This also applies to the addition of ingress routes to a stadium. Simply adding more may not solve the problem of how to increase the ingress capacity. We return to this issue in chapter 4.1.2.

3.3.3 Braess s paradox and the Green Guide

We can see that even a simple calculation based on a network can have unexpected results. This is relevant to the network example in the ***Green Guide*** for two main reasons. Network analysis is oversimplified, and the impact of the local geometry on crowd behaviour has not been sufficiently highlighted.

The time taken to exit a system in an emergency is a critical factor for crowd safety. For safety analysis, ***every factor*** has to be considered. This includes the paradox posed by Braess. The oversimplification of network analysis in the ***Green Guide*** can have hidden and potentially catastrophic consequences. When a network system offers alternatives for egress, the impact of losing some of these in an emergency has to be part of the safety calculations. The ***Green Guide*** alludes to this but does not consider the impact that Braess s paradox can have on an emergency egress system design.

The impact of local geometry also includes the visibility of signage in crowded situations, the dynamics of crowd flows as they merge and the relationship between speed and density in confined spaces.

As previously stated the ***Green Guide*** has been revised considerably in light of recent disasters; however, as regards this particular issue there are problems that need to be addressed. When a system is complex it should not be reduced to the simplistic analysis presented in the ***Green Guide***.

3.4 Review of other simulation systems

Crowd simulations fall into two main categories; ***behavioural*** and ***movement*** models. The behavioural models are essentially two types; ***conceptual*** models which include the observed, empirical and reported actions of individuals from questionnaire studies (e.g. Canter [40, 41, 42, 43]. Sime [44, 45, 46, 47] et. al.) and ***computer*** models for the simulation and behaviour of individuals with respect to information seeking and processing. Behavioural models do not include the dynamics of crowds in their analysis.

Of the movement models there are two main types; these are the fluid or particle systems and the matrix-based systems.

In the fluid category the applications of the Boltzmann Gas equations are used (Exodus, Rampage and Dirk Helbing s work). In the matrix systems (Egress, PFES and Pedroute) the use of the Fruin data is implicit.

The Author developed the VEgAS (**V**irtual **Eg**ress **A**nalysis and **S**imulation system) a prototype to the Legion system. The VEgAS system was unable to model the complex dynamics of large crowds and the system. Legion, was developed on the principles discovered during the development of VEgAS. The virtual reality system was used to prove the basic relationships of crowd dynamics.

To understand the need for an emergent system we need to examine the problems associated with modelling networks and their failure when applied to crowds.

3.4.1 Passenger Flow Evaluation System (PFES)

Toshiyuki Aoki and Hiromichi Oto are developing a system in conjunction with the Japanese Research Institute [7, 8, 9, 10]. This system is based on the principle that predefined crowd movements can be ascertained and a simulation based on these factors. Grids are laid on the floor plan (maximum number 150 x 60) and each grid indicates a general direction, flow rate and predetermined speed/density relationship. It is effective but, as with all systems in this category, dependant on operator skills in creating the correct grid parameters.

The system is basically an application of the Fruin models with suitable adjustments for the Japanese profiles and speeds measured on their transit system (1.4 metres per second for free flow and an associated graph to determine the speed in various cross flows).

Aoki et. al. are working on a micro-model which calculates individual parameters. Their input data is the Togawa data not the Fruin data (we shall compare the data in chapter 4).

3.4.2 Egress (SRD AEA Technology)

Like the Aoki system the system from SRD [50] is based on grids (in this case the grids are hexagonal). They use artificial intelligence techniques to determine how an agent will react in a variety of circumstances including fire. They have based their artificial intelligence rules on the research of Canter, Sime, and Fruin. Canter and Sime are crowd psychologists and have defined a number of important factors in crowd psychology. We examine these in chapter 4.4.

In their paper [50] SRD highlights the various speed/density curves associated with Fruin, Pauls [21, 22] and Predtechenskii and Milinskii [50] with the warning that there is significant spread in the data available.

They rely on the relationship:

$$f(p) = p * v(p) \qquad \text{(Flow rate = Density * Speed)}$$

Where f(p) is the flow rate and v(p) is the speed at crowd density p. Their approach is fundamentally a cellular automaton process in which the transition of people from cell to cell is based on an occupancy of the cells. They calibrate their data against speeds where experimental data exists. SRD demonstrate that the historical data is flawed in that it relies on homogeneous flow assumptions.

3.4.3 Pedroute

Pedroute is a computer simulation system which was originally developed by Gerry Weston at London Underground Limited. The intellectual property rights were then sold to Halcrow Fox. Pedroute has been used extensively used to model crowd parameters in underground networks around the world. It is the extension of Fruin s Level of Service and relies on that data being an accurate representation of the crowd dynamics with respect to local geometry.

During a stadia safety conference [52] Paul Clifford of Halcrow indicated that the speeds they measured were double that of the Fruin indicators [53]. The system performance therefore has to be questioned as the reliance on the Fruin data has been shown to be incorrect during their own research.

Pedroute also suffers inaccuracies when cross flows, concourses and other local effects do not have Fruin data. In those cases the closest approximations are made. The deficiencies of the Fruin data are highlighted, in particular the problem associated with applying the Fruin data for multidirectional concourse areas.

There appear to be further limitation to the Pedroute system. When creating a model, several adjustments have to be made, both to the sizes of the grids and their Level of Service usage. As with any system the output of their model is a function of the skill of the operator. The main problem is that these types of system do not tell us anything new; they are based on assumptions which, as we have seen, are questionable with respect to field observations.

Assuming an a priori speed/density relationship, as we have seen, is inappropriate to the ***understanding*** of crowd dynamics. What is required is a minimum of input parameters and a minimum of a priori assumptions. What is required is a system that can be used to analyse the subtleties of crowd dynamics. We need an aide to our understanding and a system that can increase our working knowledge of the parameters that affect crowd safety.

This is not to say that the aforementioned systems should be discarded. Indeed the limits that Fruin has set provide ample safety margins, if rigorously applied to the building design guidelines. In the hands of a competent engineer these systems provide useful information when deciding the building criteria for safety.

However, it is those cases where we do not have appropriate data, or where there is not enough space to maintain consistent low density flow rates, that we need to acknowledge.

3.4.4 Exodus

Ed Galea [23, 24], University of Greenwich, has adopted fluid dynamical models and coupled these with discrete virtual reality simulations of human movements. His product, Exodus, has been used in a number of major projects, worldwide. In his description of the Exodus system he states:

Exodus was designed to simulate the evacuation of large numbers of

individuals from large multi-floor buildings. The model tracks the trajectory of each individual as they make their way out of the building or are overcome by fire hazards such as heat and toxic gases. The model is a collection of 20 attributes that fall into four categories: Physical (age, weight, gender, agility), Psychological (patience, drive) positional (distance travelled) and hazard effects (FIN, FICO$_2$, FIH).

On the basis of each individual attribute the model activates each and every simulated human and proceeds to assess the impact on the egress statistics. These attributes add to the computational intractability of testing, for example, what is the egress rate for the overweight?

In 1986 J. P. Stapelfeldt placed 100 police cadets in a compartment containing a single exit. Paulsen [25] reported on that experiment in 1995. Different exit widths were considered 0.75, 0.80, 1.5 and 1.6 metres. Population densities at the exit were measured at 4 persons per square metre. Within Exodus a 3.0 by 8.5 metre enclosure populated with 100 males was specified. This achieved the desired density and evacuation results which were in line with the Paulsen report, namely 30 seconds to clear the area. It is noted that the flow rates here were measured at 1.96 and 2.30 occupants per metre per second. These figures are in line with the ***Green Guide*** specification as discussed earlier.

3.4.5 Rampage - Animation Science

Eyal Cohen [26] developed sophisticated particle simulation systems to animate explosions and other elementary primitives. He has modelled the human behaviour into reflex (immediate) reactions and inference (decision) reactions based on knowledge obtained from the scene. The principles behind his modelling are based on the Boltzmann gas equations which we shall discuss in chapter 3.5.6.

His company, Animation Science, has applied the model to a number of well-known situations with iterative adjustment of behaviour until empirical results are reproduced. The main source of their calibration has been Fruin [6] and P&M [51]. Calibrations to these standards have already been proved, in previous sections, to be questionable.

In discussions with Cohen [27] and Fruin [54] the author has expressed concern that certain historical data are not applicable, both were in agreement. However, although the application of high resolution graphical software is no substitute for scientific validation, it does convince the clients, it does sell. This sentiment is echoed by Galea in his discussion of the current simulation systems available in the market.

In defence of the simulations systems that are available the historical data is sparse. It is not feasible to test a large scale crowd to destruction in order to gather new data. We have seen that the use of the Fruin data may leave sufficient margin for error and, provided the limits are understood, then these systems can be used in the design and operation of places of public assembly. The Rampage product uses historical data and not the designers own field studies.

3.4.6 The social force models

Dirk Helbing [13, 14, 15, 16, 17, 18, 19, 20] has completed several years of research in the application of the Boltzmann-like gas-kinetic approaches. Helbing [18] describes a variety of human behaviours which are outlined below.

1. Pedestrians normally choose the shortest route to their next destination

which has therefore the shape of a polygon. If alternative routes have the same length, a pedestrian prefers the one where he/she can go straight ahead as long as possible provided that the alternative route is not more attractive (due to less noise, more light, friendlier environment, less waiting time at traffic lights etc). A pedestrian feels a strong aversion to taking detours or moving opposite to the desired walking direction, even if the direct way is crowded.

This conclusion is echoed by Alan Penn (University College of London - Bartlett School of Architecture) [28] in his work on space syntax. It is also the observed behaviour at Wembley turnstiles during an ingress, by the author.

2. ***Pedestrians prefer to walk with an individual speed, which corresponds to the most comfortable walking speed as long as it is not necessary to move faster in order to reach the destination in time. The desired speeds within a crowd are a Gaussian distribution with a mean value 1.34 metres per second and a standard deviation of 0.26 metres per second [11, 12, 55].***

3. ***Pedestrians keep a certain distance to other pedestrians and borders (of streets, walls and obstacles). This distance is smaller the more a pedestrian hurries, and it decreases with growing pedestrian density. Resting individuals (waiting on a railway platform for a train, sitting in a dining hall, or lying on a beach) are uniformly distributed over the available area if there are no acquaintances among the individuals. Pedestrian s density increases (i.e. interpersonal distances lessen) around particularly attractive***

places. It decreases with growing a velocity variance (e.g. on a dance floor). Individuals knowing each other may form groups which are entities that behave similarly to single pedestrians. Group sizes are Poisson distributed.

4. ***Pedestrians normally do not reflect their behavioural strategy in every situation anew but act more or less automatically (as an experienced car driver does). This becomes obvious when pedestrians cause delays or obstructions, e.g. by already entering an elevator or underground even through others still try to get off.***

Additionally, Helbing found that at medium and high pedestrian densities the motion of pedestrian crowds shows some striking analogies with the motion of gases and fluids. These include viscous fingering, propagation of shock waves in dense pedestrian crowds and pedestrian-free bubbles. Apart from these phenomena, there are some analogies with granular flow. The velocity profile is flat, the Hagan-Poiseulle law does not hold [56].

Spontaneous organisation forms in lanes of uniform walking direction once critical density is exceeded (LoS-D). Also at bottlenecks (e.g. corridors, staircases or doors) the passing direction of pedestrians will oscillate with a frequency that increases with the width and shortness of the bottleneck. This is analogous with the fluid-dynamic saline oscillator and with the granular ticking hour glass .

The observations at Wembley are in line with Helbing s research. However the work of Helbing relies on assigning complex calculus and a thorough understanding of the Boltzmann-like gas-kinetic equations. These equations are difficult for the expert to understand, let alone for those responsible for crowd safety.

The Rampage system has developed along similar lines but relies on validation against Fruin et. al.

Both Helbing and Cohen have tackled the problem using a top down approach. Given that calculus is a mathematical approach to solving some problems (such as catching a ball in flight) one has to speculate that there may be a simpler mechanism that could be applied to the problem. After all not everyone is capable of manipulating the calculus, but we are all quite good at catching things. Although the macro models have some success in their application to crowd dynamics, they have too many a priori assumptions, unmeasurable factors and therefore they may be of limited use. There had to be a simpler way of predicting the dynamics of crowds.

It was this assumption that perhaps there is an easier way to do this that led to the development of VEgAS and then Legion.

3.5 VEgAS

We began chapter 2 with statements regarding computer simulations. If we could somehow perceive the design in an emergency, visualise the problems and practice various egress strategies, we would be able to perform quantitative and qualitative risk assessment.

How can we be sure that the egress design is operationally effective and safe? One possible solution to these problems is the application of virtual reality. This allows the engineer to enter a computer simulation of his design, experience an event, use this insight to improve the design, and then test various contingency arrangements. The author originally developed VEgAS (**V**irtual **Eg**ress **A**nalysis and **S**imulation system) as a low cost virtual reality environment specifically designed for egress analysis.

The VEgAS system originally used a series of conditional IF ..... THEN .... ELSE logic statements to model the human interactions. For example, IF entity Behind Little old lady THEN overtake IF speed(Little old lady) LESS THAN speed(entity). It soon became obvious that this approach was intractable in that one cannot determine ***a priori*** all the possible conditions that could occur. The paradox being that if one could determine all the possible outcomes then there would be no real use for such a system.

In the original design some eighteen pages of conditional statements were included, along with various inputs from Sime, Canter et. al. A period of eliminating the conditions one by one followed until the system no longer supported the behaviour observed from the field studies. Examining this code led to two revelations, firstly that there were many conditions that could not be assigned a priori, for example: today I may feel like overtaking, tomorrow I may not (I am more tired). Same person, different reactions on different days. Most of the conditions could be replaced by noise. The second and most startling discovery was that the system self-organised. It did so in the same way that the bidirectional flow self organised in field observations when the algorithms were allowed to communicate, entity to entity. We discuss this in chapter 6, validation.

3.5.1 The uses of virtual reality in egress analysis.

Building information systems, which are designed to help, may at times be ineffective. The position of emergency exit signs may be obscured by smoke, or worse may suggest circuitous exit routes. The design concepts can be diluted from the architectural plans through to the final contractor selecting and fitting signs. This presents two problems. Firstly, how can we test way finding and egress routes in the building, secondly, how can we ensure that the recommendations are communicated efficiently?

To address the first problem we can create a virtual model of the building, position the exit signs, simulate smoke, place a subject in front of the screen and let them try to find their way out. We can simulate fires in the computer generated building and observe our subject's reaction during virtual egress. This will provide information about the efficiency of building information systems and way finding. Using an iteration process from human reaction to computer simulation and back to human reaction, it is possible to assess probable reactions to the ***real*** design. By using this process of test and simulation we can run as many investigations as may be required. The objective is to determine if there are any problem areas, or unforseen reactions to the design during egress.

It is unethical to expose people to the dangerous environment of heat and smoke but a virtual person does not suffer from such constraints. We can program virtual ***people*** to react as a ***real*** person during the simulation. Using a combination of ergonomics and computer generated characters, reacting to a virtual event, it is possible to simulate problems and plan for contingencies with mixed ability populations.

The obvious advantage of modeling a character's responses to a virtual world, and then producing dozens of copies, is that it provides us with the means to test a crowd. We can then participate as a character in the crowd, analyse new reactions and generate new responses. The models developed form a comprehensive library for ***what-if*** analyses. To illustrate this feature, let us assume we want to test a train station for an egress scenario. We select a library of figures (anthropomorphically correct) and program them to respond to a change in environment then, say, simulate a fire. With the appropriate responses to stimuli (heat, smoke other peoples influence) we can monitor and time them during egress. The result is a series of scale characters moving through a scale environment in real-time. What if there are a few elderly or mobility impaired people? Do they slow the egress? Are there any bottlenecks in the system? Can we increase the human flow rates safely? What if we increase the toxicity of the smoke or reduce the visibility? Does that have an effect on any potential threat of mortality? What does the signage look like when there is a crowd circulating in the area?

3.5.2 Intractable parameters

There is a problem with this approach. As we increase the number of parameters, we wish to test the complexity of the models increases exponentially. Testing just a few combinations quickly becomes intractable and we have no method of assessing their impact without an exhaustive series of tests.

When we consider the combinations of variables affecting an egress problem, number of exit routes, number of people, cross section of population, number of staff, type of staff; egress procedures, emergency services, nature of the threat, etc., we are looking at the problem from the top down. Can these combinations be reduced?

Consider a single character during the initial stages of an emergency. There are three choices of action: ignore, evacuate or investigate (Canter, Sime et. al. and Still [57, 58, 59, 60, 61]). These selections produce movement in a few predictable directions: towards the threat, towards safety (i.e. away from the threat) or no movement. The decisions involving whether to raise an alarm or tackle a blaze can produce a similar direction choice; towards or away from a location. This problem can be reduced to three variables that interact - Objective, Motility and Constraint - and one parameter which represents the reaction time; Assimilation.

To illustrate these interactions, consider the movement of people through a door. The Objective is to reach the other side. The Motility is the speed of each individual. The Constraint is the geometric size of each person, the position of the walls and the width of the gap. As the number of people increases the flow rate changes because of the Constraints on the system. Each individual will read and react to changes around themselves. These reactions are a function of the dynamics of the unfolding situation.

Applied to a virtual reality environment the result is a model that allows us to, for example, to visualize the flow through a door and then change the door width to test the effect on overall flow rates. Changing the geometry of the walls does not affect the Objective (to pass through the gap) but will have an effect on the Constraint and Motility. The interaction between these three variables may appear trivial but appear in many corners of science. When plotted against each other the results are fractal in nature [58, 59].

3.5.3 Flow through a door

To test the relationship between Objective, Motility, Constraint and Assimilation (OMCA) a model was created in virtual reality, Each entity could read and react to the aggregate behaviour, represented by speed and angle of attack, of the entities in close proximity. Several other types of behaviour were tested against a variety of geometries. These included reaction to nearest neighbours and random behaviour. This model was based on the dimension of a population of 95 percentile British males and represented the packing density observed during a normal egress from a football stadium. Each character is trying to move at between 1 to 1.5 metres per second and is constrained only by the density and geometry of the group.

One advantage of modelling in this way is that the interaction between Objective, Motility and Constraints can be seen when the geometry changes. As the density of the crowd changes the interaction between individuals changes. This has a consequence of changing the flow pattern which initially shows the sides moving faster than the centre, to an even flow distribution as the gap widens. Above a certain density-to-door width ratio there is no increase in flow as the crowd thins out and ceases to become interactive. The model displays the emergent behaviour observed in typical crowds. It does so when the entities are allows to exchange information about their angle towards the door gap.

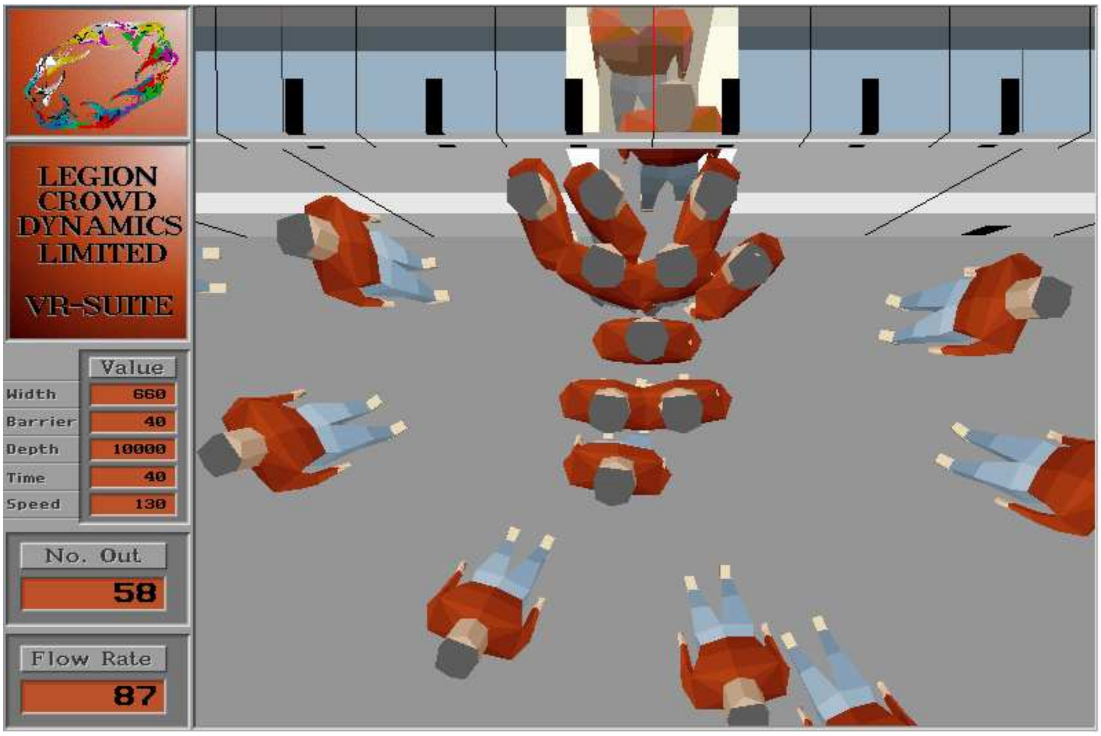

Figure 49 - Virtual reality door width model.

The model shows the time taken for a number of characters to move through the door, the flow pattern, and the density. The applications for egress design are obvious. We can alter the width of the door, speed and sizes of the individuals.

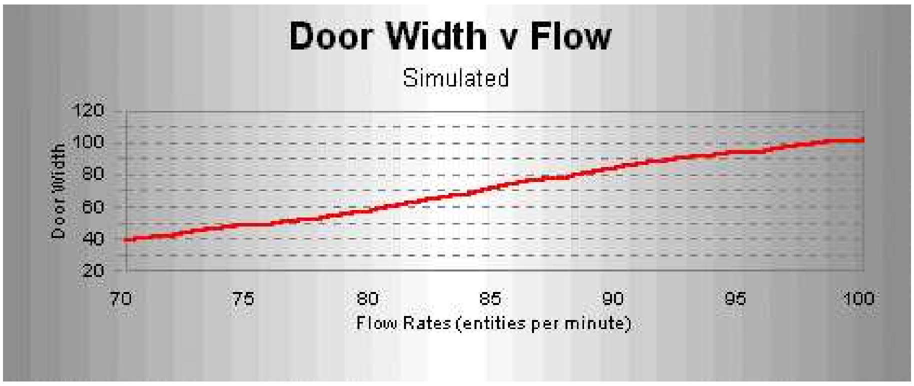

Figure 50 - The door width model showing the relationship between width and flow

Figure 49 shows a typical door with a group of individuals trying to pass through a gap. As the interactions dictated the flow, it was speculated that the addition of a central barrier, or hand rail, would alter the flow rate through the door. In an article for the New Scientist [62] relating to the optimal position in a queue to facilitate the fastest route for boarding a train, the graphics (Figure 51 and 52) were used to illustrate the article. The addition of the barrier in Figure 52 gives an improved flow (approx. 19% better in this example). By careful configuration the increase can be as much as 75%. However, the relationship is not linear.

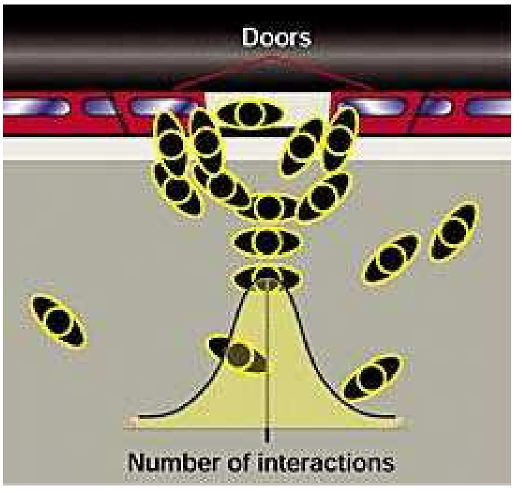

Figure 51 - New Scientist Figure 1

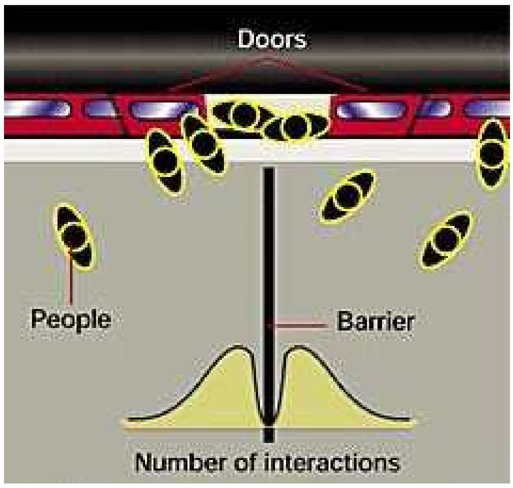

Figure 52 - New Scientist Figure 2

The graph shows the number of interactions with respect to their position. In Figure 52 a flow divider (handrail) has been included. This separates the group into two sections and the number of interactions reduces (Figures 51 and 52).

With the strategic addition of central barriers we have observed 25-75% increases in flow rates. These are virtual experiments but the considerable increase suggested a need for further investigation. There are optimum widths of doors and barrier geometries for different densities of populations. Comparisons with real-world geometries bear this experiment out.

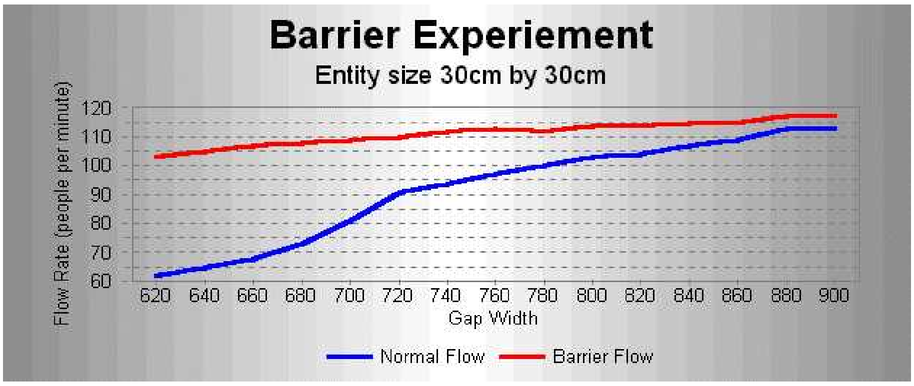

Figure 53 - Flow enhancement created with placement of central barriers.

These experiments suggest that for environments in which space and flow have to be carefully balanced (ship and aircraft design, theatres, stadia etc.), substantial flow rate improvements can be found using the VEgAS system.

Using virtual reality in this way enables the user to test very complex building layouts by programming characters for egress and testing the resultant emergent behaviour. This provides us with a powerful and easy to apply technique for flow modelling. Emergent flow techniques have applications for all aspects of human traffic analysis not just egress. The obvious question is; how does this property of emergence arise?

The answer lies in how the Objectives (to move to the end point), Constraints (to maintain minimum distance) and Motility (to maintain optimum velocity) interact. As people have a width greater than their depth, it may be expected that their sideways movement will be greater, due to streamlining. But, as our model can be set to use both square and rectangular sections to represent people, the same phenomenon occurs independently of the geometry of the individual shapes. The characteristic of sideways fastest flow emerges from the system due to these OMCA interactions. Furthermore when the model is changed from directed movement to noisy movement (by adding a random factor to the angle towards the objective) the resultant flow-rate is the same. This is a counterintuitive result, perhaps, but when we consider the number of interactions that are happening then the results are common sense. The greater the number of interactions, the more the entities have to stop and start, and the more the noise averages out of the system. Sadly, there are limitations to this type of modelling technique. The objective points had to be determined by hand and placed into the model. The number of objects is limited and (using Superscape) the developer could not be 100% certain how the software actually performed the calculation of movements. The collision detection was limited and also the scanning algorithms were limited to direct contact.

3.6 Conclusion to chapter 3

We have seen that the work of Fruin and the ***Green Guide*** have limitations. We have also seen that, in the case of new designs, these guidelines are not fully understood or applied. We could speculate that complacency, over-dependency on the ***Green Guide***, and lack of appropriate tools may be factors in the crowd disasters of recent years.

There can be no doubt that there are characteristics of crowd dynamics which do not form part of the guidelines. Network analysis has deficiencies; crowds have turning arcs, and the concept of ***even distribution*** cannot be assumed.

In the examination of other crowd simulation systems we have found that, with those systems which rely on the operator s skill, results will be limited to the interpretation of the operator. The implication here is that two differently skilled operators can produce very different results with the same system. We have also seen that the particle systems, based on fluid assumptions, are in conflict with the findings outlined in chapters 2 and 3. A solution must emerge from the simulation and not be pre-programmed as operating parameters.

We therefore conclude that there exists a need to produce a reliable, emergent system for crowd safety. It should have as few input characteristics as possible and be able to determine the relationship of the interactions between people, local geometry and space. The objective is thus to define a system that can analyse risk and demonstrate, via a simulation, the operational characteristics of places of public assembly with respect to safe operating parameters. It needs to be visual to aide the understanding of problems of crowd safety.

The original work, VEgAS, fell short of this requirement in that the entities relied on too many user defined parameters.

3.6.1 Emergent solution

When simple parts combine to produce a complex result, we call that system emergent. An ant colony is emergent in that the ants follow simple rules yet produce complex societies. The complexity of the society is not a function of an ant architect but a natural development of the interactions of many ants. [63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74].

The objective of the research described in this thesis is to develop an emergent system of human behaviour with respect to crowd dynamics and in particular crowd safety. This was partially achieved with VEgAS, and is the main motivation behind the development of Legion.

The goal was to define the parameters associated with crowd dynamics and crowd safety, develop a methodology that was less prescriptive in nature and finally to produce a simulation that would allow a user to test various scenarios. This is a formidable task as we also want to build a bottom-up tool, one in which the entities would adapt to any environment we created.

To define such a system we shall first have to define the limitations of computer simulations in general. We also have to define, and solve, the many problems associated with modelling large numbers of independent entities moving as a crowd. In addition to these problems we have to choose suitable parameters for our simulation, define the input and output characteristics and the nature of the crowd as a collective.

Chapter 4 will define the principles of a simulation. Chapter 5 defines the parameters we use in the Legion simulation and explains the relevance of these choice to the problems of crowd safety and chapter 6 demonstrates the necessary validation of the Legion simulation.

Chapter 4 Principles of a simulation

4 Introduction

From the observations in chapter 2 we have highlighted several important features of crowd dynamics. In chapter 3 we discussed the problems in both the current guidelines and existing approaches to crowd modelling. Combining these factors together we are able to define the requirements for a crowd simulation. The objective now is to focus this simulation to the purpose of evaluating crowd safety.

To summarise chapters 2 and 3 with respect to the key crowd parameters:

Crowds consist of many individuals each exploiting short cuts

Crowds do not fill to their own level

Crowds cluster

Crowds have no collective intelligence

Crowds are influenced by geometry

Crowds self-organise at high density

Our simulation has to demonstrate the above criteria, and remove any operator biases. It should also enlighten and educate the user about issues of crowd safety.

4.1 Key components of a computer simulation

Computer simulations are voids in which the rules are defined by the programmer. There is a subtle difference between a correct physical model and the simulations used by the games industry. A computer game does not need absolute accuracy for the game to be convincing - it just needs to be realistic enough to fool the player.

To illustrate this, consider the movie industry with all of its digital effects and stunts. The hero of the movie walks away from the high speed car crash, brushes the dust off his tuxedo, and makes a witty remark about the incident. In reality, the identification of the occupants may require dental records. The mind is easily fooled.

When we create a simulation, it is important to understand the limitations of that computer universe. During the research phase several virtual reality platforms were investigated to find the limits of realism. The problem was highlighted during a visit to a major international software house, as the following anecdote makes clear:

A photorealistic model of the Goodyear airship had been produced with controls that allowed the user to manipulate the simulation, thereby flying the airship in the virtual world. During the demonstration the programmer commented:

This control makes the ship go up He said as he pressed a button and the airship rose vertically from the simulated landscape. This control makes it go forward and backwards, and this control makes it go sideways .

It was a spectacular model. The rendering was superb and it was difficult to tell whether you were looking at a model or a video of a real airship.

However, the modeller had not understood that an airship is not a balloon! It flies. It is not possible for an airship to rise or travel sideways as he had demonstrated. But it was convincing, in the same way that the James Bond movie is convincing. It was an incorrect illusion.

One has to be very careful in producing simulations. Convincing animations can look far more impressive than poorly displayed, yet physically correct models.

In the crowd simulation we need to model the properties of the crowd rather than the visual images of a crowd in motion. But we also have to consider the visual impact of the model. It has to look convincing to be acceptable, to be understood. Therefore the goal is to create a realistic image ***with*** realistic physics.

4.1.1 Defining the rules in a computer simulation

The physical laws that govern our universe are still unfolding and the basic interactions that dominate everyday objects still hold on to their secrets with unyielding determination. The effects of chaos dominate our physical universe and even the simplest systems can be unpredictable. To illustrate the problems of chaos and randomness, consider a billiard table as shown in (Figure 54).

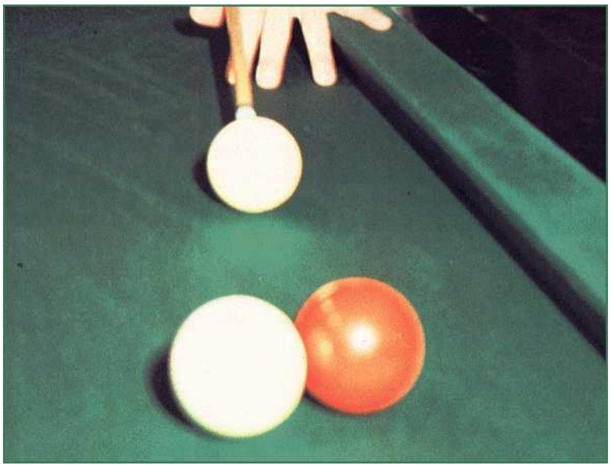

Figure 54 - A three ball collision on a billiard table.

We know the laws of physics for this example, we could predict where the balls would go if we could measure the precise location and condition of the system. If we could measure ***all*** of the parameters with absolute accuracy, we could model this system and predict the precise outcome. We could then reproduce the initial conditions and play the shot perfectly, over and over again.

However, in reality, we find that even the most rigorous measurements of the balls positions have slight errors. There is nothing in the real world that is perfectly reproducible. The player s accuracy changes with fatigue, temperature, alcoholic intake, mood, background noise - the list is endless. Even with a robot there would be slight mechanical differences in cueing position and angle. In reality, the final position of the three balls will be different every time it is played.

We live in a universe where the laws of chaos can effect the simplest of systems. That is the paradox: a computer-generated world is perfect, too perfect! To reflect our universe the laws of chaos must be included the simulated world. The goal is to create an accurate simulation of a dynamical system which includes the correct level of randomness and its consequences.

4.1.2 Modelling movement in a simulation

There are many ways to create a moving object in a computer simulation. Dynamics based on the physical properties could be created and coded into the object but this is not appropriate for modelling people. People do not behave like billiard balls. Our simulation has to capture the essential elements of how people ***read*** and ***react*** to their environment. Unlike the billiard balls in our example, people can choose their own direction, so our simulation has to reflect these behavioural choices.

There are two approaches we could use: ***Algorithmic*** or ***Dialectic***. Strictly speaking the dialectic approach does not really provide a solution, but it clearly indicates that a solution exists. But if we can demonstrate that a problem exists, then by altering the parameters of the model we can find point at which the situation becomes unsafe. It is that insight which leads us to a solution.

Unlike the dialectic approach, applying an algorithm does not enlighten the user about the nature of the problem. This is why the system of algorithmic safety levels is failing in its application. For example, a flow rate of 660 people per turnstile per hour is algorithmic. We have seen from the Wembley turnstile data that, with the appropriate visualisation, an algorithm may not be accurate. We discussed Braess s paradox in chapter 3.3, we can see that by adding an alternative route, we may not improve a circulation problem.

The guide to fire precautions in existing places of entertainment, the ***Primrose Guide*** [5]**,** has a series of calculations which fall into an algorithmic prescription for calculating egress. The following calculation is an example from the ***Primrose Guide***:

What are the exit requirements for a single floor dance hall (Class B building - requiring 2 ½ minutes of evacuation time) ?

The dance floor area is 540 m^2 . The bar area is 60 m^2 of which 30 m^2 has tables and chairs. To arrive at the answer you need to complete the following calculations.

Work out the number of people that the floor area will accommodate

The dance floor will accommodate	=	***540 / 0.5***
	=	***1080 persons***
The bar will accommodate	=	***60/0.4***
	=	***150 persons***
Total occupancy therefore	=	***1230 persons***

Work out the number of units (U) of exit width required.

The number of units (U) of exit width required is calculated as:-

U = N / (40 x T) = 1230 / (40 * 2.5) = 12.3

Note: The 0.3 attracts the rounding up rule so the total units of exit width is therefore 13. The number of exits (E) required is calculated as follows:-

E	=	***1***	+	***U/4***		
E	=	***1***	+	***13/4***	=	***4.25 exits***

Note: As the 0.25 is less that 0.75 it does not attract rounding up rules. The total number of exits required therefore = 4

The ***Primrose Guide*** also states that Class B buildings require a minimum travel distance from any point to an exit of 18 metres. We can see that the simplicity of these calculations does not consider the complexity of the environment.

If we consider that these calculations are based on densities of 2 people per square metre, then there is the further complication of an inherent speed reduction at this density. This dynamic relationship is not part of the ***Primrose*** egress analysis.

Another point to note is the definition of a unit of exit width; defined in the ***Primrose Guide*** as not less than 750mm, with the further proviso that ideally each exit should be a minimum of 2 units wide (1.05mm is stated as a minimum). Given 4 exit widths and taking the 109 people per minute per metre figure we can see that the ***Green Guide*** calculation of 1090 people in the 2 ½ minutes is less than the 1230 people calculated in the ***Primrose*** calculation. Furthermore the calculations assume that the crowd distributes evenly to all of the exits. There are many examples cited in ***Fires and Human Behaviour*** [40] that give the lie to this algorithmic approach.

Based on the observations from the Wembley turnstile data, algorithmic or prescriptive calculations do not lead to the insight necessary to understand the problems associated with the speed/density/geometry relationship. The events at Hillsborough are a testament to these dangerous assumptions.

The impact of Braess s paradox can make the addition of exit routes in an egress system lead to a slower system, for safe, overall evacuation. It is not surprising that the ***Guides*** make no mention of this, for the result is not intuitive. Network analysis and graph theory are complex mathematical subjects: their application to a design is not a trivial matter.

4.2 Computer simulation v network analysis

Network analysis and linear programming are mathematical modelling tools which have numerous applications for determining the maximum or minimum flow of elements in a network. However these techniques are not appropriate for a system that has nonlinear elements, chaos and random cause and effect [75].

Human traffic flowing through a network will have a chaotic or random element affecting the outcome. We need to know the limits of our calculations and the reliability of our results. We also need to know whether crowds are chaotic.

When network analysis techniques can be applied to human traffic analysis, the results are often difficult to visualise. Network analysis proves difficult to apply to reality, as any town traffic planner can confirm.

Our simulation has to be capable of modelling and ***visualising*** nonlinear events. The system also has to allow rapid modification of all parameters, such as behavioural dynamics, random variables and event triggering. The component elements of the system have to be programmed with decision-making criteria; individual entities have to adapt to their surroundings using simple rules. Provided we have taken care in defining the rules of the system we are left with a dialectic problem-solving technique. To illustrate this let us consider a problem of evaluating an emergency egress from a building with the same parameters as the ***Primrose*** example. We randomly populate the environment and allow each entity to choose an exit. We do this in three stages, first by allowing the entities to choose their nearest exit (the ***Primrose*** criteria), secondly by choosing a random exit, and thirdly by forcing all the entities to choose a single exit.

The results of these three tests provide us with the insight to egress that we need to satisfy our safety criteria. Clearly if all three simulations demonstrate satisfactory egress in the recommended time then we can be assured that the design is adequate. However, if one of the scenarios fails then we have a dialectic solution. We do not know why all the entities may choose the same exit from our model - but we can prove that if they do then fatalities will occur. This techniques uses the system as a what-if tool, highlight potential disaster scenarios.

Emergence, in which the behaviour of the whole cannot be meaningfully reduced to the behaviour of the individual has been applied to modelling flocks, as we now describe.

4.2.1 Flocks of Boids

An example of an emergent approach to programming was demonstrated by Craig Reynolds of the Symbolics Corporation in Los Angeles [76, 77, 78]. He formulated some rules during the creation of artificial flocks called ***boids***. These are:

Try to maintain a minimum distance from other objects in the environment, including other boids.

Try to match velocities with boids in the neighbourhood.

Try to move toward the perceived centre of mass of boids in the neighbourhood.

Computer simulations of a collection of boids demonstrate a surprising model of a flock of birds, yet their rules include a specific rule instructing the boids to flock. The rule that states moving towards a centre of local mass is a flocking rule. It is not surprising, therefore, that they flock.

4.3 Programming people

We outlined the basic rules in the VEgAS system. We can expand on these rules and outline a series of tests which prove that they are capable of modelling emergence. For our application to crowd safety we also need to highlight the requirements for applying these rules to crowd simulation. We discuss these rules with respect to the works of the crowd psychologists Sime, Canter [40-47] et. al.

The rules relating the behaviour of entities to the behaviour of the crowd: Objective, Motility, Constraint and Assimilation (OMCA), are

Objective - Try to move to a desired or intended end point.

Motility - Try to maintain your optimum velocity.

Constraint - Try to maintain a minimum distance between yourself and the other objects in the environment.

Assimilation - Delay time taken to read and react to the environment

The application of these simple rules produces an unexpected result in the flow pattern. The observed flow is concave, the sides move faster than the middle. With less distance to cover, the characters in the middle should be quickest through the exit, but this is not the case either in the model or in real life.

The applications of our simple rules here have produced the type of emergence we required. Furthermore there are no group behaviour rules involved, neither have we had to include psychological parameters.

4.3.1 Objective and Constraints

In chapter 2.6 we discussed the problems associated with Hillsborough. We shall now consider the dynamics of that situation with respect to the OMCA rules.

Consider the Objective: get to pens 3 and 4. In light of Helbing s rule (chapter 3.5.6) we see that the Constraint in Figures 19 and 132 is the turnstiles A-G. The tunnel entrance (see Figure 55) is 3 metres wide, so at 109 people per metre per minute the flow capacity of this tunnel would be 327 people per minute. The seven turnstiles, estimated at the time as 1,000 per turnstile per hour by the club, would be expected to discharge spectators at 117 people per minute. Clearly the capacity of the tunnel exceeds the capacity of the turnstiles. The exit gate C (Figure 132) is 4 metres wide, and its capacity is greater than the tunnel capacity.

The ingress at gate C (opened to relieve the pressure outside the grounds), where the observed flow was counted as 2,000 people in 5 minutes, adds to the total. Therefore we have the total ingress capacity at 517 people per minute and the tunnel capacity of 327.

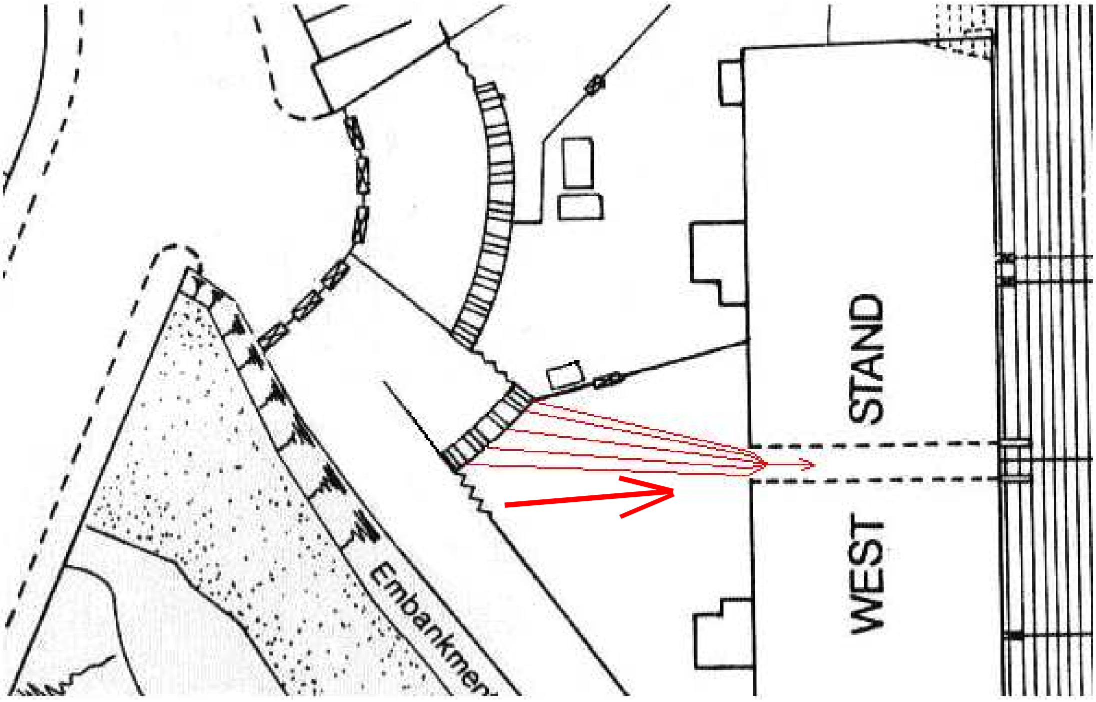

Figure 55 - The shortest routes to pens 3 and 4

In the introduction to chapter 4 we stated that a crowd consists of many individuals. If we assume that they are all trying to achieve the same objective, to go to pens 3 and 4 via the tunnel, then they will exploit the shortest route. The shortest, or focal route, is obvious in both cases. This is the path of ***least effort.***

The crowd is influenced by geometry, as we have seen from the examples in chapters 2 and 3, and this effect can be determined a priori. We can build a virtual reality model of the site to determine the focal routes, those routes that are most obvious and are visibly short cuts. This can then be used to determine the flow routes of the crowd. We can also use some simple geometric rules to determine the minimum distances an individual would travel to get to their objective. We can use the ***Green Guide*** to determine the constraints, but as we have seen those guidelines may be deficient in their assumptions.

As individuals are heading only for the short cut, we can argue that in this case the greedy algorithm is not implicit. A network model of this environment would give the wrong answer as it would assume that the greedy algorithm is implicit. However the OMCA approach provides the correct solution.

The crowd heading towards the tunnel has a unique dynamic. As an emergent system the sides of the crowd move faster simply because they are less constrained by the speed/density relationship carrying those in the centre of the crowd into the tunnel. There are no mysterious forces at play, only the simple features of the OMCA relationship. We shall discuss this in greater depth when we look the simulation output analysis.

As we can see from the postmortem analysis of Hillsborough (and many other events highlighted in chapter 2.1) people can and will put themselves into dangerous positions. It is also clear that clustering and self-organisation of crowds are essential elements of a safety system. The system has to therefore take this into consideration in order to assess the factors of risk involved in high density crowds.

We are defining the criteria for a safety analysis based on, dumb, short cut exploiting, self-destructive, individuals capable of packing to high density and following routes that are fundamentally geometric in nature. These are included in our Objective and Constraint definitions.

4.3.2 Motility and Assimilation

The Motility parameter in the crowd system relates to the unimpeded speeds of the individual. From Fruin, Helbing, Togawa, Ketchell, Paulsen, Kendik [79, 80], Henderson and Still [81] the speed distribution curves are (approximately) normal. The curves in Figure 56 were measured from a site survey.

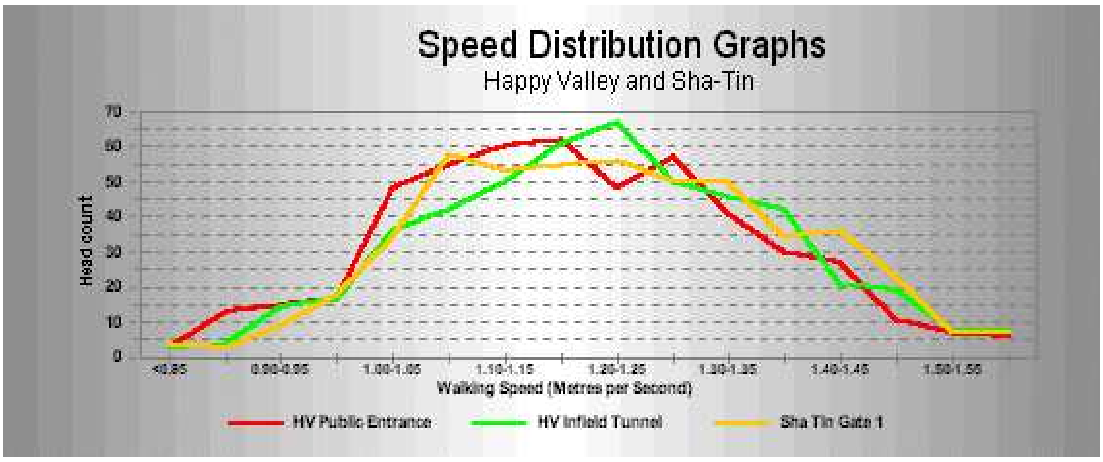

Figure 56 - Measured speed distribution curves from the Hong Kong Jockey Club

It is speculated that the speed/density relationship should be a function of the individual unimpeded speeds of the individuals. We shall discuss the effects of different speed distribution curves later in chapter 6 when we discuss the validation of the simulation. We shall also demonstrate that the speed distribution has other effects on the crowd dynamics. These relate to the clustering phenomenon.

Assimilation, the time taken to react to a change in the environment - for example, reaction to rain, warning alarms, reading signage or the movement of others - have been documented by Sime and Canter. This is a neglected factor in the ***Green Guide***, which assumes that evacuation time is a function of travel distance.

Sime in his paper on human behaviour [46] clearly identifies in field studies that a 2/3 to 1/3 rule of thumb might be applicable:

The most important finding of the research is the fact that the start up time (i.e. peoples reaction to an alarm) is as (if not more) important as the time it takes physically to reach an exit. ... On average two-thirds of the time from onset of the alarm to reaching an exit was spent by people not moving at all. On average one-third of the time was spent in moving from seat positions to an exit.

Sime[44, 45] also suggests that the two-thirds/one-third division might be taken as a rule, not for calculating exit widths, but for representing the true nature of the egress time problem. He supports his findings with numerous examples [84].

He suggests that the two factors **Time to start to move** and **Time to move** should be combined in a simple formula.

Egress time = Time to start to move + Time to move

This gives the lie to the assumption of the two and a half-minute egress time, and the egress times calculated in the ***Green Guide*** based on movement alone. In the crowd simulation we shall refer the time to react as the Assimilation time, the time it takes for the individual to start to move.

We can now simulate various scenarios by applying randomness to the models. Again these are dialectic in nature in that we need not know what factors these elements of noise represent, only that above certain levels of randomness we begin to have egress problems. We can then look to reduce the randomness in the system with more effective signage, better design or active crowd management.

4.4 Crowd psychology

Sime [43, 44, 45,4 6,47] defines thirteen parameters that are identified as important in the assessment of emergency egress. These are as follows:

Communication	Method of alerting the crowd, fire bells, warning announcements. Sime has demonstrated that the fire bell is now largely ignored. This adds to the **Time to start to move** factors. Communication is not restricted to alarms: factors such as environment (changes in temperature), other people s movement, sounds, smells and visual clues can also trigger the reaction of the individual.
Mobility	The speed at which an individual is capable of moving. Elderly, infirmed, the very young and the very old are located in different positions on the speed distribution histogram.
Social Affinity	It has been observed (Sime, Canter, Helbing et. al) that social affinity is an important factor in the dynamics of emergency egress. This relates to the position in the affinity cluster (for example, a family group father, mother and child behaviour).

Alertness	The individual will react at different rates depending on the state of alertness.
Role	Sime highlights that the role of the individual is important in their reaction to an emergency. In the Bradford disaster (referred to in the Poppelwell Report [82, 83]) the role of the police, their numbers, location and position of authority, were determining factors in the crowd behaviour.
Position	This relates to the individual, in that a seated person will react differently to a standing individual. Obviously an individual who is lying down (resting or asleep) will have different rates of response to emergency situations.
Commitment	Canter states that the individual reacts differently to an emergency (such as a fire) in the home than to a fire in, say, a hotel.
Focal Points	Sime et. al. identifies that visible egress routes are a defining factor in the emergency egress behaviour. This is also in line with the observations of Helbing and the author during site analysis.

Familiarity	The more familiar the individual is with emergency procedures and the building layout, the less the **Time to start to move** will be. We shall refer to this as the **Assimilation** time.
Visual Access	The more visible the signage, emergency egress route, or in the case of Hillsborough the ingress route, the more attractive the route will be to the individual. This is a geometric factor.
Population Density	The dynamics of the crowd dictates the egress behaviour.
Enclosure	Individuals have a desire to reach safe ground. It was noted in the King s Cross Fire [40] that there is a tendency for individuals to try to reach ground level, although it is safer to remain underground as heat, and fire, rise due to thermal effects.
Complexity	The more complex the environment the more indecision there will be during an emergency. This will add to the total egress time for both assimilation time and movement time. The combination of Braess s paradox and signage problems contributes to the complexity of the building.

Sime goes on to define criteria for changing the awareness of the above to facilitate more rapid egress behaviour. There are numerous papers on psychological factors at work in emergency egress behaviour (see the Bibliography for further references).

4.4.1 Psychology and the OMCA rules.

We can define all of the psychological factors in our OMCA framework. The assimilation times (for example time to react) can be modelled using a number of locally assigned factors. The following table indicates how the psychological characteristics relate to our framework of OMCA rules.

Communication	Assimilation
Alertness	Assimilation
Mobility	Motility
Social Affinity	Objective
Role	Objective
Position	Assimilation
Commitment	Assimilation and Objective
Focal Points	Assimilation and Objective
Familiarity	Motility, Objective and Assimilation
Visual Access	Motility, Assimilation and Objective
Population Density	Objective, Motility and Constraint
Enclosure	Objective and Assimilation
Complexity	Objective and Assimilation

The values of these parameters are user-defined, and we shall see, in some worked examples (chapters 7 and 8, the case studies), how they can be determined from video analysis and site data.

4.5 Conclusions to Chapter 4

We have discussed the various parameters necessary for a safety simulation. These include non-homogeneous flow characteristics. Treating the speed versus density relationship as a formula leads to inappropriate egress estimates, as does assuming the crowd will react immediately an alarm is sounded.

We have outlined how various psychological factors can be included in a model as they manifest themselves in the movement of the individual.

In defining the Objective, Motility, Constraint and Assimilation framework we have reduced the complexity of the system to its basic interactive elements and these are demonstrated to fulfill the Einstein criterion:

Simplify - but do not over simplify.

As the model is entity-based the effects of individual speeds accumulate, the crowds cluster and this leads to the insight of ***how*** and ***why*** the crowd displays the effects we have seen in clustering, cornering and distributing. We shall now demonstrate that the model based on the four rules fulfills the criteria of simulating the dynamics of crowds.

Chapter 5 Legion

5 Introduction

We have defined the basic criteria necessary for a simulation of large crowds. In this chapter we shall outline the parameters, assumptions and characteristics of the Legion system, which is the central topic of this thesis.

The Legion simulation consists of independent problem-solving entities which obey the OMCA rules. These entities move around a two dimensional computer-generated landscape and ***read and react*** to changes in that environment. These reactions include responses to the behaviour of other entities.

Like the ants in a colony, Legion entities are automata with limited intelligence. This fulfills one of our safety criteria for, if we were to make the entities too smart, they would never endanger themselves. The simulation is designed to discover the situations in which people can cause themselves harm and, by design, reduce or eliminate the associated risks. We discuss the reasons for the assumptions behind the methodology used in the simulation.

5.1 Choosing the simulation parameters

We need to represent the entity and the geometry on an appropriate scale. We also need to determine the scope and scale of the models we wish to build, the number of entities in a typical model, and the features that we wish to measure. We need to define the crowd parameters and how they relate to the issues of safety. The parameters of the crowd dynamic, used in the simulation include the following:

Entity Sizes Dimensions of height, breadth and depth for entities.

Space	The space entities occupy when moving, standing or changing route. That is, a plan of the building.
Time	An appropriate choice of time-slicing (dividing the time frame) to allow the simulation to be viewed in real-time.
Movement	The distance that entities advance for each unit of time.
Decisions	The algorithm for choosing where to go next.

5.2 Modelling people

People come in all shapes and all sizes and large breadth does not imply a large depth. From Bodyspace [38] we can see those individual dimensions, chest depth, shoulder breadth etc., form normal distribution curves. We also note that an individual who is tall may not necessarily be faster than a shorter person.

We need to provide a clear and anthropomorphically correct graphical representation for our simulated humans. We also need to consider their movement in steps per frame. Furthermore there is a need to consider the computational overheads in both processing and display of the entities. There are two options for our choice of entity size in the simulation.

Give each entity its own size	From the distribution histogram.
Give each entity size the same size	Taking the average, or largest size from the distribution histogram

5.2.1 Choosing the 95th percentile

If we can prove that the environment we wish to simulate works with a capacity crowd in the 95th percentile range, then we are testing the upper limits of the environment. We should not forget that there are situations where the crowd could consist of people who are ***all*** larger than this - a rugby club reunion for example, or the local weight watcher s outing to Bognor Regis.

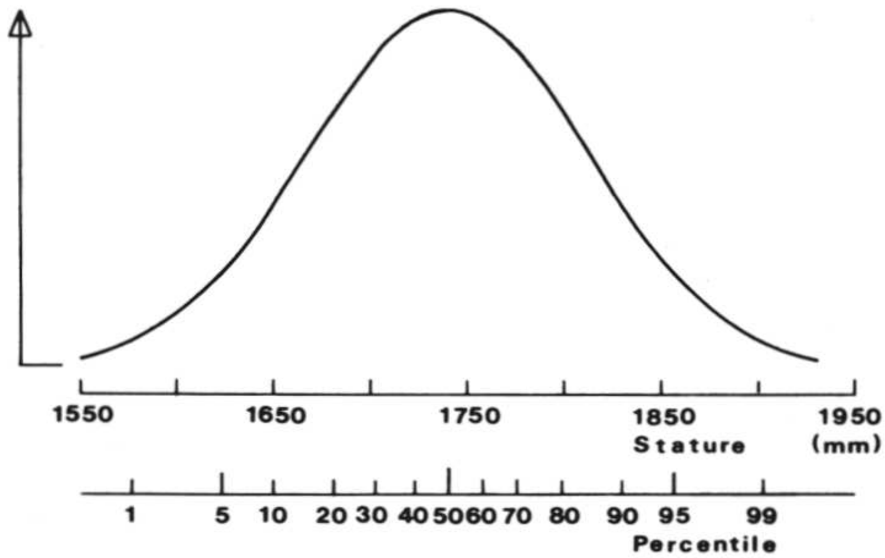

Figure 57 - From Bodyspace [38] showing frequency distribution for stature.

Figure 57 shows that the choice of the 95th percentile covers the mean population dimensions (the distribution curve is valid for breadth and depth). To facilitate the exceptional circumstances of an abnormally large framed population we shall provide scaling within the system.

However, we are considering the crowd dynamics and the evidence presented by Kendik et al. [22, 32-34, 38, 57-62, 79-87] indicates that entity sizes are distributed normally around the mean value (Figure 57).

Although there may be exceptional circumstances where members of the population are all above the 95th percentile in both breadth and depth, we are considering entity density. Our primary concern is how many people per square metre we can allow while maintaining a safe environment.

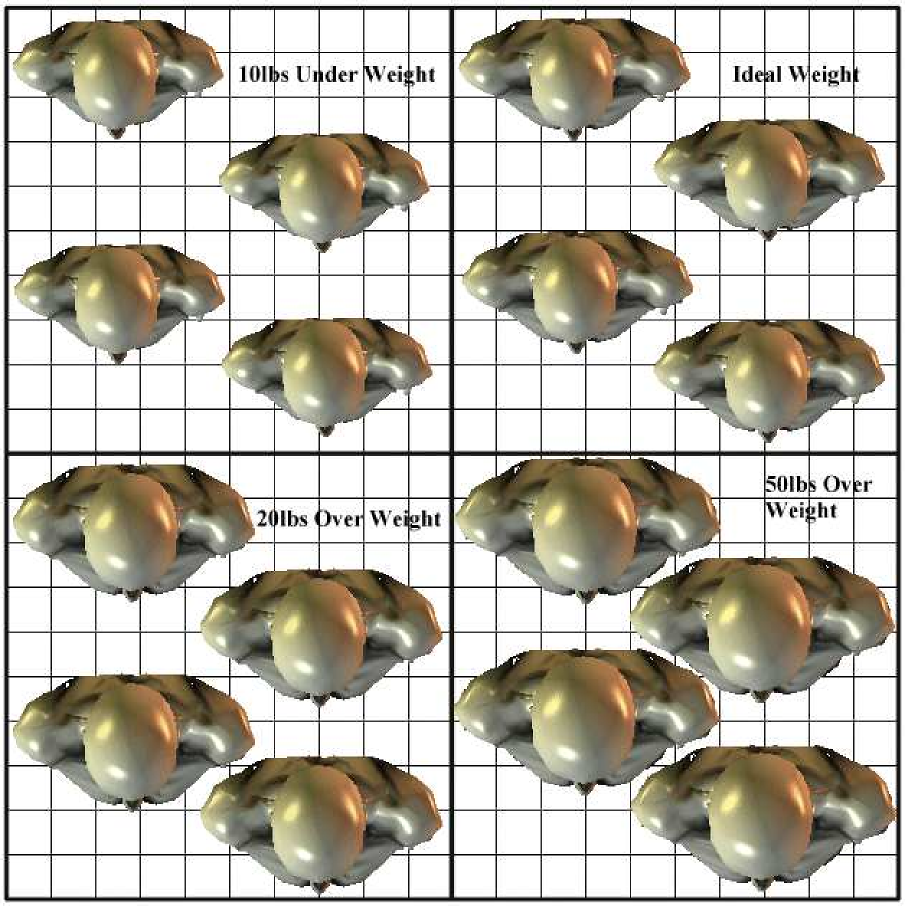

Figure 58 - Packing to four people per square metre

We can see from Figure 58 that packing to four people per square metre, even with a population of very overweight individuals, still allows room for manoeuvre. There is space for the chest cavity to expand, and people have space to move, even if it is only shuffling movement.

The packing density of 4.7 people per square metre with the 50lbs overweight grouping also appears to be within the safety limit stated in the ***Green Guide***. The value of 4.7 people per square metre applies to a stationary crowd [1, 2, 6]. However, as Figure 59 demonstrates, the area per person is not breadth times depth. We shall take the 50cm by 30cm profile, from our discussion in chapter 3.2.2, for our calculations. It represents a significant proportion of the world population in the 95th percentile range of anthropomorphic sizes and falls into a value range which can be handled by the computer, and offers the advantage of being able to use a 10 centimetre scale in the models.

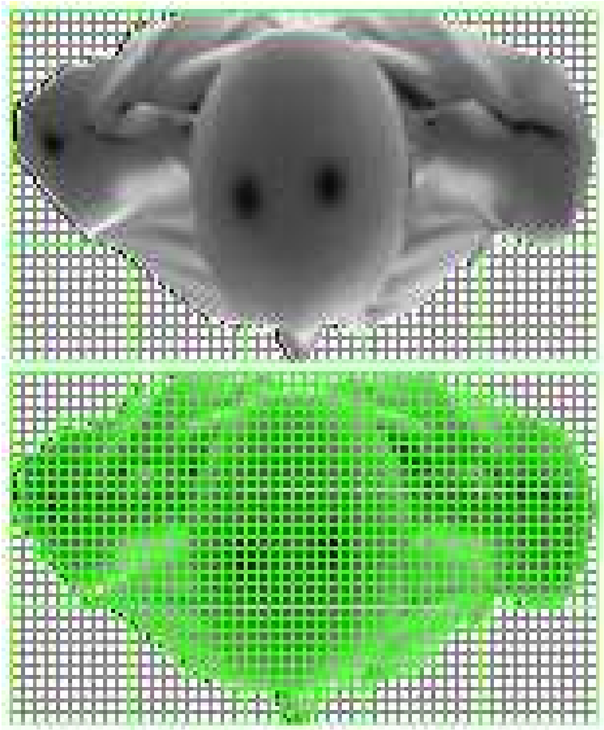

Figure 59 - 50cm by 30cm body on a 1cm grid

Figure 59 shows that although the body size is 50cm by 30cm, the area that the shape occupies is 929 square centimetres. This would represent a square section of 30.47cm by 30.47cm. Our choice of 50cm by 30cm has the additional advantage for our model; it allows us to use a 10cm resolution as our basic unit of measurement for plans. However, there is a more important reason for using these dimensions.

We know from the Health and Safety Executive experiment in the Taylor reports [32, 33, 34] and observations at Wembley that people can pack to densities approaching 10 people per square metre. We have to allow in this limit on our simulation. If we make the entities too large then the simulation will not allow them to pack to a dangerous capacity and we learn nothing. We would defeat the goal by inadvertently designing a safety margin into our simulation. Our goal is to determine the limits where people can (and will) endanger themselves. The indication is that the simulation has to have the capability of packing to a profile of 30 square centimetres.

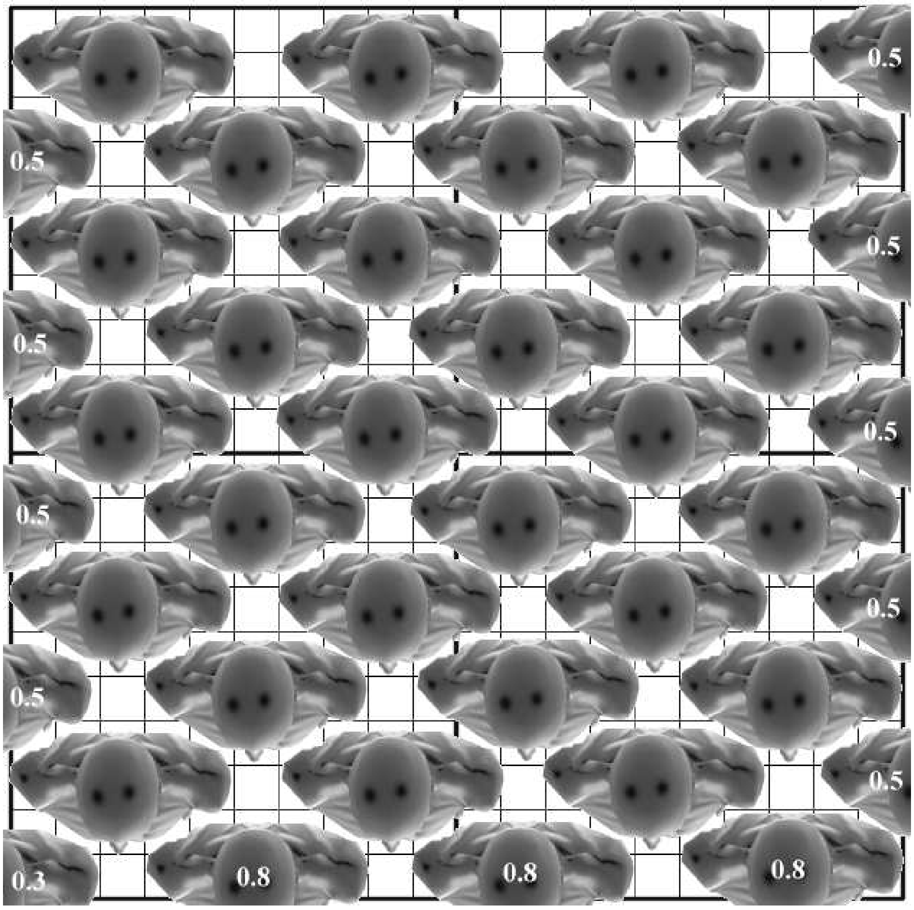

Figure 60 - packing to 8.4 people per square metre.

We also have to balance the graphical representation with the computational overhead. Figure 60 shows a packing density of 8.4 people per square metre. We can see that at this packing density, we have problems in overlapping complex graphical representations of individual entities. We need to simulate large crowds, greater than 5,000 entities, without incurring a substantial computational overhead.

Complex graphics such as those shown in Figure 60 use a large amount of computer processing. When packing them to realistically high density crowd positions (Figures 9, 10 ,22 34 and 61) we are trying to solve a problem which is know to be intractable; the ***Knapsack problem***. This is a complication we can avoid.

Figure 61 - Wembley Stadium concourse at B level, during ingress.

Figures 61 and 62 show moving crowds. At these densities there is room to breathe, space for turning and gaps between individuals. Figures 61 and 62 show that circulation is possible at these densities (estimated at between 4 and 6 people per square metre). Furthermore individuals are not aligned as in Figure 60. This is a problem when we consider the graphics we need to represent entities.

We begin to see the limits to a successful model and the practical issue of the graphics. If we try to make the entities realistic in shape we have a problem working out the high density packing graphics. This is a classing 0-1 ***Knapsack problem*** [88] and incurs a considerable computational overhead.

We have to simplify, but not oversimplify, the graphics, to make the simulation computationally manageable.

Figure 62 - Wembley Stadium, players tunnel.

We shall consider a square representation of an entity and discuss the advantages that this presents. Figure 63 shows an entity placed at 0, 45 and 90 degrees on a square grid of 10 centimetre widths. We can see how the 30 centimetre square is a good approximation at all orientations.

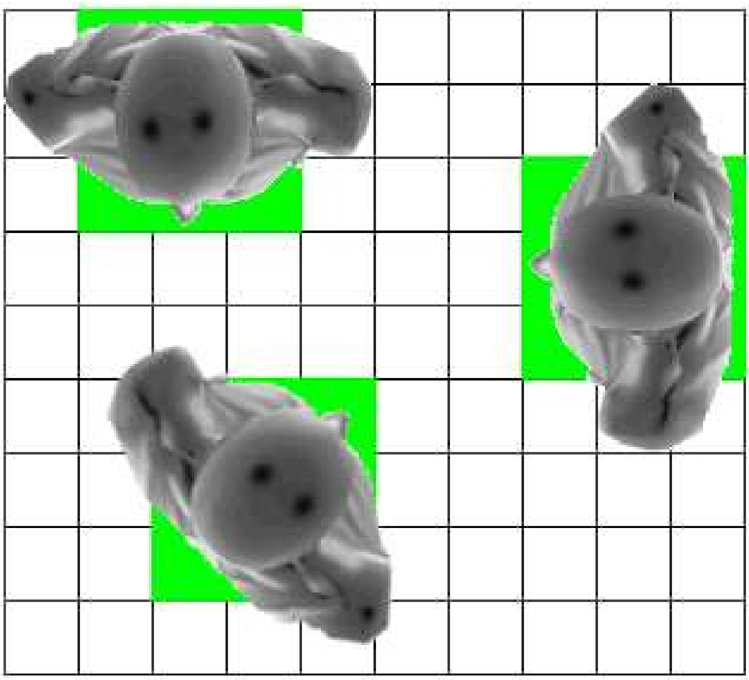

Figure 63 - Representing the entity as a 3 by 3 grid (30cm square)

Using a square section we can now define two features of our safety limits. The first is that when our simulation exceeds densities above 4.7 people per square metre it is dangerous. The second feature is that we can also time the duration of high density exposure. The square section also simplifies the display graphics yet retains a recognisable form for the individuals.

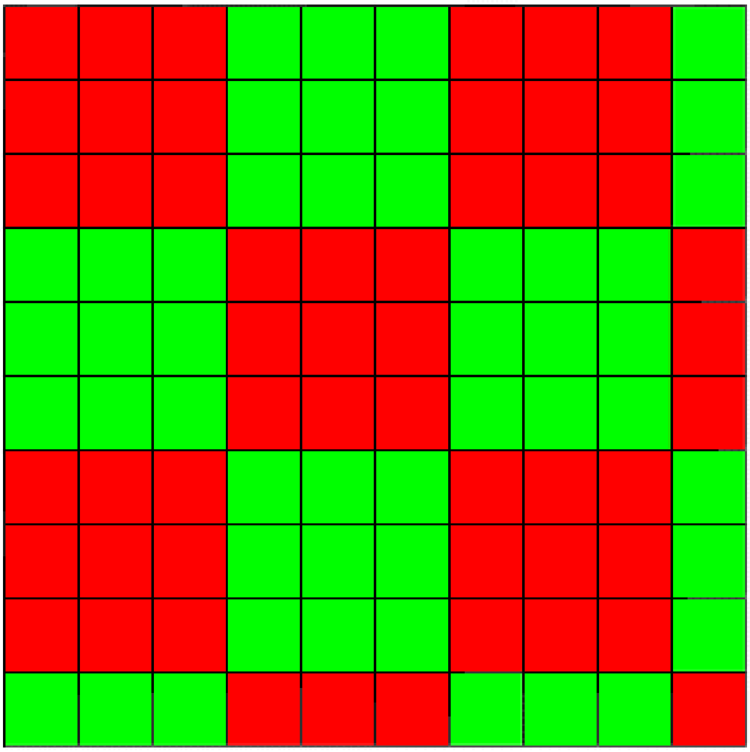

Figure 64 - 30cm grid, packing to 11.11 entities per square metre.

We can now measure the exposure limit that the entity experiences, giving us a clear indication of his level of distress, and determining the crowd risk factors.

The guidelines use the average density throughout; this is for a very good reason: it has not been possible to analyse the crowd in the above way before. We aim to set new standards in risk and safety analysis for places of public assembly.

5.3 Modelling space

In this section we introduce the concept of information space (iSpace), how it relates to the OMCA rules, and the framework in which we can define complex simulations. First we shall define some of the observations that led to the development of the iSpace concept.

The human body can read and react, at various levels, along the central nervous system. Long before the information reaches the cerebellum the hand reacts to a hot/cold surface. The arm can withdraw (react) to a pain stimulus, effectively bypassing the thought process. This is a fascinating concept in that parts of the central nervous system may be capable of acting without a central processor (the brain). If we adapt this philosophy to our crowd simulation we begin to see how layering sub-programmes, each with autonomous capabilities, can be used to create highly complex behavioural systems. Our model works like the ants in a colony, where a communication system (pheromones) passes information through the colony. Legion entities pass information around the individual entities as the simulation progresses in a similar manner within a framework of logic conditions.

5.3.1 Logic conditions

The rule based system operates with multiple levels of instruction sets. There are three types of logic we use in the model.

Proximity Logic	-	Where entities avoid collision
Conditional Logic	-	When entities determine objectives
Absolute Logic	-	Used to assign structural objectives.

5.3.2 Component definitions

There are two types of components we use in the model. These define the information processing substructure

Entity	-	Any component of a system that retains its identity over time.
Information Space	-	Any component of a system that has the ability to change over time (in size, internal programming, location). The abbreviation we use for this is iSpace.

Thus an entity contains elements of information and can read and react to the local environment. Communication occurs when entities pass information through the environment. This is equivalent to the ants passing pheromones and building complex interactive communication, and is a decentralised process.

5.3.3 Component communication

The entities contain code segments that interpret iSpace, retain information about objectives, size, velocity and position. Entities communicate with (and obtain instructions from) iSpace on a strict hierarchical structure - namely they read the region of that iSpace they are standing on, or are within. That iSpace communication is limited to a single (parent) upper level. The iSpace can then instruct the entity about its objectives.

At each communication stage (a section of the code that searches the entire iSpace structure) the youngest entity (or iSpace component) reads/reacts to the next level up. Once the oldest structure has read/reacted the sequence reverses and works (in a similar manner) from the top down.

Using this method the information is propagated up and down iSpace and all entities/iSpace components are updated (twice per cycle). This structure also allows for a sibling (two components that share the same iSpace) communication as the cycle of upwards communication followed by downward communication relays information across siblings.

5.3.4 Example of iSpace coding

Consider an entity leaving a room in iSpace, where a fire has been lit. Its information from the fire room is ***leave*** by any one of the available exits - carrying with it an information segment ***fire present***. It enters the corridor iSpace and is interrogated by that iSpace (which now knows fire is present and where - each entity carries only the flag ***fire*** and ***last destination*** the code structure on iSpace has an absolute logic map of the environment. This corridor iSpace can now inform every entity within its space of the fire and (as each iSpace module has an objective list) change the probabilities for the next entities objectives.

5.3.5 iSpace objectives

It is not necessary for iSpace to have a specific objective (point) as it can communicate an angle to the entity. This can be a collective angle of entities (flocking/migration) or assignment of last entity to next (queuing - also coupled with a speed check - move at the same rate as the entity in front - this then becomes a first in, first out stack for entities). It is also desirable to hold the potential for sorting entity lists in iSpace according to a variety of parameters (such as fuel, cash, size etc.) as conditional logic.

5.3.6 Self-organised environments

Due to the methodology of interactive programming the dynamics of communication is already self-organising. Each entity is dynamically linked to every other relevant entity (via iSpace) and with the hierarchical structure. The structure is constantly communicating across every level. This structure is very similar to that of an ant colony where every ant carries small pieces of information (pheromones) and passes these to others creating a communication system across the whole colony. The collective intelligence of the colony is not in any individual ant, but it exists as a dynamical system protocol. So long as the protocol exists, the colony exists.

In the Hillsborough example we can see that there was no communication between entities, in that the people who were pushing into the tunnel were unaware of those people who were being crushed at the perimeter fence. It is important to note that the collective intelligence of a crowd is, in this way, similar to that of an ant colony. The stadium staff, police and, via the television, millions of people were watching the match, were aware of the event, but the people at the back were not.

When building iSpace we constrain communication between entities in this manner, lest we make our entities too intelligent to place themselves in danger.

5.4 Modelling movement

It is important to define the principles of emergence and how they relate to a simulation. By definition the simulation has to have as few rules as possible to be successful. Those rules also have to represent the characteristics of individuals as they progress through complex geometries, react to differing densities, and act appropriately in a variety of conditions. The conditions can be interpreted by the entities as they navigate the simulation.

To prove the concepts and set a goal or objective for the definition of a simulation, we need to outline the principles we wish to demonstrate. These can be summarised as: To build an entity level model of the hypothetical mechanisms of a behaviour we must:

Show that, at a fundamental level, the essential elements actually exist.

Show, by simulation, that the model is capable of generating the observed behaviour (as an emergent phenomenon).

This leads us to the logical conclusion that if the simulation satisfies the process of the behaviour from the proven underlying mechanisms, we have demonstrated the existence of the phenomenon as a well-constructed scientific object.

5.5 Modelling crowds

During the early development of VEgAS and Legion several hundred hours of video footage, recorded at Wembley Stadium (UK) and a London Underground station, were observed. The qualitative analysis led to some conclusions regarding crowd dynamics which were central to the design of Legion.

Initially the dynamics of how individuals move in a crowd was observed, an algorithm for their behaviour was constructed (VEgAS) and the limitations (computational intractability) for simulation were encountered. A more comprehensive theory was developed and finally the problem of collision detections, culling and real-time analysis were overcome.

The solution to all of the aforementioned problems is encapsulated in the algorithm we call ***least effort***. As mentioned in the introduction the precise contents of this algorithm are subject to non disclosure agreements and commercial constraints. However, we can discuss various aspects of the input parameters and components of the algorithmic solution investigated during the development of the Legion suite of programmes.These include tests on the fingering effect using a random walk algorithm and Monte Carlo models of object navigation.

5.5.1 How people move: a random walk?

As real people move through their environment they can choose their own direction. We have seen in previous discussions that those choices are influenced by a range of environmental factors. We have also seen that an a priori analysis of all of the choices possible is, by definition, an intractable problem. We have discussed a framework of read and react (iSpace) which allows us to create powerful interactive environments. We have discussed the problems of chaos in computer simulations using the illustration of billiards to discuss the fundamental differences between a physics and biological system with respect to dynamics.

First, let us consider a simple model. Figure 65 shows a computer model of randomly located dots on a screen. There is a stream of entities being created at the bottom, and they navigate their way to the top of the screen.

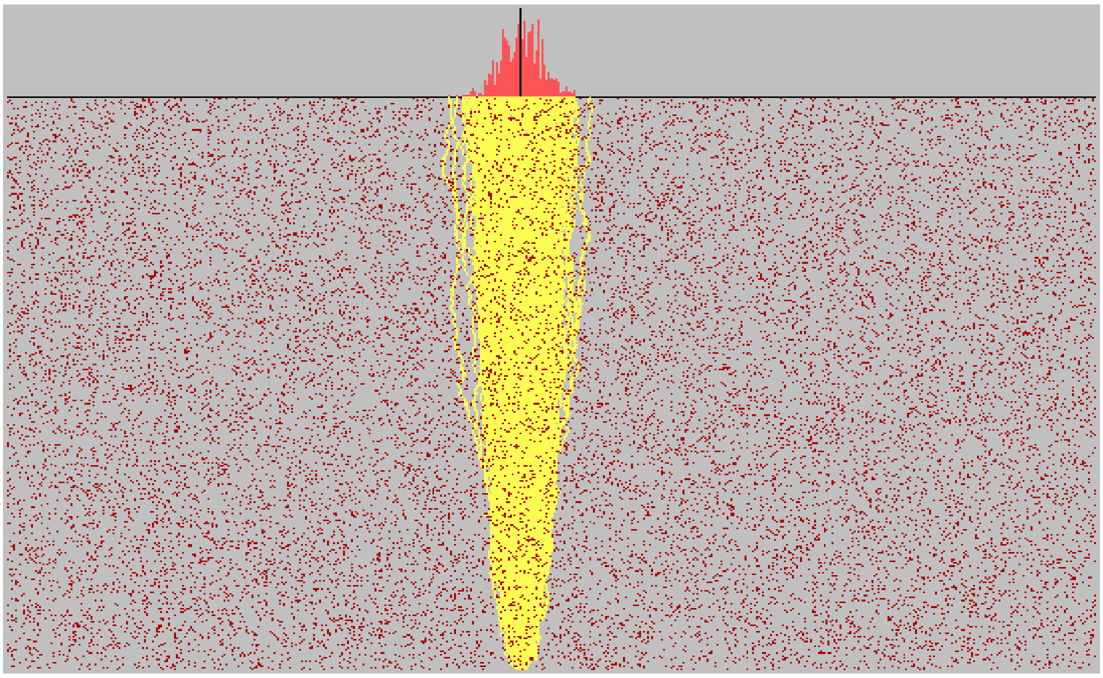

Figure 65 - Entities enter at the bottom of the screen and move, avoiding any obstacles to the top of the screen. A histogram is produced (top of screen) of the number of entities that arrive at that location).

In this model (Figure 65) the choice for avoiding the dots is random. They avoid to the left or right (with equal probabilities) while trying to move up the screen. They keep on their path until another dot (obstacle) is encountered, avoid it again randomly to the left or right and continue until they reach the top. This produces a normal distribution curve of arrivals. The model here is based on the random walk principle and we produce the expected normal distribution curve of arrivals (strictly, a binomial distribution, very close to a normal).

People don t move like this, the rounding errors in the algorithms have to be compensated for, otherwise the simulation would produce very unrealistic results.

The fundamental differences between a physics model and a biological model is that people can correct their course. The further away they deviate from their shortest route the more they try to compensate.

The field studies observed the degree of noise and course correction associated with the typical walking characteristics of people in crowds. An algorithm that course corrects in the same way that people do when moving through their environment was developed and tested.

5.5.2 Compensating for the random walk.

To ensure these rounding and chaotic errors do not create problems in the simulation we compensate by biasing every deviation choice by the value of the deviation. Thus if the entity starts to drift to the left its next random encounter is biased towards the right.

In Figure 66 we can see the effect of a simple course correction. The point of focus, which we call Objective driven, is compensated as a function of the deviation from the focus. At each stage the entities are reading their current position and reacting to their environment. By using a random function, driven by the deviation from the objective, we can compensate for random perturbations.

We force the system to behave in a more ordered, more biological manner, by this process of course correction.

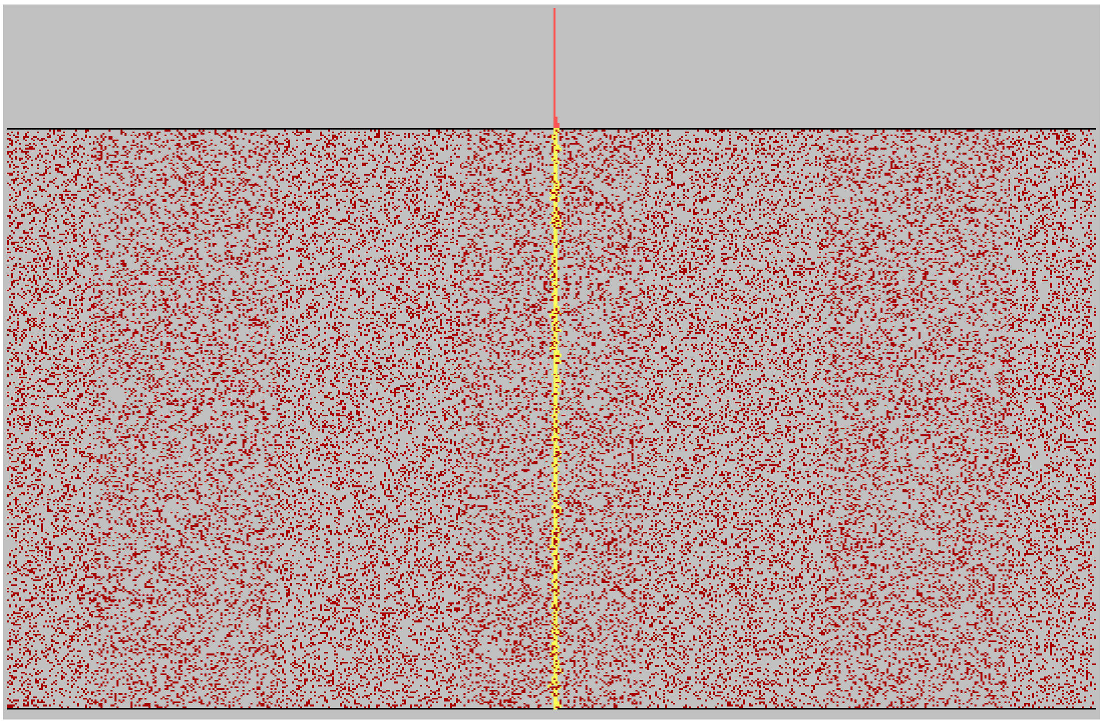

Figure 66 - Biasing the random walk (course correction) is achieved by weighting the random deviation in the direction of the objective.

5.5.3 The rules in a crowd

The simulation uses four rules to determine the functions for the flow of human traffic. These rules interact as characters come into proximity with each others space (iSpace) associated with the static (non movable) and dynamic (movable) objects in the environment. The result exhibits emergent behaviour, specifically, the entities are programmed with one kind of behaviour but the group of entities exhibits another kind of behaviour. Where the group behaviour cannot be reduced to the individuals behaviour, a system is defined as emergent.

The iSpace concept allows the design engineer to program emergent behaviour into objects ***at the object level*** and construct very complex environments from simple building blocks. This allows them to test complex buildings, part of our objectives outlined in the introduction in chapter 2.

5.6 Intractability of collision detection

Collision detection is a major problem in large scale simulation systems. The main reason why macro-models, based on fluid dynamics, use the Boltzmann Gas equations is that they bypass the problems of collision detection.

We shall define the problem, highlight its algorithmic complexity, and discuss the solution used in the simulation. First the VEgAS timing chart is presented in Figure 67. The collision detection problem can be tackled by checking each entity against every other entity but that solution is not efficient. As the number of entities increases the time to check through the whole list will rise as the square of the number of objects. Although this is polynomial time it is nonetheless computationally intractable in practice for large crowds. The algorithm is $O(n^2)$.

5.6.1 Overcoming computational intractability

As the number of the objects rises, the time to check collisions will rise considerably. The VEgAS limitation was a function of the display graphics. Our requirements for a simpler and more relevant graphic in the Legion simulation system. However, we have not yet addressed the problem of collision detection..

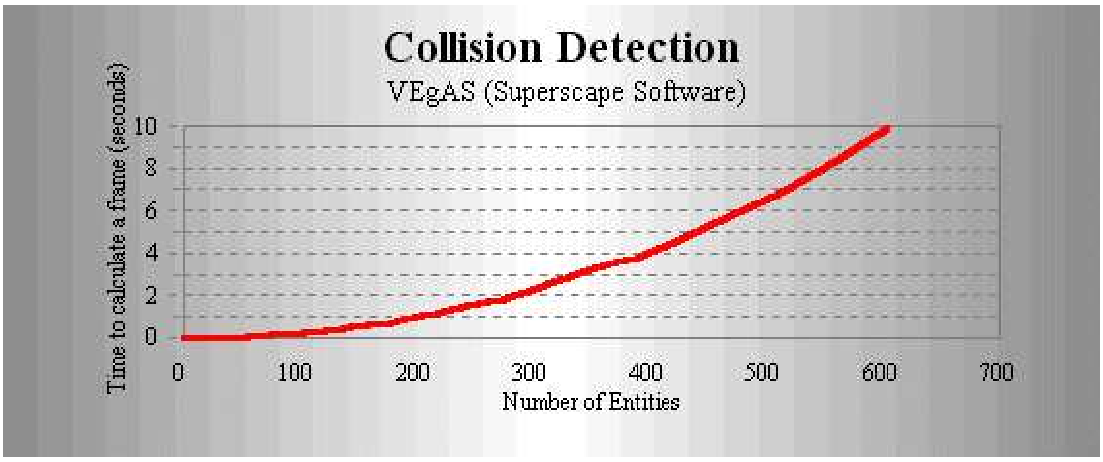

Figure 67 - The Superscape (1992) timing chart for collision detection (time v number of entities)

If we check from a list of entity positions the system suffers from the problems of computational intractability. The solution was to present the entity with a local environment which can be scanned by that entity.

The process we use, described in the introduction, is similar to the approach used for simulated annealing [89]. The least energy constraint has been replaced with a series of least effort constraints. This approach is fundamentally different to the Metropolis algorithm, although in principle the problem is the same. Figure 68 shows the efficiency of the Legion solution. We can see the effectiveness of this algorithm and the results demonstrate that the system performs in polynomial time.

The algorithm does not exceed O(n) time and in areas of high density the algorithm first performs a motility check, then a collision detection.

5.7 The Legion solution

It would be foolish to attempt to construct an algorithm of human behaviour in all its complexity, so we apply Occam s razor: Our criteria are aimed at safety and risk assessment, the elements that express these parameters are simpler that the complexity of human behaviour per se. Each entity will try to take the shortest route

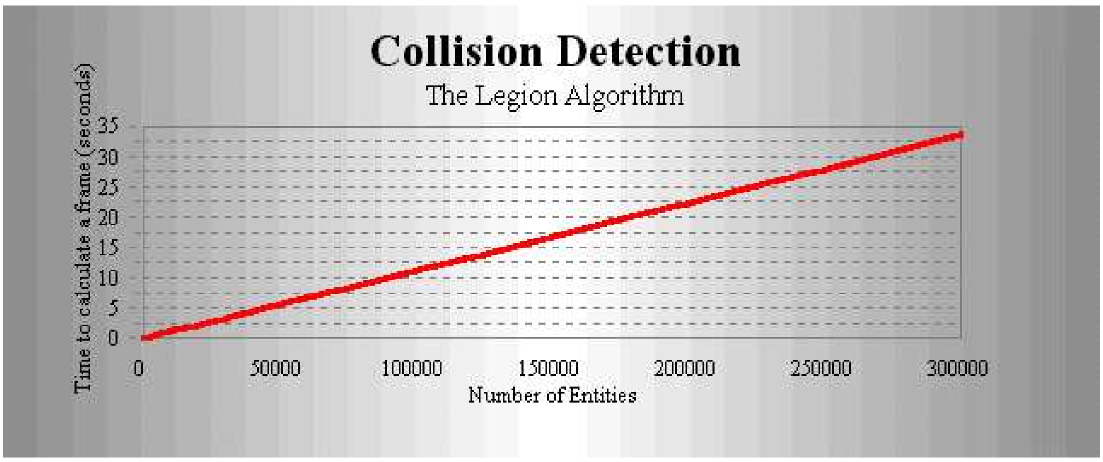

Figure 68 - The Legion algorithm for collision detection (time v number of entities)

to its objective (fulfilling our ***least effort*** hypothesis). They will react to changes around them (this is where we programme the environment in iSpace). They will have no collective intelligence (the exploitation of simple rules is done by many individuals acting independently, they do not perceive the situation as it evolves other than at a local level), they will react to the local geometry by applying simple collision avoidance algorithms, and there is an overall requirement to display self-organisation to the same degree as a high density crowd.

Simple local collision detection scanning has been applied to solve the collision detection intractability. It is simple in concept, but it leads to highly complex results because it has emergent properties.

In a broad description the algorithm scans for the easiest route which is a combination of the shortest distance at the fastest pace. The entities also course correct as they proceed towards their objective. We use the term ***least effort*** to describe this algorithm. Strictly speaking the entity is solving a problem know as a nonlinear programme [90]. It does so by taking a ***least effort*** route to its destination, working out the shortest distance in two stages: initially calculating a long range scan for the minimum angle navigating obstacles in its way, then scanning for a maximum pace along that route.

We find that the properties we are seeking are incorporated in this simple and elegant methodology. We also find that, when we test the emergent properties, the algorithm is robust and can be validated in a variety of ways against real crowds.

The introduction to chapter 4 listed a series of parameters of crowds, we now examine the performance of the algorithm against those parameters. The crowd consists of many individuals, by design our model consists of many individuals.

5.7.1 Exploiting short cuts

Since we are using an algorithm based on ***least effort***, the exploitation of short cuts is implicit. Furthermore the scan angles we choose are based on the speed of the individual and are adaptive to the local constraints.

It is worth noting that in the Building Research Establishment (BRE) document [29] the following quote appears.

Minor restrictions such as slight projections have little effect on the flow rate. Corners and ends also have no effect on the flow rate. The speed is slowed down and the crowd density is increased on the inside of the bend. On the outside the speed is quickened and the density decreased.

This is due to the people who want to, and are capable of, travelling faster relocating themselves in areas of lesser density. However, the relationship is significant and not, as the BRE document suggests, inconsequential.

5.7.2 Speed profiles in people and crowds

The crowd has a speed profile in that the average speed of the crowd is in fact a distribution of speeds. The crowd can be moving fast at its edges and slow in its middle. The field evidence for this is substantial as we have illustrated in earlier discussion. Edge effects, where the edges of the crowd move faster than the centre, can be observed in many situations. One of the most common places to observe this phenomenon is at a station where people try to get on to a train from a packed platform. We created a simulation to investigate the significance of this effect.

The ***Edge Effect*** experiment consists of a corridor with a central constriction: we will call this a bottleneck. The ***Green Guide*** suggests that no part of an egress system should be constrained in this manner, and we have seen examples that the ***Green Guide*** does not cover (networks and merged flow in particular). In our experiment we consider the space utilisation effect over much larger areas. Specifically we draw on an incident that occurred at Wembley Stadium where the suggestions of the model were implemented (1994).

Figure 69 - Outer concourse, looking towards gate J (to the right).

The merchandising stand (between the trees on the right of Figure 69) was though to be the cause of congestion in this area. Some 20,000 supporters would pass this section. As we can see from the plan (Figure 70) the area has two main directions of ingress flow (shown as blue arrows in Figure 70). The green shapes are concession stands. The red line (Figure 70) indicates the narrowest section on the outer concourse at 18 metres. The problem was related to heavy congestion in this area. The congestion was thought to be attributed to the concession stand on the right; however, the queues to the concessions on the left were actually the problem. The shortest route (Blue arrows) was to cut the corner near the concession stand to the left of the red line above. This clashed with the queue to that concession stand.

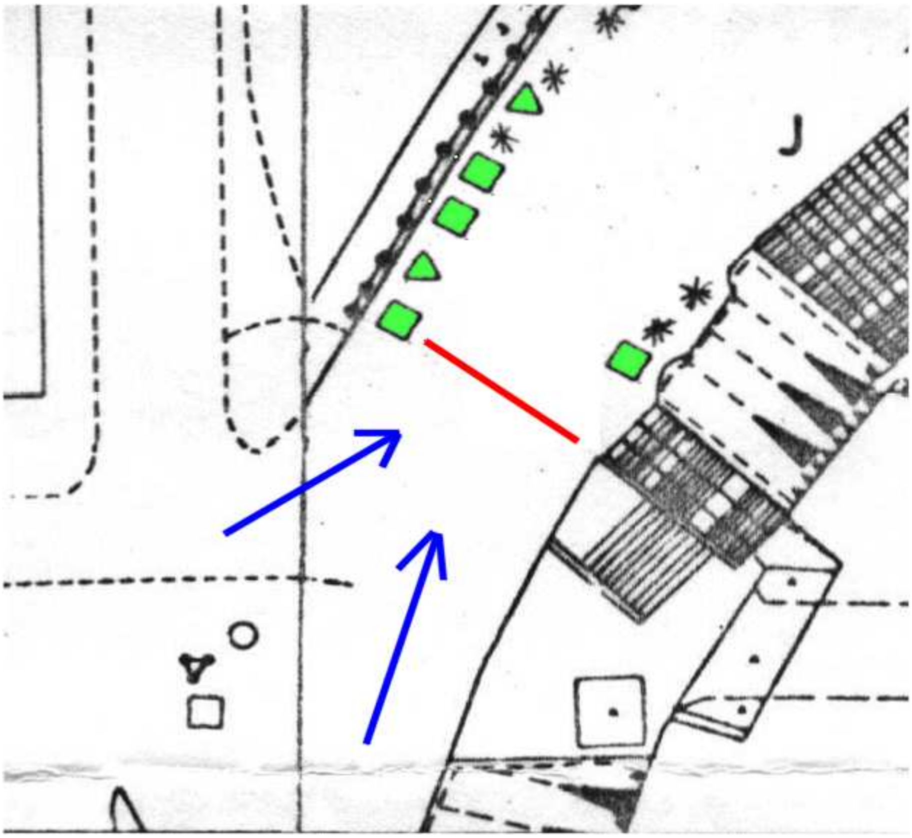

Figure 70 - The plan of the constricted area.

The ensuing flow (left-hand blue line in Figure 70) moved further to the right and the merged flows had higher density (around 5 people per square metre). This resulted in a back-up of supporters, further impeding progress. The problem was solved, not by removing the concession stand on the right (Figure 71) but by removing the concession stand on the left. The queue no longer impeded flow and the congestion was relieved. The density dropped back to 4 people per square metre.

An experiment to test the congestion was created in the simulation tool.

5.7.3 Filling space

As the entity reaches its objective we reduce its speed. Further entities entering that space then have to navigate through the entities already stationary. The result is the same patterns of filling observed in Figures 24 and 71.


Figure 71 - Packing is high density near the platform edge.

Figure 71 demonstrates the principles we need to model in this context. We can see that people proceed to fill the platform from the bridge (Figure 24), line up along the platform edge. The nearest available space on the edge becomes the next entities objective.

5.7.4 Crowd clustering

We generate each entity at random and assign its speed from the speed distribution histogram. The result is that we can create clusters of slow-moving entities. In tight local geometry we find that the model displays the clusters and bubbles described by Helbing, discussed in chapter 3.5.6. We shall demonstrate the model s ability to generate clusters and bubbles later in this section.

Clusters occur in two forms: ***Static*** and ***Dynamic***; (Figures 72 and 73).

Figure 72 - A static cluster: Standing wave

The ***Static*** clusters (Figure 72) typically occur in queuing situations. We call this ***Static*** because the clusters occur in the same place relative to a location: although the people are moving, the queue remains stationary, that is these types of cluster form ***standing*** waves.

The ***Dynamic*** cluster is observed in areas where packs of high density, slow-moving groups form for two main reasons; small groups can be seen moving together at the pace of the slowest member and the natural occurrence of the speed density clusters, where the movement of people are constrained by a slow-moving individual. These type of clusters form ***travelling*** waves.

Figure 73 - A small group forming a cluster, the same phenomenon

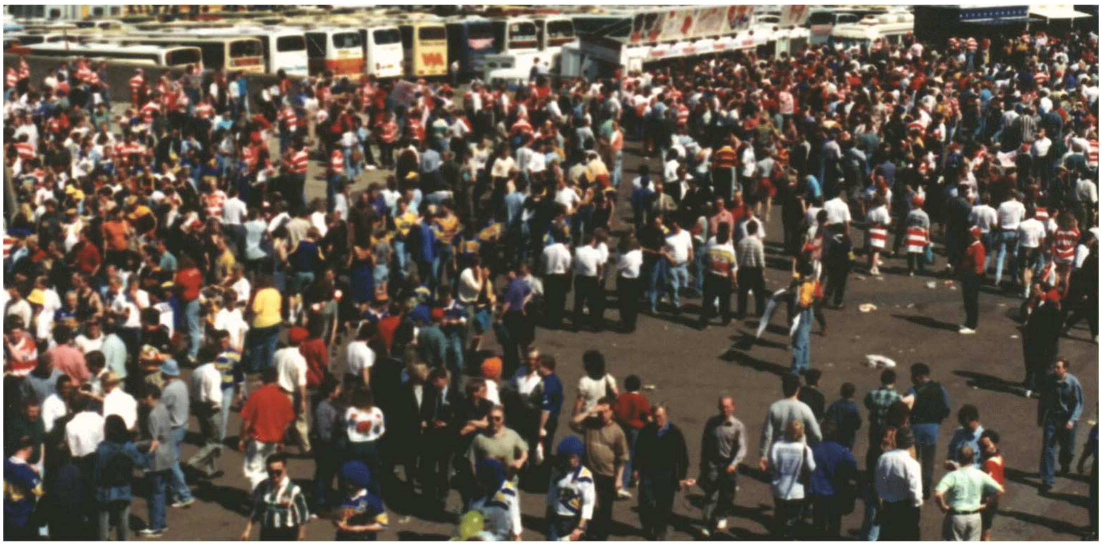
Figure 74 - Bubble and clusters in a moving crowd: standing and travelling waves

Figures 72, 73 and 74 illustrate the clustering features. We shall examine these effects in more detail later in chapter 6.4 when we discuss validation of the Legion system. Bubbles of free space in crowds, both stationary and moving, can be observed in Figures 73 and 74. Clusters, small groups of people, are an important feature in the speed/density relationship and we shall examine this in more detail, experimenting with various input parameters. The progress of the crowd is a function of the number of crowd bubbles and clusters. This gives the lie to the assumption that the speed/density relationship is a simple function of density; where density is calculated from the number of people divided by the total available space.

5.7.5 Collective intelligence

Clearly the approach we have chosen has neither collective intelligence, and introduces no a priori assumptions about the collective behaviour of the entities. The crowd may consist of intelligent entities, but their problem-solving skills are not cumulative. Given the circumstances of Hillsborough and other such crowd disasters we can see that the movements of individuals were objective driven. To gain entry at all cost is a necessary criterion for our safety assessment model. If we make any a priori assumptions regarding behaviour we neither discover the potential threats lurking in the geometry nor do we know if our assumptions relating to the crowd speed and density are correct.

Clearly information did not propagate through the crowd at Hillsborough, as people were still trying to gain entry as other died at the perimeter gate. Our model does not need inter-entity communication to evaluate the safety factors. It is far better to approach the problem using dumb entities.

The reaction to the iSpace is not an exception to this rule, as we are programming only objective functions within that framework.

5.7.6 Influences of geometry

By allowing each entity to solve their route by applying some ***least effort*** criteria, we automatically solve for the effects of local geometry.

If we consider the route that a single entity will take to navigate a corner, we can see that the minimum route assumption appears to be valid. The entity will follow a curve around the corner.

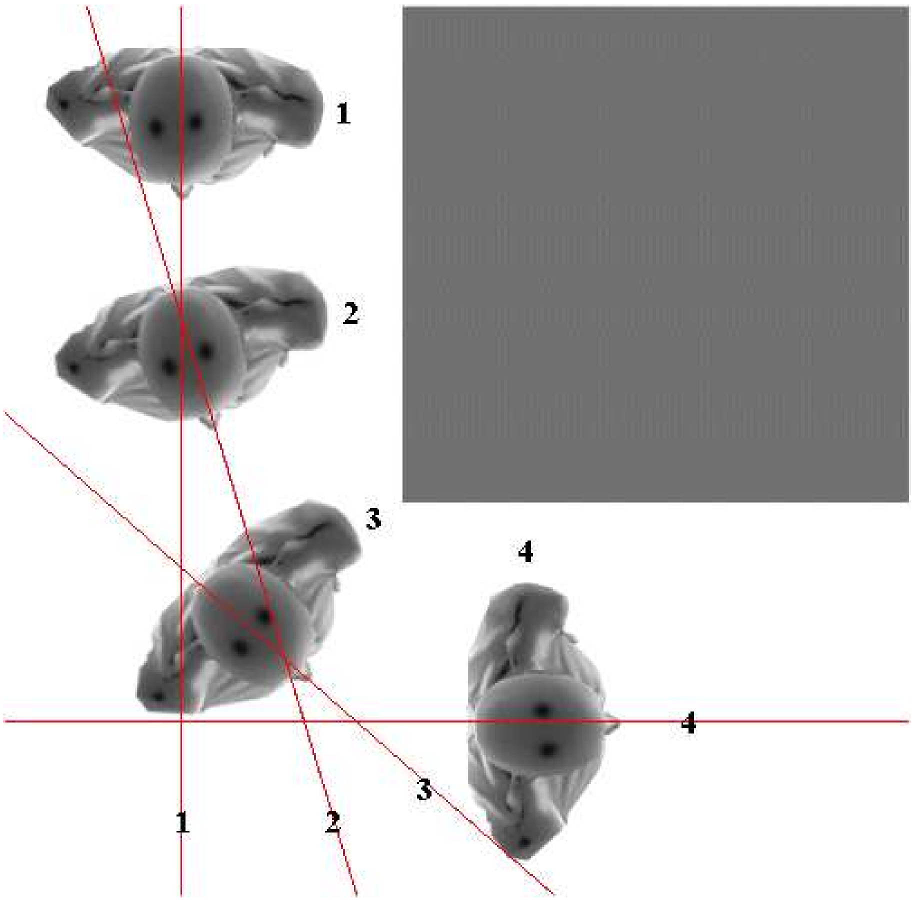

Figure 75 - Turning a corner, the lines of sight are indicated in red.

Figure 75 indicates the curve a single entity will take to turn a corner. As it turns its next objective is obscured. It is not until it is in position 3 that it can realign.

5.7.7 Self organisation

The phenomena of bidirectional flow highlighted at the players tunnel (Figures 9 and 10), is a self organised characteristic. This phenomenon must arise in the simulation as an emergent phenomenon. It is ***not*** a feature that the entities should be programmed to do as that would assume an a priori behaviour that the entities have been told to perform. There are some simple explanations of why it occurs, and we shall demonstrate a model of this phenomenon in chapter 6.

Chapter 6 Validation of a computer model

6 Introduction

Galea [24 - section 7.0] includes a thorough description of the process of validating a computer simulation. We shall use that outline as a framework for the discussion of validating the Legion models. The following section is heavily paraphrased from Galea adding comments where they relate to Legion.

Validation is one of the most often used and abused terms in computer modelling. We shall use the term validation to mean the systematic comparison of model predictions with reliable information (Fruin [6], Togawa [29], ***Green Guide***).

Fruin s measurements were detailed in his book, Togawa data is referenced in both the Building Research Establishment document [29] and from Pauls [21, 22]. Ando [7, 8, 9, 10] studies of passenger flows provides very similar speed/density relationships to the Togawa data series. Kendik [79, 80] and Pauls review a variety of data sources and outline the Predtechenskii and Milinskii [51] measurements from more than 3,600 studies of different buildings. They show a wide variance in the speed/density relationship showing a graph illustrating the differences.

From our own field observations a similar conclusion is drawn. The field data is wide ranging. The approach taken by Legion shows that these variations are explainable. This adds weight to the earlier discussion that the speed distributions are the basic measurements required to determine the limits for risk assessment. Validation is an essential step in the acceptance of any model. While no degree of successful validation will prove a model correct, confidence in the technique is established the more frequently it is shown to be successful in as wide a range of applications as possible.

Another issue which is often confused when attempting to assess or validate model concerns the question, are you assessing the model or the engineer? These are essentially two ingredients which make up a successful crowd dynamics model, the model (code and data) and the user of the model. When setting an assessment it is essential that the contributions from these two ingredients are not confused.

An excellent model in the hands of a poor engineer will not produce reliable simulations, and a good engineer with a poor model will also produce poor results. Both the components need to be assessed. It is possible to set tasks which will separately assess the suitability of the model and the engineer. To improve the engineer, training is required. To improve the model may require additional software, or a better understanding of the phenomenon under investigation. We will concentrate on issues relating to the evaluation of the model.

6.1 Validation components

For any complex simulation software, validation is not a "once and forget" task, but should be considered as an integral part of the life cycle of the software. There are at least four forms of validation/testing that the crowd models should undergo. These are

Component testing

Functional validation

Qualitative validation

Quantitative validation

6.1.1 Component testing.

Component testing is part of the normal software development cycle and involves checking that individual components perform as intended. At the lowest level this involves routine testing that the software engineer goes through to test each code fragment.

At the highest level, the user can run through a battery of elementary test scenarios to ensure that the major subcomponents of the model are functioning correctly. For a crowd dynamics model this may, for example, involve checking that a person with an unimpeded travel rate of 1 metre per second requires 100 seconds to travel 100 metres. We call this test the100m dash test. The simulation has to demonstrate that at all angles the entity is being displaced at the correct rate.

Further component testing consists of breaking the simulation into a series of geometrical tests, door width testing, barrier models, speed/density, histogram inputs and speed/density measurements as outputs. For this we apply the assimilation test (described in the previous section). The random number generators are each tested to ensure that there are no biases creeping in from numerical weighting errors. We also test the components across different platforms and on different computers. An example would be taking the original programme written in QuickBASIC and comparing the output results to the same algorithm written in C and the newer routines developed under C++.

We invert the logic conditions across code segments testing whether a specific logic statement is correct as illustrated below. This eliminates conditional errors. The two statements below are equivalent.

IF A B **THEN** A = C **ELSE** A = D **and** **IF** B A **THEN** A = C **ELSE** A = D

Wherever possible multiple programmers have tested individual sections and the process of porting the algorithms to other languages has been checked.

Quality assurance is an ongoing process of component testing, this consists of breaking the code into segments that can be tested individually. At present the source code and algorithms are being tested independently.

After every change in the library code the tests (calibration runs) are performed again.

6.1.2 Functional validation

Functional validation involves checking that the model can exhibit the range of capabilities required to perform the desired simulations; this requirement is task specific. A battery of geometric models is used: corners, corridors, single and a bidirectional flow test; the speed/density and 100 metre dash tests (where the entity is timed moving a distance of 100 metres) are also used to determine whether the model is functional. This is part of the ongoing calibration studies and prior to every job we perform a range of tests.

One test is to determine the relationship between speed distributions and local geometry. As there have been a number of field trials, confidence in the system is high. However it is under constant review and newer, more efficient algorithms are being added.

Functional validation to determine the safety limits in an environment is an ongoing process. For instance, an evacuation model which is simply used to check compliance with standard prescriptive building regulations would need to be able to calculate features which are specified in the appropriate building code, such as maximum travel distances and available exit widths for evacuation purposes.

However, a model used to demonstrate compliance with a performance building code may need to be able to predict evacuation compliance with scenario-specific conditions. This would require the capability to include response times and overtaking, queuing, turning arcs etc. Ideally each of these options should be included in the fundamental output options from the software. There are systems on the market that use the ***Green Guide***, Fruin and various other field data to prove compliance. We question the validity of those models: previous sections indicate the areas in which their results are doubtful.

6.1.3 Qualitative validation.

The third form of model validation compares the nature of predicted behaviour (in our case human behaviour) with informed expectations. While this is only a qualitative form of validation, it is nevertheless important as it demonstrates that the capabilities built into the model can produce realistic behaviour. The nature of the demonstration examples needs to be relevant to the intended application, and to be of sufficient merit to satisfy the intended clients or approval authority.

The tests against the geometry of Wembley Stadium, Balham Station and the Hong Kong Jockey club have proved the analysis capability of the Legion system but further tests are planned. The process of qualitative validation is also ongoing.

6.1.4 Quantitative validation.

Quantitative validation involves comparing the model predictions with reliable data generated from experiment. Attention must be paid to the integrity of the data, the suitability of the experiment, and the repeatability of the experiment.

Clearly there are issues here relating to the nature of crowd safety that can never fully be tested. The only reliable footage of a major crowd disaster was obtained from the Hillsborough incident. Camera technology (1989) and the resolution of video tapes is improving. Working with the Emergency Planning College and the police national operations facility (Bramshill), where reports of all major crowd incidents from around the worlds are collated, is again an ongoing process.

The question remains: which aspects of the numerical predictions are to be compared with experimental data? This is somewhat dependent on the nature of the intended application. Ingress calculations, for example, may be performed with reference to safety limits (provided that density is always below critical limits). It should be remembered that models can produce a large variety of outputs, not simply the total egress time or average density.

The aim of quantitative validation is to demonstrate that the model is capable of reproducing measured behaviour. Hence it is necessary to specify suitable acceptance levels. Do model predictions need to be within 5% or 50% of measured values? This must take into consideration not only experimental errors but also the repeatability of experimental data and whether or not data from a single or multiple experimental runs are available. To be truly useful, quantitative validation should have a diagnostic element which allows the developer (and assessor) to pinpoint areas requiring further development. In summary, the processes of model building and simulation are interactive.

Finally, at least two types of quantitative validation should be performed. The first involves the use of historic data (as discussed in the next section). In this case the user performing the validation has knowledge of the experimental results. The second type involves using the model to perform predictive simulations prior to having sight of the experimental results, a so-called ***blind*** prediction. Both are valuable: however, the acceptance level for both types of validation exercises are not necessarily identical.

In our specific case the tile prediction from Balham (chapter 7) and the turnstile prediction (chapter 9) were ***blind*** results, as was the pattern and usage of turnstiles at Wembley in chapter 3.2.3 (we predicted the pattern of usage at turnstiles a priori). Comparisons of the simulation output to Fruin, Togawa and the ***Green Guide*** are quantitative validations using historical data.

As building codes all over the world gradually move towards performance-based regulation, building designers are increasingly finding that the fixed criteria of the traditional prescriptive methods pose too restrictive demands on evacuation capabilities. This is due in part to their almost total reliance on configurational considerations such as travel-distance, exit widths etc. Furthermore, because these traditional prescriptive methods are insensitive to human behaviour or likely egress scenarios, it is unclear if they indeed offer the optimal solution in terms of evacuation efficiency. Computer-based evacuation models have the potential to overcome these shortfalls; however, if they are to make a useful contribution, they must address the configurational and environmental behaviour, and procedural aspects of the evacuation process. Evacuation models are beginning to emerge which addresses all these issues. Legion is one such tool.

While the mathematical modelling tools of the safety engineer have proliferated, there has not been a corresponding transfer of knowledge and understanding of the discipline of crowd dynamics from expert to a general user. It would be naive to assume that in the space of seven years all aspects of crowd safety have been researched and fully understood. It is the aim of this type of simulation to set the ***foundation*** for a greater understanding of problems associated with crowd dynamics with specific reference to crowd safety and risk assessment.

The computational vehicles to run the models are not, on their own, enough to exploit these sophisticated simulations. Too often, they become ***black boxes*** producing magic answers in exciting colour graphics and client-satisfying imagery. As well as a fundamental understanding of the human psychological and physiological responses to crowded environments, the safety engineer must at least have a rudimentary understanding of the theoretical basis supporting crowd dynamics truly to appreciate their limitations and capabilities.

A lack of understanding of crowd dynamics, coupled with the inevitable complacency that attaches to individuals responsible for crowd safety, is a dangerous mix. There is a need to educate governing bodies, owners, and operators of venues, and the general public, about hazards related to crowd safety.

6.2 Observations and procedures

The Legion model has two internal parameters (angle and check path). These parameters relate to the angle of deviation, weighting of course correction and scanning range. We also have to include one external parameter, the speed distribution. The internal parameters are set in the program and relate to field observations. The external parameter is user defined.

People have an anthropomorphic shape which determines their range of movement. These characteristics (size of a pace, speed of movement, length and breadth dimensions, perceptions of minimum distances and angles to objectives) are treated in the simulation as ***entity level*** code. Each entity has its own profile and can determine its own objective by reading their environment and course correcting.

The ***read and react*** cycles are coded into the basic algorithm. To determine the values of these parameters we first refer to video analysis. The required parameters were measured as follows:

Angles	The angle at which people change direction (for this a downward view of a large area was used).
Length of pace	This allows us to determine the resolution of the models. This can be achieved by measuring ground based grids. Tiled areas are particularly suited for this purpose.

To measure these we capture video footage and mark the video view with either a ground-based grid and/or a head height-based grid. This can be done by using an acetate overlay on a TV monitor and marking it with an isometric grid. Using the slow motion and pause buttons on a video recorder we can measure the angles of displacement. During the analysis of angular displacement equipment was lent by Cubic Transportation Systems and consisted of a high resolution video player with frame advance capabilities, a multiplexer unit and several dozen videotapes from Balham Station.

It is possible to track people on the video footage and follow their progress. Balham Station was tiled and those tiles provided a useful reference point for the analysis of the angles people deviate when moving through crowded and empty areas. They also provided an excellent reference for density analysis.

When we are calibrating the models, we have to check the plans to ensure that the details provided are correct. One should never assume the information on a plan to be 100% accurate for a calibration study and it is vital to measure the critical dimensions oneself. These include all dimensions of places where a crowd can accumulate, such as barrier widths, doorways, corridor widths (and lengths) and turnstiles. Site plans typically do not represent an ***as built*** environment. When the building is constructed (from the same plans) it is often not re measured to ensure accuracy. Most site owners can see that the plans are roughly right, and never question the centimetre accuracy required for a calibration study.

We also need to measure the distances over which we can observe a range of individuals over a range of densities walking through a clear path in a straight line. In all field studies the site was measured by using tape measures and electronic devices to ensure that the scales and sizes were correct.

We can determine the focal routes, those areas which have strong visual clues which act as the direction the people will move. They are constructed using a simple geometric analysis, and we describe this method in detail when we discuss the Balham study.

6.2.1 Validation stages

The three stages required for the validation study are:

Initial Survey An initial site survey is useful checking abnormalities in the site, such as lighting, egress signage, management practices and we also check the field of view from the video cameras.

Validation During this stage we measure the angles in field of view, captures the relevant video footage, digitise the plans of the site (taking care about resolution and size of the areas/density of populations). We perform a head count, to observe the typical behavioural characteristics of the crowd under examination. We also take notes of demographics, clustering (how many small groups form, for example families) and the general atmosphere of the crowd.

Simulation run Once we have entered the data into our simulation the model is run with some local objectives placed on focal routes. The models allow manual placement of these. Care must be taken over the visual perception where strong signage/floor marking or management procedures (such as marketing information handouts) impede flow of the crowd.

When we were in the early stages of developing a model for crowd analysis in a specific environment, extra care was taken to check all the assumptions relating to crowd dynamics, specifically the visual acuity of the site. As we have seen in the Wembley turnstile analysis, the location of signage can influence the crowd dynamics. The present algorithm scans an area in its field of view 7 - 8 metres ahead. This conforms to the Fruin findings [6 - page 4] where he highlights the evasive manoeuvring distance as 25 feet (7.62 metres). The studies conducted indicated that this is an average and is a function of the speed of the individual. We have linked that parameter to the individual. Future implementations may have user defined variable settings.

We enter the range of speeds of individuals (typically during initialisation of the simulation run). These are normally distributed and have been discussed in detail in previous sections (mean $1.34ms^{-1}$ std. 0.26). We discuss the field measurements in more detail below.

6.3 The validation tool

The screen layout for the validation tool (Version 1.92 Build 18b) is shown in Figure 76. The basic elements in the tool are the dual screens, top and bottom, which run different algorithms through the same geometry. The speed distribution from the top screen is shown on the left-hand histogram and speed distribution form the bottom screen is shown on the right in Figure 76. These enable us to run different types of parameters through the same geometries, and visually analyse the differences.

6.3.1 Validation tool output

The validation tool creates a variety of output data. In addition to the simulation screens we can produce numerical results in the form of spreadsheet data and we can produce screen images (grabbed in PCX format). The combination of watching the models runs and analysing the output provides us with an instrument for dissecting the forces at work within the dynamical system. We use a variety of maps in the validation tool to perform our analysis. These are:

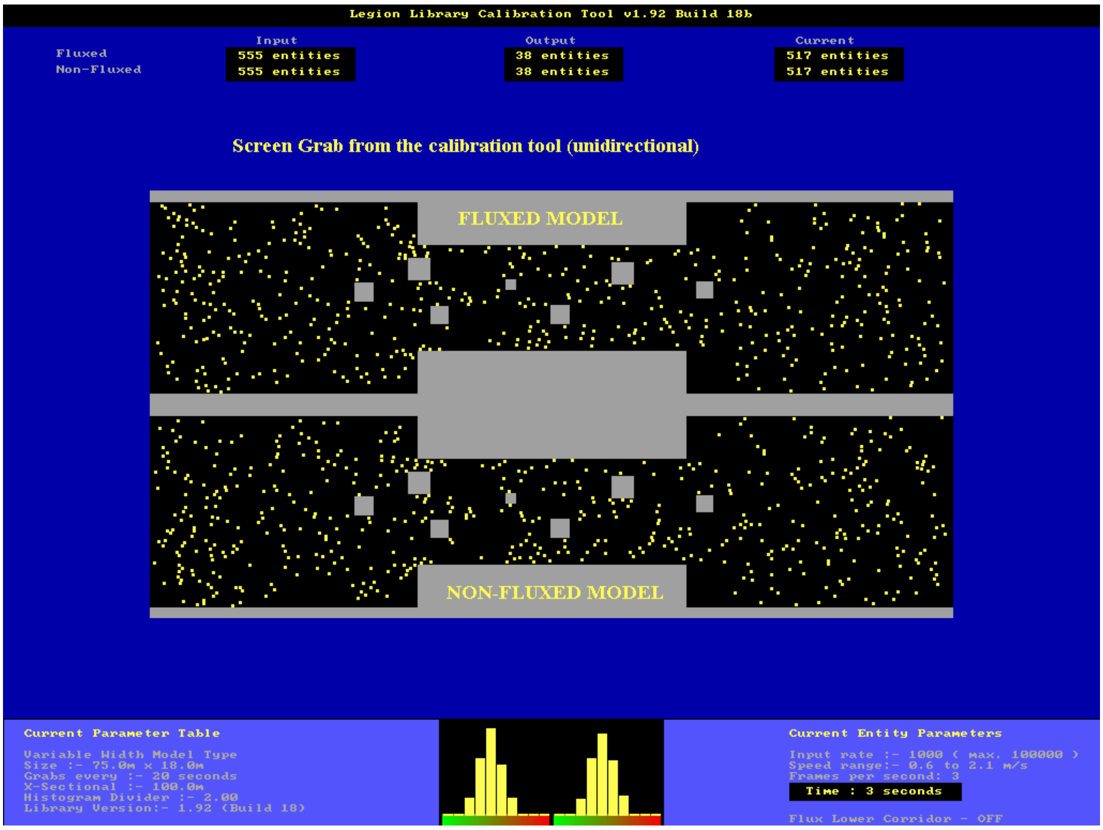

Figure 76 - The validation tool screen - Version 1.92 Build 18b

Entity position	-	The entities are the yellow squares that move in black areas (Figure 76). For models of a few thousand entities the model runs in real-time.
Space Utilisation	-	As space is occupied by the entity the colour increments per unit time. Thus a pixel becomes more red the more often it has been stepped on.
Entity Density	-	There are two ways of measuring density: taking the number of entities per unit area; and calculating the local density in a radius from the entity. We shall use the latter, which we

call the ***dynamic density***, in this analysis. This method of measuring density means we can measure the entities exposure with time.

Speed Average - This map displays the average speed of the entities at a specific location, i.e. Each location is an average of the speed of the entities that have passed it. Thus, our map relates to the speed per unit area.

Alert Map - This map indicates any area in which speed is suddenly reduced and high density is encountered. This map is important when we want to analysis the local crush areas.

Vector Maps - These indicate the predominant direction of the entities per unit area. An arrow indicates the long term average direction per unit area and its colour indicates the long term average speed in that direction.

6.3.2 Scales used in the maps

The Legion maps are the analytical output of the simulation system. They show, using a colour scale, a variety of features. A series of experiments has been created to test both the qualitative and quantitative validation of the simulation suite.

The maps we shall use in this section are taken from the validation tools and are quantitative in nature. In the validation tool we use the green to red scale for speed, and the blue to red scale for density, as follows:

Figure 77 - The validation tool Speed scale. Green (slow) - Red (Fast)

Figure 78 - The validation tool Density scale. Blue (low) - Red (high)

The tool has been designed for visualising both static and dynamic features and we shall explain these below. We also discuss the Space utilisation map which uses the same colour scale as the density map. Space utilisation is derived by incrementing using the plan of the area and incrementing the colour at each location stepped on. It thus represents the probability that some entity is at that location at a given instant, and can be considered as an approximation to a dynamically invariant measure of the crowd flow pattern. The areas used most in the model are therefore highlighted as red, those not used, remain black. We shall see how this feature allows us to derive a variety of information about how the space our model, and subsequently people, is used.

6.3.3 Fluxing and space utilisation

The validation system has dual screens. It can run two different algorithms through the same geometry; in this way, development comparisons can be made. The dual screen system also fulfills the requirements for component testing, since different algorithms can be compared both qualitatively and quantitatively.

We can also run the top screen in a mode we call ***Fluxed***. This mode is a test for emergence, and consists of altering the speed of every entity at every step. The integrity of the speed histogram is maintained but the individual speeds are not.

In the non-fluxed model (bottom screen Figure 77) the entity speeds are set from the histogram and maintained throughout their existence. We can test the effects of local clustering and the difference between the two models to indicate the importance, or relevance, of the speed and space distribution for the crowd dynamics.

In both fluxed and non-fluxed models the map production algorithm is identical but we see fundamental differences between the two: as mentioned above, we observe the concept known in the technical literature as an invariant measure. This indicates a property of crowds not previously measured in that we can determine how much of the time is this point occupied, in the long run.

Ergodic theory [93] relates two different ways to construct such measures: averages over time (space utilisation is one example of this) and averages over space (flow of the crowd). We can produce a variety of maps for fluxed and non-fluxed models testing the effects of these averages over space and time.

6.3.4 The Legion maps

The maps are necessary to understand the dynamics of a crowd, and are integral to the validation of the algorithms within the simulation. They fall into three main categories:

Location - The entity position maps, typically shown as yellow dots/boxes. These indicate the location of each entity, frame by frame as the simulation runs.

Speed - Showing the spot (instantaneous values) velocity of the entities and averages over space and/or time. The cumulative (averaged) speed maps indicate the areas which have similar speeds during the simulation run.

Density - Showing the spot (instantaneous values) density of the entities and averages over space and/or time. These indicate areas which have continual high density, an important consideration in the analysis of safety.

We also have other types of maps: for example the vector map, where the colour represents the velocity and the direction of the arrow represents the average angle moved by entities in that area, which we will also discuss. These maps are amalgams of the above and are based on the speed/density and location information.

There are many methods of calculating these values and care has to be taken when choosing the area over which we measure a value. For example, as we have seen in our previous discussion on static versus dynamic space, the value for densities (number of people per unit area) can be large in one area, small everywhere else and averaged to be nominal.

6.4 Qualitative validation of Legion

In this section we discuss qualitative tests of the simulation and determine whether it demonstrates the emergent phenomena that we observed in real crowds.

There are several emergent phenomena in a crowd flow. Many of these features have been observed by the author and others in field studies (Fruin, Togawa, Henderson, et. al). The production of a simulation, where various parameters can be changed and their effects noted bring us insights to the nature of these phenomena.

We focus on four of these, discuss how they occur in the crowd, and how the simulation demonstrates why they develop. The effects we discuss are:

Edge Effects	-	Where the edges of a crowd move faster than the centre of the crowd.
Finger Effects	-	Bidirectional high-density crowds flowing through each other with relative ease.
Density Effects	-	Crowd compression in local areas can imbalance the crowd flow.
The Human Trail	-	Erosion demonstrate the principle of ***least effort***

We also highlight the differences between static and dynamic space utilisation, and the effect that has on density calculations.

6.4.1 Validating the edge effect

We describe an experimental model (Figure 77) that tests the effect of a bottleneck on the speed/density relationship. This test is strictly qualitative and we are testing the invariant measures, the impact on flow/density with respect to the BRE [29] statement highlighted in earlier.

We initially populate the model with a random distribution of 5,000 entities. Their objective is a simple left to right movement. The entities enter from the left at a rate of 3,000 per minute. The speed distribution is set for 1.34 ms $^{-1}$ with standard deviation of 0.26 (as in Helbing). The model is 100 metres in length with three widths (18, 14 and 18 metres respectively). The entities are 30 centimetres square. We test a range of bottleneck widths.

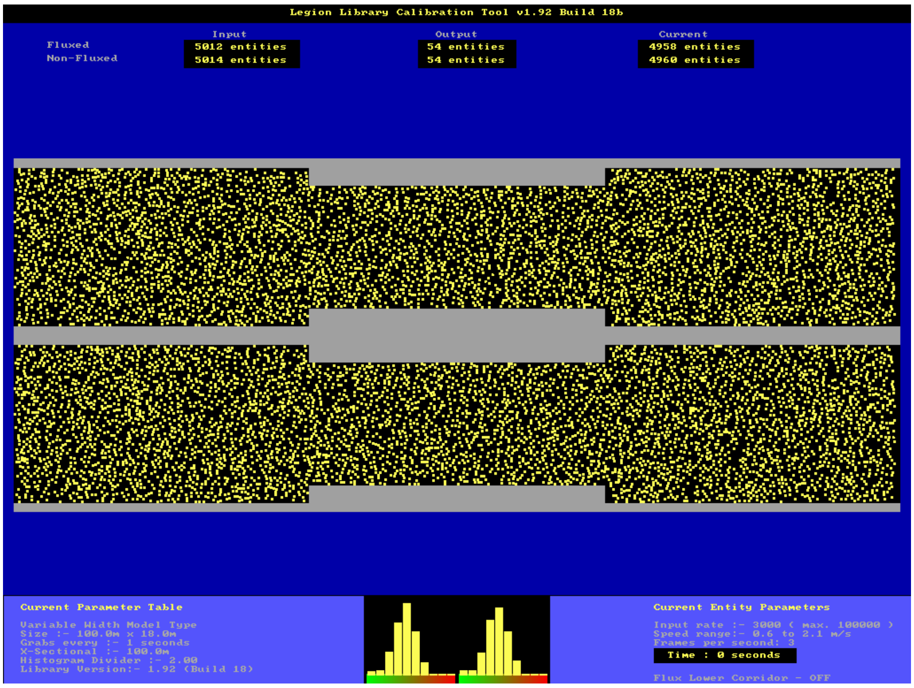

Figure 79 - The bottleneck experiment to test the edge effect.

6.4.2 The entity objective

Each entity is performing the same algorithm, but with different initial conditions. For every step the entity takes it scans the areas ahead (towards its objective) and solves the equation based on the ***least effort*** algorithm. We can state this as follows: Find the minimum distance to the objective at the maximum speed

In this example the entity is trying to reach the right-hand side of the screen at the speed it has been assigned from the speed distribution histogram. Entities are given a speed when they are created and they maintain that speed throughout.

The ***fluxed*** entities are given a ***different speed*** every incremental time step (frame). The integrity of the speed histogram is maintained in that the total entity speeds, prior to movement, are normally distributed. After movement the system collates the distance each entity has travelled. It does so in two ways. The first is to collate the distances travelled in any direction, as a scalar value, recording these against the time increment. The second is the distance travelled towards the objective, in this example that is calculated from the X, in the model this is the horizontal direction. We can then compare the input (desired) and the output (resultant) speeds.

The speed map records the scalar values and the vector map records the vectors. The speed average map then indicates the areas where, regardless of the desired speed, the invariant measures (both fluxed and non fluxed) are the same.

The speed v density results are discussed in chapter 6.5.

6.4.3 The entity position map

In the ***edge effect*** experiment the model is populated with a random distribution of entities (Figure 79). Figure 80 shows the initial movement of the entities. Figures 81 and 82 show that gaps begin to appear to the right of the bottleneck, and the density increases to the left of the bottleneck. We begin to see that the entities to the left are trying to avoid the protrusion in advance (arrow in Figure 80) but after a few seconds this movement is restricted by the other entities.

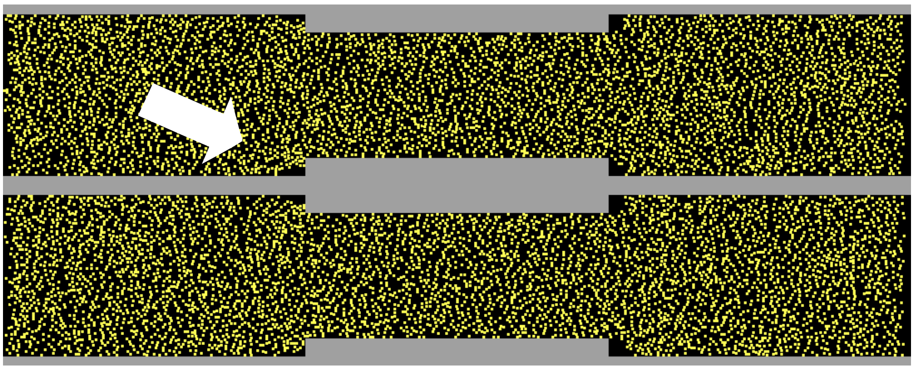

Figure 80 - 1 Second after initialisation

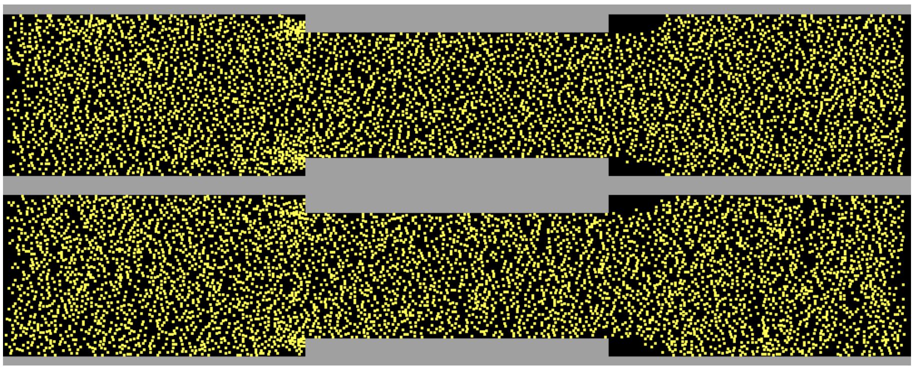

Figure 81 - 5 Seconds after initialisation

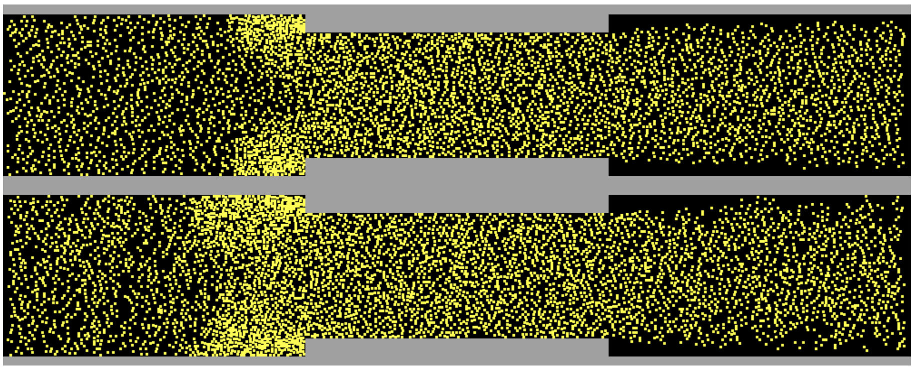

Figure 82 - 240 Seconds after initialisation.

The patterns before and after the protrusions are now forming as we might expect. After four minutes the densities in the three sections are very different. Again this is expected and we can see that the model is producing visibly reasonable qualitative results. To examine the detail of the density across the model we switch to the Dynamic Density Map and Speed Average Map (Figures 83 and 84).

In Figure 83 we can see there is a difference between the fluxed (upper) model and the non fluxed (lower model). The difference is also apparent in the

Entity Position Map. There are significant differences in the Speed Average Map as we can see in Figure 84.

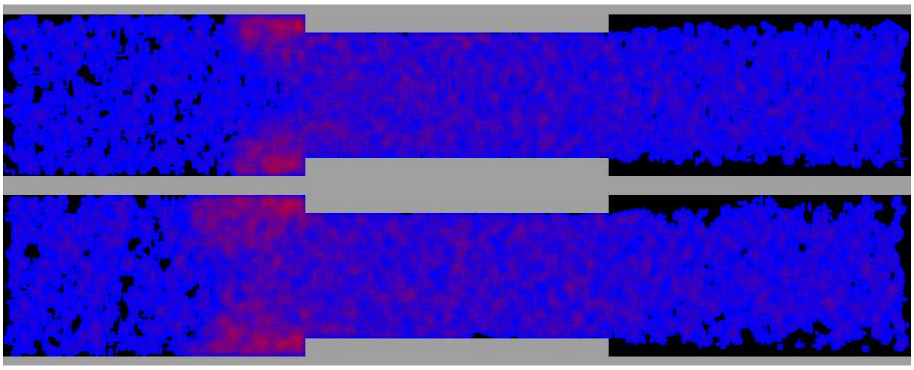

Figure 83 - 240 Seconds after initialisation. Dynamic Density Map

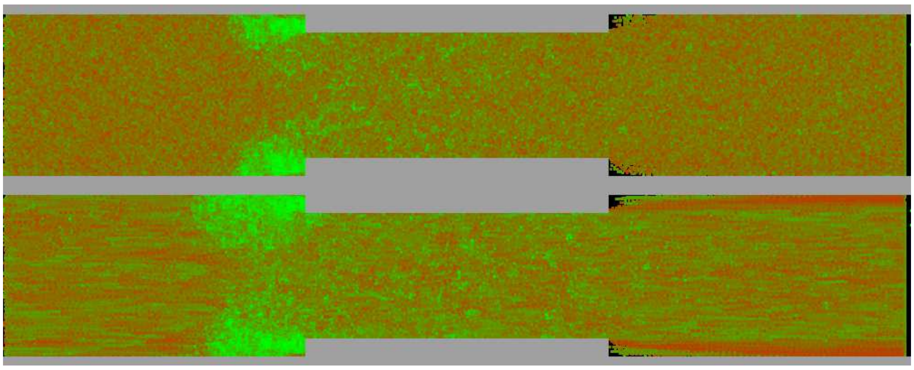

Figure 84 - 240 Seconds after initialisation. Speed Average Map

Two phenomena can be observed in Figure 84. On is the build-up of slow-moving entities to the left of the protrusion (the green area in Figure 84), and the other is the area of layering to the right of the protrusion (Figure 84, bottom and top of the bottom screen).

This layering is the result of entities that are at the high end of the speed distribution histogram, and find space to move into as they clear the gap. We should also note that there appears to be a higher level of green (low speed) colour in the central section. It is not possible to tell (visually) whether the speeds into and out of the section are different. For that analysis we look at the spreadsheet output. Figure 85 shows the speed distributions.

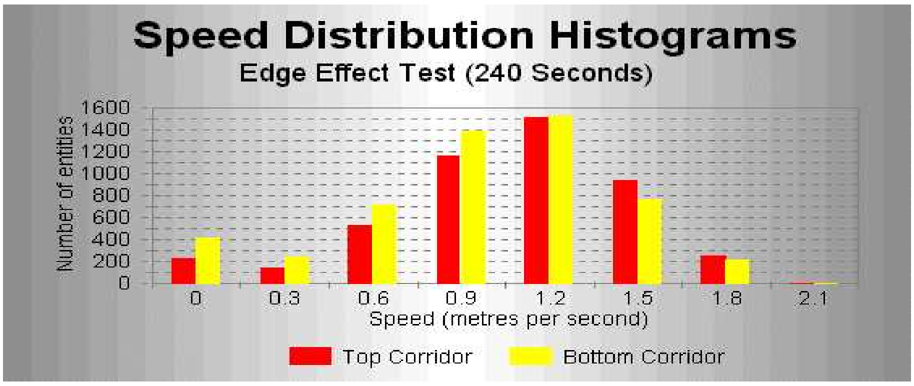

Figure 85 - Speed Distribution h istograms for the edge effect test.

Figures 86 and 87 show that an average density, or average speed, values (shown as the green lines) do not represent the dynamics in this simple model. The Density and Speed maps (Figures 83 and 84) provide a more effective qualitative analysis of this environment. Also the clustering of the crowd is apparent.

The wake (Figure 82) to the right of the protrusion is caused by the entities not using in the space beyond the protrusion, they are walking forward - not sideways. There is an area where the dynamic crowd does not occupy (or fill).

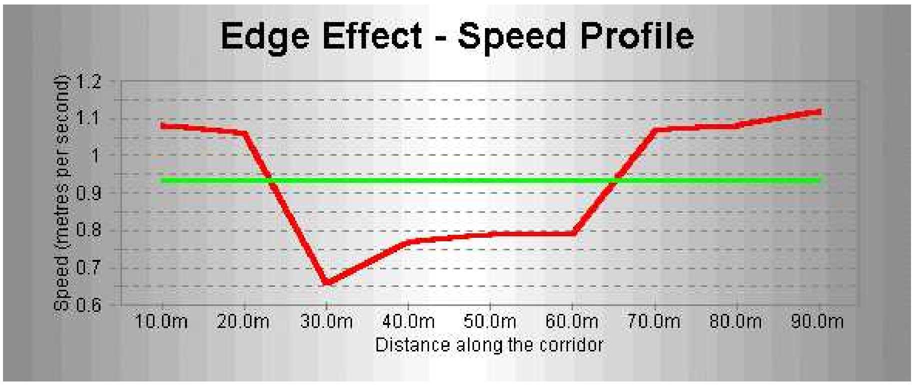

Figure 86 - Speed profile along the corridor (240 Seconds after initialisation)

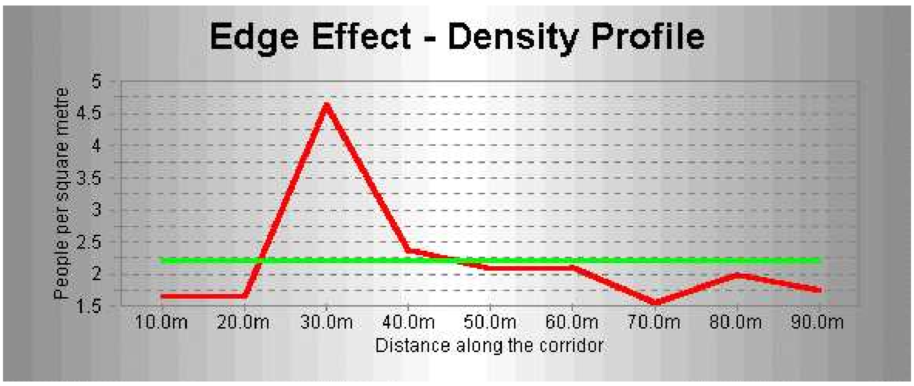

Figure 87 - Density profile along the corridor (240 Seconds after initialisation)

6.4.4 Dynamic and static density.

We now examine the shadow beyond the protrusion at a higher resolution. In the ***edge effect*** experiment we have narrowed a 18 metre corridor by 4 metres (2 on either side). We see from the model that the entities do not fill the area evenly, and as Figures 88 and 89. The calculation for density is measured from the ***total area*** available to the crowd. As the crowd does not use all of the available space the calculation for the speed and density would appear to be incorrect.

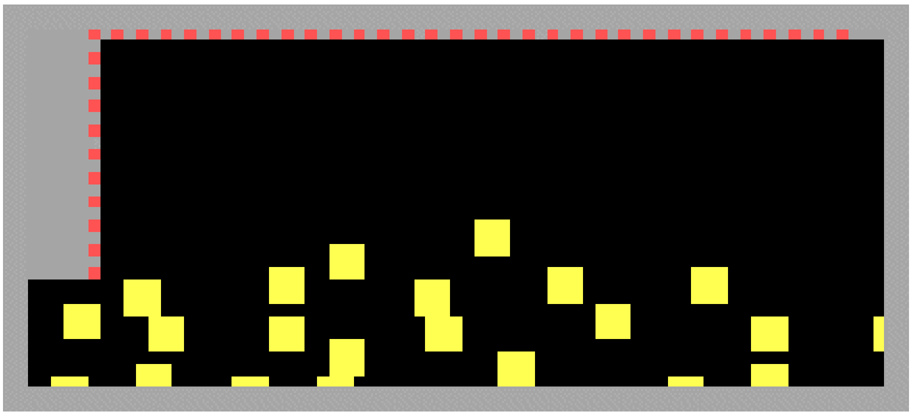

Figure 88 - The wake or unused space.

Figure 89 - The officers (bottom left) affect the crowd - leaving unused space.

6.4.5 Space utilisation

The space utilisation map was presented in the introduction (chapter 1). In this section we discuss its application for determining the location for signage.

The entities seek a least effort route through complex geometries. As each entity takes its step the space utilisation of that point is incremented. We shall use points to mean the pixelation scale of the model.

In the simulation an entity advances to a new point and the point it then occupies is updated with the information relevant to its movement. Hence the maps represent the updated information of the entity. The same principle applies to speed.

The information we obtain from the map relates to the total usage of that space over the simulation run. In effect the space utilisation (as we discussed in the assimilation experiment) is the erosion factor.

From the space utilisation map we can determine the areas which would best serve the placement of information (signage) or act as an observation points for ground staff. These points are important for the design and optimisation of passive or active crowd management features. For example, a merchandising goal is maximum revenue, so the areas which have the most concentrated flows are naturally the most attractive for the concession stand. They are also the areas where the crowd would be most disrupted by queues.

Another type of space utilisation map is dynamic space utilisation. This increments ***each*** point per usage and decrements ***all*** points over time. The use of this map relates to the space utilisation time factor where we may be interested to examine the differences between the ingress space utilisation, egress space utilisation and the emergency space utilisation. Equally we can use this map to determine the required space for different densities and different speed distributions.

Supposed we wanted to design a suitable route emergency egress route through one, two or three doors. The ***Green Guide***, assumes a linear (double the width double the flow), relationship but the speed/density implies a nonlinearity.

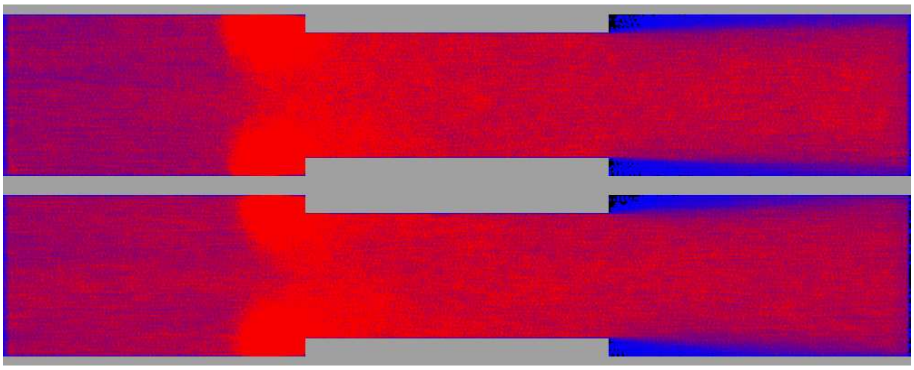

Figure 90 - Space utilisation, after 60 seconds, of the edge effect

Figure 90 shows a space utilisation map from the ***edge effect*** experiment. We can see some interesting features from this map. Firstly, the areas to the left of the protrusions are similar in both the fluxed and the non fluxed map (Top = fluxed). This is because the space utilisation measure is an invariant measure: the feature it is detecting is ***how much has this space been used over this period of time.*** From Ergodic theory we can see that wherever the crowd density is high, the samples over time can be replaced with samples over space, the instantaneous flow-patterns in different runs taken under corresponding conditions will, with high probability, look the same as each other.

The space utilisation map in the Figure 90 is demonstrating that the space utilisation is not a function of the instantaneous speed, but is a function of the speed/density relationship.

We can also see the space utilisation to the right of the crowd compression, at the left end of the bottleneck (Figure 90). To the right of the bottleneck we see that the crowd is expanding into the free space; the rate of expansion is a function of the speed distribution of the entities.

6.4.6 Dynamic and static maps

The dynamic maps refer to instantaneous values such as the entities speeds. The static maps relate to an average over space or time. The nomenclature is arbitrary, these definitions serve to classify the different types of maps we use in the simulation. Let us examine the cross sectional density in the ***edge effect*** experiment.

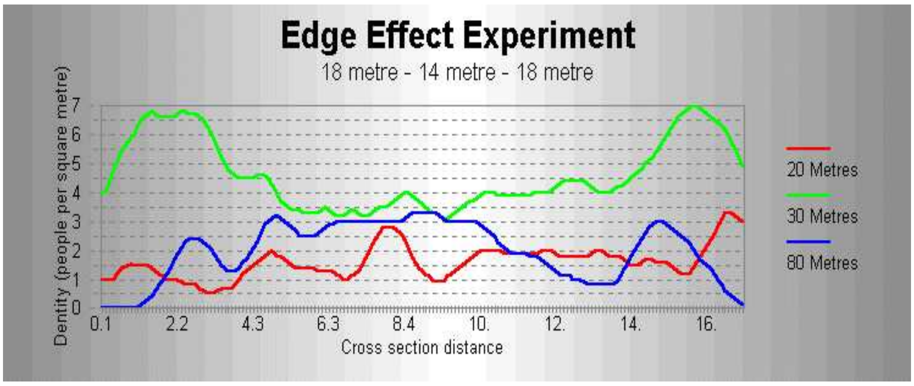

Figure 91 - Cross sectional density from the edge effect experiment.

Figure 91 shows us sections along the horizontal axis of the density across the vertical axis (note: the model is symmetrical but we are using a moving average to clarify the graph, hence the apparent left to right bias in the cross section).

We can see that the cross section produces different information from an average over area value. There are sections in this model which are ***constantly*** in high density and others which are ***constantly*** in low density. We do not perceive this information from a single value, for example an average of 1.5 people per square metre may be true in the above example. Once again this highlights the assumptions of speed and density used in the safety guides are not appropriate measures.

We need to know the time an entity is exposed to high density we can monitor this by recording its density exposure as it progresses through the model. This is a very important measure when we are trying to assess the safety of the individuals in the crowd.

We are now facing a problem of potential intractability in that we could test every parameter against every other parameter in every geometry. Which parameters are important ones depends on the type of environment we are analysing. There is no generic solution to the problem: it is a question of experimental design.

For example the concourse outside gate C would be suitable for a maximum density, maximum time exposed measure, but space utilisation would not provide any insights in this area. The concourse area we described in chapter 3.3.4 would be more suitable for space utilisation analysis as the feature we are most interested in is the exploitation of short cuts, where the space is most used, and to what extent does the density effect the flow rates. The total space utilisation is of interest in concourses during ingress and egress. We may want to isolate a feature of a specific area and determine the maximum capacity across a range of densities. We may also want to examine that area for the last five minutes, or five hours. Such an evaluation would be of relevance if, for example, we wanted to test the potential damage to a grassed area in an open air concert.

Equally the measure of density in a static environment, for example, an area where crowds move slowly (say gate C at Wembley) should not be compared against a measure for density in an area where high speed may be expected. They represent different levels of safety. Therefore we use different maps in different applications.

6.4.7 Validating the finger effect

The second emergent effect discussed in the introduction is the ***finger effect***. (Figures 9 and 10). We now examine how this effect arises, and give further evidence that the Fruin assumptions cannot be universally applied.

It takes less effort to follow immediately behind someone who is already moving in your direction than it does to push your own way through a crowd. We can set up an experiment model to test if this hypothesis pertains to the bidirectional behaviour of a crowd and gives rise to the finger effect in high density areas.

Figure 92 - Red entities move from left to right, Blue from right to left

Figure 93 - We can see that random generation creates bubbles and clusters of entities.

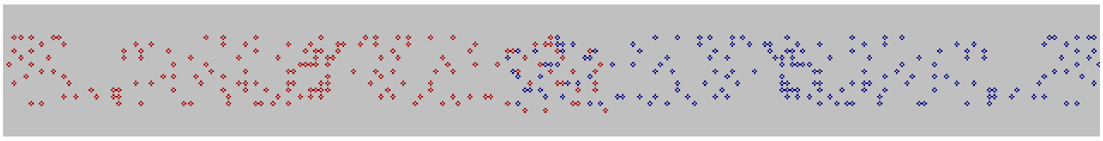

Figure 94 - As the two crowds meet they begin to interact with each other

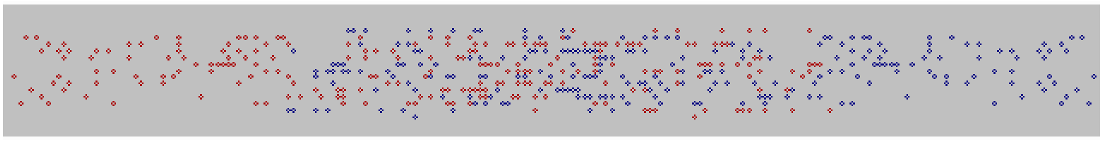

Figure 95 - We can now see several lines throughout the model

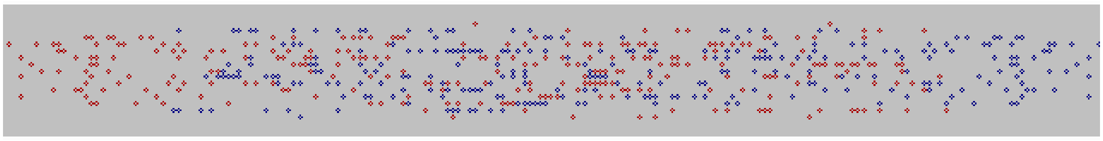

Figure 96 - Advancing frame by frame towards and then past each other

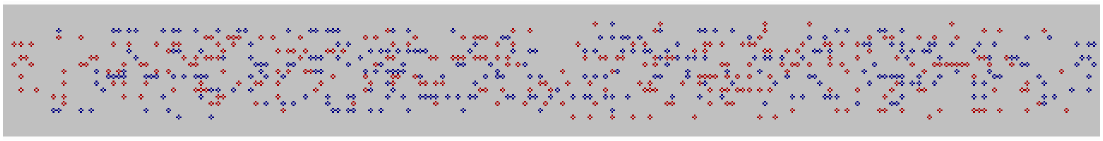

Figure 97 - The model is showing the fingering effect

Figures 92 to 97 show a simple model of entities moving from left to right (red), and right to left (blue). To the left and right the entities are being created at random entry positions. Their algorithm is simply to avoid at random (up or down in the model) whenever they encounter an entity moving in the opposite direction. This action forms chains of entities walking in line, as we would expect.

When we create a simple model that displays some of the underlying mechanisms of a crowd we must examine whether those principles are representative of human behaviour.

Figure 98 - Follow the people in front of you is less effort.

The mechanism for crowd self-organisation appears to be linked to both space exploitation and the propensity for people to choose the ***least effort*** route. This is modelled in our simulation by random avoidance. Examination of video footage has shown no predominance for handedness and the ***finger effect*** appears with equal frequency left and right. The entities in the model all move with the same speed. As a real crowd increases in density we find that the slowest members of the crowd throttle back the speed. This is due to the reduction of overtaking opportunities.

The model can be confirmed from video footage, or walking through a high density crowd. At this simple level the mechanism for the ***finger effect*** appears qualitatively correct and, in this respect, it confirms the ***least effort*** hypothesis.

6.4.8 Validating crowd compression

We have seen in chapter 3.3.4 that the crowd compresses when turning corners. We also see from the ***edge effect*** experiment (Figures 80 to 91) that the compression in the bottleneck has a definite density/speed profile. Furthermore we have seen (chapter 6.4.4 and from Figures 88 and 89) that this effect can create problems for general density calculations. At low density the effect is negligible, but at high density our models indicate that this effect will create flow restrictions.

Another effect to note from Figures 88 and 89 is that the crowd does not expand into free space after a constriction. As the crowd is moving the available dynamic space is less than the static space used in the calculations in the ***Guides***. This is an important consideration for the calculation of density, and does not appear in the literature, guidelines or egress calculations in the building regulations.

The simulation contradicts aspects of the guidelines and the evidence from the field observations supports the model. When the building has sufficient area available for crowd expansion (holding reservoirs) and no constrictions, then the existing guidelines have proven sufficient. However, where compromises have been made, where space is at a premium, and where the guidelines leave room for interpretation there is a requirement for an appropriate model.

6.4.9 Validating the human trail

During the development of Legion it was conjectured that the space utilisation map could be applied to the problem of path formation. Helbing [13] describes a process where human trails form across a Stuttgart campus. If a space utilisation map were used to re-create the plan and the model rerun then the iteration of space utilisation map and plan ought to produce a similar result.

In this experiment we shall use another of the development tools (the QB45 interface). Four points (North, South, East and West) are created around a circle.

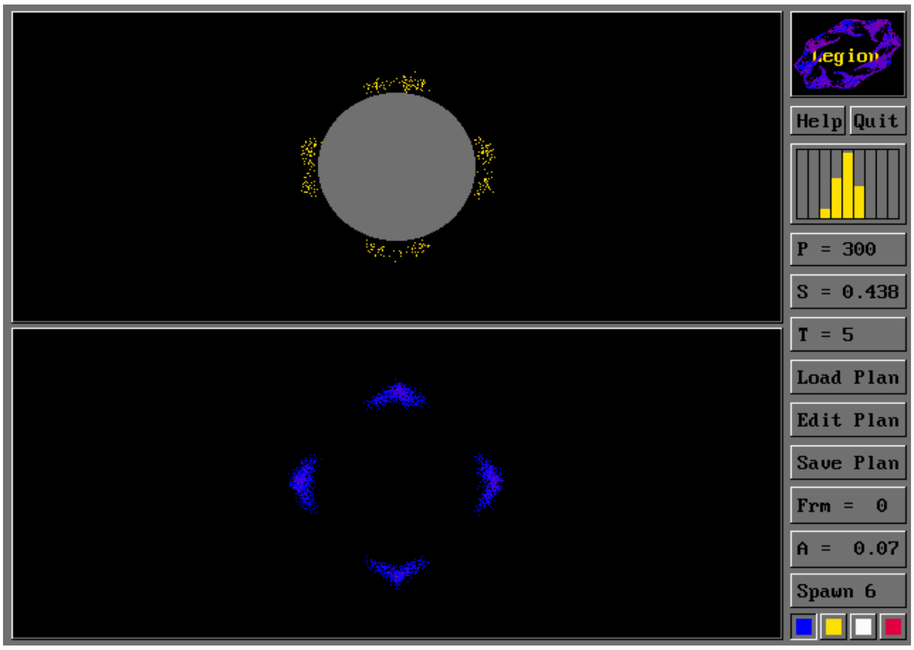

Figure 99 - The initial screen in the human trail experiment

In this model (Figure 99) the top screen is the model plan and entity position map, the bottom screen is the space utilisation map. After a few hundred frames we will use the space utilisation map to redraw the plan (the top screen in Figure 99). Taking a limit of 0-3 hits on the space utilisation map to represent little use, for example, if this is grass then it is growing unimpeded. 3-7 hits represent retarded growth, and 7-13 hits to represent a die back; where the grass is being destroyed.

After every pass the entities are reset and move towards a randomly selected objective (N, S, E or W). The algorithm allows them to navigate through the available space and the iteration process erodes the circle on the routes used more often. One would expect the ideal network to be a cross within the diamond. The model evolves to this ideal as it represents the dynamic equilibrium of erosion and growth given that the entities are seeking a ***least effort*** route.

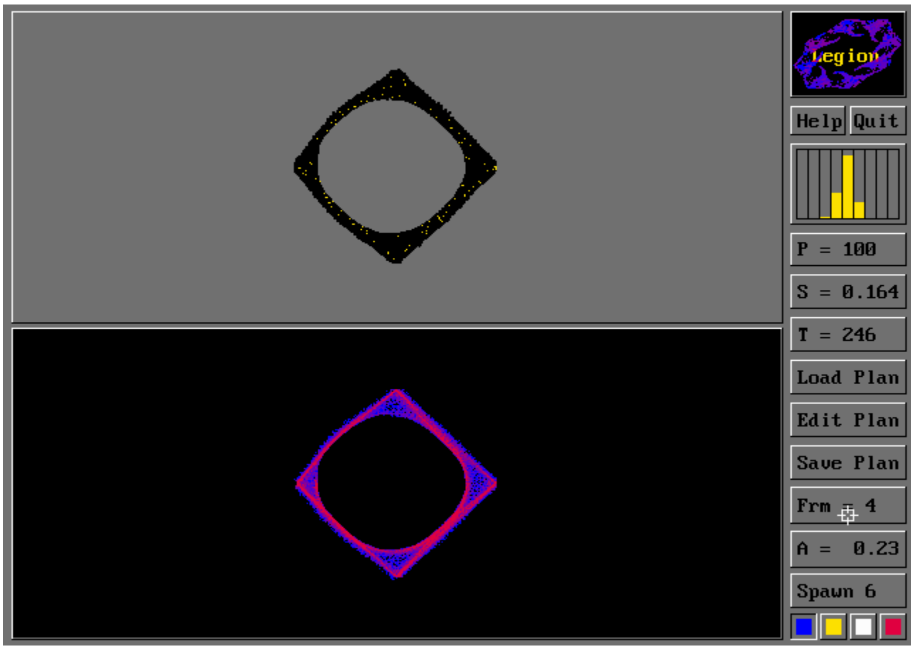

Figure 100 - After the first iteration the unused space is filled in, in grey.

After a few frames the circle has developed a lopsided appearance. This is due to a slight bias in the selection of the East objective. At 15 frames the symmetry in the process is observed. At 23 frames a route (top right) is underused and the grass closes that route in the next iteration. This symmetry-breaking is typical of the assimilation algorithm. Figure 106 and 107 show the entities moving through the model and we can see that the high density cluster of entities (at the centre of the model in Figure 107) is similar to the behaviour we discussed in chapter 3.2.

In Figure 109 the paths are nearly straight. The entities moving E-W and W-E hug the shortest path round the bottom the NW triangle. This erodes the lower edge of that section. It is thus not surprising that the ideal solution is achieved. We have created a model which is seeking a path of ***least effort***. The entities try to take the shortest route, and the rate at which we permit ***evolution,*** competition between the entity and the environment, erosion and growth will eventually lead to the ideal.

Figures 111 and 112 show the experiment with different parameters for assimilation rates and number of entities.

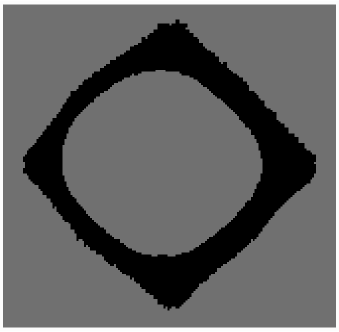

Figure 101 - After 5 frames

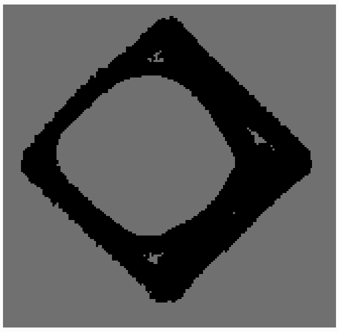

Figure 102 - After 10 Frames

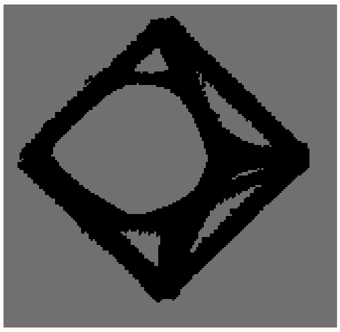

Figure 103 - After 15 Frames

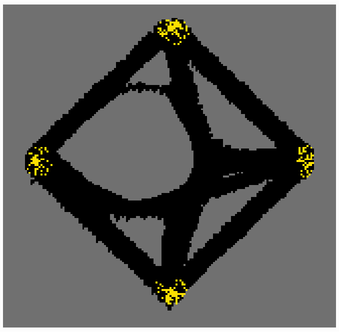

Figure 104 - After 19 frames

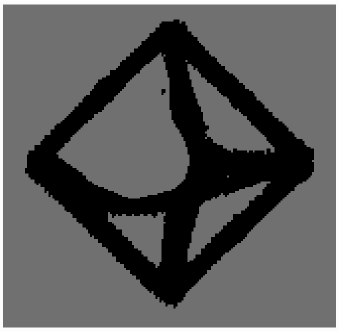

Figure 105 - After 20 Frames

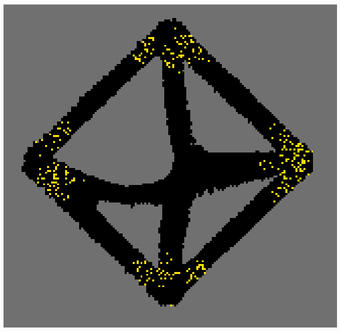

Figure 106 - After 23 Frames

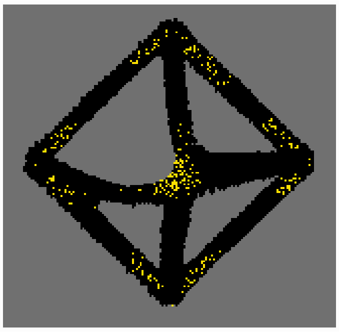

Figure 107 - After 23 Frames

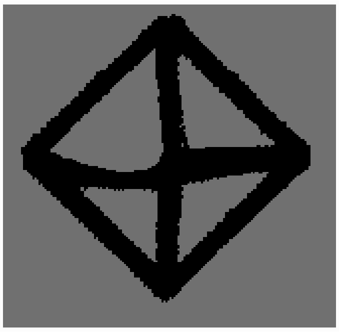

Figure 108 - After 25 Frames

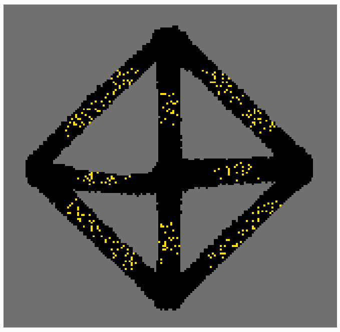

Figure 109 - After 27 Frames

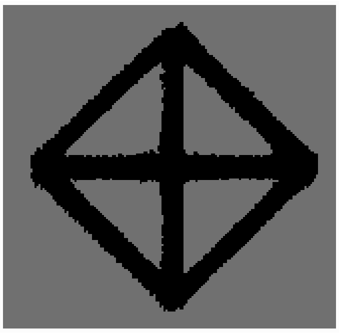

Figure 110 - After 30 Frames

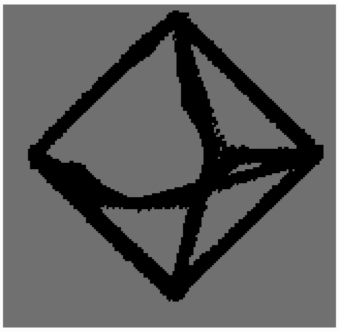

Figure 111 - After 20 Frames

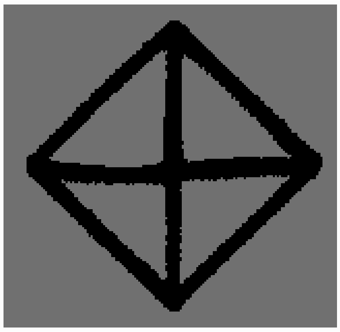

Figure 112 - After 30 Frames

The symmetry-breaking feature in this experiment is interesting. To examine this we can set the parameters to 100 entities and 400 seconds (Figures 113 to 124) and observe that at 15 frames the solution is similar, but different paths are forming.

To analyse the nature of the symmetry breaking in this algorithm we construct a test where the rate of growth and rate of erosion are more evenly matched. We use 100 entities and 200 seconds per frame. Figure 115 shows that the West to North route is going to fail through under-usage. In Figure 116 the effect of the algorithm closes that route and in Figure 117 two pockets of entities, the N-W and W-N groups, cannot reach their objectives. We also observe a symmetry along the NW/SE axis.

There is a feature we can use in this algorithm. Consider Figure 117: here the two groups (N-W and W-N) are oscillating at a location which is poised between two equidistant routes (the algorithm can perceive neither alternative as shorter). The algorithm has no solution from that point and the entities oscillate at random until they escape. This is the ideal location to place signage and the algorithm has determined this location for us. The oscillations increase the space utilisation in that area, and ***nodules*** (wide gaps) begin to form. In Figure 119 we can see another example of this phenomenon. These areas are places where the appropriate use of signage, or other crowd management measures are required. We therefore have a semi-automated method of establishing these locations.

In reality there would be a requirement for signage along the route but the model demonstrates one of the dialectic solutions; we are discovering that there are going to be problems in areas where a decision has to be made. In field studies we notice this effect at the top of escalators in railway stations. Without appropriate and clear signage the people hesitate, causing temporary blockages, then move off. This forms standing waves and congestion. Figure 124 is the final solution, and we observe a further feature of this type of analysis; the widths of paths (Figures 110, 112 and 124) are proportional to the number of entities, the required crowd width.

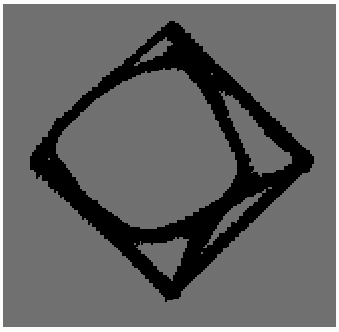

Figure 113 - After 15 Frames

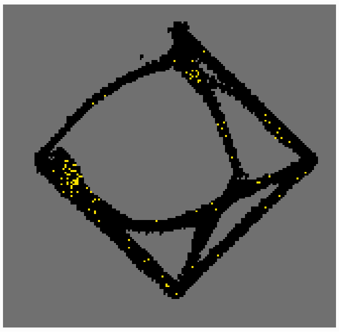

Figure 114 - After 18 Frames

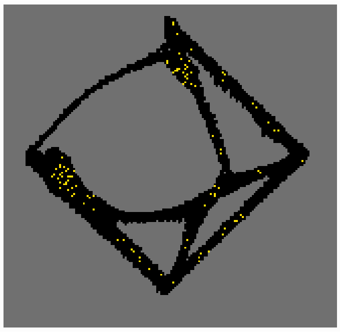

Figure 115 - After 19 Frames

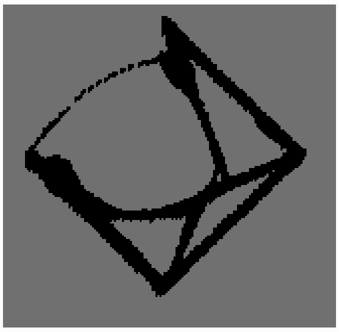

Figure 116 - After 20 frames

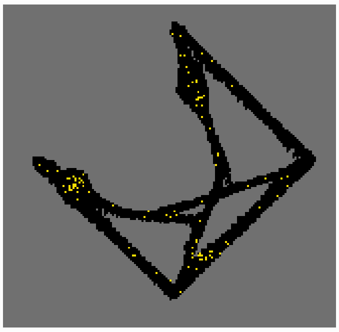

Figure 117 - After 23 frames

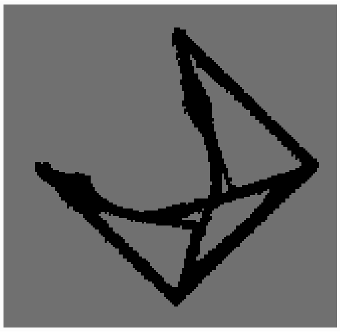

Figure 118 - After 25 frames

Figure 119 - After 30 frames

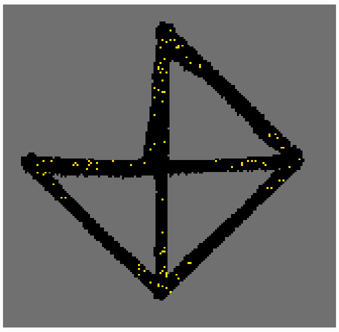

Figure 120 - After 39 frames

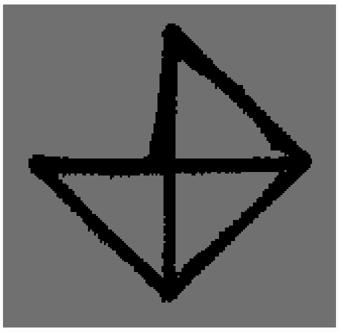

Figure 121 - After 40 frames

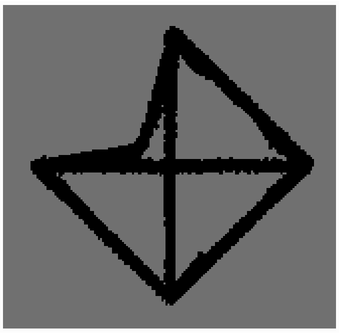

Figure 122 - After 40 frames

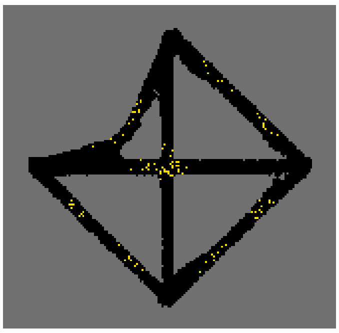

Figure 123 - After 48 frames

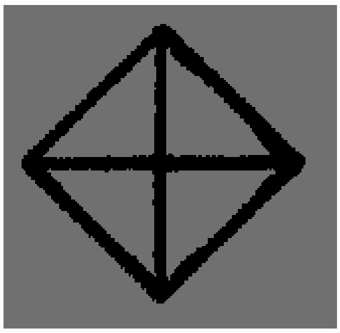

Figure 124 - After 60 frames

In Figures 121 to 124 we see the evolution of a short cut as it develops. We can now look for an examples to see if this phenomenon occurs in reality.

Figure 125 - A path is forming towards a gap in the fence.

Figure 125 shows a gap in the wire fence (circled) and a trail beginning to form through the grass (towards the camera position on the designated path Figure 126). This route is a short cut to the bus stop (out of shot, to the left of Figure 125).

At this stage of evolution the trail is in the general direction of the road, snaking to the left and right of a straight line path. The erosion is beginning to kill the grass, the condition we defined in our model as the 3-7 hits range. Erosion and growth are poised in a form of dynamic equilibrium. We returned to this site several months later to see the development of the trail.

In late Summer the photograph Figure 126 was taken and we can see the erosion more clearly. The grass is more difficult to navigate and the trail straightens out. This is now similar to the scenario in Figures 121 to 124 where the erosion occurs at the edges of the path and the length of grass prevent a major deviation from the path. The evolution of the path has parallels in many biological systems which benefit from ***least effort*** which minimised the energy expended by the entity.

Figure 126 - Returning to the path in late Autumn we can now clearly see the path.

The evolution of animal trails, and in particular ant trails, is a well-documented process [63 to 75]. Figures 125 and 126 demonstrate that examples of the human propensity to take the path of ***least effort*** can be validated in everyday examples. People exploit short-cuts. Thus we have developed an algorithm based on the assumption that humans ***will*** exploit, wherever possible, the shortest route to their objective. Within this algorithm we have confirmed the findings of Helbing [13] and have offered new evidence that the problem of short cut exploitation is an underestimated phenomena in that design of places of public assembly.

The discussion relating to Wembley Complex Station (chapter 2.8) show that a model of the Stadium to Station area would have uncovered the alternative ***least effort*** short cuts. In that example it takes less effort to walk further than to queue for a long time.

The algorithm can be used in two different ways. Firstly we can use it to determine the location of appropriate signage. Secondly, we can use it to determine the optimal shape for corners, concessions and the development of human trails.

6.5 Quantitative validation of Legion

Galea [24] states that systematic comparison of the model s predictions with reliable information is essential to the validation of a computer model. We now address the issue of ***reliable*** information.

Fruin [6] is an excellent reference but the environments he measured involved low density occupation, less than 2 people per square metre compared to the 4 people per square metre in a typical sports environment. Furthermore the pedestrian environment of a city street, with its many distractions, is very different from the designs intended for emergency egress. However, the Fruin data is available and we need to discuss how well the model performs to that data.

6.5.1 The Fruin data

Fruin used time lapse photography to measure the forward displacement of pedestrians along a city street. He measured a variety of density and speed relationships and we can draw his results in two ways (Figures 127 and 128).

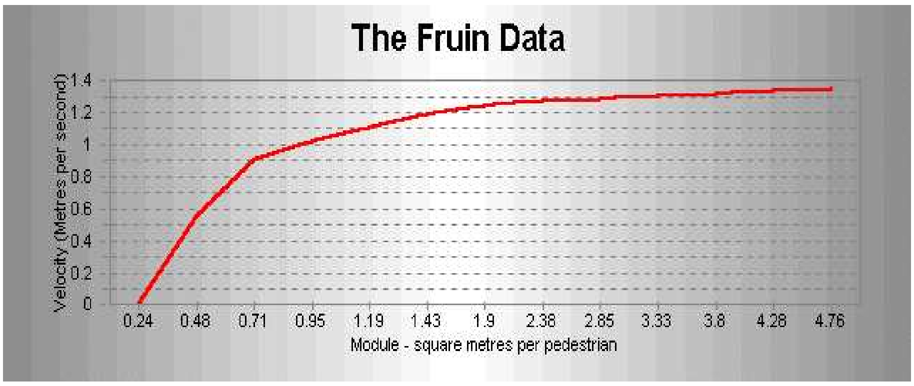

Figure 127 - The Fruin data on a square metre per pedestrian scale

The Fruin Level of Service (LoS) has been used in pedestrian planning since 1970. Fruin [6, 54] has expressed concern that LoS is applied with proficiency.

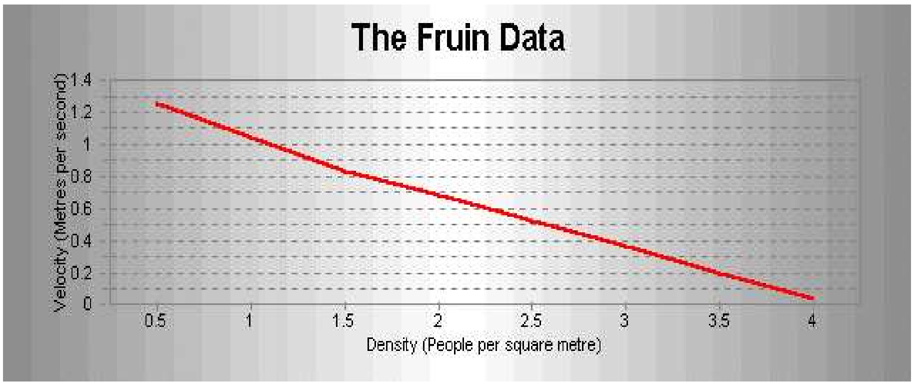

Figure 128 - The Fruin data on a people per square metre scale

We note from Fruin s observations [6 , page 73] that the sidewalk has an approximate width of 3 metres (10 feet). We also note from Fruin [6 , page 44] that a clearance of 1 to 1.5 feet is observed from the edges of the walls and pavement (sidewalk) edge. In our model we allow no clearances for edge avoidance, to do so would negate our ***dumb*** people hypothesis). We need to create a model 2.1 metres in width and set up the speed distribution to the Fruin data.

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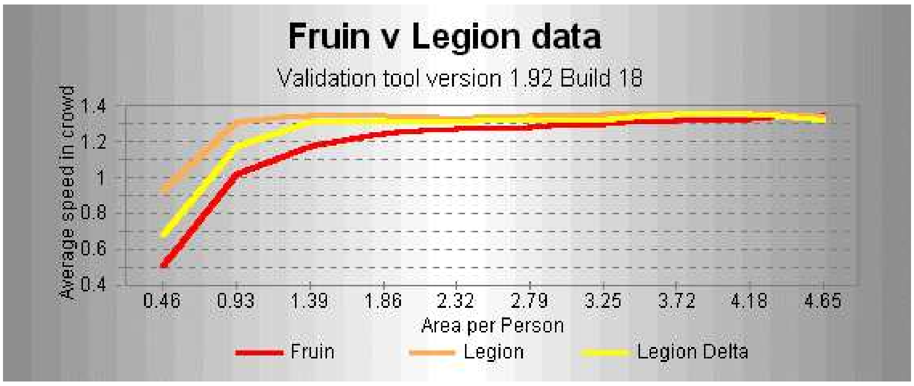


Figure 129 - Fruin data versus the Legion simulation output

The orange line (Figure 129 - Legion) is the speed in any direction: the entities, if necessary, can move in a diagonal overtaking step. The yellow line (Figure 129 - Legion Delta) is the forward speed (the delta X displacement), measured along the X axis.

At high densities the fit to the Fruin curve is not close. We saw in previous chapters that Togawa and the ***Green Guide*** also do not agree with the Fruin data.

6.5.2 Validation against Togawa

We saw from chapter 3.1.6 that Togawa [3], Ando [26, 27, 28] and the ***Green Guide*** [19] are in close agreement. We use the Togawa formula (V) = V_o $^{-0.8}$ Where is the density in persons per square metre. Togawa used V_o as a constant ($1.3 m s^{-1}$). We will use $1.34 ms^{-1}$ as the constant, V_o, to keep it in line with observations of European crowds. Capping the upper speed value at 1.34 we get:

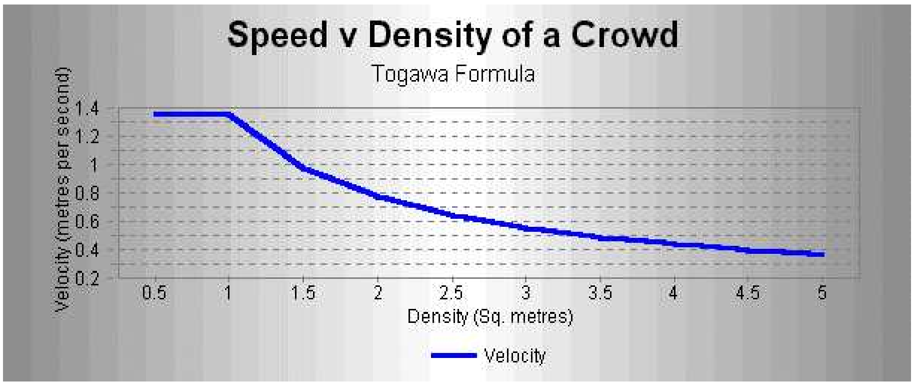


Figure 130 - The Togawa data on a people per square metre scale

Comparing the Fruin, Togawa and ***Green Guide*** data together:

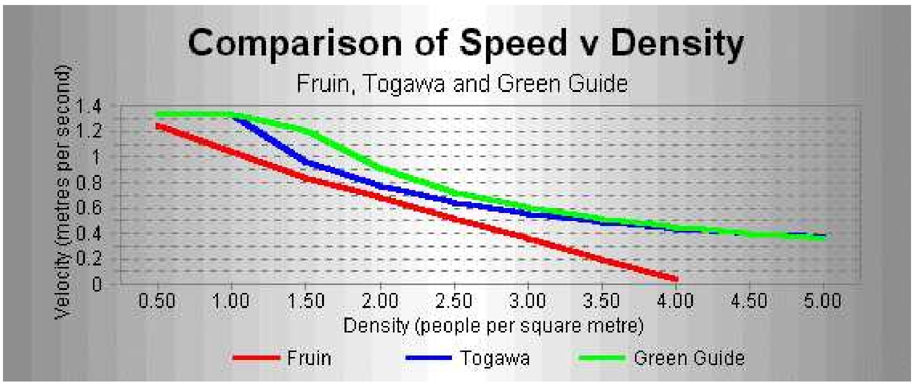


Figure 131 - Comparison of the Fruin, Togawa and ***Green Guide*** data

We can see from Figure 131 that there is a similar curve for the Togawa formula and the ***Green Guide***. As both were empirically derived from large crowds, this is expected. However, it does highlight the differences from the Fruin data.

6.5.3 Validation against the Green Guide

The ***Green Guide*** data have been measured in and around Wembley Stadium (along with many other venues around the Great Britain). Comparing the simulation results to the ***Green Guide*** data we get:

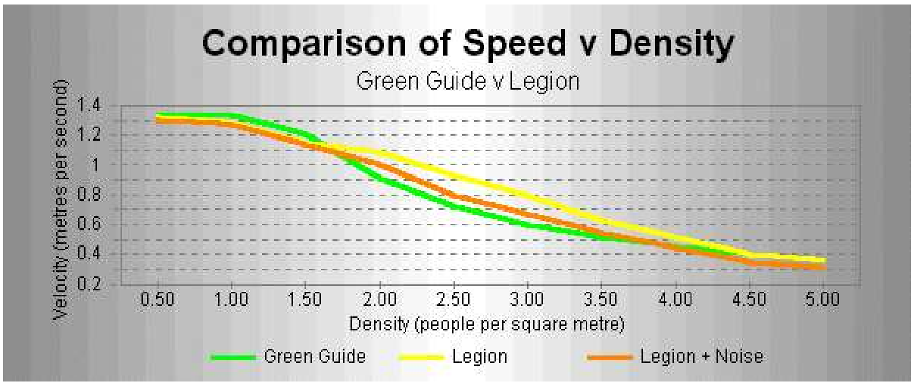


Figure 132 - Comparison of the Legion data versus the Green Guide

The Legion simulation is in good agreement with the ***Green Guide*** data. As the simulation is noise free, in that people in our simulation do not stop, hesitate, deviate, get distracted or fall over. By adding a 25% noise level to the entity interactions we can improve on the fit. The noise was implemented in the overtaking algorithm and we add a rule: 25% of the time the entity will choose to slow down and match speeds with an entity moving its direction instead of taking an optimal overtaking manoeuvre.

This lowers the curve, as in Figure 132. In low density this noise value has no effect as there are fewer overtaking opportunities. At higher densities the entities are affected more, hence the nonlinear relationship between curve of the noise free algorithm and the noisy algorithm. Field measurements confirm the overtaking value matches the overtaking potential in high density crowds. The relationship is a function of the local geometry and density. As the density increases the opportunities for overtaking decrease and their speeds homogenise.

6.5.4 Validation against Fruin

We plot the Legion output data against Figure 128 to see where the Legion simulation and the Fruin data differ. We also add different levels of noise.

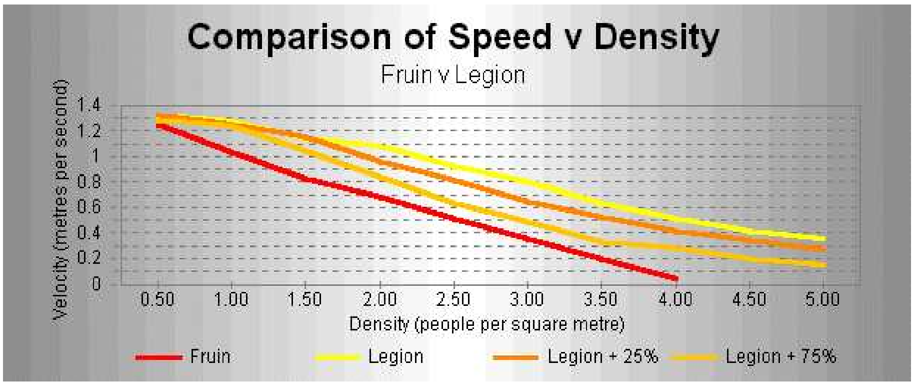


Figure 133 - Comparison of the Legion data versus the Fruin data

The addition of further noise brings the Legion curve down to the Fruin curve. From this we might conclude that the main difference between street crowds at low density and crowds in sporting grounds can be attributed to the distractions (noise) in the city street. We never reach the zero velocity that Fruin predicts as, in this experiment, there is always an egress route, our corridors are open-ended.

We can also look at experiments with the speed distribution curve adding wider ranges, skewing the graph away from the normal, and a variety of other factors. These changes are the subject of further field studies.

We made some measurements of speed v density at a London Station (Liverpool Street Station - underground platform section).

Speed Range	1.1 to 1.2	1.2 to 1.3	1.3 to 1.4	1.4 to 1.5	1.5 to 1.6	1.6 to 1.7	1.7 to 1.8	1.8 to 2.0
Percentage	4.9	4.9	4.9	31.7	36.6	9.8	4.9	2.4

Table 6 - Data from a field study at Liverpool Street Station (London Underground)

When we compare these data to Fruin, Togawa, and the ***Green Guide***, the density was measured at 1.48 people per square metre, we get:

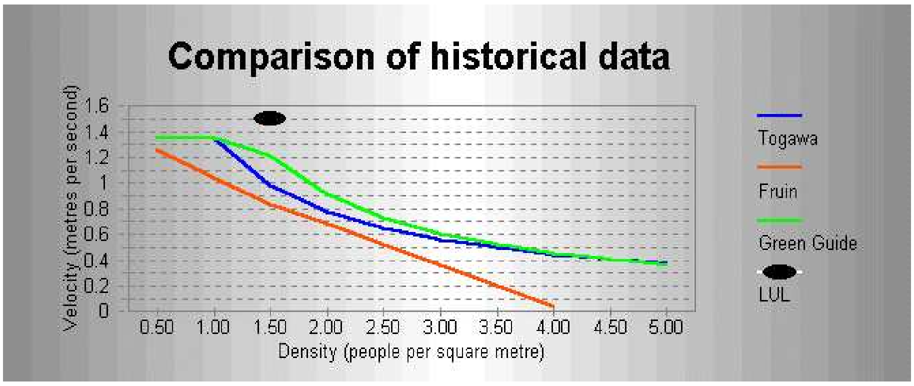


Figure 134 - Data measured from London Underground against the historical data.

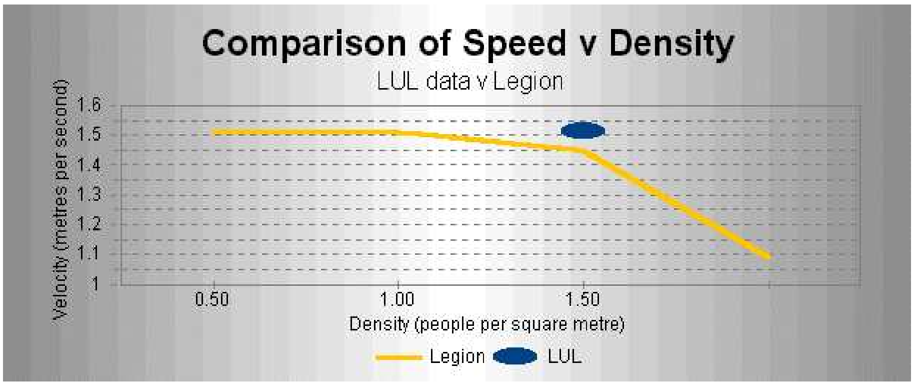


Figure 135 - Speed v density of Legion with a 1.5 ms^{-1} input against the LUL data

The Liverpool Street Station (London Underground) data (Table 6, 7 and Figures 134 and 135) is outside the Togawa, Fruin and ***Green Guide*** data.

	Speed	Density
Mean	1.51	1.48
Std.	0.16	0.19

Table 7 - Speed and Density

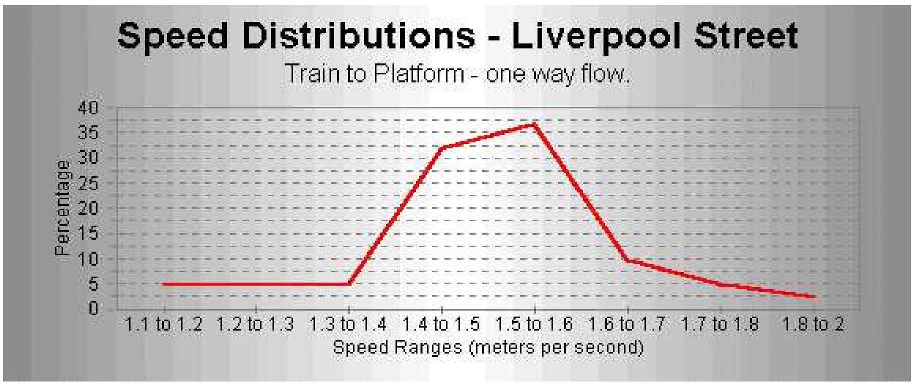


Figure 136 - Speed distribution curve - train emptying onto a platform.

These results looks like statistical outliers, but when we alter the speed distribution in the simulation (Figure 137 and Table 7) we match the data.

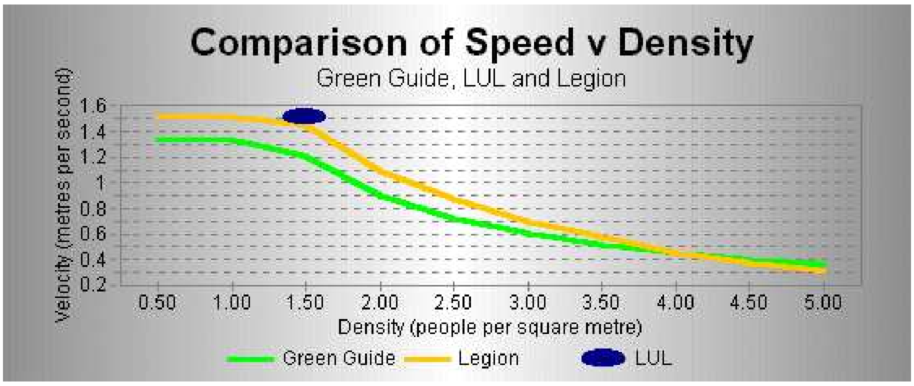


Figure 137 - ***Green Guide***, LUL and Legion.

As we can see from Figure 137, altering the speed input to the simulation produces a fit to the LUL data (using a higher speed distribution as the input, in this case 1.51 mean with std $0.16ms^{-1}$). No other parameters of the simulation are altered. In this way we can demonstrate that the speed distribution of the entities is a controlling factor in the dynamics of the crowd. Our model is robust.

Figure 137 shows that the high density v speed relationship does not appear to be a function of the individual speed, but a function of the ***emergent speed*** of the crowd. A valuable insight to the nature of the high density crowd flow characteristic.

6.5.5 Validation against Paulsen

The Paulsen evacuation test (chapter 3.4.4) is an experiment in which he emptied a room 8.5 metres by 3 metres filled with people (door width of 1.5 metres). The results were mean 30.26 seconds, standard deviation 2.64 seconds evacuation time. We find that the results are sensitive to the speed distribution but taking the Helbing speeds (mean $1.34ms^{-1}$ with std $0.26ms^{-1}$) with the 25% noise algorithm the results were a mean of 29.9 seconds and standard deviation 2.07 seconds for egress.

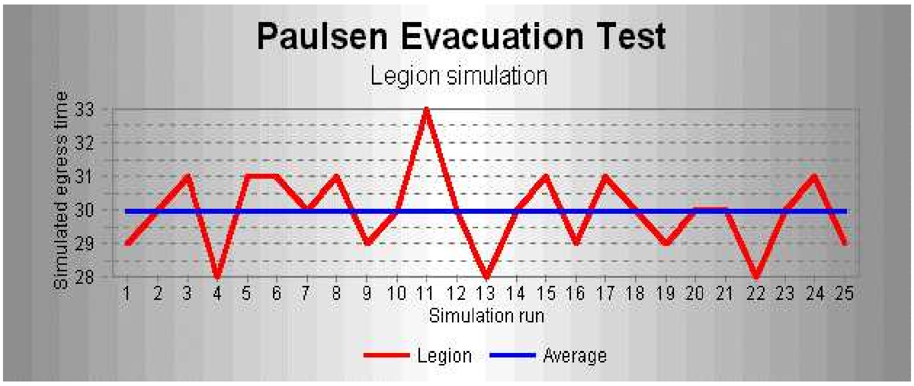


Figure 138 - Results from the Paulsen evacuation test - using Legion + Noise

6.6 Conclusions

We have seen that short cut exploitation can prove fatal (Hillsborough) and how the simulation can provide insights to the nature of these problems.

The data we have examined come from reliable sources. Coupled with our own field studies, we find that the speed/density relationship is a function of the speed distribution histogram. We also find that local geometry has a dominant effect on the speed/density relationship. The Legion simulation has the ability to differentiate the effects imposed by these relationships.

Our goal in this section was to prove that the simulation can reproduce the necessary data for crowd dynamics. Adding a level of noise brings the simulation from a sports environment into a street environment. The system can explain a range of behaviour including the edge effects, crowd compression effects, and the finger effect. The simulation can also determine the appropriate location for signage, and it allows the designer to determine the speed/density distributions in an environment.

Altering the speed distribution curve and the noise levels aids our understanding of how these parameters affect the crowd dynamics. We can be confident that the values are appropriate and we have a robust explanation of the mechanisms that drive crowd dynamics.

Chapter 7 Case Study 1: Balham Station

7 Introduction

The study of Balham Station was undertaken at the request of Cubic Transport Systems (CTS) who produce passenger-operated gates and ticketing machines for underground stations. CTS required an analysis and suggestions for resolving a problem of congestion in the main concourse area and to investigate if their equipment contributed to the congestion. We will examine the site, produce a model of the typical queuing and crowd movements, then analyse the results.

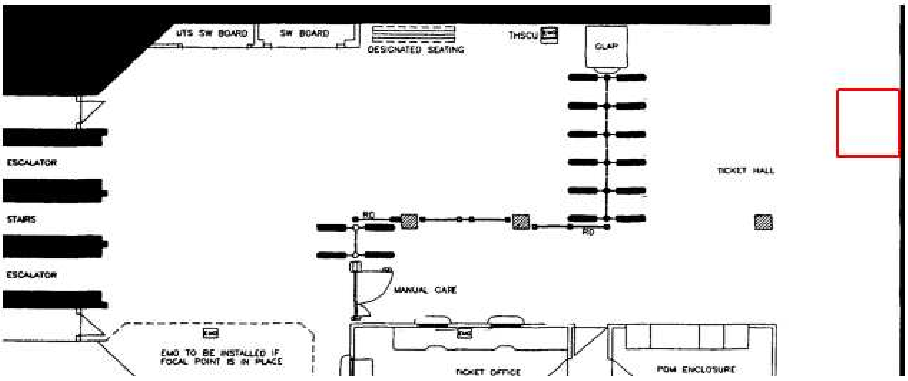


Figure 139 - The CTS plan of the station (existing guard enclosure in red)

Figure 139 shows the plan of the station. The red box (top left) indicates the position of a booth. This was though to be the cause of a congestion in the area marked Ticket Hall. However its removal did not relieve the congestion.

We went to the station and observed the morning crowds, taking notes, video and photographs of the area. Two months of 24 hour video footage in total were collected during the Christmas and New Year holidays. Wednesday 3rd January (first commuter day of the year) and January 29th were singled out as the two busiest periods. London Underground Limited are very sensitive to the release of commuter data due to the continual threat of terrorism, therefore we present the data in summary form only as specified by LUL and CTS.

7.1 Ticket hall operation

The majority of passengers enter the ticket hall from the top right (Figure 139), the commuter main line station entrance. These patrons then either go to the passenger operated machines (POM - marked POM enclosure bottom left Figure 139) or to the ticket office.

Once the passengers obtained a ticket they then pass through the gates to the bottom left (down) escalator. If they hold a season, weekly or monthly ticket they can go straight through the gates from the entrances. Figure 140 shows the ticket hall during a typical morning.

Figure 140 - Ticket office camera looking toward the top right of Figure 139

Analysis of the video footage of this area saw the number of people averaging 125 with a normal distribution during the peak period.

We note that the entrance routes to this area are 3.09 and 2.89 metres. The flow rates through these entrances (Primrose Guide) would be 123 and 115 people per minute respectively. The peak arrival rates did not exceed the maximum value for ingress so the system does not suffer from any ingress limitation.

7.1.1 Poisson probability distribution.

From Queuing Theory [92] we can assess the probable depth of the queues at both the ticket machine and the manual operator windows. For this we can use the Poisson probability distribution function. In queuing theory this is expressed as:

$$P(x) = \frac{\lambda^x . e^{-\lambda}}{x!} \qquad \text{For } x = 0, 1, 2, 3, 4, ...$$

x = Number of arrivals in a specific period of time

λ = Average number of arrivals for the specific period of time

e ≈ 2.71828... (Euler's number)

7.1.2 Service Time Distribution

We are measuring the time it takes to perform the operation of obtaining a ticket. Whilst many patrons will complete the process in a very short time others may take a lot longer. The appropriate model for the time taken is an exponential probability distribution function. In queuing applications this is expressed as:

$$F(x) = \mu \, e^{-\mu x}$$

x = service time (time taken to perform some specified function)

μ = average number of units that the service facility can handle in a specified period of time.

The videos revealed that during the busiest period (7.00 - 7:15 am) the ticket issuing machine operation (service time) was 22 seconds. The manual ticket operators service rates were timed at an average of 75 seconds.

7.1.3 Queuing models

This system meets the criteria for a simple queuing model.

1. The pattern of arrival follows a Poisson probability distribution.
2. The service time follows an exponential probability distribution.
3. The queue discipline is first come, first serve
4. Both waiting lines have a single channel. Patrons use either the machine or the manual operator.

λ = Average arrivals for the specific period of time (mean)

μ = Expected number of services possible per time period (mean)

For the concourse area we test the arrival range of $\lambda = 75$ to 200 and $\mu = 22$ and 75 second respectively. Using the assumptions of Poisson arrivals and Exponential service times the following quantitative analysis can be applied where the following formulas apply.

1. Probability that the service facility is idle (probability of 0 units in the system)

$$P_0 = 1 - \lambda / \mu$$

2. Probability of n units in the system (waiting time and service time)

$$P_n = (\lambda / \mu)^n \cdot P_0$$

3. Average number of units waiting for service

$$L_q = \lambda^2 / (\mu(\mu - \lambda))$$

2. Average number of units in the system.

$$L = L_q + \lambda / \mu$$

3. Average time a unit spends waiting for a service.

$$W_q = L_q / \lambda$$

4. Average time a unit spends in the system (waiting and service)

$$W = W_q + 1 / \mu$$

5. Probability that an arriving unit has to wait for service

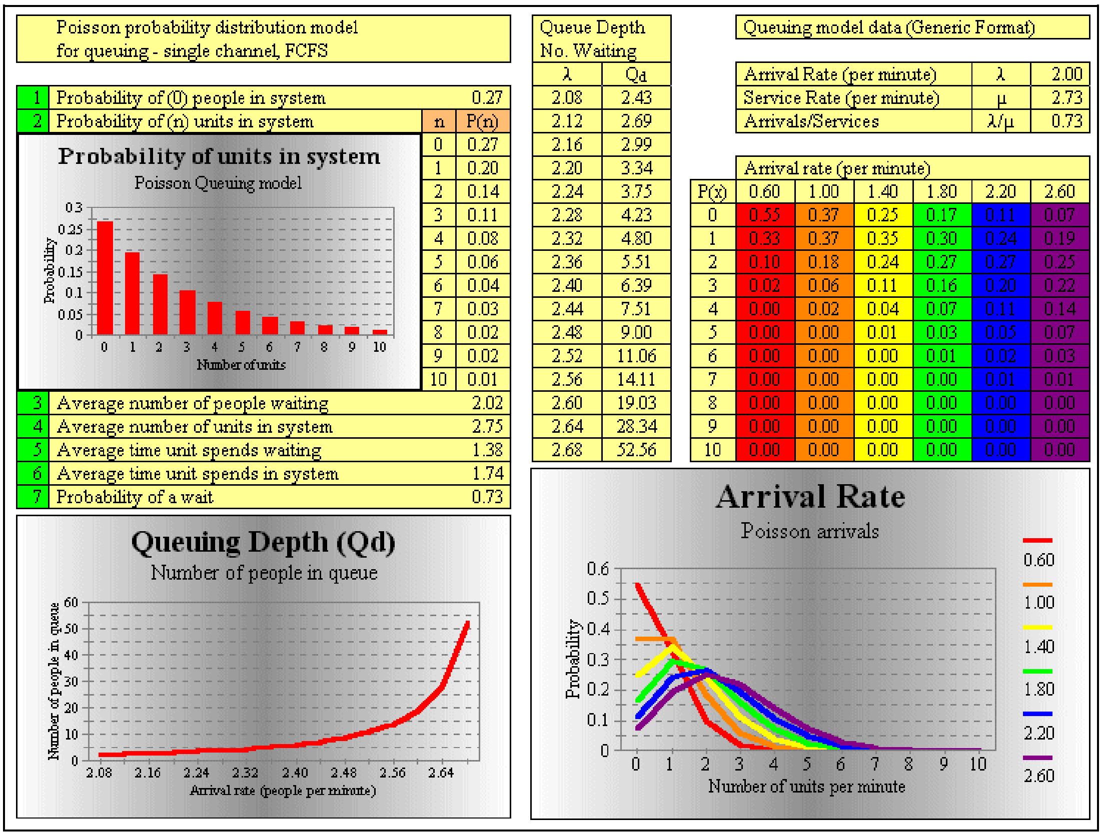
$$P_w = \lambda / \mu$$

The values of the mean arrival rate and the mean service rate are clearly important components in the above calculations. We can see that the ratio of these two values, λ / μ, is simply the probability that an arriving unit has to wait because the server is busy. Thus λ / μ is often called the utilisation factor. The formulas for determining the characteristics of this type of system are applicable only when the utilisation factor $\lambda / \mu < 1$. This condition occurs when the mean service rate (μ) is greater than the mean arrival rate (λ) or the system can process the arrivals.

First we need to consider the average depth of queue and test for the failure criteria (congestion). If the queue builds to sufficient depth this identifies the nature of the congestion, namely the queue blocks the available route. To do this we can create a spreadsheet model of the station. As we have discussed throughout this thesis the simulation has been designed to resolve the uncertainties of the guidelines. This case study relates to the accepted techniques of applied queuing theory. We introduce the concept of a focal route analysis and highlight the deficiencies of applying a queuing model in isolation.

7.1.4 Spreadsheet modeling.

The first stage is to create a spreadsheet model of the arrival and service rates, taking a wide range to examine the resulting queuing depths.



	Poisson probability distribution model for queuing - single channel, FCFS	
1	Probability of (0) people in system	0.27
2	Probability of (n) units in system	
3	Average number of people waiting	2.02
4	Average number of units in system	2.75
5	Average time unit spends waiting	1.38
6	Average time unit spends in system	1.74
7	Probability of a wait	0.73

n	P(n)
0	0.27
1	0.20
2	0.14
3	0.11
4	0.08
5	0.06
6	0.04
7	0.03
8	0.02
9	0.02
10	0.01

Queue Depth No. Waiting	
λ	Qd
2.08	2.43
2.12	2.69
2.16	2.99
2.20	3.34
2.24	3.75
2.28	4.23
2.32	4.80
2.36	5.51
2.40	6.39
2.44	7.51
2.48	9.00
2.52	11.06
2.56	14.11
2.60	19.03
2.64	28.34
2.68	52.56

Queuing model data (Generic Format)		
Arrival Rate (per minute)	λ	2.00
Service Rate (per minute)	μ	2.73
Arrivals/Services	λ/μ	0.73

	Arrival rate (per minute)					
P(x)	0.60	1.00	1.40	1.80	2.20	2.60
0	0.55	0.37	0.25	0.17	0.11	0.07
1	0.33	0.37	0.35	0.30	0.24	0.19
2	0.10	0.18	0.24	0.27	0.27	0.25
3	0.02	0.06	0.11	0.16	0.20	0.22
4	0.00	0.02	0.04	0.07	0.11	0.14
5	0.00	0.00	0.01	0.03	0.05	0.07
6	0.00	0.00	0.00	0.01	0.02	0.03
7	0.00	0.00	0.00	0.00	0.01	0.01
8	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00

Figure 141 - Spreadsheet model of the queuing for the ticket machine.

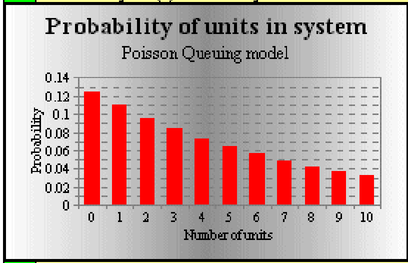
Figure 141 shows a spreadsheet analysis of the queues and service times for the ticket machine. The mean service rate is 2.73 people per minute and we are testing various arrival rates in the range of 1 to 2 persons per minute.

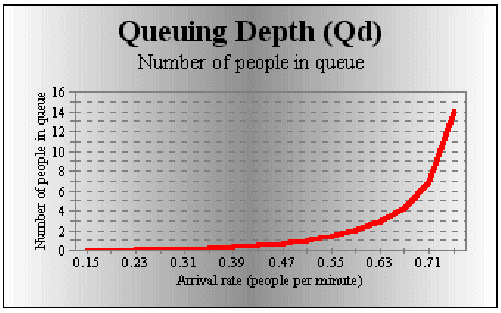
We can see from the graph of queuing depth that the number of people rises exponentially where the arrival rates begin to reach the service rates. Taking the flow rates from the Primrose [5] we have an extreme value of 238 people per minute that could arrive in this area. It is therefore possible that the arrival rates can exceed the service rate and we have queuing models to assess the need for additional machines.

Using the same methods we can analyse the manual ticket operation.

	Poisson probability distribution model for queuing - single channel, FCFS	
1	Probability of (0) people in system	0.13
2	Probability of (n) units in system	
3	Average number of people waiting	6.12
4	Average number of units in system	7.00
5	Average time unit spends waiting	10.00
6	Average time unit spends in system	11.25
7	Probability of a wait	0.87

n	P(n)
0	0.13
1	0.11
2	0.10
3	0.08
4	0.07
5	0.06
6	0.06
7	0.05
8	0.04
9	0.04
10	0.03





Queue Depth No. Waiting	
λ	Qd
0.15	0.04
0.19	0.07
0.23	0.12
0.27	0.17
0.31	0.25
0.35	0.34
0.39	0.46
0.43	0.62
0.47	0.84
0.51	1.12
0.55	1.51
0.59	2.07
0.63	2.92
0.67	4.32
0.71	7.00
0.75	14.06

Queuing model data (Generic Format)		
Arrival Rate (per minute)	λ	0.70
Service Rate (per minute)	μ	0.80
Arrivals/Services	λ/μ	0.87

	Arrival rate (per minute)					
P(x)	0.20	0.30	0.40	0.50	0.60	0.70
0	0.82	0.74	0.67	0.61	0.55	0.50
1	0.16	0.22	0.27	0.30	0.33	0.35
2	0.02	0.03	0.05	0.08	0.10	0.12
3	0.00	0.00	0.01	0.01	0.02	0.03
4	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00

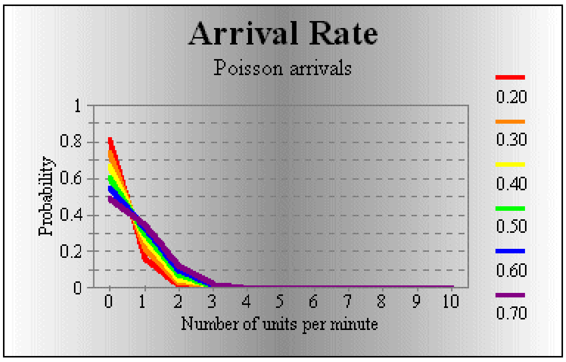


Figure 142 - spreadsheet model of the manual ticket window.

Figure 142 shows the same model applied to the manual ticket operators. There are two operators and this model is not strictly appropriate. But, as we shall reveal, the single channel calculation is very relevant to the congestion problem.

Figure 143 - Composite multiplexer view showing the ticket queues.

7.1.5 The queuing problem

From Figures 141 and 142 we can see that if the arrival rates approach the average service time then the queues build up very quickly (Figure 144).

Figure 144 - The average queue depth conforms to the model (some out of view)

It is a financial consideration which determines available space and equipment installation. Hence, if the peak period has a duration of 15 minutes, then a peak loading of the system may well exceed the service rates with minimum cumulative effects. Thus, provided there is sufficient room for the queue, the overall impact to the patrons is minimal. At all other times the arrival rates are very much lower than the service rates. We have a range of tools that can be used to produce probability distribution models to determine the peak loading, its duration and the need for the additional space, number of machines, gates etc. but we are missing an important feature of these types of system with this approach.

The information missing from queuing models is the shape of the queue. In Figure 144 we see the queue forming and backing across the path of the ticket gates. This can effectively block the entrance and contribute to the problem of congestion.

Figure 145 - Only one window operating.

Figure 146 - Both windows operating

Figure 145 and 146 show the difference in queue lengths between a one and two operator configuration. The space appears adequate during busy periods with two operators and we can see that the arrival rates and service rates are well matched. So what leads to the congestion in the ticket hall? How and why does it fail?

7.1.6 Focal route analysis

When we find a situation where there is sufficient provision for the queue criteria and yet the system fails (as it does in this example) we need to consider the effects of the focal routes on the mean arrival rates. Figure 147 illustrates a simplified model of the ticket hall.

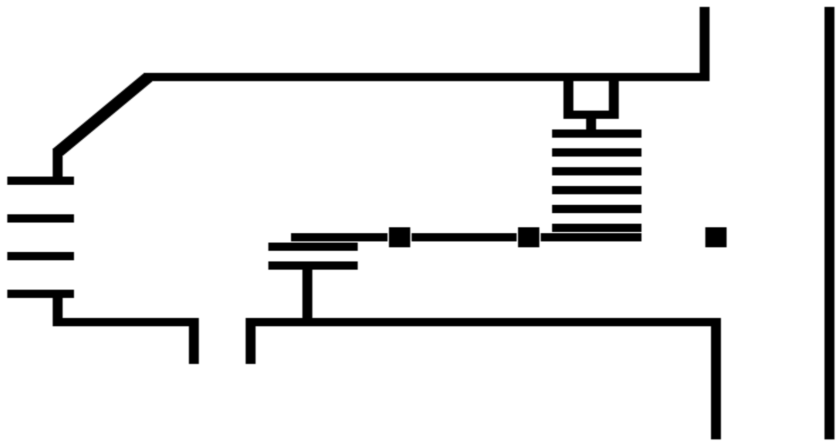


Figure 147 - The ticket hall - stylised graphic

The escalators are positioned on the left-hand side of Figure 147 and the British Rail entrance is at the top right-hand corner. From both site observations and video analysis the routes that people take through the station were observed. By placing a sheet of acetate on the monitor screen and using the frame advance function we can time and measure individual steps, the average length of walk and any directional changes. To do this we plot the head positions frame by frame on the acetates. After several of these sheets are created, we simply superimpose them and can now observe the deviations people take from the focal routes.

From this analysis the speed/density and angle of deviation are derived and used in the algorithms for the routes taken by the entities.

7.1.7 Determining the focal routes

In the Balham ticket hall the principle focal routes can also be determined by drawing a line from each entrance to each exit, or delay point. The focal route analysis shows the typical morning rush hour arrangement with three gates (lower three) for incoming flow. Note the convergence of the focal route at the lower left.

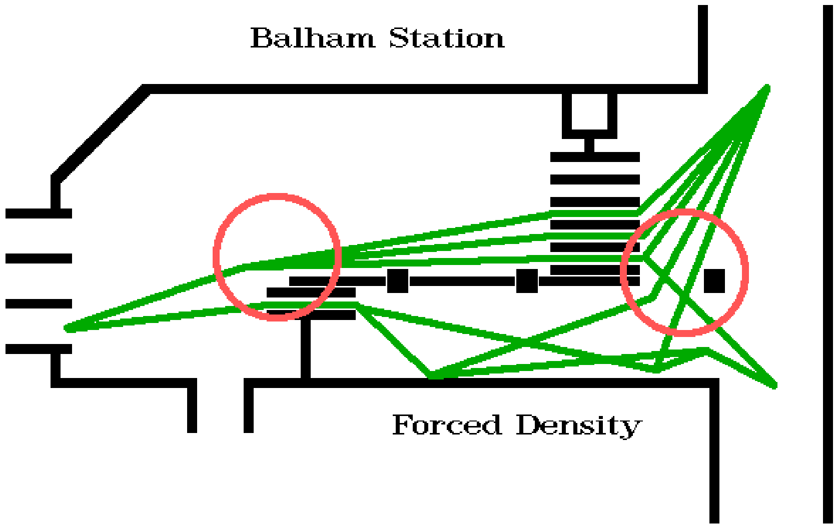


Figure 148 - Focal route analysis can show the conflict zones.

Figure 148 shows that the configuration is not ideal; there are areas where focal routes cross each other. This reveals two areas where crowd density will be forced (red circles in Figure 148) and where collisions, delays and avoidance manoeuvres will occur. At the convergence point (bottom left of Figure 148) is a tile which was frequently replacement indicating excessive use. It is interesting to watch the shuffling gait at this point to align the person with the top escalator step.

The congestion was noted to be particularly bad on Monday mornings, when the queue formed back to the entrance at the top right of Figure 148. Figure 144 shows this queue beginning to form crossing a focal route.

7.2 Balham Station operation

The station passenger flow routes are illustrated in Figure 149.

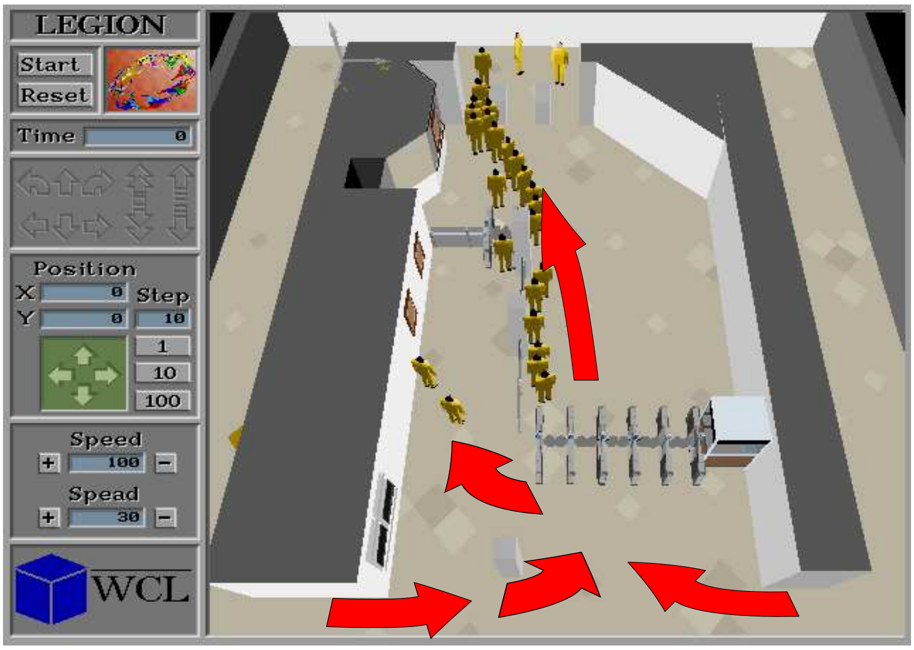


Figure 149 - From the virtual reality model of the station - showing the routes.

We can use a virtual reality model (VEgAS) to illustrate the depth of queues and the routes through the station. This is a very powerful technique in assessing the overall impact of a queue as you can move around the model in realtime 3D. As the crowd progresses through the simulation this techniques allows the user to see the station in operation and assess the decision making criteria that a passenger would take in similar circumstances. We enter the simulation and this assist in determining the factors, parameters and measures required for model building and calibration. We may expected congestion at the top of the escalators (Figure 149).

7.2.1 The Legion model

From our previous discussion we can see how the queues build up but we do not know under which conditions the ticket hall becomes congested. We know that, in part, this due to the location of the equipment but we need to quantify the problem. Although queuing theory can provide an accurate model, the analysis of the depth of the queue is only part of the problem. We need to assess how this queue interferes with the flow of people who wish to pass through the queue. Congestion occurs when the mean arrival rate approaches the mean service rate. In practice when the utilisation factor = 1 ***any*** randomness in the system will result in a rapid increase in the overall depth of queue. The shortcomings in focal route analysis is that we cannot ascertain the arrival times of passengers, their distribution to manual or automatic machines, or the nature of the interaction on the focal routes.

The analysis of crowd dynamics is complex and to try and apply a single mathematical solution to the problem, as we have seen from queuing theory and focal route analysis, results in partial solutions. However, we can simulate the environment and simplify the analysis by using the combination of queuing theory, focal routes and the Legion simulation. Let us break the problem into components and apply a more comprehensive analysis to the problem.

7.2.2 Determining focal routes with Legion.

We can determine focal routes by hand by connecting the entrances to the exits and looking for the areas of most overlap. This method gives us a good first pass approximation to potential problems in normal operational use but it is a qualitative not quantitative analysis. In a more complex environment it would prove difficult to analyse ***all*** of the available routes by this method. We may also miss some routes, especially those we did not anticipate (as we saw in the gate C short cut and the Wembley Complex Station example in chapter 2). We automate the focal route analysis process.

7.2.3 Short-cut analysis - the ant algorithm .

The objective is to automate the process of finding all the shortest routes on a plan of the environment. The appropriately named ant algorithm achieves that goal by imitating ants. This algorithm works by using the dynamic space utilisation map as the objective, creating a feedback loop from the entity to the environment. The entity goes to the nearest point of highest space utilisation, thereby reinforcing it (a similar mechanism to the erosion experiment discussed earlier). A timed decay erodes unused trails. Using entities of different speeds then straightens the trails and we are left with the map of all of the straightest, shortest routes.

The tricks that ants use require no mathematically ability. An ant trail straightens itself to the optimal, shortest route because the ant lays its pheromones with its hindquarters and detects the trail with its antennae. Corners are rounded by the length of the ant with each successive ant the line straightens by a small fraction. The action of many ants performs the mathematical function of straightening the line. By copying the ant we have developed a searching algorithm which reveals all the focal routes automatically. However, as some of those routes are available only at certain times of the day, so the technique requires some manual intervention.

7.2.4 Ticket hall - space utilisation

Using the algorithm with a combination of varying step sizes and erosion rates the model combines a geometric analysis with a space utilisation map in a single pass. Figure 150 shows the trails (bottom screen). Note that the intermediary process of excluding certain routes has been omitted. To achieve this in the simulation we paint no-go areas by hand, the algorithms treats those as walls.

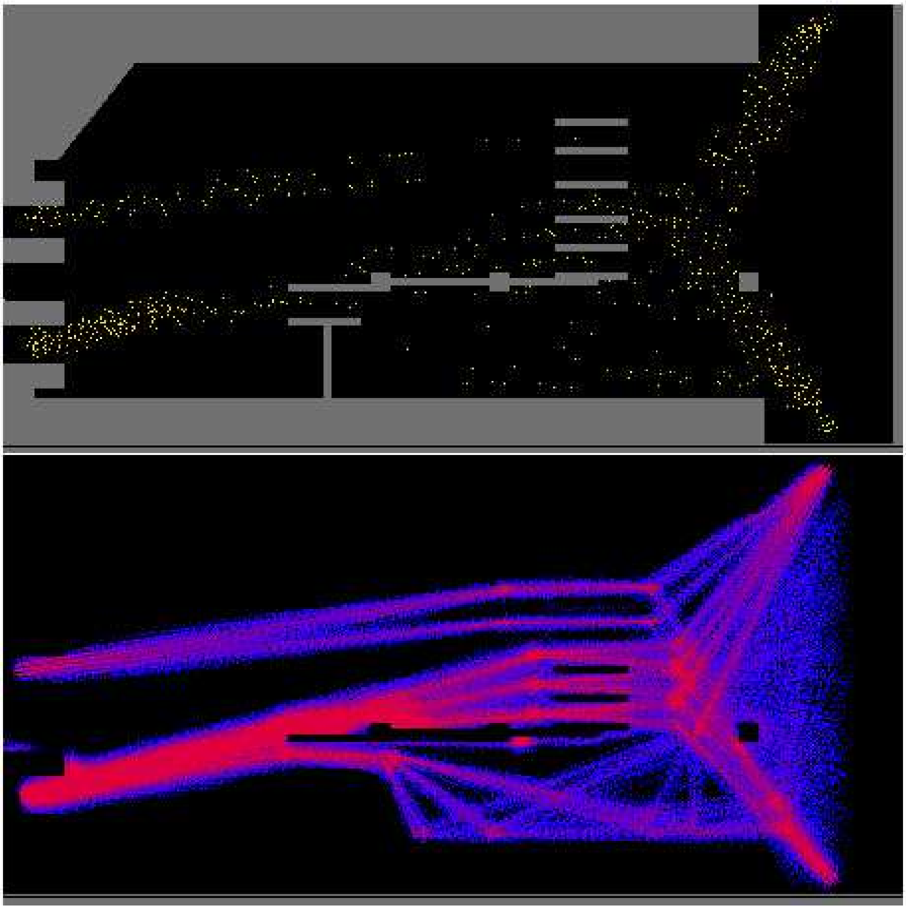


Figure 150 - The evolution of the automated human trail, the short-cut analysis

This technique allows us to evolve a short-cut analysis, the straightest routes apply to the free space individuals but the space utilisation map is cumulative in nature. The long term evolution of the shortest route is independent of any individual entity but is a function of the crowd dynamics. Namely the width of the space used across the shortest route relates to the number of entities using that route over time.

We can now combine the results of the space utilisation with queuing theory to produce a more appropriate analysis of the ticket hall. This is the superposition of the queue depth with the space utilisation map. Where the two overlap we can tell the areas of highest use, shortest path and, as that focal route crosses the average depth of queue, we now know the areas that will appear congested. The solution to the problem is now obvious, either to shorten the queue or allow more space for queuing.

7.2.5 Ticket hall - creating more space

As the walls and support pillars cannot be moved we consider the re-location of the equipment. Figures 151 and 152 illustrate that a subtle can change create more space for the queue. We run a before and after simulation to quantify the change.

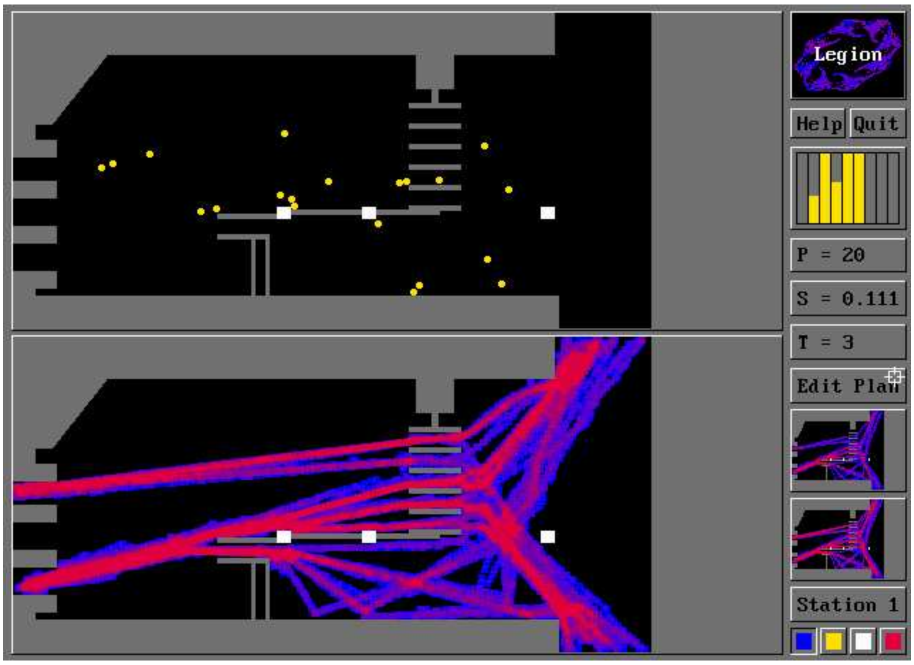


Figure 151 - Space utilisation for original design

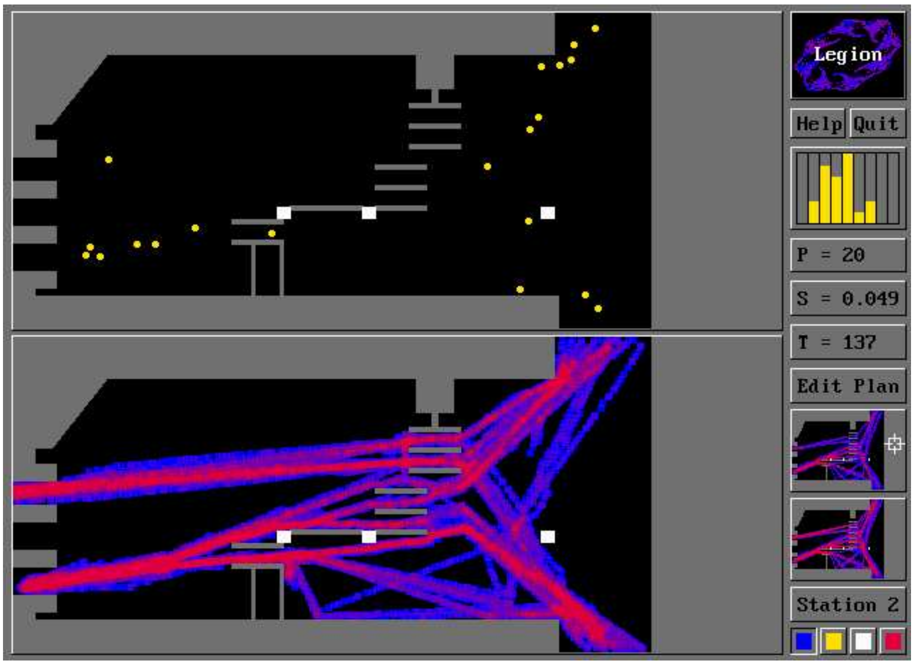


Figure 152 - Space utilisation for modified design

The differences between Figures 151 and 152 can be seen in the area to the right of the ticket gates. We have straightened the route by using an offset gating array. The combination of focal routes and space utilisation, within the Legion simulation, provide us with a powerful methodology to understand and design space around people. Space utilisation can also be used to determine optimal designs by evolving human trails (as we saw in chapter 6) where the function of minimising the space utilisation is used. But we have not addressed the problem at Balham.

As we can see from Figures 151 and 152 that there should be sufficient space for queuing without the need for increasing space, the depth of queue appears to be below the focal route requirements, there should be no congestion in this area. We have to return to the site to see where the model and reality differ.

7.3 Queuing

When we began the Balham project there was a guard enclosure to the right of the plan (along the right-hand wall indicated in red in Figure 139). They removed that enclosure to try and alleviate the congestion but it had little effect.

From the models (see Figures 151 and 152) it is clear why; the enclosure was not on a focal route, it did not contribute to the problem. We can now see that adding more space in areas that are neither on the focal route or queue path will have no effect on the congestion, an obvious statement perhaps but now quantified.

The problem in the ticket hall can be seen in the analysis of Figures 141 and 142 in which, with two independent queues (single channel) there should be a queue of average depth 7-14 people as the arrival rate approaches the service rate.

However, the manual ticket operators are a two channel system so that queue depth should reduce to an average of 0.187 people [for details see Gross 93].

Queues interact with the focal routes. The queue from the manually operated ticket windows backed up through the ticket hall (Figure 147). This produces a very different result from the one that two channel queuing theory would predict. We use a multiplexer to analyse the problem from the video tapes.

7.4 Multiplex views

A multiplexer is a device that combines several video cameras views onto a single image. The advantage is that you can see several views, of different parts of the ticket hall, at the same time. The congestion problem suddenly became apparent when we analysed the multiplexed view of the ticket hall in peak time operation.

Figure 145 shows the queue backing into the ticket hall (bottom left quadrants). There is only one operator window open (Figure 145 - bottom right).

Figure 146 shows that there is no queue in the ticket hall (bottom left quadrants) when both windows are open. That is consistent with the queuing theory.

The congestion problem was that one of the operators would take his coffee break during the morning rush hour. A single channel model in this area (Figure 141) matches the observed queue depth and we now understand the congestion problem. It was solved by rescheduling coffee breaks.

7.5 Problem analysis

This problem was associated with the operation of the manual ticket process. Making more space available was thought to be the solution, but the dynamics of the situation were not simply a function of the geometry, number of people and queuing.

The model can demonstrate the effects of design on the crowd dynamics, but we still have to be aware of the human element and its effect on crowd problems. In the case of Balham Station the queuing space can be alleviated by design (Figures 151 and 152) but the operation of manual ticket issue coffee breaks will still create a problem where the depth of queue backs into the focal route. It is therefore important to understand the operations of a site from the perspective of site management.

A model does not provide all the answers as we saw from queuing and focal route analysis. But it does provide the necessary tools to quantify the requirements and the effects of change. In this case the measure of the mean arrival rates, service rates and the appropriate queuing model tells us the required space for the queue.

The combination of the simulation, the conventional queuing models and some operational knowledge provides the complete solution to the problem.

7.6 Analysing crowd behaviour.

There is much debate as to whether people behave differently in a crowd than they do in free space [94]. The ideas of ***a group think*** provokes heated debate among the psychologists. There are many psychological factors which influence human behaviour, both in free space and in a crowd. The Legion simulation is not a model of these psychological factors, neither is it explicit in modelling human behaviour (such as coffee breaks). It is a model of the dynamics of crowd movement.

By dynamics we mean the influence that density has on flow rates, that geometry has on density and that the speed distributions of the individuals have on the overall crowd. It is a solution to the less obvious problem of exploitation of short-cuts and the effects of cross flows (collision and avoidance effects).

We have discussed in chapter 4.4 how the psychological factors relate to dynamics of crowds. Although we cannot define the exact numerical values of those factors it does not prevent us from experimenting with the a range of values.

7.7 Conclusions to the Balham study

Generally simulations and models provide two types of information. They prove or disprove a theory by way of supportive data or they provide an insight to the nature of the problem. Often the need to visualise the problem is required to appreciate and understand the extent of the problem and impact of the solution.

Combining the visual aspect of virtual reality with the use of the Legion simulations (to determine the space utilisation and focal route analysis) provides a foundation for quantitative modelling of crowd dynamics and analysing operation performance. The interactive design modelling capability of Legion also provides some level of assessing the impact, for example, the location of ticket machines, the interaction of queues and clearways, and the optimal use of space. Queuing theory provides the quantitative data for the depth of the queue. The combined system produces comparative analysis when locations are tested. This can be used in micro analysis; such as door widths, gate entrances and testing the differences that an additional barrier would make to the flow rates. It can also be used in macro analysis, such as the Sydney Olympics.

Balham Station s crowd flow would be improved by staggering the input gates to reduce multiple route interference. Also the gate located nearest the escalators could be moved back toward the ticket hall area. This would allow more space for the predicted depths of queues. The operator now has the data to assess the relative costs of these design changes against the relative benefits.

The analysis of the focal routes would save the cost of relocating the booth (Figure 139). Operational analysis would determine the ideal time for coffee breaks.

7.8 Implications for Legion

The Balham model led to some meaningful conclusions for further development of the Legion simulation. Firstly, an important relationship between the distribution of the speed of the entities was the primary factor that determined crowd parameters. This, coupled with multiple focal routes, produces a space utilisation map which can then be used to determine the optimum design parameters.

Multiple crossing focal routes determines the number of interactions, which in turn determine the natural crowd flow and, to some extent, the forced crowd densities. This idea could be expressed as a series of mathematical formulas once the techniques were established. The models could also be used to produce empirical mathematical formulas by experiment. Experience in model-building will lead to greater understanding of these phenomena and a more robust guideline for designing space around people. In its present form the analysis is both quantitative and qualitative. Analysis of queuing theory breaks down in multidimensional, multi-objective space, as does network flow analysis. The combination of focal route analysis and Legion simulations prove to be more intuitive and easier to use than the calculus involved in purely numerical methods.

Finally, Legion can be used to automatically find the focal routes and short-cuts that may be exploited in reality. The algorithms can be set to iterate, as we saw in the validation of the human trails, leading to optimal design configurations. The technique provides an accurate method for planning and design for a variety of crowd parameters.

Chapter 8 Case Study 2: The Hong Kong Jockey Club

8 Introduction

In January 1998 the Legion simulation was used to model five sections of the Hong Kong Jockey Club. This section is a summary of the application of the Legion system and presentations of some of the simulation data and results. The project covered two different race courses in Hong Kong; Happy Valley and Sha Tin. Three areas at Happy Valley and two areas at Sha Tin were modelled. The areas had a major impact on the smooth and safe running of events at the two venues.

The scope of the project was to identify the problems, propose solutions, and finally to produce a comparative analysis of the effect of the suggested changes. In this case the simulation provides us with a method for qualifying the ***before*** and ***after*** scenarios. We illustrate four of the five areas; area II (Figure 155) has been excluded.

8.1 Overview of the Hong Kong Jockey Club

There are two racecourses in Hong Kong; Sha-Tin and Happy Valley. Both are owned and operated by the Hong Kong Jockey Club and both are in urban areas, surrounded by high rise blocks of flats and office buildings are served by the MTR (Mass Transit Railway).

8.2 Attendance statistics

Legion was provided with a series of statistics, data and video footage for the five areas covering several race meetings. Figure 153 shows the graph of number of patrons attending the two venues. During a season the attendance fluctuates with peaks at 80,000 for the most popular events at Sha-Tin and 40,000 at Happy Valley. These data indicate the ingress (arrival) rates and we can use this type of data to assess the field data against the peak and normal attendance figures.

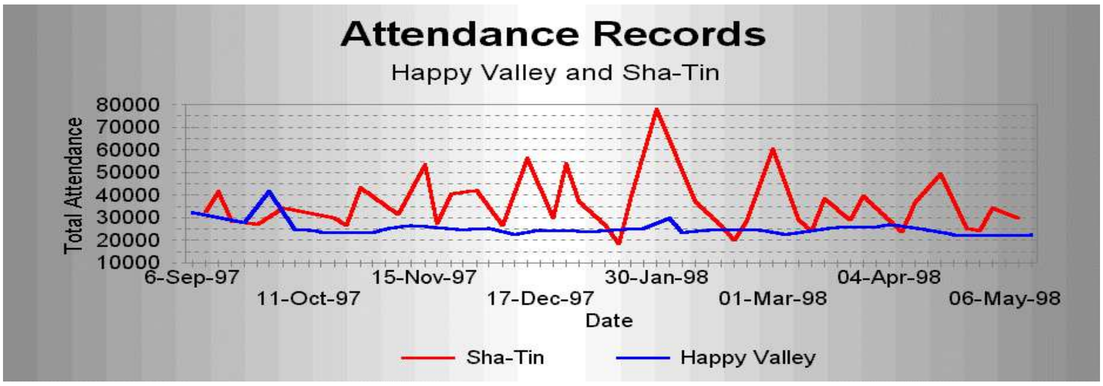


Figure 153 - The attendance records for the two Hong Kong Jockey Club racecourses.

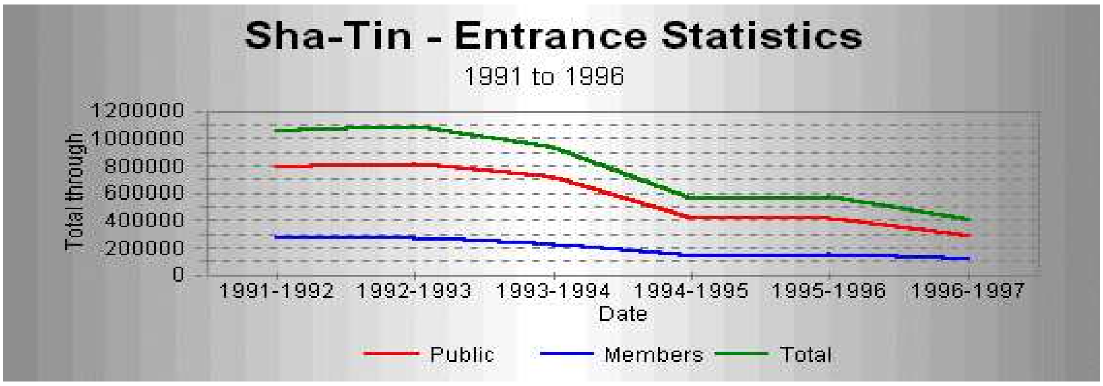


Figure 154 - Sha-Tin entrance statistics showing the drop in attendance from 1991 to 1996

Figure 154 shows the drop in attendance for the period 1991 to 1996. We use this data to assess the long term trends in attendance, if the graph were rising we can estimate the future attendance and design crowd management factors in accordingly.

8.3 Area I - Happy Valley public entrance

The racecourses have two types of patron; members and public. The members pay an annual subscription and use different entrances from the public. The public pay on entry to the racecourse and their entrances are via coin operator turnstiles.

The public entrance at Happy Valley consists of a bank of seventeen turnstiles (Area I in Figure 155). The turnstiles are approached from both left and right (in Figure 155).

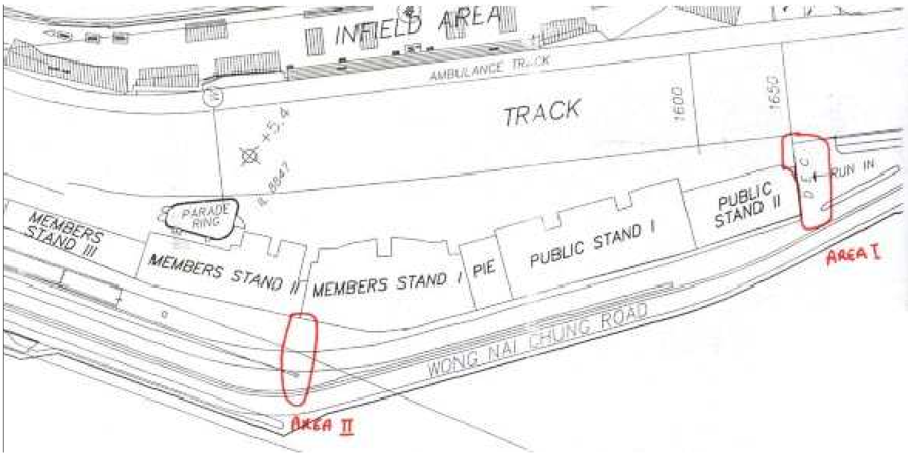


Figure 155 - Plan of Members and Public entrances

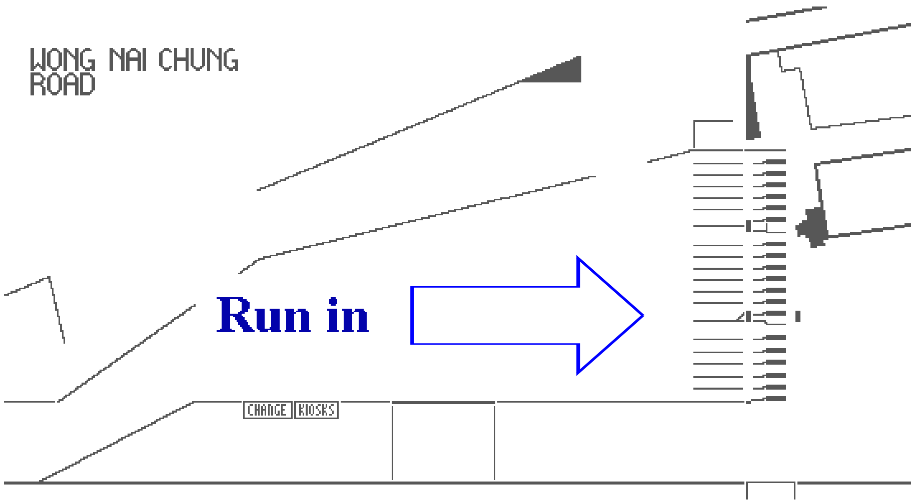


Figure 156 - Plan of the Happy Valley public entrance (note: rotated 180 degrees from Figure 155)

Figure 157 - The turnstiles at the public entrance (Happy Valley)

Access is by correct change only. Change kiosks are located near the entrance along the approach path (Figure 153). The location of these booths was based on the observation that the bulk of the public pass this area.

To the left (Figure 157) are two turnstiles which go into the grandstand; this is where the on-site betting takes place. These two turnstiles are used for Staff and season ticket holders. The middle section has a solid brick wall (Figure 158) immediately behind the turnstiles..

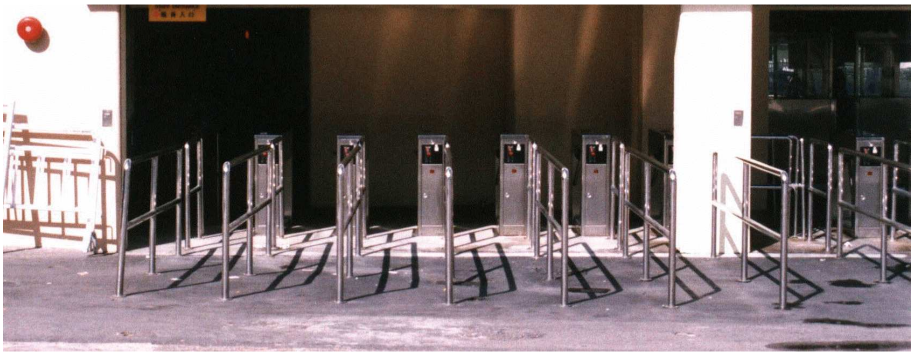


Figure 158 - The view of the wall behind the turnstiles at the public entrance.

8.4 Public entrance - focal route analysis

Focal route analysis requires very little operating knowledge of the site. In Figure 158 we show the primary routes to the turnstiles and change kiosks.

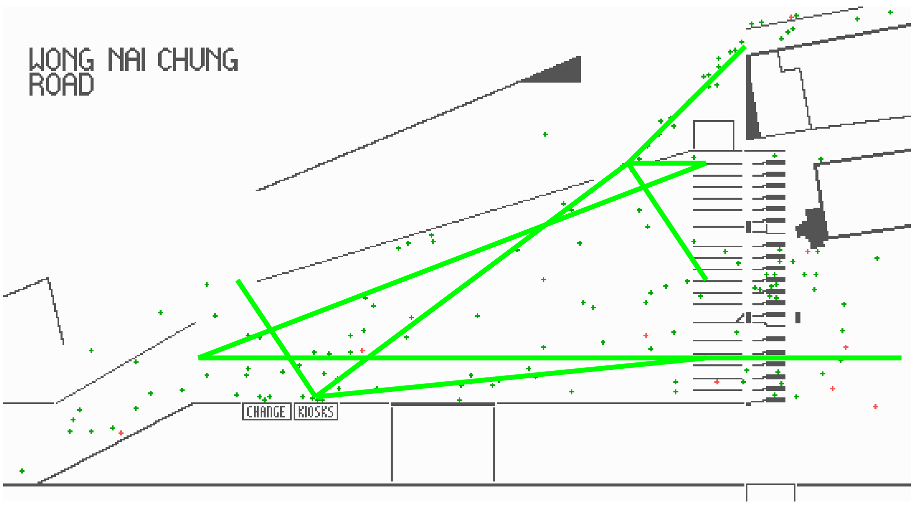


Figure 159 - Focal route analysis of routes to change and turnstiles

Figure 159 shows an immediate problem in the area. There are ***Multiple Path Interferences*** where focal routes to and from the change booths cross the focal routes to the turnstiles. Figure 160 shows the distribution statistics from the turnstile computer average over several events. We see that the triple peaks are as expected from a normal distribution curve with the focal routes indicating the centre of the three peaks.

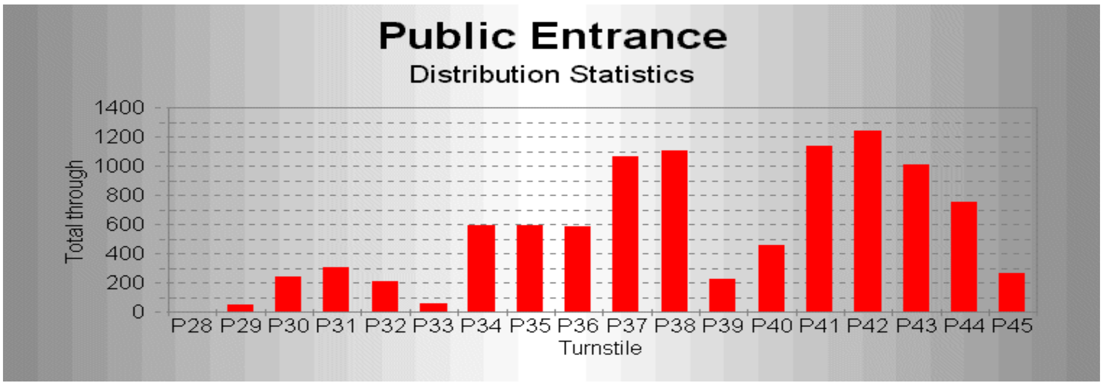


Figure 160 - Happy Valley turnstile distribution statistics (averaged over several events)

The right-hand side of Figure 160 is to the top right of Figure 159. P39 is obscured due to the pillar in Figure 159 (middle right-hand side). There is very little clearance behind the turnstiles in this area. The turnstile distribution statistics show this. The wall (Figure 158) has an impact on ingress rates and the total number of people trying to enter this area (arrival rate) is considerably less than service capacity of the turnstiles. A multi-channel queuing model of this area would not show the bias to the turnstiles which have a clear view beyond the entry system.

The problem we were asked to address, in this area, related to congestion in the run in and around the change kiosks, which were described as chaotic .

8.4.1 Public entrance statistics

The graphs (Figure 161 and 162) show the ingress flux (flow rates across time) and are averaged over the multiple events. As we can see, the maximum flux occurs at the periods 13:00-13:30 and 19:00-19:30. These rates are the maximum operational flux and the relevant video footage was used to calculate the numbers, distribution, direction and patterns of crowd movement.

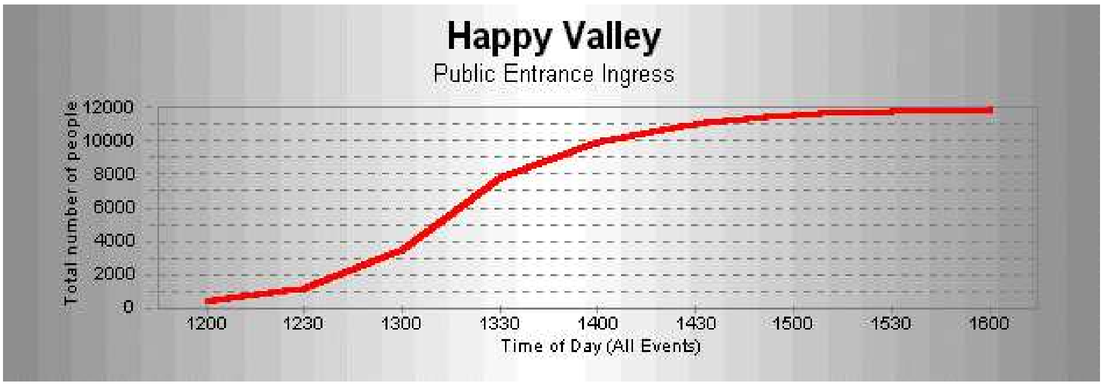


Figure 161 - Happy Valley public entrance ingress graph (afternoon session)

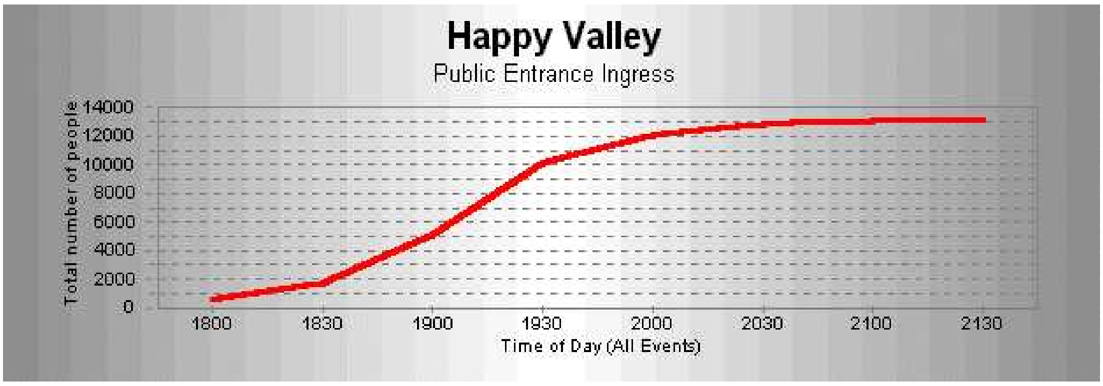


Figure 162 - Happy Valley public entrance ingress graph (evening session)

The maximum flux occurs at the steepest slope on the graph (Figures 161 and 162) which is 5000 people in 30 minutes. We can test the multi-channel queuing of the turnstiles, but with 18 available with service rates of 50 people per minute (total of 900 people per minute), the arrival rate of 166.67 people per minute the arrival rate is very much less than the service rate. There are ample (wasted) turnstiles and both theory and field observations confirm that the problem is not at the turnstiles.

8.4.2 Ingress rates - flux

From the video analysis we found that 20 to 30 percent of the patrons used these two change booths to obtain correct change for the turnstiles. We also measured the ingress rates (flux) to determine the peak periods for the model. From the focal route analysis we identified the potential cause of the complaint.

From the Wembley ingress capacity analysis (Section 2.7.2) we discussed how the flux (an ingress rate) can provide useful data. The Hong Kong Jockey club archives the ingress rates, and we can use these data to assess the maximum flux rates, together with how they change with time of day, time of year and year by year.

Video cameras were used to record the ingress and head counts were made at every focal route. The results can be seen in Figure 163.

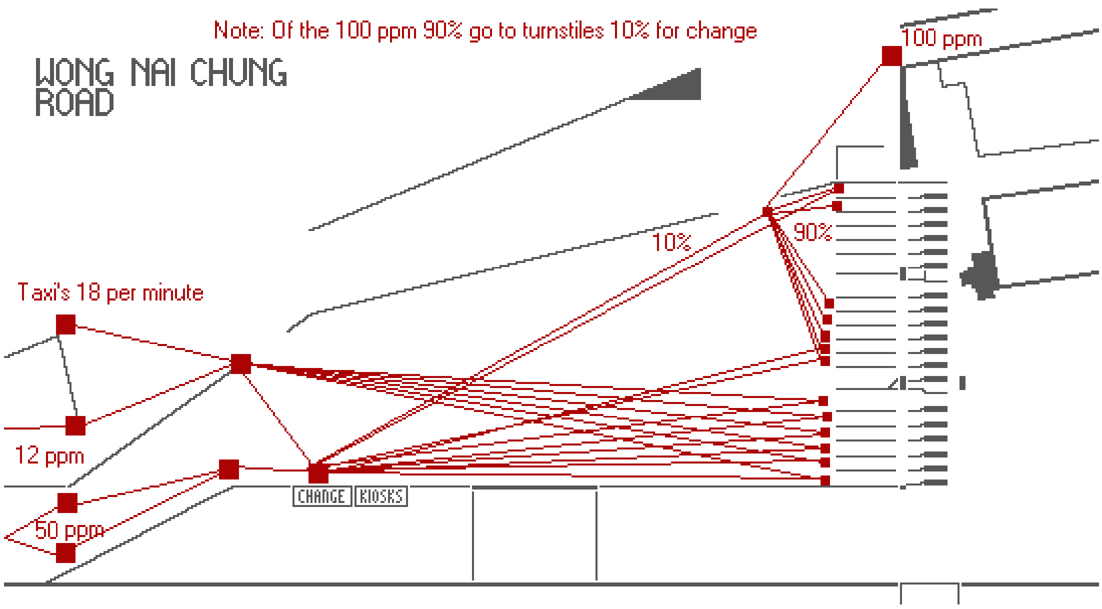


Figure 163 - Measurements of people per minute through various areas in the public entrance

By using the same acetate overlay technique developed in the Balham study we can measure the focal routes. We note that each route is normally distributed in width in that people overtake left and right with equal frequency. The width is a function of the number and speeds of people using that route.

8.4.3 Public entrance - present design

From the figures supplied by the HKJC of majority of attendees arrive within one hour of the start of the first race. In the entrance area patrons have a number of choices: the can enter the stands via the season ticket holders turnstiles or via the coin turnstiles. Some have to go to the kiosks to get correct change.

People who need change have to cross the path of those who have either the correct change or have already been to the kiosk. This results in a multidirectional flow as can be seen in the focal route analysis in Figure 159. Figures supplied by the HKJC show that during one monitored event 2,396 people out of 9,774 (24.5%) used the change kiosks. The service times were 3 seconds with a choice of two kiosks.

At these rates queuing theory predicts between 2 and 7 people waiting !

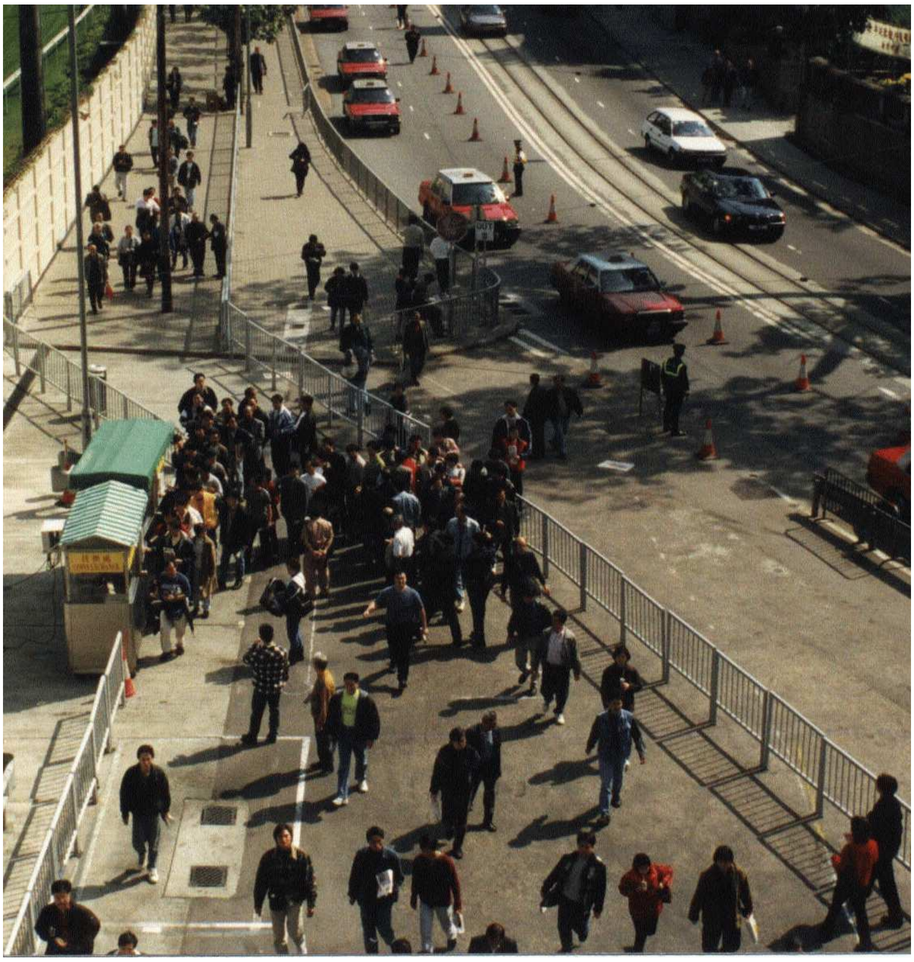


Figure 164 - The queue for change blocks the main route into the public entrance

Figure 164 clearly shows a congestion problem in this area. The queue starts to build as people wait for change. The approach to the main area is through the queue (Figure 159). This quickly fills the area in front of the kiosks, and the approach to the public entrance is blocked. Queuing theory alone did not quantify this problem. The main cause for the apparent chaos is the ***location*** of the change booths (on a primary focal route), leading to multiple path interference. We have confirmed our hypothesis and can now postulate some rules for optimal design of an environment where large crowds need access.

Rule 1: ***Keep the focal routes clear.***

Rule 2: ***Focal routes should not intersect.***

The present locations of the kiosks have another effect on the crowd, apart from the potential of blockages seen in Figure 164. As the position of the change kiosks is located far from the turnstiles, customers have to queue twice, once for the correct coin and once more to gain access to the stands. The two queues, approaching from opposite directions, clash and the congestion is a not just the result the service rate, but also of the additional time it takes to navigate back through the crowd.

In practice we could add this time to the service rate however the simulation can be applied to assess the impact of moving the change booths without the need for complex analysis. Furthermore the methodology of focal route analysis allows us to use simple geometric rules to determine the optimum location for the change booths. Using the above rules we can assess how closing the gap in the fence and routing all the patrons in the same direction would eliminate the congestion.

8.4.4 Alternative designs

There are then two locations for the change booths (Figures 165 and 166) which allow a more streamlined flow pattern. One of these (Figure 165) can be configured as single or double sided booths. A fourth alternative, using smart cards instead of correct change, was also simulated.

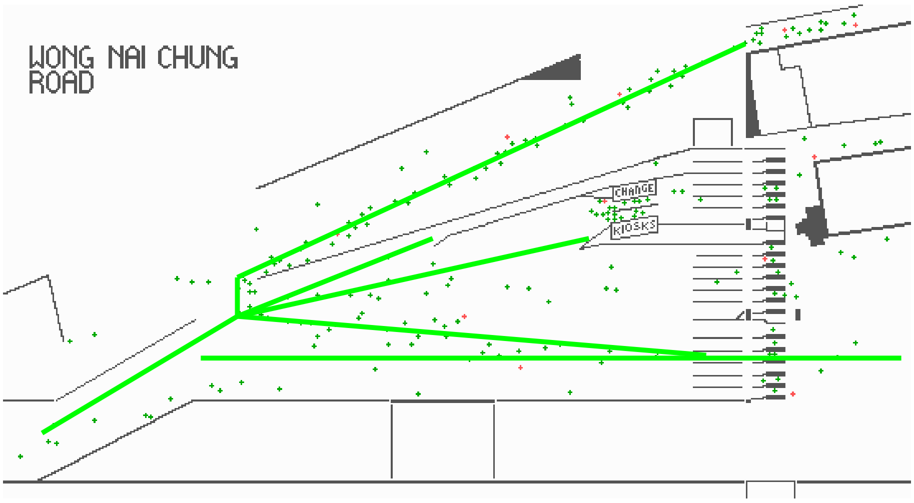


Figure 165 - Scenario 1 - Two single sided change booths

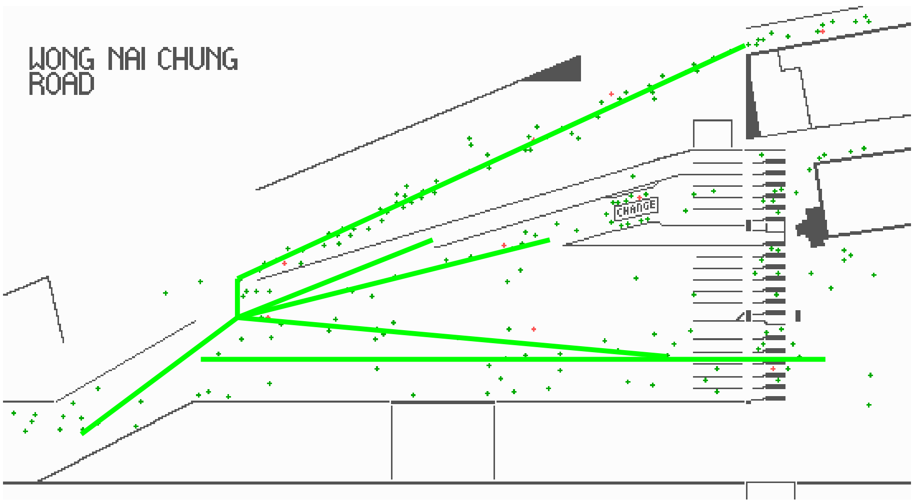


Figure 166 - Scenario 2 - One double sided change booth

Queuing theory gives the same quantitative results for the depth of queue with respect to arrival and service rates for Figure 165 and 166. The simulation provides us with a quantitative analysis of the distribution and use of the booths.

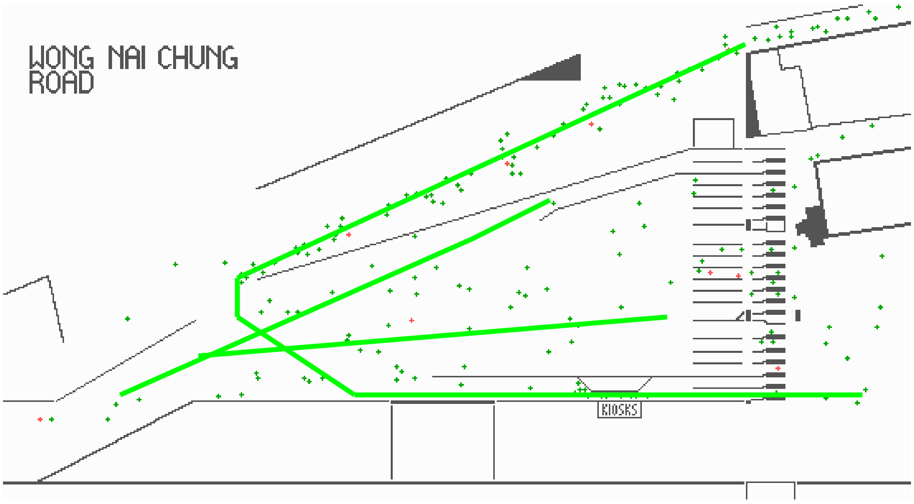


Figure 167 - Scenario 3 - Change booth on lower right

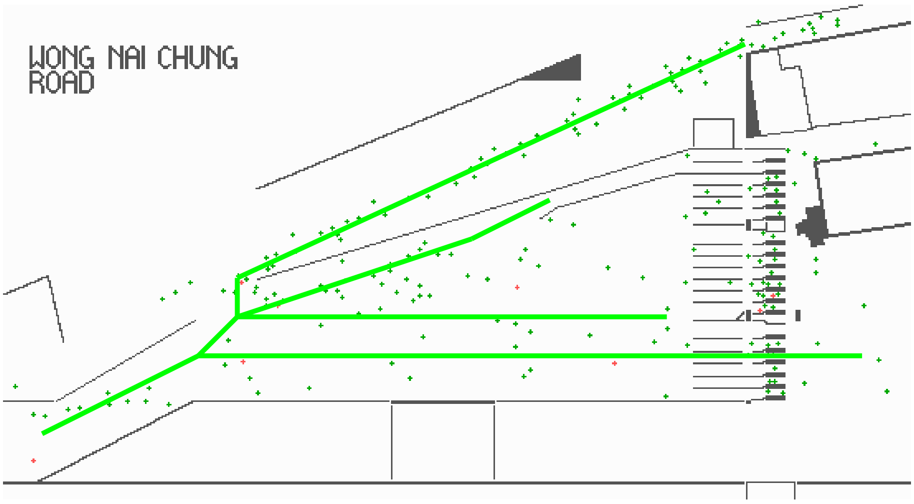


Figure 168 - Scenario 4 - Smart Card operated turnstiles

The design for scenario one (Figure 165) shows a range of changes to the present layout, the gap in the fence has been closed, there is now a larger area between the corner of the stand and the entry point to this area. If a problem arises in this layout there is an area where people can queue which does not impede other activities (such as the Members, Staff entrance etc.) or the major flow routes. Also, the flow of people entering this area results in more evenly distribution of the space usage (the space utilisation function). This is created by better overall lines of sight and direction choices. Other changes are the location of a new barrier running parallel with the original. This forms a sterile area allowing season ticket holders access to their turnstiles. Further changes include the positioning of the change kiosks which would be located in front of the group of turnstiles that at present are underused (Figures 165 and 166).

The new position levels the crowd distribution at the turnstiles whilst streamlining the flow of people entering the area behind the change kiosks. From the focal route analysis we can see that there is still some multiple path interference, but it has been minimised. Scenarios 1 and 2 have the fewest focal route intersections as they progress towards the turnstiles. We now use the Legion simulation to analyse the impact to the crowd with these configurations. This is quantitative analysis comparing the same arrival and service rates but changing the geometry.

8.4.5 The Legion simulations

The stylised plan used in the Legion simulation is annotated in Figures 169 and 170.

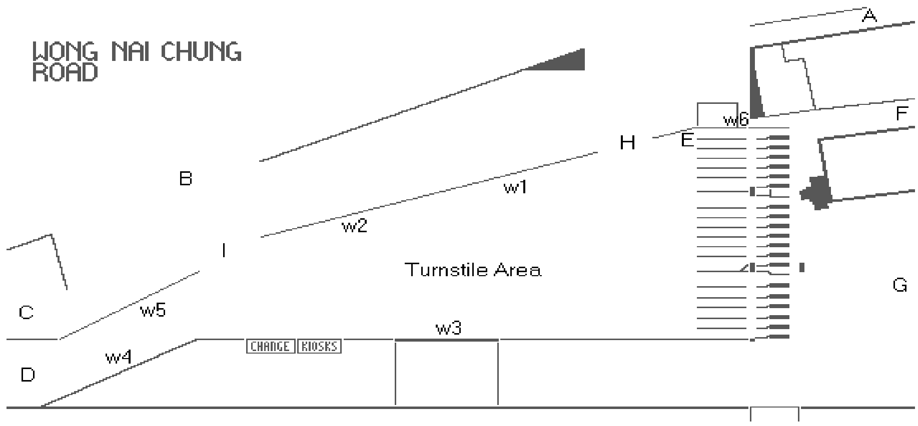


Figure 169 - Labeling the public entrance for analysis of crowd movement.

People enter at A, B, C and D. Area B is where people alight from vehicles (for example taxis) area E are the members/staff turnstiles. People leave via A, F and G, areas w1, w2, w3, w4, w5 and w6 are where people were observed to wait.

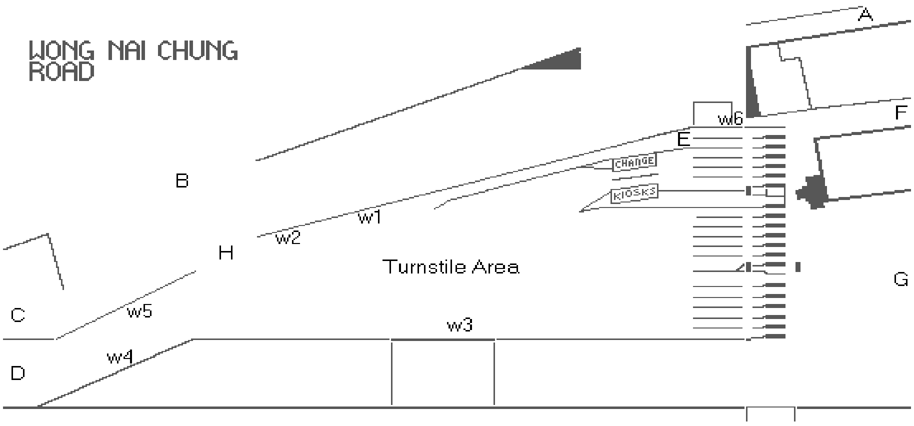


Figure 170 - Annotated diagram of scenario 1

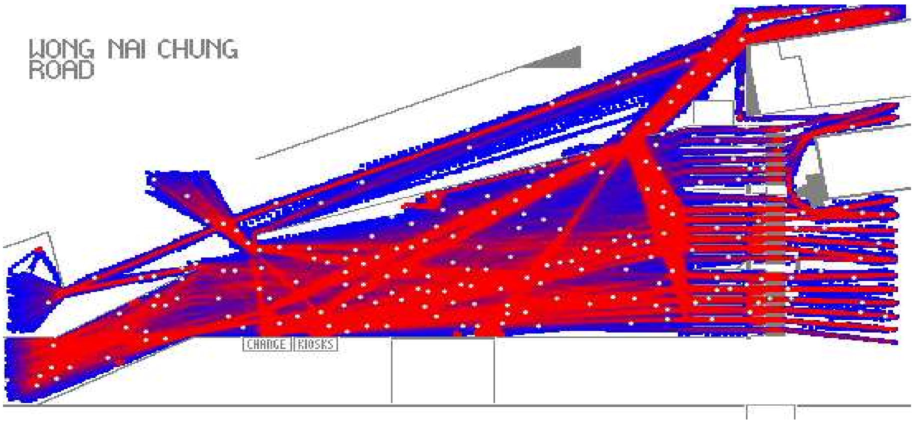


Figure 171 - Public entrance, present layout

Although not part of the congestion problem it is worth illustrating the turnstile counts from the simulation with the measured turnstile data (Figure 172), in order to verify the consistency of the Legion system

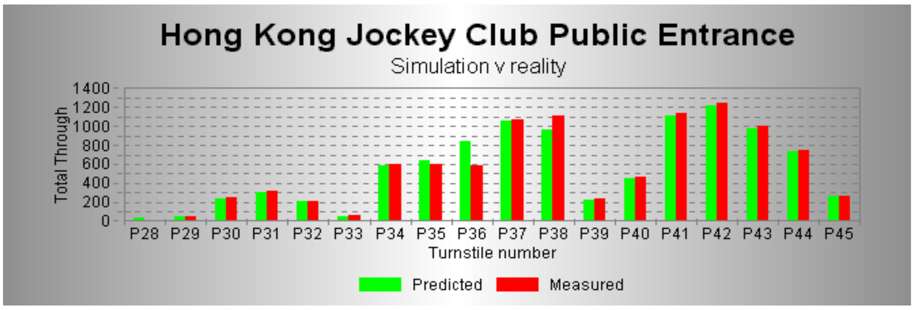


Figure 172 - The results from the counting the entities through each turnstile

The simulation demonstrates that the entities are behaving as if they were real people, reading and reacting to the environment, as we anticipated. These results are not related to the kiosk problem but they illustrate the uneven turnstile usage.

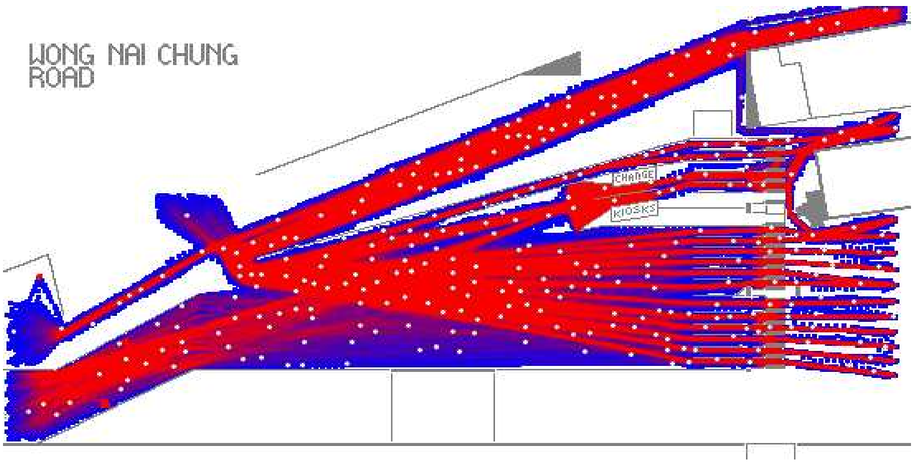


Figure 173 - Public entrance scenario 1

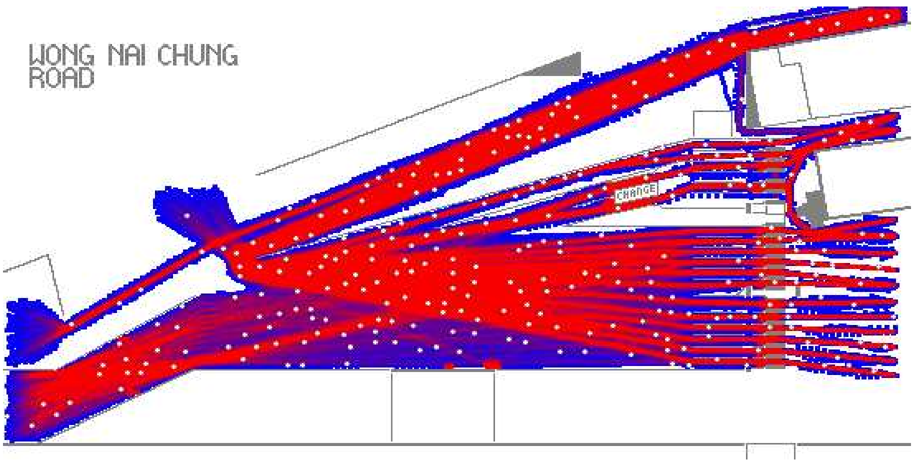


Figure 174 - Public entrance scenario 2

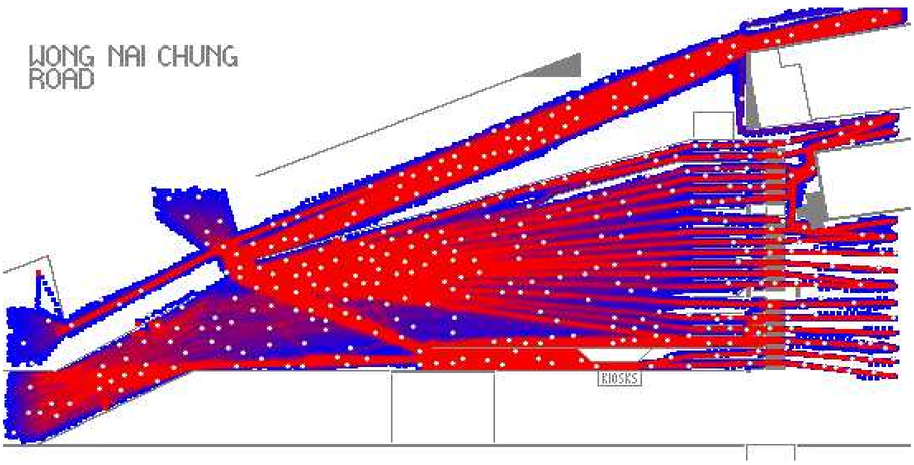


Figure 175 - Public entrance scenario 3

The space utilisation maps are cumulative. Whenever an entity occupies a point in space, the colour increments. By using the same input data (from Figure 163 and allowing the entities to navigate their own space we create comparative maps.

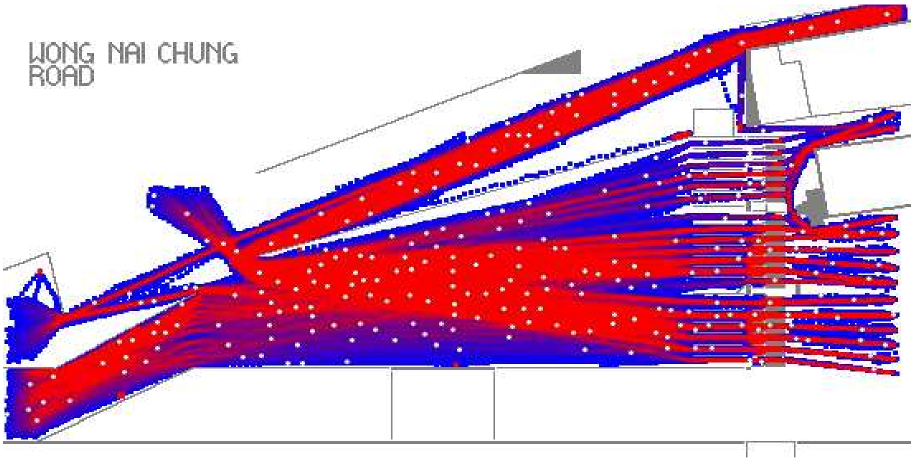


Figure 176 - Public entrance scenario 4

After N minutes we can capture the maps and process the images. By simply counting the pixels of different colours we can measure the ergodic nature of the crowd dynamics for different designs and compare their effectiveness.

A single red line, for example, represents no-overtaking in any section as the focal route has encountered no instant over the period of time (N) where any entity has ***had the need*** to deviate from that route. By adding a flux to the speed of the entities and degrees of noise in their objective direction we can also test different types of behaviour. This is useful when assessing the impact of two different designs.

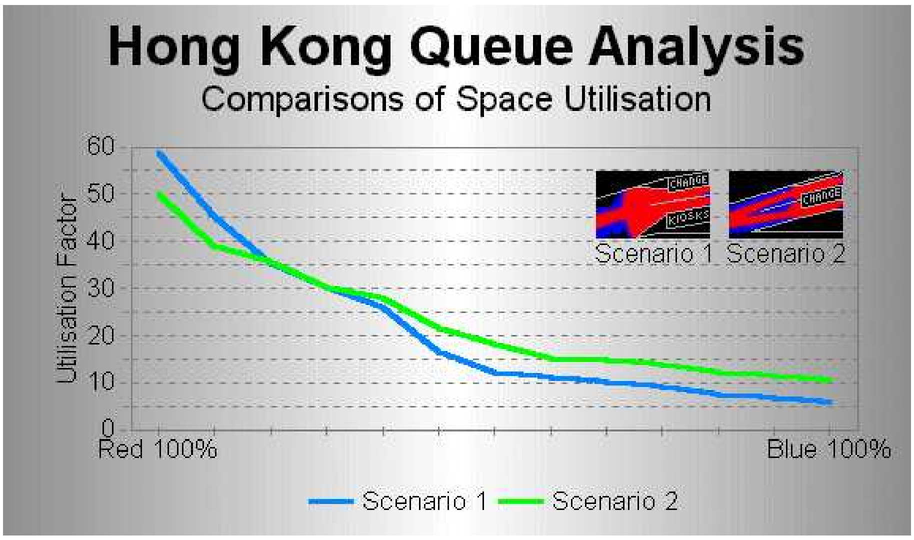


Figure 177 - Queuing comparisons from Scenario 1 and 2

8.4.6 Conclusion: Public entrance

Queuing analysis for a two channel system with Poission arrivals and Exponential service times would not discriminate two designs which differ in geometry. This has been a weakness of Queuing Theory. Waiting and service times are influenced by the interaction of the crowd with the local geometry, both before and after the queue. Comparing space utilisation maps, in different configurations, provides us with a qualitative and quantitative analysis which supplements queuing theory and the gradient (Figure 177) is a measure of the interactions between entities. If we narrow the width and extend the barriers we can measure the fairness , or stability, of the queuing system. In this example, the steeper the slope the more jostling, and opportunities for queue jumping exist, hence instability.

In the original design the approach to the kiosk (from left and right) was not fair in that a delay on one kiosk prompted queue jumping. Good design forces perceived fairness on the system, it reduces the opportunity for queue jumping.

Our entities are trying to exploit ***least effort*** and in doing so they show us the weakness in both our design and in the conventional numerical solutions to these type of problems. Space utilisation for widths of corridors, the effects of right and left hand turns, the interactions of crossing flows, all of these factors now become quantifiable when designing a system for maximum efficiency using ergodic maps.

With the combination of the space, density, speed and alert maps (where high speed reduction occurs in areas of high density we call the interface an alert zone: the areas where the highest potential for crushing exists) we have developed a system that can measure the effects of the geometry on the crowd. When these results are coupled with conventional techniques a clearer understanding of the human behaviour in confined spaces emerges.

8.5 Area III: Happy Valley - Infield tunnel

The third area we modelled was the infield tunnel at Happy Valley. This is located at the opposite side of the racecourse (Figure 178).

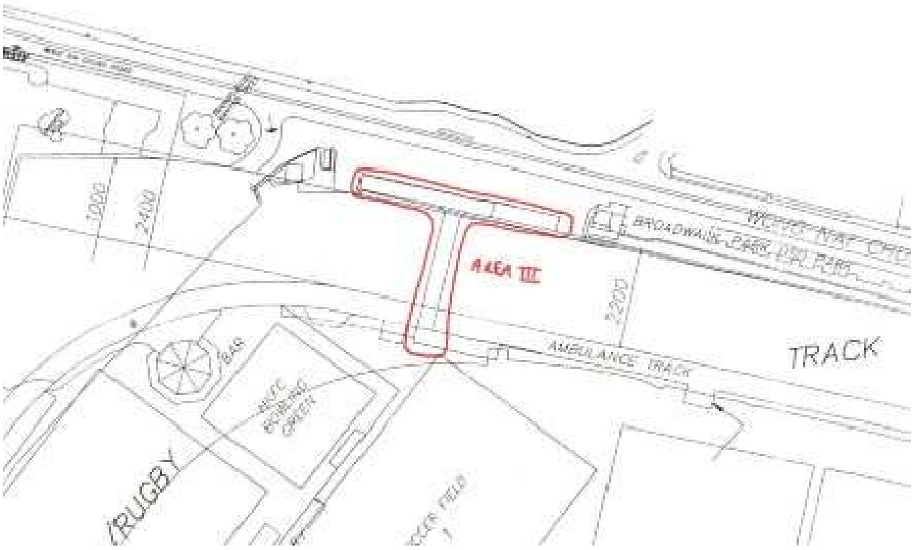


Figure 178 - The plan of the infield tunnel

This area is a public entrance to the infield area (the viewing area is cheaper than the grandstands). The capacity is 6,000 but can be increased during the event. Although the entry to the tunnel is marshalled by police there are no checks on the numbers entering. From the entrance there is a left turn down a flight of stairs.

Figure 179 - The entrance to the infield tunnel. Turn left down flight of stairs.

Figure 180 - Looking down the entrance stairs to the infield tunnel.

Figure 181 - Looking up the entrance stairs

Figure 182 - On the right at bottom of stairs. Turnstiles at far end of the tunnel.

Figure 183 - Exit from the tunnel to the infield - turnstiles on the lower left.

8.5.1 Infield tunnel statistics

The distribution of the turnstiles was obtained from information provided by HKJC. Video footage in this area (coupled with the poor lighting) could only proved us with general flow patterns at the end of the tunnel furthest from the turnstiles. However it was as expected with the turnstile utilisation being highest on the shortest route through the infield tunnel. P06 is located on the inside bend of the tunnel. Focal route analysis predicts the highest utilisation as the records confirm.

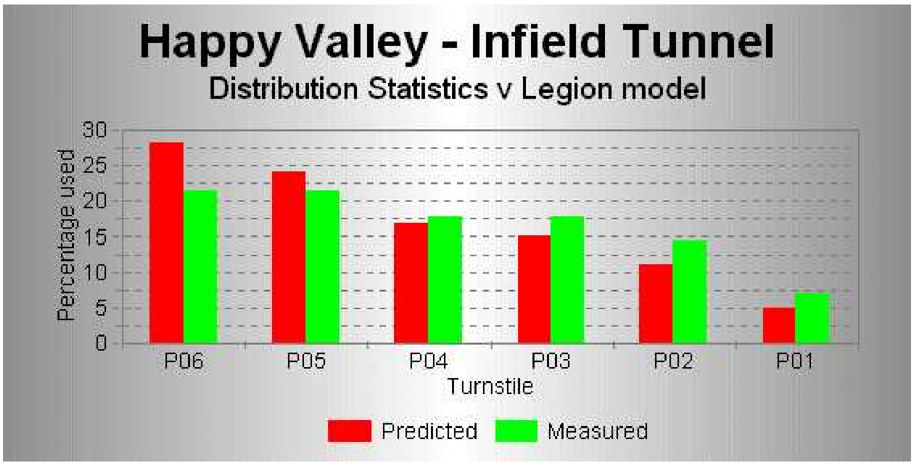


Figure 184 - Infield tunnel ingress turnstile statistics.

We can see (Figure 184) that the model has a higher usage at P06. In the model we simulated an even distribution across the whole period whereas in reality the people arrive in small clusters (train loads). By altering the input distribution curves we can change the goodness of fit . The skill involved in the analysis of the arrival rates, as in queuing theory [92] is an important aspect in assigning the correct values for the model, namely we need to apply the correct arrival and service values.

8.5.2 Infield tunnel entrance

When the racecourse is used for other events such as New Year celebrations and pop concerts ingress capacity can increase to several thousand patrons flowing through this area. The infield tunnel is 4.5 metres wide and 48.6 metres long (on the lowest section). With the potential of a large crowd descending the stairs, any blockage at the turnstiles would quickly fill the lower tunnel and the consequences could be catastrophic.

Figures 185 and 186 show the ingress rates for the afternoon and evening race meetings. The bulk of the patrons arriving in the hour prior to the first race.

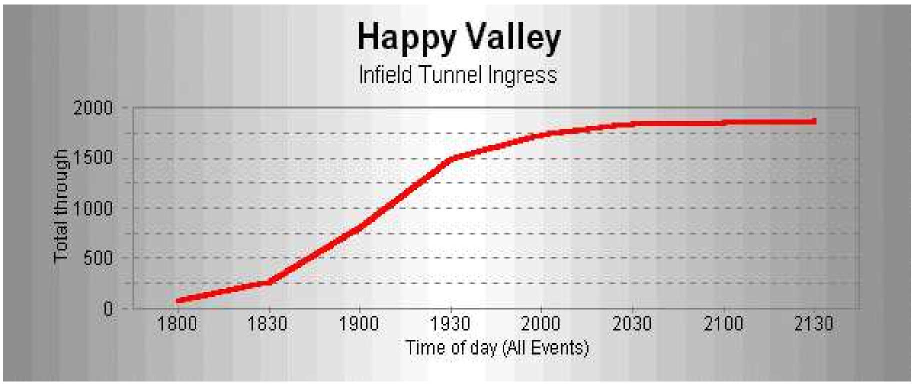


Figure 185 - Ingress rates at the players tunnel - evening session

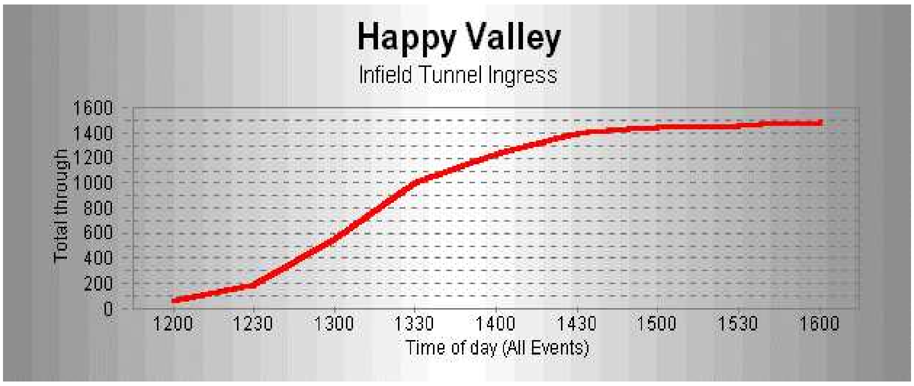


Figure 186 - Ingress rates at the players tunnel - afternoon session

It was noted that the periods of highest flow rate were similar in time to those at the public entrance, but with a larger number of patrons using this area in the evenings (by 25%). The highest measured ingress rate was approximately 1,000 people per hour. The capacity of the infield, during race meetings, is 6,000. The tunnel capacity exceeds that volume at 4.5 metres we have a measured flow rate of

1000 ÷ 60 ÷ 4.5 = 3.704 people per metre per minute

From the Green Guide we note that the safety limit of 109 people per metre per minute for level ground (the tunnel) and 73 people per metre per minute (for stairs). Therefore the maximum flow rate in this are is 73 people per metre per minute (limited by the stairs 2 * 2.9 metres wide). We have 6 turnstiles with a service rate of 360 people per minute (1 second per person average) and an arrival rate (maximum) of 73 people per minute over 5.8 metres = 423.4 people per minute. These lead into a corridor of 4.5 metres (which would allow 490 people per metre per minute). We use the lower figure of 423 people per minute for the arrival rate. These are the typical calculations used in safety analysis. However they assume even distribution across all turnstiles. However, these calculations, used for the assessment of how many turnstile are required are constrained, during ingress by the width of the door (2 metres) so given that the maximum flow rate the ***whole*** system can allow is 2 * 109 = 218 people per minute - less than half the capacity of the tunnel. At those levels the requirement is 3.6 turnstiles (218 ÷ 60 people per minute), so 4 turnstiles would be the minimum requirement in this area. There is a similar constraint when people move from the infield back through the tunnel (two 1 metre sections either side of the turnstiles). The main problem is the lack of control on entry. In January 1993 at Lan Kwai Fong, not far from the Happy Valley Racecourse a disaster occurred. More than 20 people died in a crowd crush on a busy street. From Mr. Justice Bokary s Interim Report into that disaster [95].

A number of persons, more or less in a row and more or less at the same time, lost or were deprived of their footing and fell. Because the press from behind was overwhelming, more and more people started falling. People piled upon those who had gone down before them. The pile grew until it reached such a height that the people immediately behind it were propped up by it and pinned against it by the press of people behind and upslope of them. Thus came about what some witnesses have called a human wall . Tragically, men, women and children had the breath of life crushed out of them. 20 persons died very quickly, one more died in hospital some days later...

Also from The Daily Telegraph, June 1, 1999

An unprecedented tragedy happened on May 30 in the centre of the Belarusian capital. Over 50 people died and some 300 were wounded in a crush at the entrance to the underground station...The tragedy was caused by heavy rain that started at about 8 p.m....A few thousand Minsk residents, mostly young people, had gathered ...The first thunders and rain drops made people rush to find shelter in the underground crossing...Somebody fell down on the concrete floor and the first blood was shed. People were slipping over and trampling those lying on the floor...People were falling at the feet of the crowd. Over two thousand people poured into the 10-metre wide underground crossing thus creating a dense moving jam...there were people literally smeared against the walls, pressed into the floor, ...Meanwhile, screams of those who were unable to escape on their own, kept echoing from this hellish meat grinder...

We are soccer fans, so we know what to do in a crowd cover your head with hands and make your way to the exit. ..."People kept arriving until there was almost no space and then the whole mess started. There was no escape. The people surging in from behind just left the others lying and walked over them," one of the survivors told Russian television.."About 300 people were lying here, one layer on top of another," a policeman said "We were carrying out the top layer of people and they were still alive. Those in the bottom layer were either dead or injured."

Two policemen were caught in the crush and also died as they tried to rescue those who had fallen...More than 150 people were taken to 10 hospitals in Minsk as doctors battled through the night to save the lives of the victims in the tragedy. In his speech president Lukashenko said There is nobody to blame,

there is no one to make a claim to, it happened because it happened, even if there was anybody responsible it was the rain that caused the disaster.

It only takes one or two people to trip in a high density, high speed crowd and the consequences are disastrous. At Belarus the combination of factors should have been countered by good design. The combination of a large crowd flow, steep stairs, a narrow enclosed space is, without question, unsafe. The design was to blame.

8.5.3 Details of the infield tunnel

The approach to the entrance has wide footpaths, a large passenger drop off area, and a good clear walking route from Station (to the right of Figure 179). The flow of people entering the tunnel is monitored by video cameras. Should a problem arise, either on the stairs or in the tunnel, there would be nothing that the ground staff could do to prevent further ingress in this area.

Figure 187 - Nomenclature used for the infield tunnel model

People enter at A and leave at B. Areas w1, w2 and w3 are areas where people were noted to wait. An area of concern is the position of the turnstiles (on a 90 degree turning point - Figure 187). The simulation shows how quickly that flow can congest in the tunnel (Figure 188). A point to note is lack of ventilation in the tunnel. This leads to discomfort and a potential risk to health in moderate congestion.

The problems can be addressed in a single solution. First we simulate the present scenario using the ***Least Effort*** algorithm.

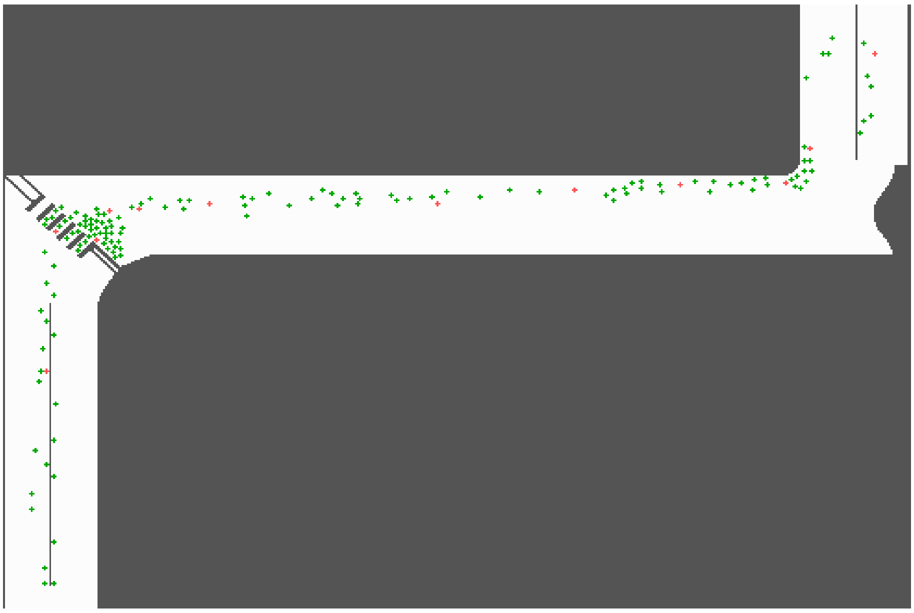


Figure 188 - Simulation of the infield tunnel.

8.5.4 Resolving the problems

If you can hold people in open space outside the tunnel then they can be regulated as they move into the tunnel. With appropriate crowd management this will stop any congestion occurring within the tunnel. To achieve this the turnstiles were moved to street level and relocated in place of the solid wall (Figure 179).

Further crowd control measures are positioned two metres in front of the turnstiles. This will slow down people approaching the turnstiles and allow time to complete their transactions.

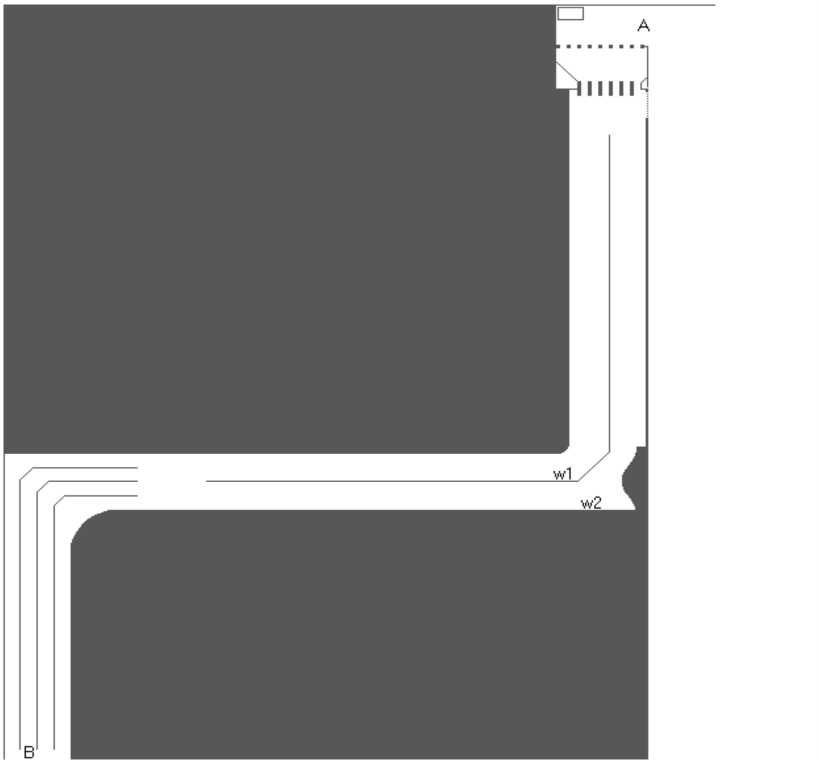


Figure 189 - Suggested improvements for the infield tunnel

The second improvement was the crowd-controlling measures inside the tunnel. Figure 189 shows additional barriers. These barriers ensure an even flow of people through the tunnel with gaps to allow lane changing if one of the routes becomes congested. The space utilization map is shown in Figure 190.

Crowd segregation, using barriers, alleviates dangerous congestion. Any congestion or problems are now in free space, in areas outside the tunnel entrance.

8.5.5 Conclusion - infield tunnel

The resulting alterations would have a direct impact on safety for higher density crowds; which can be the case for as few as 1,500 patrons passing through this tunnel during a racing event.

There would not be any requirement for any increase in manpower to manage these changes for normal use as this is passive safety design. If staff have to be used to control crowds then the opportunities of human error are introduced.

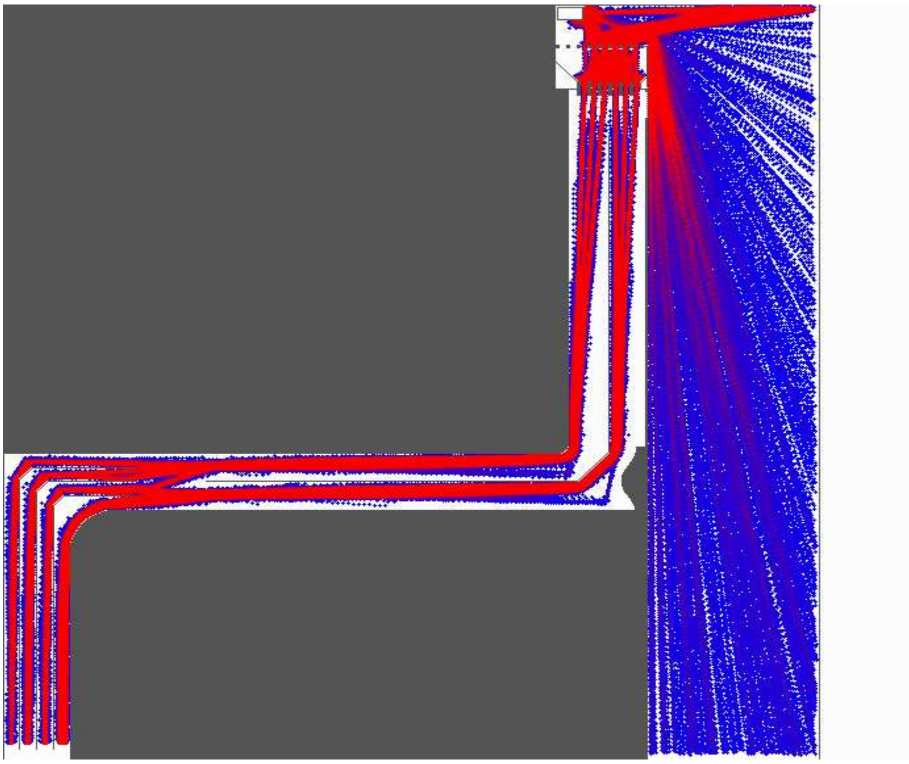


Figure 190 - Space utilisation of the infield tunnel improvements.

Figure 191 - The available space by the side of the infield tunnel (See Figure 182)

There is a need to design a passive crowd control system. People approach from the camera position in Figure 191, pass through a series of barriers, into the change turnstile area, then down the stairs. This regulates the flow and any congestion or sudden surges have no potential of rippling down the stairs. The proposed design would eliminate any potential for a repeat of the Belarus incident .

8.6 Area IV - Sha-Tin - Gate 1

The fourth area we modelled was gate 1 (indicated on Figure 192). This is a public entrance to the Sha-Tin racecourse and is approached from the bottom left (Figure 192). Due to the land reclamation, which results in substantial subsidence, the approach to gate 1 is on an upward slope, with an over-pass from the road sloping downwards. The view from the approach road, shown in Figure 193, has a disused guards booth on the left and directly in the field of view are the two change kiosks .

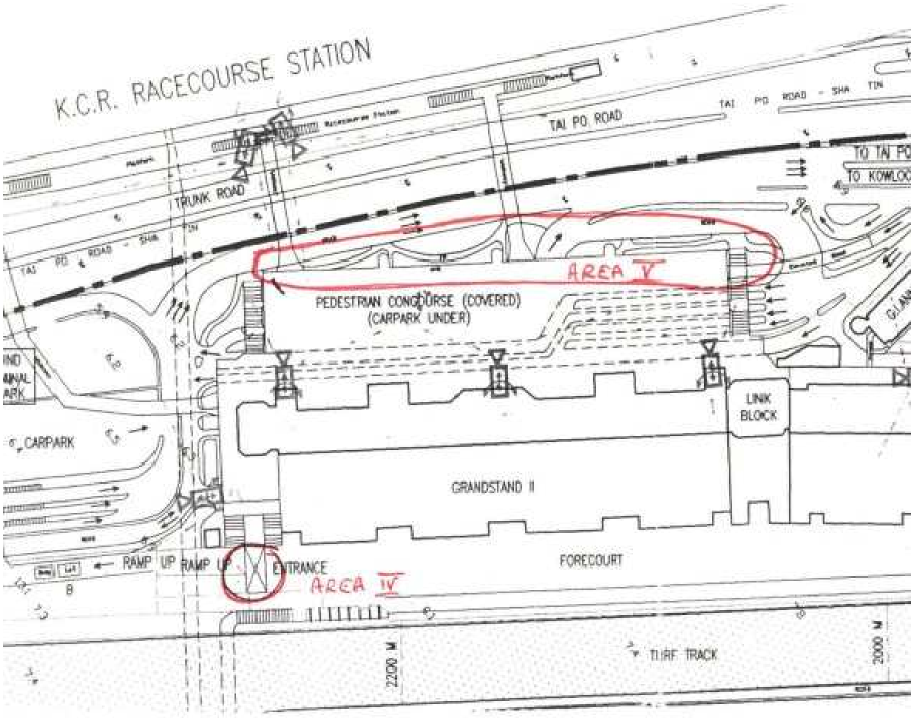


Figure 192 - The plan of the Sha-Tin racecourse showing the two areas modelled.

The members gates are located to the right of Figure 193 and in direct line of sight from the approach road. From the overpass members have to move diagonally across the area in front of the turnstiles. The problems here are mainly layout-related. Queues around the change kiosks and the location of the guard booth obscure the lines of sight. Security staff were observed using a loud hailer (foreground in a white shirt Figure 194) to direct patrons to the public gates. This area appears chaotic.

Figure 193 - The approach to gate 1 at Sha-Tin.

Figure 194 - Area between the change booths and the turnstiles.

8.6.1 Gate 1 statistics

Figure 195 shows the distribution statistics from the turnstiles, averaged over several events. There are two superimposed normal distribution curves here (as expected) with a disproportionate flux at P3. This is due to the lines of sight and location of the turnstiles and members entrance (as seen from Figure 193). This is the reason why the security guard has to shout at people to move them away from that area and towards a less used turnstile. In one recorded event (Jan 30th 1998) it became apparent that the distribution changes dramatically if P5 is taped off and P4-M1 are used for Members/badge holders. The focal route analysis shows the routes.

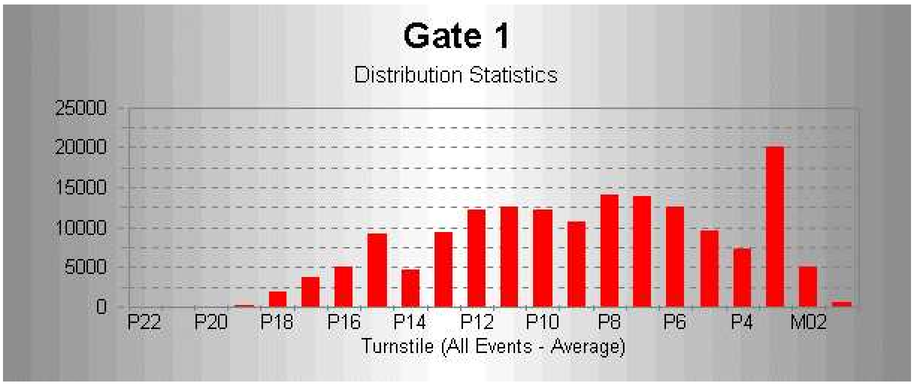


Figure 195 - Gate 1 turnstile usage (averaged over several events).

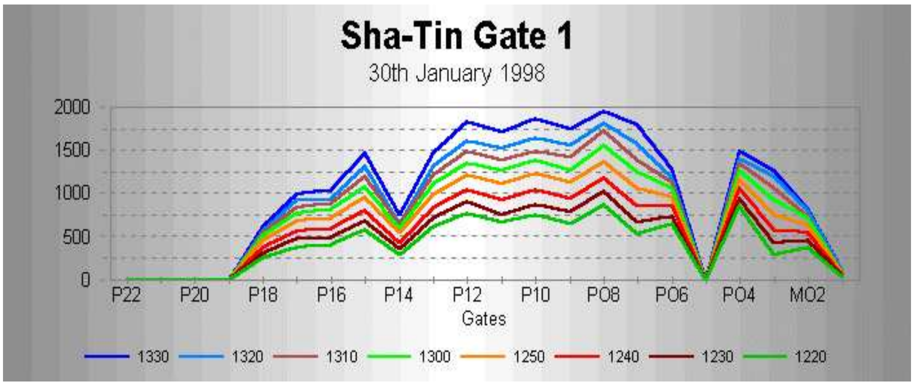


Figure 196 - Turnstile statistics for a single event (30th Jan 1998)

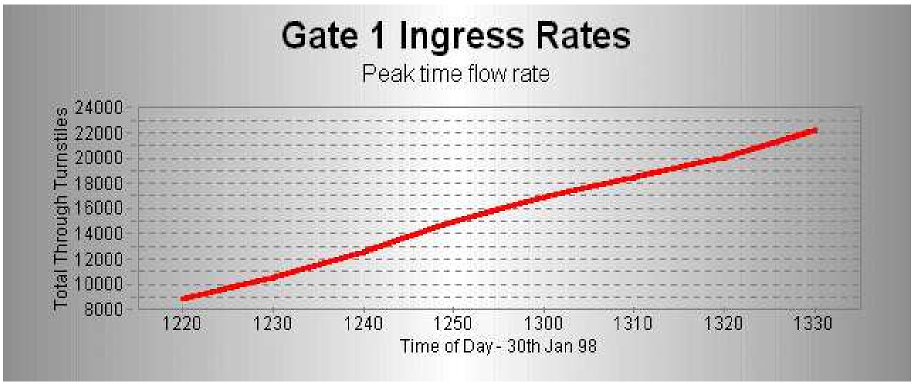


Figure 197 - Ingress flow rates - measured for the peak period from videotape

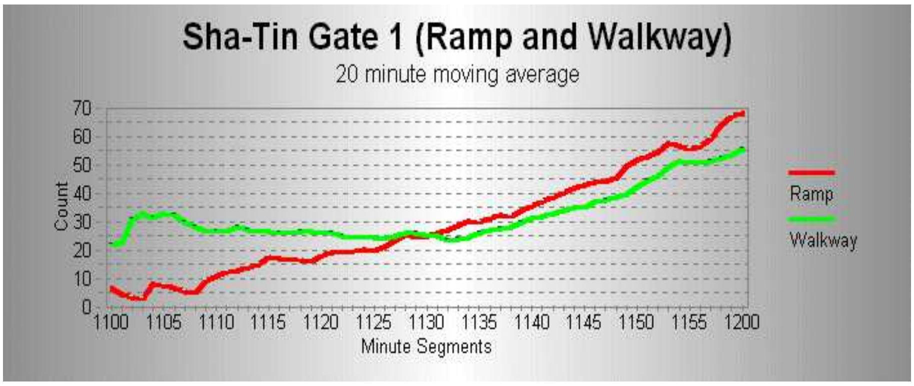


Figure 198 - 3 minute increments for head counts on the ramp and walkway

For the event (30th January) we also measured the peak time flow rates (Figure 197). This shows a steady flux of patrons during the peak period.

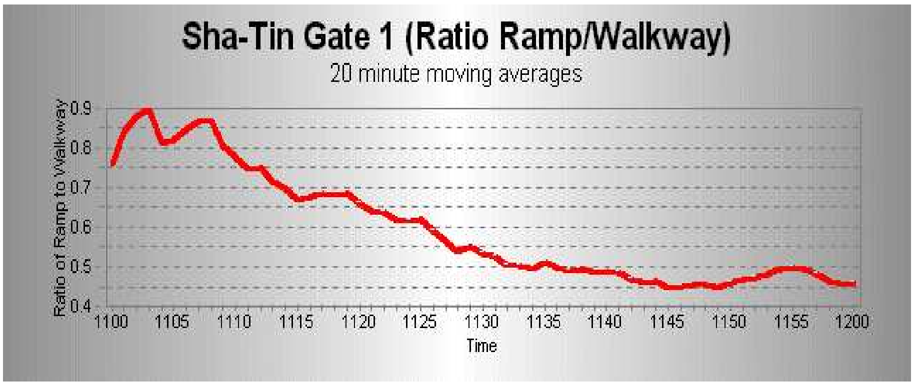


Figure 199 - Ratio of ramp to walkway. Indicates ratio of public to members.

A further set of statistics was obtained by counting heads for one event relating the usage for the walkway to the down ramp (Figure 198 and 199). This shows that the walkway has a steady stream of patrons increasing by 50% near the start of the event start, while the down ramp has a steady increase. The net effect is that patrons crossing to the members entrance find it more congested closer to the start of the event (due to the problems of cross flow).

8.6.2 As-is model: Gate 1

Gate 1 is situated away from roads and parking facilities with a long approach. However, there are areas that will benefit from design changes and clear signage. The one area that cannot be altered is the gradient leading up to the turnstiles, which causes a line of sight problem. The present design, signage and gradient can be clearly seen in Figure 196 along with the tarmac repairs which act like a runway beacon guiding patrons along a desired central route (probably more by chance than design). The attraction of people following lines has been documented by Fruin [6] et. al. and skews the input for a queuing model.

The signs indicating each section of the turnstiles are difficult to read, even when the area is deserted. The distractions that occur when moving in a crowd add to that difficulty. The inability to select an optimum route from a distance creates cross flows and uncertainty closer to the entrances. This area is not laid out to facilitate ease of use by the patrons.

The second obstruction is the disused guard booth, which blocks the view of people who do not need to use the change kiosks. The third problem area is the location of the change kiosks, which has a considerable effect on the freedom of movement in the surrounding area. With the barrier system presently in use only the front four people are queuing, and order quickly deteriorates behind forming a huddle (Figure 200). Patrons then do not know if they are queuing for change or if this is the turnstile queue. This is accentuated by the slope towards the kiosks (Figure 193).

The ***Least Effort*** algorithm and focal route analysis is most effective in these situations as it tells us where the natural flow lines of the crowd should be. We can then design around the ***Least Effort*** and focal paths.

Figure 200 - Change booths or turnstile queue ?

On the approach side of the kiosks, this congestion compounds when people approaching the kiosks either join those already there or walk around the queue.

The proposal is to redesign the layout of this area using the same principles applied in the Happy Valley public entrance. Several models were suggested; we describe two of them here. In all of the alternatives the guard booth was removed and clear signage was installed with appropriate respect to the layout.

8.6.3 The Legion models

People enter via the ramp (A) and the walkway (B) and move, via the turnstile to C. D and E are change booths. F is the members entrance. Area w1 are where the season/concession tickets are collected. The focal routes have many intersections.

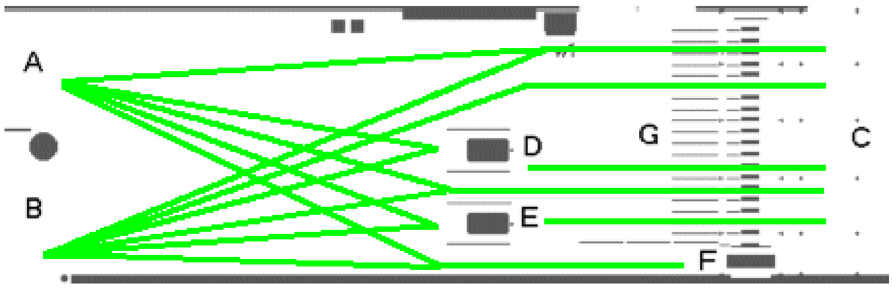


Figure 201 - Plan of the approach to gate 1- showing the focal routes

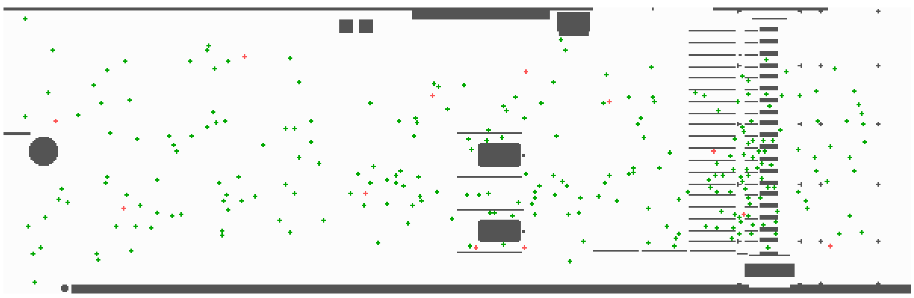


Figure 202 - Simulation of the approach to gate 1

We can see the effect of the multiple focal routes, the nature of the problem between the change booths and the turnstiles (not enough space) and the heavy congestion on the central turnstiles (Figure 203) as the focal theory predicts.

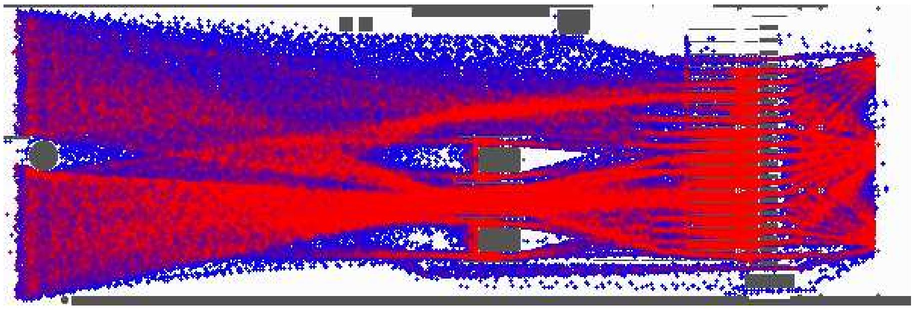


Figure 203 - Space utilisation of the approach to gate 1

8.6.4 Shortening the distance

The area can be altered by providing more space, or by reducing the distance between the change kiosks and the turnstiles (Figure 204).

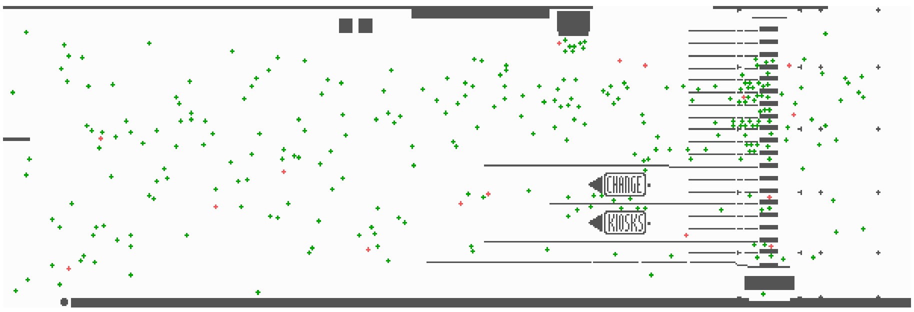


Figure 204 - Gate 1, Scenario 1

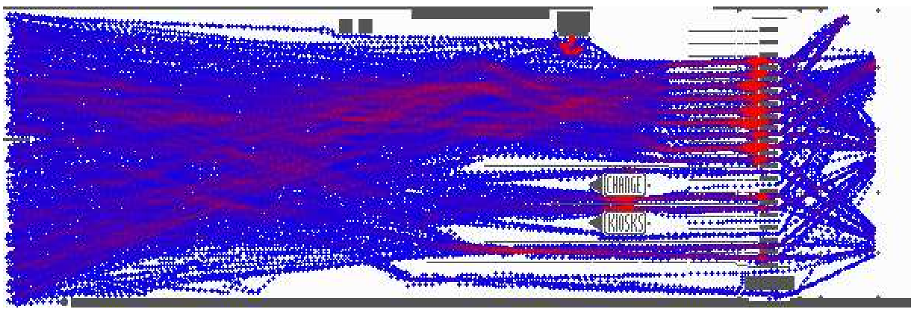


Figure 205 - Gate 1 Scenario 1, Space utilisation map

The two kiosks have been moved towards the turnstiles and brought closer together. This does not alter the operational efficiency of the kiosks. Barriers have been erected around the kiosks, back along the entrance routes, allowing people who wish to use the facility to form orderly queues rather than spreading out into the focal routes of other customers.

Moving the booths closer opens more space in the run-up and allows greater clearance. With this design the turnstiles have been split into five main areas. From right to left they are:

1. Members
2. Promotional/Season Ticket Holders
3. Change Kiosks
4. General Admission
5. Exit Only

This layout takes away the problems caused by the unchecked build up of people and sight line difficulties experienced at present, but in doing so it takes up six turnstiles solely for the benefit of those using the change kiosks.

Using figures supplied by the HKJC, out of 10,482 people using this entrance 1,740 used the change kiosks. The figures do not justify six turnstiles used for 16.6% of customers, leaving 83.4% to enter via the remaining nine.

Figure 205 and 206 shows the space utilisation map for the people passing through the model after fifteen minutes. This demonstrates that efficiency is impaired, and flow is less than the original. We redesign the area distributing the turnstile in a more representative allocation. Note, that in moving the change booths closer we are allowing more space for patrons to choose their appropriate route. This occurs in an area which is larger than the present scenario and we can see the effect on the space utilisation maps.

8.6.5 Arranging the space

Figure 206 shows the space utilisation map with change booth relocation and turnstile reallocated in the appropriate ratios for members and public.

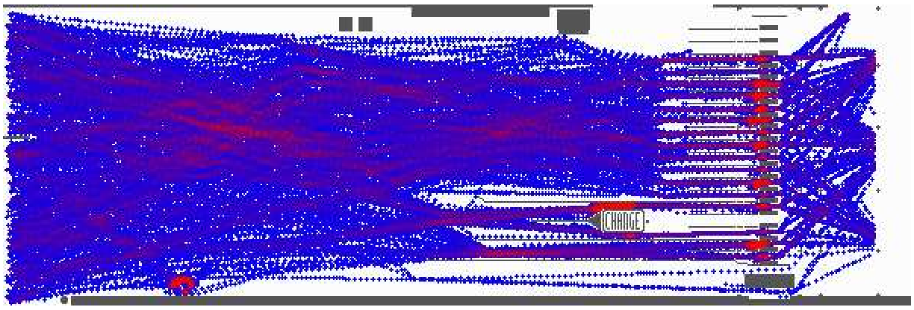


Figure 206 - Gate 1, scenario 2

We can now use either the dynamic space utilisation map (points incremented by usage and decremented by a time factor, for example every 50 frames the whole map decrements one colour bar) or the cumulative (static) space utilisation. This allows us to compare any time segment for cumulative utilisation from time 0" or space used in last X minutes . As patrons arrive (Figure 198 and 199) at different rates from different directions we quickly saturate a cumulative space utilisation maps, hence the use of the dynamics maps.

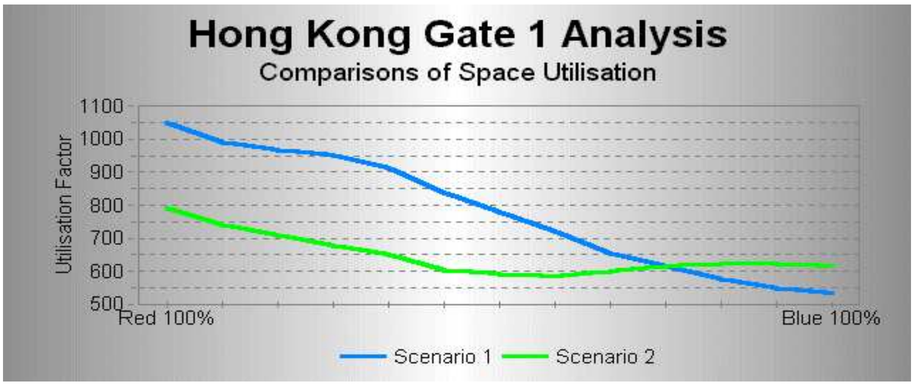


Figure 207 - Comparison of 15 minute Space Utilisation Ergodic Maps.

Comparison of the 15 minute dynamic space utilisations for scenarios 1 and 2 we see that there is a more even use of space in the second scenario. We designed the allocation of the turnstiles and the positions of the change booths to suit the focal route requirements and the patrons needs. We can measure the effectiveness of our design from the slopes of the two lines in Figure 207: a 15% improvement.

8.6.6 Conclusion: Gate 1

The two alternative scenarios offered for gate 1 both improve the public's approach to the turnstiles. However, scenario 1 has a higher space utilisation curve. This can slows the ingress flux compared to scenario 2, which is 15% more efficient.

For average attendance figures this would not have any adverse effects, for example, from queuing theory, we can see that the Poisson distribution of arrivals can have clusters causing queues to form. Scenario two gives the best results whilst maintaining the benefits of more logical and evenly distributed space. The improved space utilisation of the same area means that the clustering effect will not add to the service rates through this area.

We also observe different patterns of use for different time periods. An interesting analysis is the differences seen in the space required for ingress and egress. The two different modes of movement, slow ramp-up for ingress and sudden large movements for egress have very different space requirements. Figures 8, 38, 40 and 42 of Wembley turnstiles and Figure 193 (right) show exit gates either side of ingress turnstiles indicating that quantitative space utilisation analysis may save considerable costs in the design of these areas. Combining effective ingress systems with effective egress systems has enormous cost benefits to stadia and racecourse by reducing the need for real-estate.

The gate 1 example demonstrates that using space more effectively improves the quality of the experience of the patrons. This can increase the numbers attending the venue and hence the issues of safety, both for queuing and for emergency egress, need to be tested. The graph of attendance in Figure 154 indicates a drop in attendance over the years. We can test the scenario for different ingress numbers, at different times and different ratios, using Legion as a what-if tool.

8.7 Area V - Sha-Tin - Concourse

Area V is shown in Figure 192. This area is both an ingress and egress route for 40 to 60% of the patrons via the Kowloon-Canton Railway (KCR). The crowd flow from the station to the racecourse is regulated by the train capacity and the KCR timetable. Ingress rates present no problems for the existing design.

Problem occur when 20,000 to 40,000 patrons leave at the end of the event and the concourse area is inundated. The crowd is restrained by the use of holding pens (Figure 208 to 210). Figure 211 shows the movement of people through a section of the pens. and Figure 212 shows the exit from the pens, across the bridge to the station platform.

The platform capacity is 3,500 people which is the same as the train capacity. The first problem is the delivery of 3,500 patrons (trainloads), in controlled bursts, to avoid dangerously overcrowding on the platform. The second problem is, in the event of an emergency, the need to disperse patrons held in the pens quickly and efficiently.

Typically around the patrons (30,000) arrive within 15 minutes of the end of the races. This need regulation of the crowd flow from the concourse to the station platform to prevent serious injury due to dangerous over crowding in the station.

HJKC have designed a queuing system to regulate the crowd flow via a complex series of barriers, pens and manually operated gates. The system relies on the experience of key personnel using their judgement of the flow rates through the pens. Any system that has to rely on a few individuals to make spot decisions involving safety is high risk. A moments lapse of concentration, a poor line of sight or an incident that diverts the focus of the staff attention from the queuing, for example, a fire, traffic accident etc, would have catastrophic consequences.

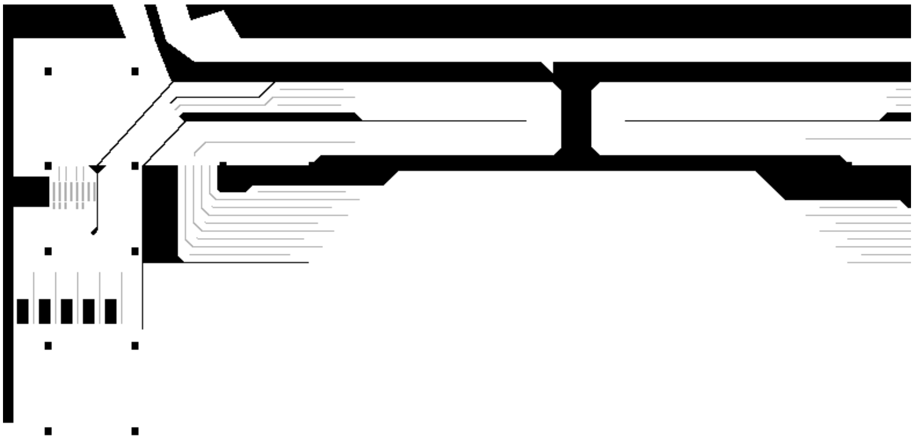


Figure 208 - Concourse area, left hand side. Gate 3 on the left - gate 4 on the right

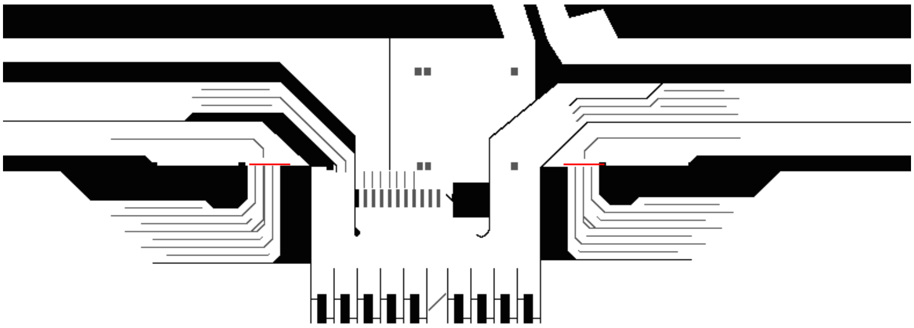


Figure 209 - Gates 4 (left) and 5 of the system. **Red** line indicates manual barriers.

Figure 210 - Gates 5 (left) and 6 of the concourse area.

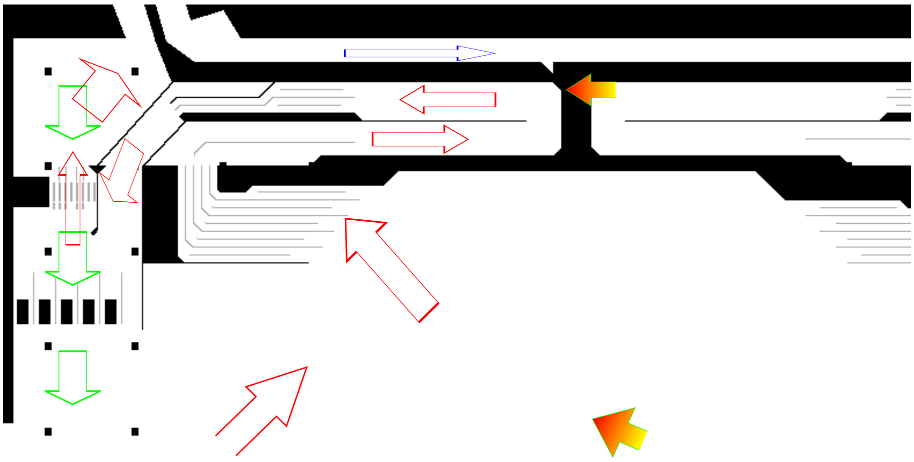


Figure 211 - Gate 3 routes: Ingress: **Green**, egress: gate 3 **Red**, gate 4 **Blue**

Figure 212 - View of gate 3 (empty). Viewed from A (Figure 211)

Figure 213 - Gate 3 at end of event showing the build up in crowd density.

Figure 212 shows the empty gate 3 barrier and pen arrangement. Figure 213 shows the crowd overflowing the barriers. Gates 4, 5 and 6 are equally full. Figure 214 is a photograph taken of the inside section of the barriers, taken from position B in Figure 211.

Figure 214 - Full pens looking towards gate 3

Figure 215 - View of the bridge leading from gate 3 to the platform.

The staff assess the crowd flow and density in the pens (Figure 214) taking the numbers on the bridge and platform (Figure 215) into consideration and shut the barriers (Figure 209) when they judge the numbers of people exceed the safe packing density on the platform. This decision includes a phase delay in that they have to judge not the present platform density, but the platform plus bridge density.

With training this can be achieved, but there are two bridges serving one platform. The system relies on one central controller, with a walkie talkie radio, telling the other three barrier controllers to shut the gates .

Two bridges (called the Middle Bridge and South Bridge) lead from the concourse to the station. A third bridge (to the North) has a lower flow rate but serves the same platform. That bridge has no flow control although it can be accessed from the concourse (Figure 192 top left). Once patrons choose a gate they are committed to a fixed route through the system. Subsequently, in the event of an emergency egress they are equally committed to the same route back.

8.7.1 KCR entrance/exit system - present design

At present the operational procedures and responsibilities for egress at four gates (Figures 208 to 210) are divided between the HKJC, the KCR and the Police. Responsibility for the areas is subdivided into regions. Division of responsibility is by the arrival and departure of trains (KCR), volume flow of passengers (HKJC), and by physical area (Police). The overall safety of patrons is the responsibility of the Hong Kong Police.

Ingress considerations for these areas are dependent on the KCR timetable, and the number of people using the service. The station is used solely for the racecourse and services the concourse area only. The concourse doubles as a golf driving range during non-event days so there is no potential to increase the barriers and pens into the fee-earning space of the concourse.

The design for ingress requires no modifications. Egress presents problems for all aspects of design and operational safety. The main area of concern is the barrier control system which has been designed to regulate the crowd flow and allow rapid egress in event of emergency evacuation, for example, a train breakdown.

8.7.2 Egress considerations

The train departs with a frequency of one train every 3-8 minutes; therefore, 6 to 12 trains are required to clear the crowd from the concourse. There is 2,918.4 square metres in the pens for a throughput of 30,000 people.

Walking the distance through the pens takes 90 seconds (on average) in free space (120 metres). The bridges have 4.4 metres of effective width which, at 109 people per metre per minute, is equivalent to a flow rate of 479.6 people per minute.

With the available width of the two bridges it therefore takes approximately 7 minutes to reach platform capacity of 3,500 people (at the highest possible flow rates according to Green Guide calculations) from empty.

The bridge is 50 metres long. Allowing a packing density of 4 people per square metre we have 4.4 metres (width) * 50 metres (length) * 4 = 880 people per bridge. After 7 minutes a total of 1,760 people are on the bridge and 3,500 on the platform. As the rate of filling the bridge is more than the rate of trains extracting people from the concourse we cannot devise a system that allows the bridge to have less than a full load of people. Otherwise, with 3 minutes between trains at peak periods, most of the trains would leave partially empty.

Furthermore, from the end of the last race it takes 15 minutes for all of the patrons who want use the station to arrive. The 5,200 are on the platform and bridges in the first 7 minutes. We therefore need capacity for approximately 25,000 people. At 4 people per square metre we need 6,250 square metres of space. There are 2,918.4 square metres. We proposed extending the barriers by 1,000 square metres to accommodate those arrivals without a significant encroachment into the driving range space. This has the additional benefit of allowing a more even distribution to all of the gates. In the original design there was a bias to gate 3, 5 and 6 due to sight lines. As previously stated, to fill the platform takes two bridges worth of people. A simple measure for the staff is to follow a person moving across the bridge, when he reaches the far side, follow a second, you now have an approximately full platform. This method is unreliable, but it does provide a rough estimate for practical purposes.

8.7.3 Evacuation procedures

We were asked to design an appropriate egress system for the barriers and pens. A number of procedures would be required to handle this situation in the present design.

A) Stop any further patrons entering the queuing system.

B) Close the first manually operated gates and reverse the flow back through the concourse area.

C) Ensure the second manually operated gate is open and that people are moving forward in order to get clear of the centre section of the queuing system.

D) Open the HKJC turnstiles shutters to allow passage of the crowd back to the safety of the concourse area. These, along with the KCRC turnstiles, should be allowed to free flow , or the leg barriers should be held open.

E) Release people heading to the platform to egress via the turnstiles, leaving space for any train evacuees.

F) Evacuate of the train and station areas.

This is a complex process and a simpler and faster method was sought.

8.7.4 Modelling evacuation

We modelled the evacuation of the platform via the bridge and the turnstiles. The as-is model gives rise to two major areas of concern with this evacuation. The first area is the central section of the queuing system, which is closed by a high mesh fence. Once this section has filled with patrons, lines of sight become restricted and, in an emergency this would lead to confusion and distress.

The other area of concern is the area between the second gate and the KCR turnstiles. This area is prone to high density crowds and requires a method for rapid clearance to prevent injuries. Two model were created and evacuation times were compared. We will focus our attention on the gate 3 egress section to illustrate the principles as, in essence, the whole system consists of four very similar sections.

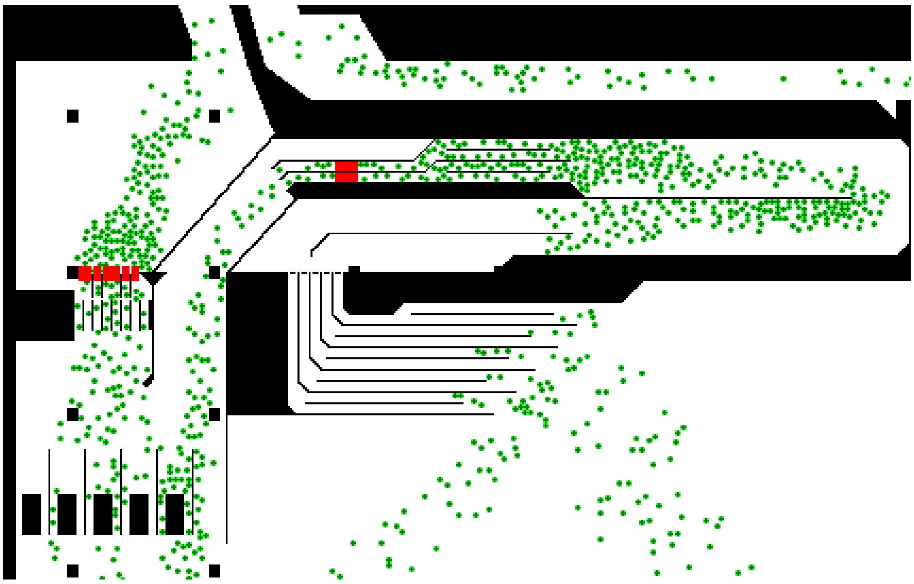


Figure 216 - The bottlenecks in the existing system (in red) at gate 3.

To assess the egress capacity of the existing design we look for the narrowest points (bottlenecks) along the egress route and calculate, using the ***Green Guide*** values, the flow capacity. This is a rough-cut analysis in which we determine the scale of the problems. Figure 216 shows the bottlenecks. We have assumed the manual gate is closed and the patrons in that area are moving back into the concourse area. The dimension of the egress routes are: 40, 40, 90, 40, 70, 60, 60 cm. Although this is a total of 4 metres of exit width (426 people per minute), no single route meets the minimum safety requirement as stated in the Green Guide. It is important to note that the ***Green Guide*** is a British document and, although internationally accepted, it is not as rigorously applied around the world. We note that people are packing to 6 people per square metre in the existing pens. Hong Kong has the highest population density in the world so people are used to packing to these levels. The rough cut analysis using the higher figure of 6 people per square metre highlights the problems of an emergency egress from this area. We may have as many as 18,000 people in the pens, a further, 2,640 people on the bridges at 6 people per square metre and flow rates of up to 180 people per metre per minute. The huge differences are partly due to the smaller frame (80% of the area a UK shape occupies) and partly due to a high density tolerance.

There is space on the left-hand side (Figure 216) for a crowd, in excess of the egress rate, to be held in relative safety. The pens to the right are a more serious problem and they both narrow along their route, and the potential for a crowd crush is self-evident. We are now able to use the anthropomorphic tables from (Table 4) the speed distribution (Figure 56) and the speed density curves (Figure 135) to assess the local characteristics of this population.

8.7.5 Alternative for safe egress

Two alternative designs were tested. The changes relate to the evacuation process and consist of a three-metre wide sliding gate in the perimeter fencing. The gate would be opened only if an evacuation were necessary. Once opened the police would direct the crowd from the rear of that area out to the relative safety of the concourse. Figures 217 to 224 show the existing system

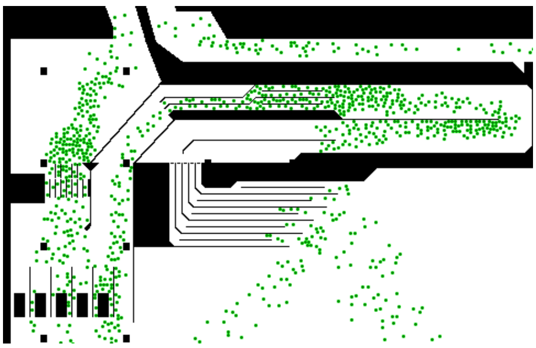


Figure 217 - 15 second entity position

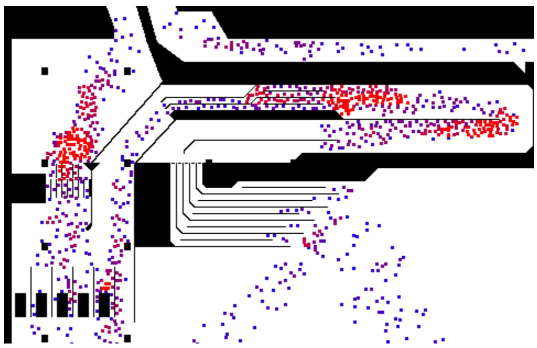


Figure 218 - 15 Second entity density

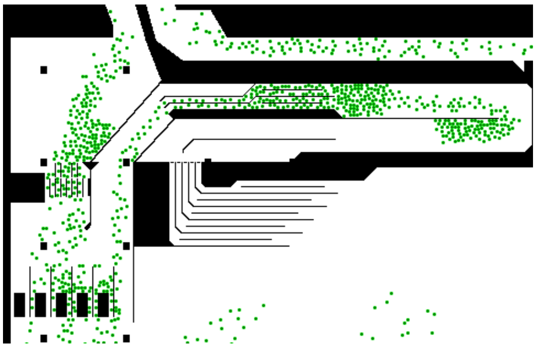


Figure 219 - 30 Second entity position

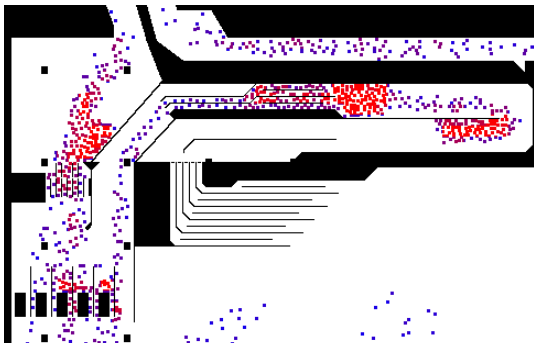


Figure 220 - 30 Second entity density

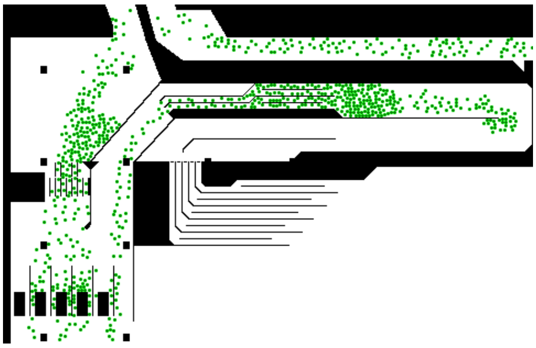


Figure 221 - 45 Second entity position

Figure 222 - 45 Second entity density

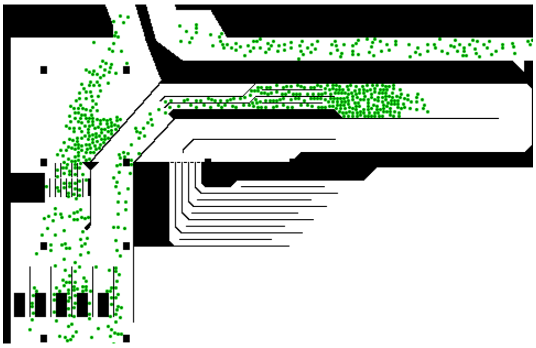


Figure 223 - 60 Second entity position

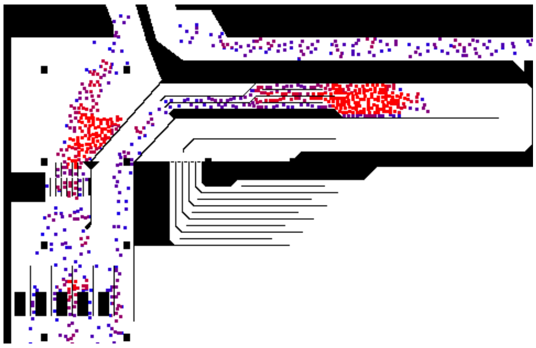


Figure 224 - 60 Second entity density

Using the Legion simulation we can assess the densities during egress, high density exposure, the total evacuation time and the flow rates at various sections in the model. This allows us to assess where the design needs to alter.

From Figure 223 and 224 we can see that the people in the middle of the barrier/pen configuration are trapped. They cannot escape in either direction and there is danger of crowd crushing in this section. We can remove a section of the perimeter to allow these entities to find a better egress route.

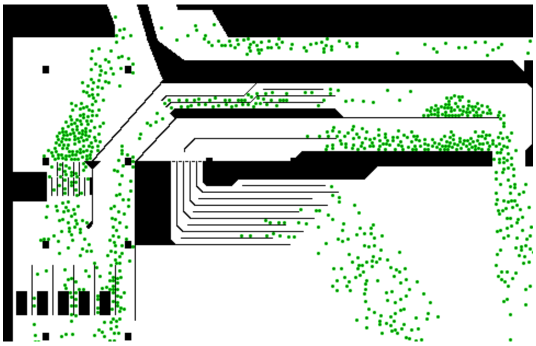


Figure 225 - Scenario 1: 15sec entity position

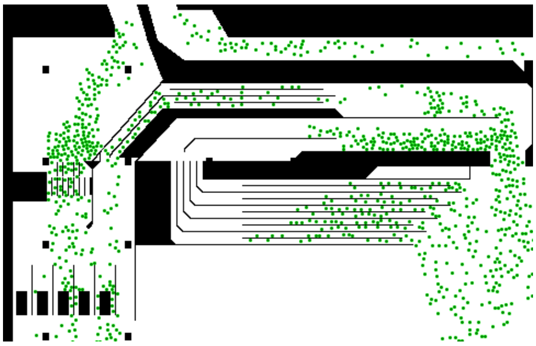


Figure 226 - Scenario 2: 15sec entity position

In Scenario 1 (Figure 225) we open a section of the perimeter (during evacuation only) and find that there are still problems when the entities try to find a way out of the system. Scenario 2 (Figure 226) has a different configuration or the internal barriers allowing the entities to flow more efficiently, yet still be controlled by the existing gating system. Figures 227 to 232 show the simulated egress for the two alternative solutions (side-by-side).

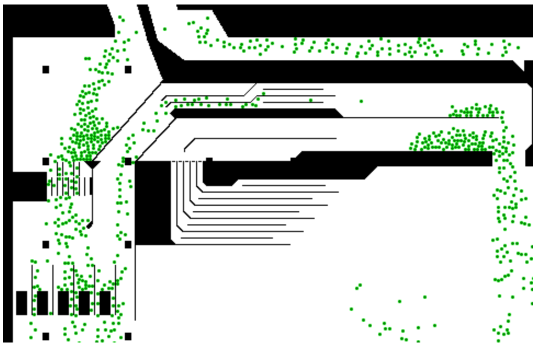


Figure 227 - Scenario 1: 30s positions

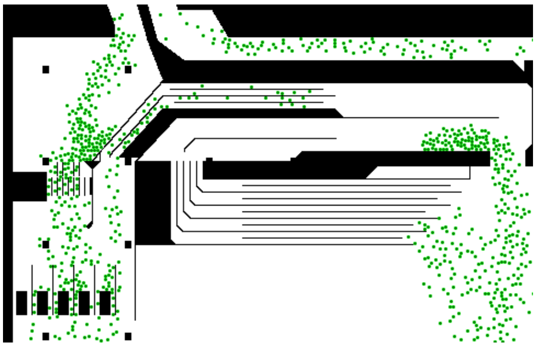


Figure 228 - Scenario 2: 30s positions

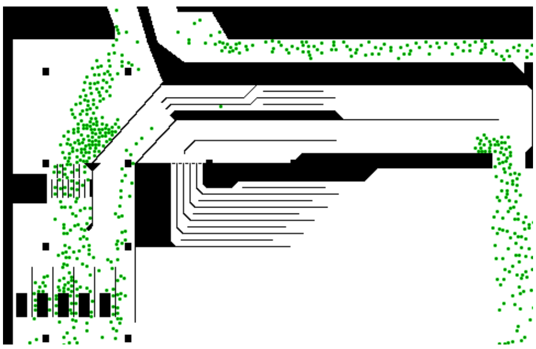


Figure 229 - Scenario 1: 45s positions

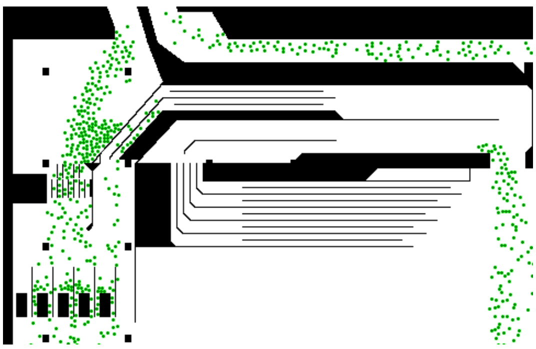


Figure 230 - Scenario 2: 45s positions

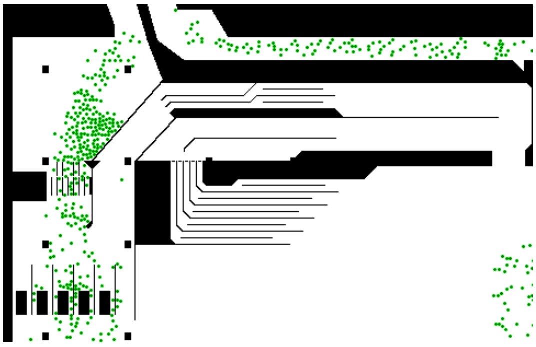


Figure 231 - Scenario 1: 60s entity positions

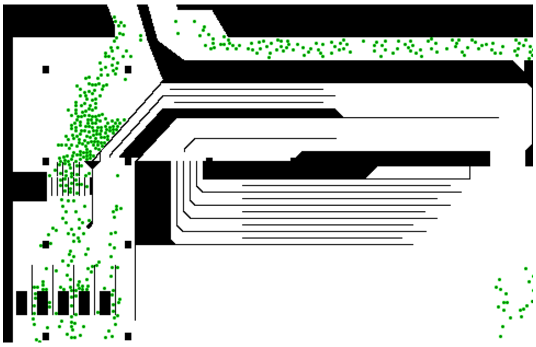


Figure 232 - Scenario 2: 60s entity positions

8.7.6 Study points for the simulation

The three issues that were studied in these scenarios were:

a) The queuing system leading up to the first manual gate (note the extension to the barrier in Scenario 2 in Figure 232). These extensions balance the crowd distribution in the barriers and spreads crowd over a further 1,000 square metres for all four barriers (3,4,5 and 6) and changes the ingress focal routes.

b) The gate installed for an evacuation (to the right in Figures 231 and 232).

c) The relocation of the second manual gate along with the extension of the redesigned barrier lanes. This change is applicable only for gates 3 and 5.

The as-is model shows the uneven distribution between gates 3 and 4. The shorter sections of barriers were changed resulting in people merging prior to the corners - giving more time to self-order before channelling through the manual gate.

The evacuation gate has been installed into the high fence using the same dimensions and operational requirements in both scenarios. This addition is the most important safety feature of the proposed changes to this egress system.

The third change is the second manual gate and the queuing system that lead up to gates 3 and 4. After study of the plans and testing the simulations for a number of different scenarios, it was observed that changing the design to mirror those of the gates 4 and 6 was the most effective. Changes to procedures were also noted:

a) Individuals are required only to move forward rather than reverse flow.

b) The repositioning of the second manual gate restricts the unregulated area allowing for greater control throughout the system.

c) In the case of an evacuation this design would have a major advantage with a more ordered egress.

In all of the above scenarios no changes have been made to the evacuation procedures for moving people away from the train and platform. Figure 233 shows the comparative egress times for the pens in the three configurations: as-is, scenario 1 and 2. We have taken these times for the central pen area to clear of entities.

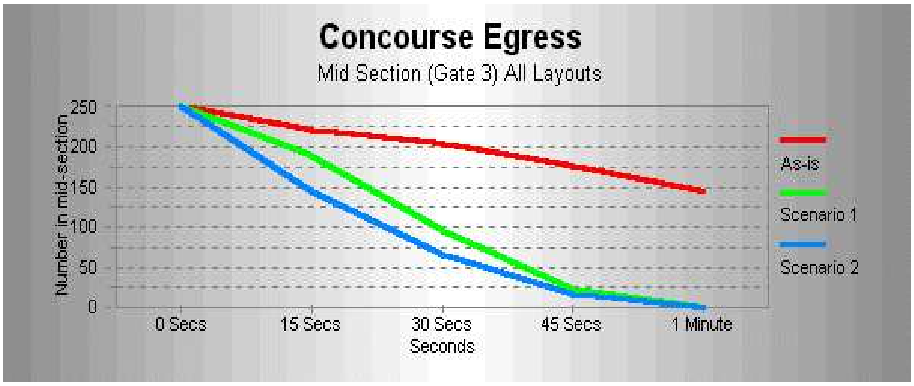


Figure 233 - Comparison of the evacuation time for the three models

8.7.7 Conclusion: Concourse simulation

Operational procedures are dependent on available platform space and hence the frequency of train arrivals. The areas modelled relate to proposed design changes which will improve the egress of the pens. These changes reduce the high density ingress and improve crowd safety both for normal and emergency egress.

Chapter 9 Conclusions

The Sciences do not try to explain, they hardly even try to interpret, they mainly make models. By a model is meant a mathematical construct which, with the addition of certain verbal interpretations, describes observed phenomena. The justification of such a mathematical construct is solely and precisely that it is expected to work. - **John Von Neumann.**

9 Introduction

There were three objectives to this research: Firstly, to understand the nature of crowd dynamics with respect to crowd safety. Secondly, to develop a more appropriate risk analysis methodology for the design and management of places where crowds may develop. Finally, to create a tool that allows others to understand the nature, problems and necessary components of crowds and crowd dynamics.

Crowd dynamics are complex, therefore it is not enough simply to build a model as Von Neumann states. There was a need to construct a model that explains how and why people can die in a crowd. There was also a need a build a model that explains the many different types of crowd behaviour we observe in stadia and stations. With Legion we begin to understand the reasons why specific areas produce predictable crowd behaviours and the effects that can have on crowd safety.

The original VEgAS algorithms contained many different behavioural rules. It was apparent that this approach is fundamentally intractable. Some recent research [96, 97] using rule based cellular automata demonstrate similar speed density relationships as the Legion model.

To investigate the nature of crowd dynamics, we need to satisfy Occam's Razor. By a process of elimination behavioural rules can be reduced to four interactive rules, Objective, Motility, Constraint and Assimilation. These four rules produced crowd behaviour that was too regular compared to reality. This problem was solved by the addition of noise which produced realistic crowd dynamics.

Noise is added to the distribution of entity speeds and to their direction (Objective). By varying the speed distribution curve we can alter the composition of the crowd. Homogeneity produces marching armies of entities whereas heterogeneity produces indecisive and wandering crowds.

This is a form of simulated annealing which provides a tractable solution to problems of N-dimensional control spaces (Metropolis [89]). We note that the geometric constraints impose a self-organisation effect on the crowd and homogenises the noise. Entities solve for the least effort from their present position to their destination using focal routes. The entities are self-contained problem solving individuals, each following simple rules with limited intelligence, which produces the emergent behaviour.

We have outlined some of the interactions between the crowd and its environment. We have also outlined the development, application, validation and results of a simulation technique for determining the character and critical dynamics relating to crowd safety. We have seen that the addition of noise can produce different types of crowd dynamics. This is important in testing different phases of a stadium design, for example, where 2 hours prior to gates opening the crowd has few objectives and drifts in random-like patterns. As the gates open the crowd becomes more focussed towards the entry points. Finally after the gates open, but before the match begins, the crowd becomes highly directed in its dynamics. We can model different types of crowd behaviour in this way.

The aim was not to reproduce an individual entity with complete certainty, but to produce graphical representations of the space required by the crowd and to assess the crowd safety issues. Legion models crowds, not individuals. The distinction between the individual and the crowd lies in the relationship of speed, density and the effect of entity interactions with each other and the local geometry.

The speed, density and space utilisation maps allow us to qualitatively and quantitatively analyse the use of space over time. This in turn facilitates a greater understanding of the nature of the dynamics of the crowd to space requirement.

The two dimensional maps, where differences between two maps and differences in the same map (at time t0 and at time t+n) developed into a complex analysis tool. The author has applied this technique to reclaim underutilised space in high traffic areas with significant commercial success.

The Legion simulation highlights problems with the present legislation, examining specific cases where it demonstrates that a more appropriate methodology could be applied for safety analysis and risk assessment. Legion was specifically developed as a testing tool for architectural designs. It is based on empirical observations made by ourselves, and compares favourably with previous and more recently published data [96, 97].

It is clear that the present legislation has areas where the Legion simulation could be applied to determine the necessary dimensions for a given crowd. From the Green Guide:

From new constructions: It is difficult to recommend precise dimensions in order to ensure the safe circulation of people, or to calculate appropriate holding

capacities for concourses.

Clearly, however, the width should take into account the entry, exit and emergency evacuation capacities required, as for any circulation route. The width should then be increased to take into account the additional anticipated usage of related facilities. Experience shows that this usage may be greater than is often expected.

In addition, consideration should be given to the potential usage of concourses by spectators at events other than the sport for which the ground is primarily designed. This usage can be considerable if the event spans several hours, if inclement weather conditions prevail, and if large numbers are in attendance (as, for example, at a concert, for which the pitch or area of activity is used for viewing).

The development of the simulation system extends beyond this thesis. The author lectures to building control officers, licencing authorities, stadium ground staff and the Police. Crowd dynamics workshops and training courses are planned at Easingwold (the Home Office Emergency Planning College). The models have been used around the world including the Sydney Olympic Games 2000.

9.1 The crowd simulation criteria

We began chapter 5 with a list of criteria that a simulation had to manifest as an emergent behaviour rather than specific rules built into the system. We conclude with the same list, and discuss how the various observable crowd phenomena and criteria have been satisfied.

9.1.1 A crowd consists of many individuals

Each entity is calculating its least effort at every step and will react in different ways depending on its local objective at its maximum motility bounded by the prevailing constraints. Each entity has the capacity to reacting differently according to its internal parameters and the changes in the environment as the simulation proceeds. The dynamics of the crowd emerge and are not implicit in the entities reactions to the changes in their environment. Press et. al. [89] demonstrate that the principles of taking a step from x, y to x_1, y_1, by a random choice, is not efficient when a good local move exists. The process of an objective driven first choice route (focal route) is both analogous to the individual behaviour and to the crowds capacity for overcrowding (packing). The simulated annealing approach to the problem provides us with a technique for modelling a dynamical system that can be efficient in free space and endangering in confined spaces. In this way we model both the individual entity and the emergence of the crowd dynamic.

9.1.2 Individuals exploit short cuts

Short cut exploitation is a function of the ***least effort*** algorithm and the assimilation algorithms demonstrate that this feature complies with human behaviour. It is an important consideration when we are analysing different ingress and egress scenarios to model crowds behaving in a competitive manner in which every entity is trying to get in (or out) of its environment by the most efficient, ***least effort*** route.

We need to find out, by applying the simulation, where such routes exist. A priori assumptions can be erroneous. Rules of a thumb are applied without due consideration and lives have been lost as a consequence. The simulation can be applied to search for these routes. Therefore replacing the present network analysis with a more appropriate ***focal route*** analysis will not only lead to a safer environment, but to a more efficient pedestrian planning and design criteria.

9.1.3 The crowd does not fill to its own level

Using the information space concept we can halt or slow entities accordingly, this allows us to assess realistic filling capacities. We have examined the differences between ***static*** and ***dynamic*** space, this would be a more appropriate methodology than the area divided by 0.5 recommended in the various building codes and guidelines. ***Static*** area calculations overestimate the crowd flow parameters and such calculations can be inappropriate, especially when the Fruin Level of Service is applied to larger, more ***dynamic*** areas of crowd flow.

Consider the following example to illustrate this point. The total area in a circulation zone is calculated, for example 18,200 square metres. We want a Fruin Level of Service C, (some restrictions to speed: 2.32 to 1.39 metres per person) therefore the holding capacity for this area is 6,300 people. According to this calculation that area will facilitate 6,300 people. This was the calculation applied to a rotary system at the Sydney Olympics and is not only an oversimplification, but does not take the problems of dynamic circulation into consideration.

We find in the analysis that there are bottlenecks and compression zones where crowds will accumulate to dangerous proportions. Crowds do not fill space evenly: they cluster, they exploit short cuts, they flock and they herd like sheep. Once committed to a route it takes more than passive signage to disturb them from their chosen course as was the case at Hillsborough. It is recommended that an overhaul of the safety guidelines, which includes some simulations or models, are used for safety analysis in existing and proposed designs.

9.1.4 Crowds cluster

Clustering is a function of the speed distribution of the crowd. We could include a clustering function in the simulation; by programming groups that move together. But we find that such clusters occur naturally as a consequence of the speed distribution. In the edge effect model we saw that the geometry retards the entities and a cluster formed at a specific location. The Legion simulation, and in particular the dynamic density maps, allows us to calculate the impact of local clusters on the overall crowd flows. This is an important factor in designing efficient and cost effective pedestrian areas where high density crowds are expected.

9.1.5 Crowds have no collective intelligence

In the simulation it is clear that we attribute no collective intelligence to the crowd. However, it is a feature of the algorithm that a complex problem can be solved without collective intelligence. This is a fascinating insight to the nature of intelligence and in particular colony intelligence. Furthermore there are no collective rules, the dynamics of crowds emerge from the interactions of the individuals in the crowd and not a ***group*** think, or crowd psychology. This may lead to a more sophisticated model of how the individual contributes to the overall behaviour of the crowd.

9.1.6 Crowds are influenced by geometry

We can now see the mechanisms that lie behind this statement. We briefly discussed the impact this fact has on network analysis (recommended by the ***Green Guide***). We expanded on the problems of geometry and discussed Braess s paradox which, during the design of egress routes, can lead to problems in calculating the effective egress routes.

Focal routes were discussed and the following example will demonstrate the impact of these on egress analysis. Consider the ***Green Guide*** calculation for the following example from Wembley Stadium. There are two egress gates (A and B in Figure 366), each 3 metres in width. The total capacity for egress is therefore 3 x 2 x 109 = 654 people per minute.

We have seen, from the examples in chapter 3.4, the imbalance of utilisation in an ingress. We have also seen, from the many examples of exploitation of short cuts that the shortest, straightest routes are the most exploited.

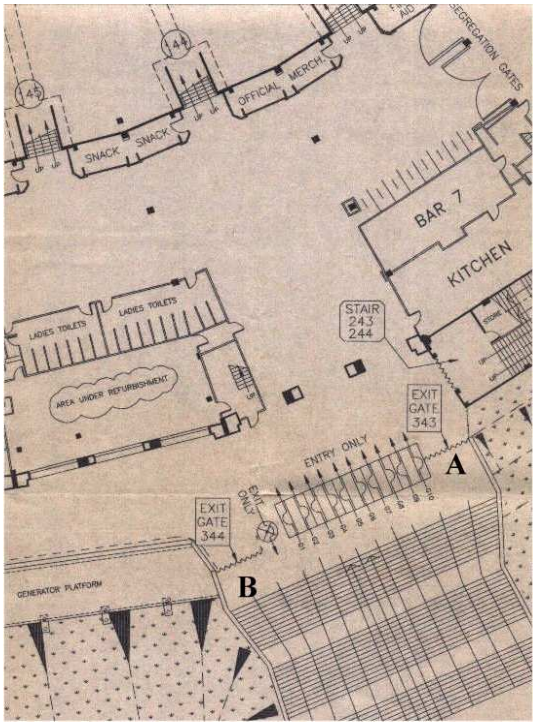


Figure 234 - Egress analysis (1)

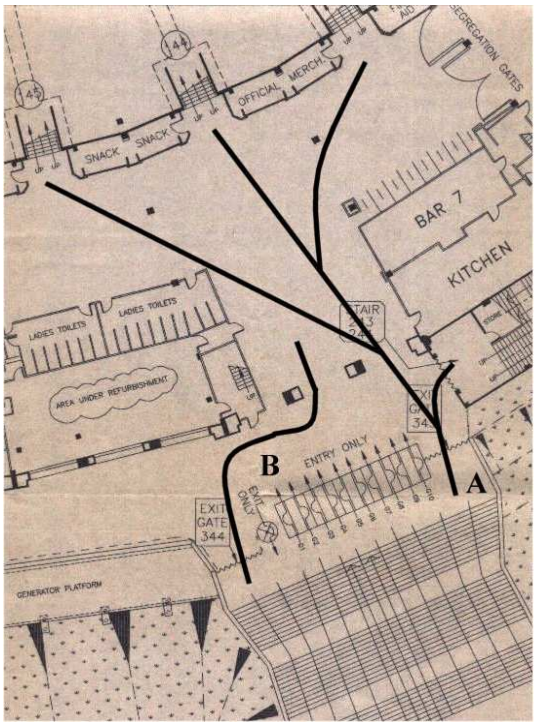


Figure 235 - Egress analysis (2)

One can now apply some simple geometric rules to assess the impact of the crowd during ingress or egress. Taking straight line routes, widening these line to the anticipated flows and trying to reduce the multiple path interference routes by design. We have seen from our example of gate 1 at the Hong Kong Jockey Club how difficult it is to direct people from those apparently optimal routes. A focal route analysis of the egress example (Figure 234) leads to the network (Figure 235).

The application of a simple geometric rule would give some more realistic limits for egress calculation. The principals of ***focal route*** analysis should be part of our limits for egress calculations. If we add thickness to the line appropriate to the crowd flow then effectiveness of the egress routes can be more readily estimated.

Adding noise to the direction of each entity ***after*** it has solved the ***least effort*** algorithm is the parameter named ***focus***, this allows us to model the likely usage against the prescriptive people per metre per minute presently used in the guides.

It is apparent that the emergent behaviour of the crowd is, to a degree, predictable. It is also apparent that the principles of ***focal route*** analysis should supersede the use of network analysis for ingress and egress analysis.

From Figure 235 we can see that route B will begin to be used only when the route A has reached capacity. Route B is not in a line of sight (the pillars obscure the view). Our entities are designed to take these egress scenarios into account and behave in a more realistic, more human manner.

9.1.7 Crowds self organise at high density

The mechanisms of how this self organisation occurs are apparent from the model. The Legion entities neither communicate with each other nor are aware of the global nature of the crowd, they are selfish ***least effort*** exploiters. What emerges is the outer fringes of the crowd moves faster than the inner core. This produces different effects in different densities. The nature of self organisation at high density has implications for safety design and general circulation.

9.2 The work to date

There has been considerable commercial success with the model s applications, and the company recently won a contract to model the Sydney Olympics against international competition. We have demonstrated two examples of its application (Balham and the Hong Kong Jockey Club), at present several international projects are being completed by the London-based company, Legion Crowd Dynamics Limited including the new Wembley Stadium design.

It is worth noting that the statistics gathered at the Hong Kong Jockey Club, in particular the ingress data, provides an important analysis in the future risk to crowds. The data relating to the entry numbers, turnstile distribution and geometry provide us with a profile of the arrival rates. This data, coupled with information from the train services represents a typical event ingress and the model can be scaled to accommodate larger numbers, capping the limits by the transportation modes. This is called the ***modal split*** where numbers arriving by car, train, bus or foot determine ingress flow rates. This data is essential to the analysis of crowd behaviour and dynamics so should be recorded, analysed and extrapolated to provide a more comprehensive risk analysis for future crowd arrival profiles.

It is worth pointing out that Wembley did not gather that data, but did conform to the ***Green Guide***, whereas the Hong Kong Jockey Club did gather the data and, in the concourse egress system, did not conform to the ***Green Guide***.

It is a recommendation of this research that the ingress data illustrated by the examples of the Hong Kong Jockey Club be universally accepted as good working practice. It is also the recommendation that, if in any doubt about the effectiveness of a safe and efficient event that a suitable simulation be tested against a suitable range of parameters.

9.2.1 The applications

We have seen how the simulation can be applied to the modelling of safety criteria. We can also see that elements of design, routing, location of signage and the speed/density relationship effects both the comfort and safety of the patrons. We have also seen how the simulation can be applied as a ***what-if*** analysis tool for risk assessment. By monitoring the effects of density on the entities in the model we are effectively testing the effects that a ***dumb*** crowd may exhibit and experience..

The entities in the simulation do not have any form of artificial intelligence, they are following simple rules which allow them to endanger themselves. By this method we can assess the risk to the individuals and, through simulated experiments, using Legion, we can reduce these risks. It has been argued that people are smarter than the model and so it is not realistic. One need only look at the number of people who have lost their lives in crowd related disasters, such as Hillsborough, to realise that smart people have little choice in their actions.

We conclude by restating that it is vital to the analysis of places of public assembly that something other than the prescriptive ***Guides*** are used. Simulation is a useful tool, as we have illustrated, for it provides insight and understanding to the users, owners and operators. For example, an exit is of little use in an emergency if it deviates from a ***focal route*** as Sime [43, 44, 45, 46, 47] demonstrates.

We are not alone when we state that people will tend to use the route with which they are familiar, so basing evacuation plans on equal egress (especially where emergency exits are included) is erroneous. That sentiment has been stated many times, by many experts (Sime, Canter, Proulx et. al) yet this single factor has been the cause of many deaths in during emergency egress. In November 1998 400 people rushed a single exit at a discotheque in Gothenburg during a fire.

Safety design methodology based on the present guidelines using unit widths of exit with no consideration to familiar routes, ***focal routes***, psychological factors or crowd dynamics require reconsideration. One has to question the wisdom of these guidelines in the face of the physical evidence. Taken without the interpretation of a ***competent*** person, the relevance of exit widths meets the statutory requirements but, as we have demonstrated they may not meet the physical needs to safely and efficiently to evacuate the occupants in an emergency situation.

It is only by the continual development of tools like Legion that we can make progress towards understanding the complexities of crowd dynamics, and thereby develop safer environments for large scale crowds.

There is a continual development of these methods and algorithms, the end of this thesis does not mean the end of the author s study of crowd safety. Perpetual development of more efficient algorithms, more user friendly interfaces and a more powerful analytical output will allow the dissection of the parameters of crowd dynamics relevant to crowd safety in even greater detail.

The ultimate goal is to drive through the legislature that a simulation be a statutory requirement of a licence to operate a place of public assembly. We propose replacing the need for a competent person with the need for a competent simulation. It is hoped that Legion represents a new wave in the understanding of crowd safety through the study of crowd dynamics.

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