Crowd Dynamics under Emergency Conditions: Using Non-human Organisms in the Development of a Pedestrian Crowd Model

By

Nirajan Shiwakoti

B.Eng., M. Eng.

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Institute of Transport Studies

Department of Civil Engineering

Monash University

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To my wife Raxchaya, son Nirvan and parents
for their love and support

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Abstract

The rapid movement of large numbers of people is critical in emergency and/or panic situations, such as during the evacuation of buildings, stadiums, theatres, and public transport stations; outdoor events such as public assemblies, open concerts, and religious gatherings; and community evacuations following natural disasters or terrorist attacks. Perhaps the most critical reason for studying collective pedestrian dynamics under emergency/panic conditions is the lack of complementary data to develop and validate an explanatory model. That lack of data is likely to explain why very few models focus on panic situations. The bulk of the literature is restricted to the study of normal evacuation processes. Even the researchers responsible for developing the few existing models of crowd panic have identified the need for more rigorous modelling frameworks and the development of approaches to assess the reliability of model predictions.

The broad aim of this dissertation is to use empirical data from non-human organisms in the development of a pedestrian traffic model under emergency conditions. Experiments undertaken with non-human organisms under panic conditions are a crucial component of the research reported here. Those experiments are found to be a promising and feasible means of circumventing the limitations posed by the scarcity of complementary human data under panic conditions. Argentine ants (*Linepithema humile*) were used as test organisms in the experiments reported here because they are abundant and simple to maintain in the laboratory. The experiments reported in this thesis reflect an original attempt to study the effects of structural features, that is, the layout of the escape area, on the collective movement patterns of non-human entities during rapid egress and to translate those results to the study of human panic. Large potential effects from the adjustments of small structural features of the escape area have been demonstrated via experiments with panicking Argentine ants.

Insights from the experiments with panicking Argentine ants, along with previous studies on animal dynamics and pedestrian dynamics, have been used in the development of a simulation model called EmSim (short for **Em**ergency **Sim**ulation).

The formulation for the model recognises the role of both attractive and repulsive forces in maintaining the coherence of collective dynamics under panic conditions. To date, consideration of both repulsive and attractive forces has received limited attention in studies of crowd panic reported in the literature. Also the granular forces for pushing behaviour were modified to consider the case of discontinuity when the relative velocity is zero or near to zero. A first attempt has also been made to scale the model parameters for collective pedestrian traffic via ant traffic, based on a scaling concept commonly used in biology. With this innovative framework combining insights from biology and traffic engineering, there is scope to compare the collective movement patterns of non-human biological entities and pedestrians in order to devise sound strategies to aid evacuation. The proposed model also provides insight into the minimal interactions or physical mechanisms required for the emergence of collective dynamics. The nature of those underlying mechanisms was investigated through experiments with panicking ants.

The proposed model is first calibrated and validated (with independent data) through simulation of panicking ant traffic as observed from the experiment and then scaled up for the human panic situation. Since data does not exist for direct measurement of model parameter values appropriate for panicking humans, the parameter values in the model were *allometrically* scaled up from the ant values to human values. The model predictions for collective pedestrian traffic were consistent with observations of collective traffic for ants. This consistency suggests that there are fundamental features of crowd behavior that transcend the biological idiosyncrasies of the organisms involved. The effectiveness of the proposed modelling framework is also validated through the comparison of the simulation results for the pedestrian traffic with the observed data from the experiment (under non-panic conditions). For normal (non-panic) conditions, the model was validated with experimental data on pedestrian traffic; specifically through comparisons of:

- headway distributions in uni-directional traffic,
- speed distributions and lane formation in bi-directional traffic, and,
- outflow from bottlenecks of various widths.

The results provide reassurance of the robustness of the model in explaining the collective dynamics of the panicking individuals despite the differences in speed, size and other biological details between ants and humans. The results also demonstrate the capability of the EmSim model to represent both non-panic and panic conditions within the same modelling framework.

The model organism approach is commonplace in medical research but not in engineering, yet it is shown in this dissertation that it has enormous potential to provide insight and theoretical understanding of crowd panic. It will enhance understanding about what properties of panic are inherent to the physical nature of crowds, and what properties depend on idiosyncratic details. Also in biology, little attention has been given to the study of the effect of nest design elements on collective movements of social insects. The experiments that are reported here address those gaps in the study of alarm traffic in social insects by focussing attention to the relationship between nest architecture and internal traffic under alarm conditions. It is expected that the experimental studies and modelling framework presented in this dissertation will appeal to a broad audience, including researchers interested in social insects and nest architecture, self-organization, evacuation and traffic dynamics and engineering.

Author's Declaration

This thesis contains no material that has been accepted for the award of any other degree or diploma in any university or institution. The author affirms that to the best of his knowledge this thesis contains no material previously published or written by another person, except where due reference is made in the text.

Nirajan Shiwakoti
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Associated Publications

<u>Journal</u>

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- **Shiwakoti N.,** Sarvi, M., Rose, G., Burd, M. (2010), " Biologically inspired modeling approach for collective pedestrian dynamics under emergency conditions", In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2196, pp. 176-184, Transportation Research Board of National Academies, Washington, D.C., USA.

- Burd, M., **Shiwakoti, N.,** Sarvi, M., Rose. G. (2010), "Nest architecture and traffic flow: large potential effects from small structural features", *Ecological Entomology*, Vol. 35, Issue 4, pp. 464-468.

- **Shiwakoti N.,** Sarvi, M., Rose, G., Burd, M. (2009), "Enhancing the safety of pedestrians during emergency egress: Can we learn from biological entities?", In *Transportation Research Record: Journal of the Transportation Research Board*, Transportation Research Board of National Academies, No. 2137, pp. 31-37, Washington, D.C., USA.

Peer-reviewed Conference

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- **Shiwakoti N.,** Sarvi, M., Rose, G., Burd, M. (2009), "A hybrid model for collective motion of pedestrians", *32nd Australasian Transport Research Forum (ATRF),* Auckland, New Zealand.

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- **Shiwakoti N.,** Sarvi, M., Rose, G., Burd, M. (2008), "Exploring crowd dynamics under emergency conditions: Simulation perspectives and experiments with panicking ants", *Third International Symposium on Transport Simulation (ISTS08)*, Gold Coast, Australia.

CHAPTER 1 INTRODUCTION

1.1 Background

Movement of people forms an important component of a multi-modal transportation system. Promoting walking is an important part of the shift to more sustainable transport (Cotter and Hannan1999, OECD guidelines 2002). Thus the planning and designing of amenities for efficient, comfortable and safe walking in public places is a great challenge to planners seeking to create liveable communities and sustainable travel behaviour (Devlin et al. 2009). The movement of large numbers of pedestrians is important in many situations, such as the evacuation of buildings, stadiums, public transport stations, etc., following natural disasters, terrorist attacks or other causes. Numerous incidents have been reported (for example Crowd Dynamics 2010) in which overcrowding has resulted in injuries and death during emergency situations. A quick scan of those documented incidents shows that 3000 people have been killed and more than 3500 people have been injured in crowd related disasters over the last 10 years (Crowd Dynamics 2010). Modelling and empirical study of pedestrian behaviour under emergency conditions is imperative to assist planners and managers of emergency response to analyse and assess safety precautions for those situations.

The potential societal benefits of modelling and simulating pedestrian behaviour include:

- Planners and managers can use simulations to gain insight into possible problems regarding the evacuation of public buildings early in the planning of those facilities.
- Evaluating evacuation strategies through simulation can provide insight on efficiency of evacuation processes and subsequent optimisation of the evacuation plans. It could be particularly important in case of building evacuation or natural disasters like bushfires and earthquakes.

- Managers of large events can use simulation to enhance their understanding of how to control crowd movements in different situations.
- Assessment of safety for passenger vessels is of particular importance and so evacuation simulations are being performed for trains, aircraft and ships to assess the safety of those vessels.
- Pedestrian dynamics, as an important component of group dynamics, is interconnected to several other fields including traffic engineering, architecture, socio-psychology, biology, safety science etc. Therefore the insight from the study of pedestrian dynamics has wider application and can contribute to advancement in knowledge in different fields.

As with vehicular traffic, pedestrian traffic has been studied mainly from macroscopic and microscopic approaches and in some cases even from mesoscopic approaches (Shiwakoti et al. 2008a) as will be explained in more detail in Chapter 2 Literature Review. Although initial scientific studies on pedestrian evacuation were carried out as early as 1930's (Kholshevnikov & Samoshin 2008), the problem of enhancing pedestrian safety under emergency conditions still exists. This difficulty may be due to the complex behaviour of humans under those conditions and their continuous mental, social and physical interactions with the surrounding environments. In these earlier studies, the focus was to determine the level of service for pedestrian facilities and architectural and building codes based on them were developed (Henderson 1971, Fruin 1971). Many of the pedestrian planning and design, contingency planning and architectural and building codes used in practice are based on understanding developed from macroscopic models. However, with the advancement in computer power, recent trends have been towards microscopic modelling with a focus on emergency evacuation/panic situations. Microscopic modelling has the potential draw on the socio-psychological literature (Mintz 1951, Quarantelli 1957, Mawson 2007) to represent the influence of socio-psychological factors under emergency conditions. Those socio-psychological studies highlight that crowd behaviour during normal and panic conditions are entirely different. Interactions among individuals form an important component and, as stressed by Quarantelli (1957), the nature of the interaction that occurs prior to and during panic flight is of utmost importance. Sime

(1995) argues there is a need to concentrate on crowd psychology in the context of crowd safety engineering concerns.

The problem with few existing models of emergency/panic situations is that complementary data on panic to develop and validate a model's prediction are rare, as they are difficult to capture. Therefore, a genuine question arises: can one depend entirely on the mathematics before scaling up and applying a model prediction in a human situation? Or can there be alternative empirical ways to demonstrate that what a model predicts is actually efficacious and improves safety for pedestrians? One of the interesting aspects of pedestrian crowds is the collective behaviour during emergency/panic situations (Quarantelli 1957, Kelley et al. 1965, Sime 1995, Helbing & Molnár 1997, Farkas & Vicsek 2005). The nature of collective behaviours during egress has an important role in determining the safety of a crowd. Collective patterns are not restricted to humans, but have been observed in other biological systems that display herding, flocking, schooling and swarm intelligence (Okubo 1986, Kennedy et al. 2001, Charlotte 2005, Pfeil 2006). Mathematical simulation models have been used since the 1970's to study the collective movements of animals (Okubo 1986, Reynolds 1987*)*. However, findings from such work are seldom applied to the study of collective human dynamics.

In this dissertation the terms *panic* and *emergencies* refer to situations in which individuals have limited information and vision (due to high crowd density and short time for egress), and which result in physical competition and pushing behaviour. That is different from the meaning of the term that most social scientists have used, i.e., "panic" is restricted to instances when both high emotional arousal and irrational behaviour occur. There have been many instances in the past where people have displayed physical competition and pushing behaviour during emergency evacuation, as well as instances where people behaved in much calmer way. The focus on the former issue is more critical, whatever the emotional state of mind of the participants in the evacuation.

1.2 Research aims

The broad aim of this dissertation is to use empirical data from non-human organisms in the development of a pedestrian crowd model under emergency conditions. Consistent with that broad aim, this research aims to answer following three questions:

(a) Can non-human biological organisms be used to study collective pedestrian crowd dynamics under panic conditions?
(b) Can principles of the collective animal dynamics be applied to model collective pedestrian dynamics?
(c) Can a robust model be developed to explain the collective behaviours of different biological entities despite variation in size, manner of locomotion, cognitive abilities, and other biological traits?

To address these aims, specific objectives have been outlined along with a research methodology to achieve those objectives. The research methodology followed in this dissertation will be explained in Chapter 3 after the Chapter 2 Literature Review.

1.3 Thesis structure

This dissertation consists of nine chapters as shown in Figure 1-1. This Chapter (Chapter 1) has set the scene for the research, identified the overall aim and key research questions. Chapter 2 reviews the literatures to provide insight on existing theories, models, and empirical studies pertaining to pedestrian crowd dynamics. It also identifies the gaps in knowledge to which this research responds. Chapter 3 presents the specific objectives of the study along with an outline of the research methodology designed to achieve the stated objectives. Chapter 4 discusses the viability of using non-human biological organisms in the study of human crowd panic via experiments with panicking Argentine ants. It presents the results from experiments and their relevance to crowd dynamics. That chapter also examines the foundations for the assumptions which must be made in the development of a model for collective pedestrian traffic.

Chapter 5 is dedicated to the development of a simulation model, termed EmSim (short for **Em**ergency **Sim**ulation). The assumptions underlying the model and its mathematical derivation are provided along with a flow chart of the simulation model's operation. Chapter 6 and 7 describe the calibration and validation of the developed simulation model for the ant traffic and pedestrian traffic respectively. In Chapter 6, the simulation model is applied to replicate the scenarios from the panicking ants experiment. In Chapter 7, the same model is applied to simulate pedestrian traffic with model parameters scaled up for pedestrian crowds from ant traffic. Chapter 8 describes the application of the model in developing strategies and practical design solutions to enhance the safety of crowds. Finally, Chapter 9 concludes the dissertation highlighting its contribution to knowledge and discussing future research directions.

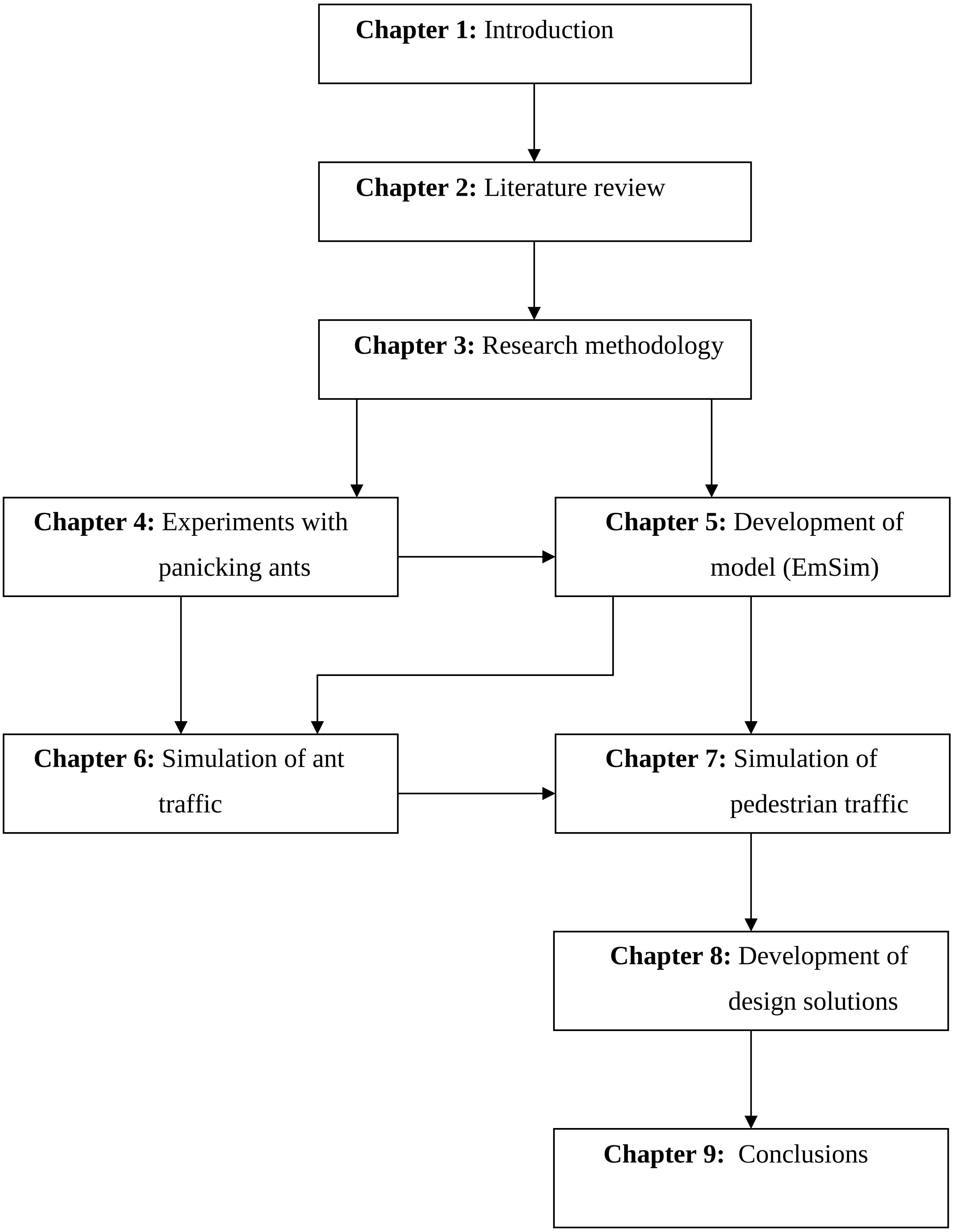


Figure 1-1: Structure of this thesis showing relationships between nine chapters

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

This chapter reviews the existing literature on the study of pedestrian crowds. Items from the biological literature which are relevant to crowd study are also covered. Most of the existing literature on crowd dynamics focuses on non-panic conditions. Only a few researchers focus specifically on pedestrian behaviour under panic conditions. To study and represent the complex phenomena of crowd movement, investigations have been carried out by researchers using different approaches (Shiwakoti et al. 2008a). Figure 2-1 shows a classification of the existing research which highlights a higher order grouping depending on whether studies have used mathematical modelling and simulation, experimental studies or drawn on socio-psychology approaches.

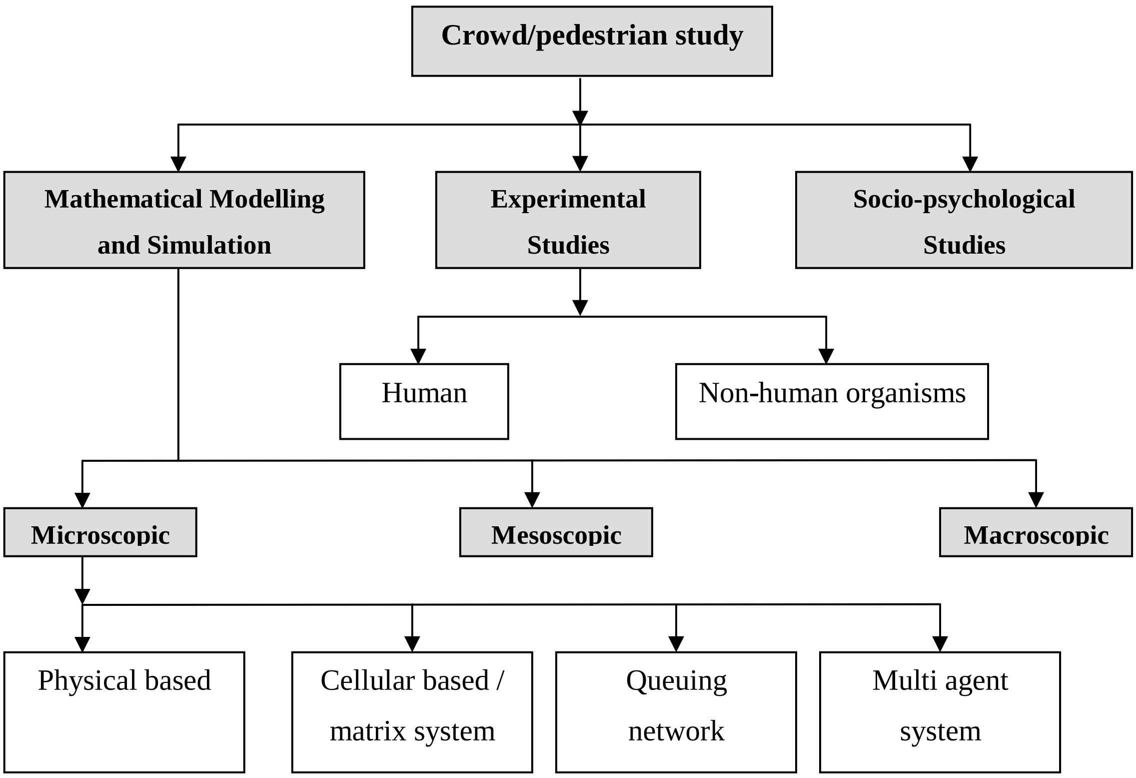


Figure 2-1: Study of crowd dynamics from different perspectives

Mathematical modelling and simulation can be further classified as microscopic, mesoscopic and macroscopic depending on the level of detail. In microscopic modelling approaches, there are various techniques such as physical based, cellular based, queuing network and multi agent system to model pedestrian dynamics. The experimental studies have been carried out with both human and non-human organism to study collective dynamics. The remaining subsections present in detail the approaches from different perspectives and highlight the limitations of the existing studies.

2.2 Mathematical modelling and simulation

There are many simulation models and software packages for simulating pedestrian motion. Those models can be classified based on their space representation (continuous / grid based / network structure), purpose (specific purpose / general purpose), and level of detail (macroscopic / mesoscopic / microscopic). Dedicated theory and models focused especially on panic/emergency conditions are, however, still at an early stage of development (Helbing et al. 2000). It is not the focus of this section to review commercial software packages for evacuation simulation but rather to examine the underlying theoretical foundations on which they are based. The discussion here is structured on the basis of the level at which the system is represented and followed with consideration of the validation approach for those models.

2.2.1 Macroscopic models

Macroscopic models focus on the aggregate representation of pedestrian movements in a crowd through flow, density and speed relationships (Fruin 1971, Still 2000, Daamen 2004). The macroscopic behaviour reveals that the pedestrian average speed is reduced as the density increases. The flow equation, derived from analogy to fluid flow, is given by

Flow (Q) = Average Speed (V) x Average Density (K) (2-1)

The reciprocal of the density is called the Space Module or Area Module (M) which is a more convenient way to describe factors affecting pedestrian flow in humans (Teknomo 2002). This lead to,

Pedestrian Flow (Q_p) = Average Speed (V_p) / Area Module (M) (2-2)

The Highway Capacity Manual (Transportation Research Board 2000) categorises level of service for footpaths, stairways and cross flows based on the relationship between space, average speed and flow rate. Daamen (2004) outlines flow, density and speed relationship for pedestrians as proposed by several researchers based on empirical observations and also presents a macroscopic model (SimPed) for modelling passenger flows in public transport facilities. This simulation tool, which is meant as an aid in the planning and design process, covers route choice, boarding and alighting as well as walking.

Macroscopic models treat pedestrian movement like a continuous fluid and rely on the behaviour of the fluid as a large scale interactive system. Macroscopic analysis may be suited for very high density, large systems in which the behaviour of groups of units is appropriate. However, by representing the particles (pedestrians) as unthinking elements, these models do not account for the fact that varied behaviour of individual particles can significantly change the way in which the fluid (crowd) as a whole behaves, especially in emergency situations. Hughes (2002) proposed a theory for the flow of pedestrians based on continuum modelling which attempts to model the flow of pedestrians as a “thinking fluid” based on well-defined hypotheses. The theory has been designed for the development of general techniques to understand the motion of large crowds; however, it has the potential to be used as a predictive tool. The behaviour predicted by the proposed macroscopic model has been compared with aerial observations for the Jamarat Bridge near Mecca, Saudi Arabia. The continuum hypothesis is stated to be invalid for a supercritical flow (low-density) and thus there is scope to extend in a probabilistic manner the continuum theory of pedestrian flows to low-density flows. Such an extension is believed to provide an important interface between discrete and continuous models of human flows (Hughes 2002). Lee and

Hughes (2005) have reported that the theory (Hughes 2002) was able to identify the dangerous locations for a crowd-related accident and to explain the development of trampling and crushing accidents.

Most building codes of practice for pedestrian planning and design rely on macroscopic models. However, the assumption of a linear relationship between space and flow at the macroscopic level has been questioned by several researchers based on microscopic simulations. Teknomo (2002) illustrates with an example that the performance of the movement of two opposing pedestrian streams can be enhanced by assigning the movement of pedestrians in only one direction to each door of a two-way door instead of letting them move through either of the two doors. Hence, by controlling the interactions of pedestrians, a more efficient pedestrian flow can be achieved with less space. Consideration of these interactions enables better estimate of delays to pedestrians, which is particularly important in emergency situations (Shiwakoti and Nakatsuji 2006). These are some of the prime reasons for a shift of modelling approach from macroscopic to microscopic.

2.2.2 Microscopic models

Microscopic models treat each pedestrian in a crowd as an individual agent occupying a certain space at an instant in time. These models can provide valuable insight over a wide range of behavioural inputs. The microscopic models deal with the factors that drive pedestrians towards their destination by considering the interaction between pedestrians (Helbing et al. 2002, Teknomo 2002, Asano et al. 2009). Such models give a more realistic representation of pedestrian movements. However there are problems of analytical manipulability and computational effort (Still 2000). These models can be classified broadly into four groups: Physical based models, Cellular based models, Queuing network models and Multi-agent models. The following sections review those approaches.

2.2.2.1 Physical based models

The physical based models recognise that the crowd is made up of individuals who react to events around them. These models have been primarily used to study indoor emergency and panic situations to design evacuation strategies. In the physical based model, optimal acceleration is determined based on various physical forces. By applying equations of motion, the simulation is updated in each time step. Some of the emerging models based on this concept are Magnetic Force Model (Okazaki & Matsushita 1993), Social Force Model (Helbing et al 2000), and NOMAD (Normative Pedestrian Behaviour Theory) (Hoogendoorn 2002).

The Magnetic Force Model (MFM) (Okazaki & Matsushita 1993) represents the movement of each pedestrian as if it was a magnetised object in a magnetic field. The movement is based on two forces. Magnetic forces from Coulomb's law drive the pedestrians to their goal while other forces come into play to avoid collisions with other pedestrians. The MFM is simple in terms of its formulation. Collision avoidance is considered in the model. Variations in microscopic pedestrian characteristics have not been considered. This model has been applied to two simulation examples under non-panic conditions (Okazaki & Matsushita 1993):

- Evacuation from an office building
- Movement of pedestrians in queue spaces

It was reported that the simulation examples demonstrated the capability of the model to generate flows and congestion occurring in the architectural space. It is to be noted here that these examples were hypothetical and no comparison was made between the model predictions and actual data. The parameters used in MFM used are not directly estimable. For example, it is hard to estimate the intensity of magnetic load of a pedestrian or intensity of the magnetic pole. Thus the challenge lies in calibrating the parameters of the model and in validating its predictions.

The Social Force Model (SFM) (Helbing et al 2000) is based on social field theory. In the simplified version of this microscopic model, the dynamics of each pedestrian is determined by three kinds of forces:

- Driving forces (that direct the pedestrian towards their destination),
- Social or pedestrian forces (that avoid collisions between two pedestrians through repulsive forces) and
- Granular forces (that come into play when two pedestrians touch each other and start pushing each other in a panic situation).

The philosophy of SFM is similar to MFM. However, in SFM, pushing and frictional forces are considered (via granular forces) which is important under panic conditions. It is to be noted here that in the early 1970's, similar modelling approaches considering the repulsive forces were proposed for the simulation of motion of fish (Sakai and Suzuki 1973) and panicked pedestrians (Hirai and Tarui 1975). Despite its simplicity, SFM has been successful in reproducing several collective pedestrian flow phenomena and analysing different characteristics of pedestrian flow. Its strength lies in dealing with panic situations and several simulation case studies on escape panic from a room have been performed using this concept (Helbing et al 2000). The parameters used in the model have physical meaning and can be measured (Helbing et al 2000), unlike the abstract values used in the MFM. However, Helbing et al (2000) call for the enhancement in the modelling framework for crowd panic and explore ways to assess the reliability of the model due to the lack of complementary data on human panic.

NOMAD (Hoogendoorn 2002) has a theoretical background based on the micro-economics of cost minimisation. It describes the execution of human control tasks where pedestrians are assumed to minimise the so called "running cost of walking". It has been reported to be successful in reproducing collective pedestrian flow phenomena. The model is capable of showing formation of lanes and homogenous strips in crossing pedestrian flows as well as behaviour at bottlenecks under non-panic conditions. The model is also reported to be consistent with important empirical and experimental findings on microscopic pedestrian behaviour. It has been further shown that NOMAD provides a generalisation of the SFM (Hoogendoorn 2004) under non-panic conditions.

2.2.2.2 Cellular based models

The basic idea of a cellular based, also known as Cellular Automata (CA) or matrix-based system, is to divide a floor area into cells. Cells are used to represent free floor areas, obstacles, areas occupied by individuals or a group of people, or regions with other environmental attributes. People transit from cell to cell based on occupancy rules defined for the cells (Klüpfel 2003).

Blue & Adler (1999) present a CA micro-simulation model for a bidirectional pedestrian walkway. Simulation experiments indicated that the basic model was capable of realistically simulating flows in walkways of various lengths and widths and across different directional shares of pedestrian movements. The results of the simulation are reported to be consistent with the well-established fundamental properties of pedestrian flows (Blue & Adler 1999). Schadschneider (2002) presents a cellular automaton model and reports (Burstedde et al. 2002) that the model is able to reproduce collective effects and self-organisation phenomena encountered in pedestrian traffic, e.g. lane formation in counter flow through a large corridor and oscillations at doors. Furthermore, simple examples are presented where the model is applied to simulate evacuations. However, no indication of validation of the model has been reported. Klüpfel (2003) proposed a cellular automaton model for handling complex scenarios and egress simulations under non-panic conditions. The simulation results have been validated by comparing evacuation time from evacuation trials for a theatre, primary school and ship. Kretz (2007) presented a cellular model under non-panic conditions. Kretz's model was basically an extension of previous studies (Schadschneider 2002) with the capability to simulate wide range of evacuation scenarios. Kretz (2007) also reports that the developed model is computationally efficient with the capability to simulate scenarios with a few million persons. The model has been validated by comparing the evacuation time from evacuation trials for a school. Kretz (2007) reports that the model's prediction is in good agreement with the observed empirical data from the experiment.

Although researchers have demonstrated the potential of cellular automata to model pedestrian dynamics, problems with the simulation of crowd cross flows and concourses have been reported (Pan 2006). The models are focused only on explaining normal evacuation processes. Also, the movement of people appears unrealistic, particularly when the model is illustrated graphically and people appear to hopping on or across the cells as the simulation proceeds (Pan 2006).

2.2.2.3 Queuing network

Queuing models have been applied to model evacuations from buildings (Løvas 1994). Løvas (1994) proposed a discrete event based model which uses a probabilistic approach to represent pedestrian movement toward a destination, with priority rules governing the interaction between pedestrians. Queuing models are based on the following assumptions:

- Any pedestrian facility can be modelled as a network of walkway sections, and
- Pedestrian flow in this network can be modelled as a queuing network process, where each pedestrian is treated as a separate flow object, interacting with the other objects.

The proposed theoretical model has been illustrated by several examples showing the effectiveness of the model for estimating the congestion and evacuation time in a building network (Løvas 1994). There is however no indication of the validation of the model.

2.2.2.4 Multi-agent modelling

Multi-agent based modelling is a particular type of computational methodology that allows the building of an artificial environment populated with agents that are capable of interacting with each other (Pan 2006). In these models, a set of agents follow strategies that promote their own benefit. An agent is an identifiable unit of computer program code that is autonomous and goal-directed. Agents may also possess other capabilities such as intelligence and adaptability. The agents usually act on the multi-agent system interacting with the other agents and the interactions can be characterised by certain conditions of mobility such as following other agents, leading other agents, and the inhibition of travel through congestion. These multi-agent simulations are thus quite appropriate for space-time dynamics in that they allow exploration of relationships between micro-level individual actions and emergent macro-level phenomena (Batty & Jiang, 1999). For large scale evacuation scenarios, and complex systems, multi-agent based modelling has been the preferred approach.

However, multi-agent simulations generally do not account for the force effects, which are particularly important in modelling crowd behaviours. Although people generally try to move toward goals, force effects can cause them to be pushed away from their desired trajectories and accurate models must reflect this. Also, the presence of crowd members injured by excessive force can significantly affect the ability of others to move freely. Models that do not represent pushing forces therefore cannot directly account for all these additional causes of delay.

Pan (2006) prototyped a multi-agent system framework able to model emergent human social behaviours, such as competitive behaviour, queuing behaviour and herding behaviour. Pan simulated the behaviour of human agents at a microscopic level. In the framework, each person is modelled as an autonomous agent who interacts with a virtual environment and other agents according to an 'Individual Behaviour Model' and some global rules on crowd dynamics. Pan (2006) reports the comparison of the simulation results (crowd flow rate for different passageway width) with the results obtained by other evacuation models and software. The developed model have been applied to simulate and replicate a case of crowd evacuation and also to facilitate egress design analysis for a multi-storey university building.

2.2.3 Mesoscopic models

Mesoscopic modelling of vehicular traffic does not focus on single vehicles but considers groups of vehicles in an identical environment, for example, where a group or platoon of vehicles is travelling at the same speed and in the same section. The idea of grouping individuals has seen the development of mesoscopic pedestrian flow models. For example, Hanisch et al. (2003) developed a simulation model of pedestrian flow in public buildings. Instead of modelling a single pedestrian, groups of pedestrians are used and every group has its own rules of behaviour. The main components of the model are groups of pedestrians and an abstract network to represent the environment. The groups move through a network consisting of nodes and links. Nodes are subdivided into sources, sinks and storages. Sources generate and sinks respectively destroy groups. A storage represents an area and this node can delay the pedestrian flow. Storages are basically internal resources in the environment which are used by pedestrians. Similarly, Tolujew & Alcalá, (2004) follow a mesoscopic approach for the simulation of pedestrian traffic flows in public buildings. The philosophy of the model is similar to that of Hanisch et al. (2003).

The models as described above seem to be a theoretical proposition only, with no indication of the validation approaches. However, Tolujew & Alcalá, (2004) mention that in order to test both the accuracy and performance of their mesoscopic approach a prototype simulator was designed and implemented. It is designed to be used in a control centre of a train station or an airport to deliver information on expected system behaviour to a decision support system. Likewise, Hanisch et al. (2003) also mention that a prototype simulator of their mesoscopic approach has been set up at the Fraunhofer Institute of Magdeburg, Germany. The concept of dealing with groups of people may have potential in the context of the microscopic models in order to reduce the simulation time, especially when a large number of people are to be simulated. Mesoscopic modelling techniques have specific application, especially for real time pedestrian flow to determine the delay and congestion in public areas. They may not be suited, however, to study panic / emergency scenarios.

2.2.4 Mathematical model and simulation summary

Several models for pedestrian dynamics exist, but most of them are concerned with explaining crowd dynamics under normal conditions or normal evacuation process and only few actually focus on panic (the noticeable model for panic being the SFM). Like vehicular traffic, crowd dynamics has been studied from both macroscopic and microscopic perspectives, while fewer studies attempt to study it at a mesoscopic level. The macroscopic behaviour reveals that the pedestrian average speed is reduced as the density of pedestrian flow increases. Many of the previous studies on crowd dynamics have been based on empirical study and macroscopic modelling. Interaction among pedestrians in a crowd forms an important component of microscopic study and as the movement quality of a crowd can be improved by controlling the interaction between pedestrians, microscopic study has an advantage, particularly when dealing with emergency or panic situation. Mesoscopic modelling techniques have specific application, especially for real time pedestrian flow to determine the delay and congestion in public buildings or public transfer stations. The concept of dealing with groups of people may have potential in the context of microscopic modelling in order to reduce the simulation time, especially when large number of people are to be simulated.

It is emphasized here that microscopic modelling approaches are more suitable to study relating to panic /emergency situations due to their ability to account for additional delays from interactions between individuals. The force model also has this potential, especially in devising strategies and design solutions to enhance the safety of crowds under panic situations, which is the focus of this research. Table 2-1 compares and contrast the features of the different approaches to microscopic modelling. It can be observed from the table that these approaches rarely involve calibration and validation of the model. Most of the models are either tested visually with the fundamental properties of pedestrian flow or compared with other evacuation models. Some researchers have compared their models with the data (such as evacuation time) from evacuation exercises. However, those evacuation drills do not represent the real emergency /panic conditions. Hence, the lack of real-life data under panic /emergency conditions has been a major problem in the development of theoretical models.

Table 2-1: Comparison of different approaches to microscopic modelling

Microscopic Model Approaches			
Physical based	**Cellular based**	**Queuing network**	**Multi-agent**
General Procedure to Develop the Model			
• Continuous-space • Optimal acceleration based on physical forces • Equations of motion determining the movement of people in each time step e.g. SFM, MFM, NOMAD	• Discrete-space • Space divided into cells • People transit from cell to cell based on occupancy rules defined for the cells in each time step e.g. Schadschneider (2002), Tobias (2003)	• Pedestrian facility modelled as a network of walkway sections • Pedestrian flow modelled as a queuing network process-oriented discrete-event simulation e.g. Løvas (1994)	• Each individual is modelled as an autonomous agent and process-oriented. • Agents characterized by certain conditions of mobility such as the following the other agents, the lead to the other agents, the inhibition of travel with congestion etc. e.g. Pan (2006)
Strengths			
• Even without 'decision making' capability, pedestrians keep distance from each other and shows self-organization phenomena • Suited to help design evacuation strategies	• Simple to develop and fast to update. • Suited for simulations of large complex structures	• Simple to develop and computationally efficient • Suitable to assess critical events in flow of people (like congestion) in a building and also assessing effectiveness of evacuation	• Possible to assign "decision making" capabilities to agents • Suitable for large scale evacuation scenario and complex system
Weaknesses			
• Crowd does not completely follow laws of physics • Complex structures may be hard to simulate.	• Difficulties of simulating crowd cross flow and concourses have been reported • The movement pattern seems unrealistic with the people hopping on the grid cells	• Heavily based on probabilistic assumptions • Visualization of actual movement patterns of each individual not possible	• Formal basis of the model is weaker than other modelling approaches. • Additional delay due to force effects are not considered which is important in emergency situations
Validation			
• No indication for emergency validation except visually verified observed behaviour. Validated for normal situation with experiments on human.	• Comparison with evacuation exercises for egress time from buildings, and even ships.	• No indication	• Comparison of simulation results obtained by other evacuation models for egress analysis.

2.3 Experimental studies

This section reviews the experimental studies carried out to study crowd dynamics. The focus will be on experimental studies on pedestrian traffic and non-human biological organisms.

2.3.1 Pedestrian crowds

Complementary data are required to test theoretical models quantitatively for their validity and reliability and also to compare the performance of alternative models. Data under emergency and panic conditions are rare as they are difficult to capture. Attempts have been made to validate the predictions of models through evacuation trials (Klüpfel 2003, Kretz 2007) and comparison with existing models and software (Pan 2006). Experiments using human subjects have been also performed to understand the behaviour and characteristics of human flow under normal (non-panic) conditions. Teknomo (2002) used video recordings of real life data of pedestrian crossings in normal situations to validate his model. In contrast, models simulating the behaviour of crowds in emergencies have been mostly inspected, verified and validated visually based on computer graphics.

Some researchers have tried to perform experiment on humans to understand the behaviour and characteristics of human flow. Delft University of Technology has collected video-based data from experimental pedestrian flows (Daamen 2004). These experiments have been used to observe pedestrian walking behaviour and characteristics under different conditions. Free speed, walking direction, density and bottlenecks were the experimental variables considered. Experiments have been performed for one, two and four directional traffic flows; and with bottlenecks of varying width. The experiments produced insight into the free speed distributions, speed variances, fundamental diagrams, self-organisation, and capacity of bottlenecks both for one directional and multi directional flows. Hoogendoorn (2004) reports that many of the observations made in these experiments were reproduced by the NOMAD model. Based on a frame-by-frame analysis of video recordings, Helbing et al. (2005) determined the passing times of pedestrians at certain cross sections and the related time headway (gross time gap) distributions for the following situations:

- Uni and bidirectional pedestrian streams in corridors with and without bottlenecks,
- Two intersecting pedestrian streams, and
- Pedestrians rushing toward an exit with and without an obstacle in front of it.

Evacuation exercises for buildings and passenger vessels can provide data for model validation. Evacuation trials in the past have considered public buildings (Proulx 1995, Weckman et al. 1999, Olsson 2001), industrial premises (Ko et al. 2007) and passenger vessels (Galea & Galparsoro 1994). Usually evacuation times, response time of the occupants and movement of the occupants have been observed from such evacuation trials. One particular problem with trying to perform such evacuation trials is that a large number of repetitions are likely to be required given the variability in results across runs. It might not be desirable to perform large number of repetitions from a cost point of view. Also researchers have to confine themselves to small numbers of participants with no control on level of panic, which then does not represent the true scenario for crowd behaviour. Klüpfel (2003) validated a proposed cellular automation model by comparison to empirical data from the literature and evacuation trials from a theatre, primary school and ship. The egress time based on evacuation trials of people with that of egress time obtained from simulation for those scenarios were compared. Deviations between simulations and evacuation trials exist. However it has been reported that the deviations are mainly due to subtleties in the behaviour on a microscopic level and thus on a macroscopic level (like the overall evacuation time), the differences are reported to be small (Klüpfel 2003).

It is to be noted here that experiments on humans as performed above during non-panic conditions are of fundamental importance in understanding the behaviour of people under emergency conditions as well as the calculation of evacuation time. For example, experiments with bottlenecks represent the congested part of buildings. Bidirectional flow experiments are important when both rescuers and the victims have to use the same path during emergency evacuation. However, the problem with models dealing with emergency/panic situations is that complementary data on panic to validate the model's prediction are rare as they are difficult to capture. Also, it is not desirable from either an ethical, safety or a cost point of view to perform controlled experiments on humans under emergency conditions.

2.3.2 Non-human organisms

Studies that included experiments with mice and rats (Hirai and Tarui 1975, Saloma et al. 2003) and ants (Altshuler et al. 2005) have demonstrated the viability of using these organisms to inspire designs for safe egress for pedestrian traffic under emergency conditions. The following sections review experience using these and other biological entities.

2.3.2.1 Rats and mice

Rats were used to study emergency evacuation in the early 1970's (Hirai & Tarui 1975). Hirai & Tarui (1975) performed an experiment with 10 panicking rats under emergency conditions. The experiment revealed that rats that were familiar with the exits took less time, in general, to get out of the exit than naïve rats. With the proposed model, they simulated the case of pedestrian evacuation in an underground arcade, and found that pedestrians who were familiar with the exit or followed the guiding signs were able to evacuate faster than naïve or uninformed pedestrians. Saloma et al. (2003) performed an experiment with a group of 60 mice escaping from a water pool onto a dry platform through doors of various widths and separation. The results showed that mice behave in much the way computer models predict for panicked pedestrians. When their escape route was only large enough for a single mouse, the mice made the most efficient escape to the safety of the dry platform by self-organized queuing; but as the width of the door was increased, the queuing phenomena disappeared and the mice started competing with each other, resulting in blockage and inefficient escape.

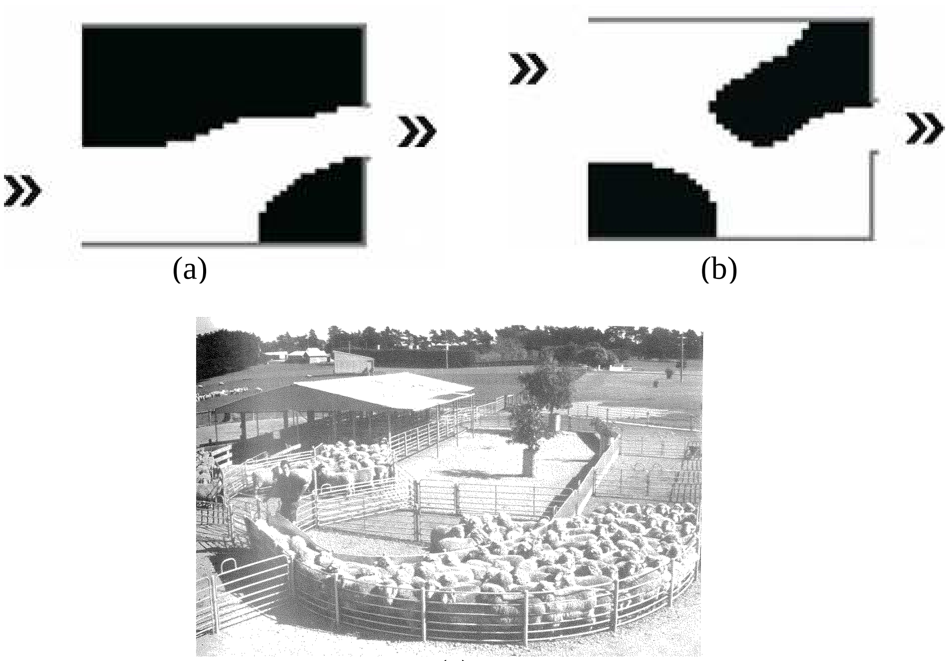
2.3.2.2 Ants

An experiment by Dussutour et al. (2004, 2005) revealed that foraging ants cope with traffic control problems much as human beings do. In the experiment, they allowed black garden ants to forage at a food source, but to reach their goal they had to cross a diamond-shaped bridge network that gave them the choice of route once they started their journey. It was observed that the mean rate of encounters per ant on a narrow arm of the bridge was lower than that on a wide arm, which suggests that ants regulate their density to cope with the delay incurred by a high rate of contact. The number of head-on encounters was lower on the narrow bridge because ants progressed on the bridge as clusters of individuals moving in the same direction, rather than as isolated individuals. Similar processes of temporal organization of bi-directional pedestrian flows moving through a narrow bottleneck have been reported by Helbing et al. (2005). As in ants, clusters of people, rather than single individuals, traverse the bottleneck before people from the other side have a chance to pass through the bottleneck.

Altshuler et al. (2005) report experiments on Cuban leaf-cutting ants that agree with symmetry breaking (ineffective use of exits) by panicked crowds. They monitored the reaction of ants to an insect repelling liquid that was introduced in an enclosed acrylic circular drum cell with two opposite, symmetrically located exits. Use of only one exit was dominant in this panic situation, while symmetrical use of the two exits prevailed in normal situations (without the repellent). Differences in the use of the two exits averaged 10.4% (± 0.1%) in a normal situation, but increased to 50% (± 4%) for a panic situation. Similar inefficient asymmetry by humans escaping from a smoky room with two identical exits has been predicted by Helbing et al. (2000) using a social force model. Escobar and Rosa (2003) highlight that seemingly small features of the physical environment may result in disproportionate influence on the escape dynamics.

2.3.2.3 Sheep

Although, to the author’s knowledge, there have been no reports of “traffic” experiments with sheep, such experiments could be highly useful to test suitable architectural adjustments for safe pedestrians egress under emergency conditions. Johansson & Helbing (2005) used a genetic algorithm and social force model to identify architectural design solutions which maximized pedestrian outflow at exits or bottlenecks. The proposed designs included a funnel shape adjustment and a compartment structure as shown in Figure 2-2(a) and 2-2(b) respectively. These adjustments were reported to increase the pedestrian outflow (in the simulation) by as much as four times. The solutions currently lack support from empirical data. However, in the early 1990's, similar funnel shaped / compartment shaped sheep yards (Casey & Hamilton 1990) were found to be up to 35% more efficient than the traditional rectangular yards for handling large numbers of sheep (over 10,000), as shown in Figure 2-2(c).



(a) (b)

(c)

Figure 2-2: Recent predicted best design solutions for emergency egress for pedestrian crowd (a) (b) (Johansson & Helbing 2005) while similar design solutions have been implemented in the past for efficient sheep flow in sheep yards (c) (Casey & Hamilton 1990).

Likewise, large mobs of sheep are normally broken down into smaller mobs in the drafting race by a divider (Casey & Hamilton 1990). Mathematical models (Still 2000, Helbing et al. 2005) have predicted the divider / barrier approach to be suitable for human crowds. The divider breaks up the tremendous pressure generated in crowds by separating the crowd into sections and thereby minimizing the local interactions. Research at the University of Leeds revealed that humans flock like sheep (University of Leeds 2008). In a series of experiments, groups of people were asked to walk randomly around a large hall. Within the group, a few were informed in detail about where to walk. Participants were not allowed to talk or gesture to one another. The findings showed that in all cases, the 'informed individuals' were followed subconsciously by others in the crowd in a self-organized manner, much like a flock of sheep. It took a minority of just five per cent to influence a crowd's direction, and the other 95 per cent followed them without realizing it. The researchers expect the findings could have major practical implications for directing the flow of large crowds, in particular in disaster scenarios, where verbal communication may be difficult.

2.3.3 Experimental studies summary

Most experiments with humans crowd aim to understand the behaviour and characteristics of pedestrian flow under non-panic conditions. Although such experiments are of fundamental importance in understanding the behaviour of people under emergency conditions, comparisons with real life data are necessary to validate any model's prediction. To provide data for model validation, evacuation exercises have been carried out by some researchers. These trials have been conducted in public buildings, industrial premises, and passenger vessels. However, a problem with such evacuation trials is the high number of repetitions required for statistical significance. Also, there are ethical and safety concerns that prevent creating a real panic. Researchers have to confine themselves to small numbers of participants with no control on the level of panic, which then may not represent the true scenario for pedestrian crowd behaviour. Experiments with non-human organisms offer the potential to overcome such limitations as demonstrated by some limited studies on rats/mice and ants.

2.4 Socio-psychological studies

In general, the dictionary definition of the word "crowd", as stated in the website of Lexico Publishing Group (2007), means a gathering of people. However, from the socio-psychological point of view, "crowd" is understood in a different way. Crowd studies from a socio-psychological (sociology) perspective have been carried out over many years and the focuses have been to study the crowd characteristics (collective behaviour) and their mental state in a given situation. Crowd (rather psychological crowd) is the formation of collective minds with new distinctive characteristics very different from those of the individuals who constitute the crowd. Sentiments predominate over intelligence and the transformed sentiments can lead to heroic or criminal crowd (Bon 1960). Special characteristics of psychological crowds are (Bon 1960):

- The turning in a fixed direction of the ideas and sentiments of individuals composing such a crowd, and the disappearance of their personality
- The crowd is always dominated by considerations of which it is unconscious
- The lowering of the intelligence and the complete transformation of sentiments
- The transformed sentiments may be better or worse than those of the individuals of which the crowd is composed.

2.4.1 Crowd and panic

The dictionary definition of the word "panic" as stated in the website of Lexico Publishing Group (2007) is a sudden overwhelming fear, with or without cause, that produces hysterical or irrational behaviour, and that often spreads quickly through a group of persons or animals. But from a socio-psychological point of view, the word "panic" for a crowd is much more complicated than its literal meaning. Piere (1938) states that the panic behaviour of a crowd is the consequences of the agglomeration of many factors in an entirely unpredictable way. According to Piere, the only thing which can be said with any certainty is that the behaviour of the individuals in a panic situation will not be a direct consequence of their inborn natures. It will be a fortuitous synthesis of their acquired patterns of response. The origin of panic behaviour lies in two circumstances:

- Any occurrence of a crisis that is a source of danger or personal threat and
- Lack of leadership in the crisis.

Mintz (1951) stated a new paradigm of panic which contradicts the assumption of personality alterations of people due to crowd membership in panic, i.e. the common tendency to view emotion as a predominantly destructive factor in behaviour is questionable (Turner & Killian 1962, Brown 1965). Mintz argues that the competitive behaviour or dispersal occurring in panics suggests that group cohesion disappears and that people begin to behave purely as individuals in accordance with their selfish needs. Mintz believed some "unstable reward structure" is the essential condition for the occurrence of panic rather than "extreme fear". The proposed theory has been partially backed up by a subjective model experiment of penalty and reward. In the experiment, aluminium cones with attached strings were put in a large bottle, the bottle having a narrow neck such that only one cone at a time could be withdrawn. If two cones arrived together, they would jam the neck of the bottle. Experimental subjects held the ends of the strings. In one condition water was gradually admitted to the bottle from below and each subject was told that they would be given twenty-cents if they removed their cone from the bottle while it was still dry or else a fine would be imposed on failure. As the wet area of the cone increased, participants would be expected to pay increasingly large fines. The water is Mintz's fire, the neck of the bottle his exit, and the cones are people. In these conditions, intended to duplicate the conditions of panic, traffic jams invariably occurred. Some groups of subjects were allowed to make a plan of cooperation. Even when such plans were made, however, serious traffic jams usually occurred. On the other hand, when the water and the rewards and penalties were removed and the subjects were simply told to draw the cones from the bottle, no serious jams occurred even though Mintz instructed some subjects to make noise and do their best to "panic" to others. So it is basically the unstable reward structure of the situations which is responsible for non-adaptive behaviour of groups in panic situation. Kelley et al (1965) criticised Mintz's procedure and conceptualization. They mentioned that Mintz's method cannot be considered to test the effects of danger. They believe that the monetary reward /penalty do not provide insight on behaviour under conditions of high stress. Kelley et al (1965) argues that the degree of threat or danger is important and demonstrates that the higher the threatened penalty for failure to escape, the greater is the degree of un-coordination.

Based on the data collected from interviews of approximately 1000 persons involved in a variety of community-wide and localized disasters, Quarantelli (1957) postulated several hypotheses for crowd behaviour in panic. According to Quarantelli, panic participation flight (panicking crowd) is not necessarily non-functional or maladaptive. Sometimes it is adaptive and sometimes not. For example, physical barriers might lead to panicky participants trampling each other even if their coordinated action is functional. This phenomenon has been simulated based on a mathematical model by Helbing et al (2000) where the victims in a smoky room lying in the floor acted as physical barriers to people fleeing from a smoky room, thus generating more chaos. Aspects of panic behaviour as presented through several hypotheses by Quarantelli (1957) are:

- The panic participants experience, whether individually or through interaction with others, situations involving a direct threat to one's physical existence. This is different to other panic situations like bankruptcy which are not related to physical bodily terms. Participants can orient themselves in time and space to the situation and can flee.
- Participants who panic are focused on future-threat rather than past-danger and anticipate possible entrapment and so rapid reaction of some sort is considered necessary for survival. However, the reaction depends on how the person perceives the situation and how it is defined by the reactions of others. Consequently, panicky reactions can occur in situations involving no real threat.
- Participants who panic are self-conscious and fearful. The more threatening they regard the situation, the greater awareness of themself.
- Panic flight is directed toward the goal of getting away from the area of danger although sometimes the person may appear to move in the direction of threat. Convergence of fleeing persons in a collective panic frequently occurs.

- Participants who panic exhibit non-rational flight behaviour; however, their thinking is not necessary “irrational”.
- Panic is not necessarily non-functional or maladaptive. Sometimes it is adaptive and sometimes it is not. Physical barriers might lead to panicky participants trampling each other.
- Panicking persons act in a non social way. The non-social aspect of this panicky reaction is primarily in regard to failure to play conventional social roles and to follow the expected interaction patterns.

Sime (1995) argues that engineering studies focus directly on design issues such as entrance and exit widths while psychological studies are more concerned with the motivations of people, the nature of the behaviour and the way it is interpreted. He argues there is a need to concentrate on crowd psychology in the context of crowd safety engineering concerns. Mawson (2007) provides a synthesis of the mass panic studies and proposes a social attachment model that highlights the consideration of attachments in mass panic study. He argues that increased affiliation and companionship are the major factors that lead people to response to frightening stimuli or threat rather than flight /fight or social breakdown as has been conceived in previous models.

2.4.2 Socio-psychological studies summary

Studies on behavioural models of panic/emergency situations have been conducted by sociologists over many years. However, relatively few studies of irrational/non-adaptive behaviour exist in the literature prior to the 1970’s. There is debate among researchers regarding whether or not people are rational under panic conditions. It is for those reasons that some boundaries on the interpretation of emergency/panic were specified in Chapter 1 so that there was clarity in the meaning of those terms in the context of this research. As mentioned in Chapter 1, the focus should be on addressing physical competition and pushing behaviour, whatever the emotional state of mind of the participants in the evacuation.

The collective behaviour of a crowd during emergency (panic) situation is different and quite complex compared to a normal situation. Perceived threat and mutual influence are key factors (but not sufficient) for the development of non-adaptive panic behaviour in a crowd. The degree of threat / panic is seen to determine whether individuals constituting a crowd lose identity and follow the crowd or whether the group cohesion disappears and people begin to act individually (either rationally or irrationally) according to selfish needs. How crowds escape in panic is thus highly dependent on how the group goals and individual goals are constituted and coordinated in the panic situation. Having said that, the panic escape of a crowd is not only dependent on the degree of threat/panic, but also on the physical space/layout through which they escape. For example, exits with/without a physical barrier, and victims (acting as barrier) can produce chaos and panic in an escaping crowd. Thus, although the socio-psychological theories may explain why an individual becomes panicked, these theories however do not explain the dynamics of crowd. They might not also consider the effect on panic escape from the layout of the escape area. These could be some of the reasons that results of these socio-psychological studies can not often be directly applied to enhance the safety of pedestrian facilities.

2.5 Gaps in knowledge

Based on the literature survey, it was observed that there are certain major gaps in knowledge of crowd dynamics under emergency conditions. They are summarized below:

- ***Lack of complementary data***

Complementary data are required to develop and to test the theoretical models quantitatively for their reliability and also to compare the performance of alternative models. Data under panic conditions are rare as they are difficult to capture. The techniques required to extract the required data are also of concern for model calibration and validation. Models simulating the behaviour of crowds in panic have been mostly inspected, verified and validated visually with computer graphics due to lack of data, while other models have been validated by comparing egress time based on evacuation trials. But the actual control on level of panic is not possible in such experiments. As panic tests in humans are not desirable due to ethical, safety and cost concerns, there is an urgent need for exploration of some alternative empirical measures to address the problem of data scarcity. Also the repetitive nature of the experiments makes it necessary to explore some alternative approaches.

- ***Lack of quantitative theory and simulation model for crowd panic***

Systematic studies of panic behaviour and quantitative theories capable of predicting such collective dynamics are rare. Even those existing limited models of crowd panic are in need of a better modelling framework. That difficulty is due to the lack of complementary data to test the model's predictive capability as mentioned above. Hence, most study on crowds focuses on modelling normal evacuation processes rather than panic situations. There is also a gap in testing the model with a detailed analysis of the effect of change in behavioural variations (model parameters appropriate to individuals of diverse sizes and behaviours) on the outcome of the crowd panic model. Such analysis has not been conducted in the existing studies. It is necessary to consider those factors to assist emergency planners in making safer decisions. Such tests of model robustness help to identify whether the core theory underlying the model is correct.

- ***Application of knowledge on collective dynamics of non-human organisms to pedestrians***

Limited studies on the collective dynamics of animals highlighted the importance of dynamical features of collective patterns. However, findings from these studies have seldom been applied to the study of human collective dynamics. There is a lack of knowledge on how and to what extent the study of the collective dynamics of non-human biological organisms can be applied to the study of crowd panic. There is potential opportunity to explore the contribution that research with non-human organisms could make to understand the complex pedestrian behaviour and the enhancement of pedestrian safety during emergency egress.

The above mentioned major gaps in the existing knowledge have influenced the framing of the aim and objectives of this dissertation. The following chapter outlines the research methodology and the approach taken in this study to address the gaps in knowledge highlighted above.

CHAPTER 3 RESEARCH METHODOLOGY

3.1 Objectives

Based on the knowledge gaps identified in the Chapter 2, the following specific objectives have been developed to fill the gaps. These objectives are consistent with the overall aim described in Chapter 1.

1. To establish the viability of using non-human organisms in the development of a pedestrian crowd model.
2. To develop a simulation model for crowd dynamics under emergency conditions based on animal dynamics, which is capable of simulating the effects of microscopic variations in pedestrians' egress behaviour.
3. To develop a method for scaling the model parameters from non-human organisms to pedestrians.
4. To test the application of the model in assessing the effectiveness of practical solutions for improving the safety of crowds.

3.2 Methodology

Achieving the research objectives requires that this study draws on concepts from traffic engineering, micro-simulation and biology. The overall research approach is summarised in Figure 3-1.

The extensive literature survey, reported in Chapter 2, provided the foundations for the study by drawing insight from literature covering both pedestrian traffic and biological perspectives. This provided a basis for assessing the existing theories and models for collective pedestrian dynamics and animal dynamics; relevant existing empirical data; and most importantly identifying the knowledge gaps.

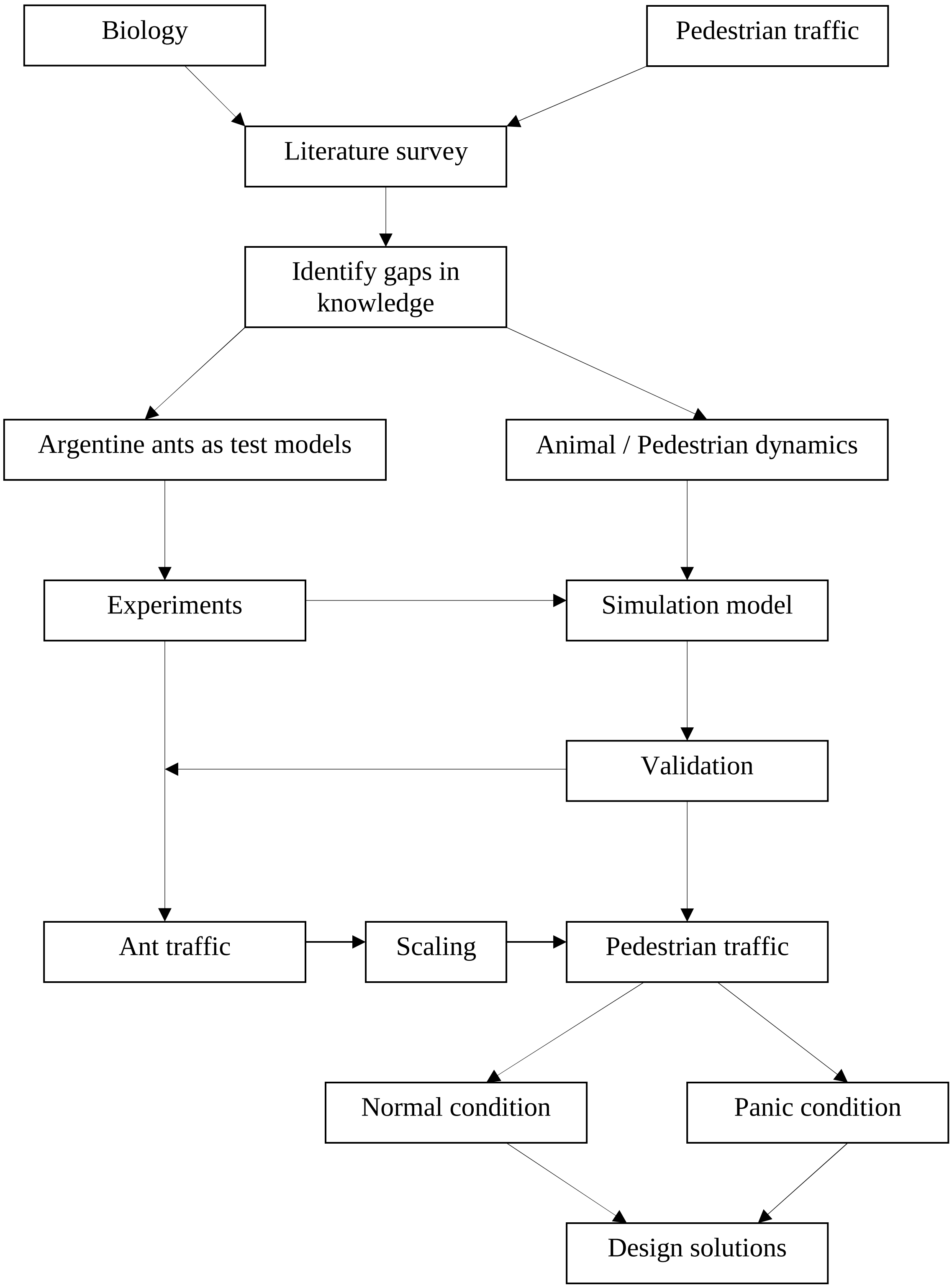


Figure 3-1: Conceptual flow chart of the research approach

The lack of complementary data on human panic is a critical gap in the study of collective human dynamics that has limited the development and assessment of models in this context. That lack of data is most likely a major factor explaining why very few models focus on panic situations. The bulk of the literature is restricted to the study of normal evacuation processes. Even the researchers responsible for developing the few existing models of crowd panic have identified the need for more rigorous modelling frameworks and the development of approaches to assess the reliability of model predictions.

To overcome the severe limitation that lack of complementary data on human panic has on the development of pedestrian models, experiments with non-human organisms under panic conditions represent a promising and feasible opportunity. As highlighted in literature review, studies that included experiments with mice and rats (Hirai and Tarui 1975, Saloma et al. 2003) and ants (Altshuler et al. 2005) have demonstrated the viability of using these organisms to study collective pedestrian dynamics under emergency conditions. Using ants to model pedestrian traffic behaviour shows promise, since they naturally form collective traffic and follow physical paths in ways that resemble human crowd movement.

Ant-inspired solutions to crowding problems might be especially useful, in that humans have been dealing with traffic congestion for only a few hundred years at most, while ants have been dealing with congestion over millions of years of evolution. Any common features of dynamical behaviour of ants and human pedestrians could make ant colonies a potentially valuable resource for testing models of panic behaviour and designs to ameliorate crowd disasters (Burd 2006). Nishinari et al. (2006) state that there are similarities between ants on a trail and pedestrians in evacuations, since both try to follow the signals of other individuals (through pheromone on a trail and information from one’s eyes and ears, respectively). They proposed a pedestrian model based on the application of the concept of ants trails to model normal (non-panic) evacuation processes. Altshuler et al. (2005) suggested that some features of the collective behaviour of humans and ants can be quite similar when escaping under panic, despite sizable differences between traffic in humans and ants in normal conditions.

The above mentioned experiences of using ants in previous studies implied that ants may be effectively used as model organisms for testing theories of escape panic. However, there have been no further studies using ants as test organisms to study crowd panic. Ants offer a number of advantages compared to other organisms for the study of crowd panic, including their ready availability, ease of handling, and the simplicity of the equipment needed to perform the experiments (Shiwakoti et al. 2009a). Also they are social organisms (Hölldobler & Wilson 1990) which make them generally comparable to human. Likewise, there are many species of ants (Hölldobler & Wilson 1990) which may enable researchers to conduct studies around specific properties that a species may possess.

One needs to be careful however when comparing ants to humans. There may be some large taxonomic differences that should be explored. Also ants are generally believed to be non-selfish in nature (Hölldobler & Wilson 1990). However, new research suggests that ant society is also rife with corruption and cheats similar to human society and that they are not always non-selfish (Hughes and Boomsma 2008, BBC 2008). In the study, researchers used DNA fingerprinting on five colonies of leaf-cutting ants. They found that the offspring of some fathers (called "royal ants") were more likely to become reproductive queens than others. These so called "royal ants" pass the gene on selectively, to ensure that their offspring become reproductive queens, not only workers. Previously it had been thought that ant queens were the products of nurturing i.e. some larvae were fed certain foods to prompt their development into queens (Hughes and Boomsma 2008). However, the research revealed that these "royal ants" cunningly spread their offspring to several colonies, so that the unfair advantage to their offspring is not spotted. The researchers with those findings also underline that social evolution in very different taxonomic groups can be understood from the same general principles (Hughes and Boomsma 2008).

Bourke & Franks (1995) mention that both co-operation and conflicts exists in ants society. Thus, it can be expected that ants also show selfish behaviour depending on circumstances. It is also to be noted that ants were chosen for the experiment under panic conditions and not for non-panic conditions. In panic conditions, collective intelligence dominates the individual intelligence unlike in non-panic conditions where it is vice versa. Likewise as mentioned in previous study (Altshuler et al. 2005), there are some similarities between human and ants panic escape. If one could observe those similarities for relatively adequate time in a situation that is comparable to escape panic in people, then one can assume that ants were behaving selfishly.

With these previous researches in mind and based on the resources availability and limitations, Argentine ants (*Linepithema humile*) have been selected as test organisms in this dissertation. One of the advantages of using Argentine ants is that these species are reported to display natural evacuation process (LeBrun et al., 2007). These ants are native to the Río Paran´a drainage of subtropical South America (Wild, 2004), where flooding regularly forces colonies to evacuate their nests and seek refuge in trees (LeBrun et al., 2007). Thus, the dynamics of collective movement during the abandonment of a nest are likely to be a part of the natural repertoire of behaviors in this species. In areas where Argentine ants has been introduced, colonies seem to abandon nests frequently (Heller & Gordon, 2006), suggesting that the dynamics of departure from a nest may have large effects on colony fitness. Also these species are found in abundant in Melbourne, Australia (ABC 2005) for conducting the experiments. They have become invasive worldwide and are major ecological concerns in many countries including Australia (ABC 2005). There is also no animal ethics clearance required for performing experiments with these species of ants at Monash University. According to Monash University (2008), only live non-human vertebrate or live crustaceans, octopus or squid require animal ethics clearance in research.

Insights from the experiments with panicking Argentine ants, along with previous studies on animal dynamics and pedestrian dynamics, are then used in the development of a simulation model. The simulation model has been calibrated and validated on the basis of its ability to accurately simulate both panicking ants' and pedestrians' traffic. Scaling concept derived from biology has been employed to enable the model to simulate the collective dynamics of individuals which range in size from ants to human. The model has been tested for collective pedestrian traffic both for panic and non-panic (normal) situations in order to demonstrate the capability of the model in accommodating both panic and normal conditions within the same framework. For panic scenarios, the model has been validated through scaling of the ants experiments scenario to a human case. For normal situations, the model has been validated through experimental data on pedestrian traffic. With the developed model and knowledge gained from the ants experiments, various design solutions has then been tested to assess their potential to enhance the safety of pedestrian crowds.

In the next chapter, experiments with panicking Argentine ants are presented to gain insight into human panic.

CHAPTER 4 EXPERIMENTS WITH PANICKING ANTS

4.1 Introduction

As discussed extensively in the literature review and research methodology chapters, using ants to model pedestrian traffic behaviour shows promise. To gain insight into human panic, a series of experiments were performed with Argentine ants under panic conditions. The main motive for the experiments was to observe and study how the collective movement patterns of the organisms are affected by the layout of the escape area or the presence of certain geometrical structures in the vicinity of the exit. These experiments reflect an original attempt to study the effect of geometrical structures on the collective movement patterns of non-human entities during rapid egress and translate those results to the study of human panic.

Pedestrian models have generated a number of surprising or counterintuitive predictions. For example, escape rates will be enhanced if there is a partial obstruction or barrier (such as a column) on the "upstream" side of an exit (Helbing et al. 2002), although empirical validation of such models in panic situations remains incomplete (Shiwakoti et al. 2009a). Also in biology, little attention has been given to the study of the effect of nest design elements on collective movements of social insects (Burd et al. 2010). Social insect colonies face a number of threats that may require rapid movement. For example, ant colonies often abandon their nests in the face of flooding (Wilson, 1986), attack by predators (Wilson, 1976; Droual, 1983), or raids by slave-making ants (Trager and Johnson, 1985). These movements are often described qualitatively and anecdotally, but there has been little in the way of quantitative or experimental tests of nest evacuation. The experiment that is reported here addresses those gaps in the study of alarm traffic in social insects as well, by drawing attention to the wider issue of the relation between nest architecture and internal traffic under alarm conditions.

The experimental scenarios presented here are not limited only to ants, but could be tested with other biological entities like mice, sheep, etc., according to resource availability. Ants, however, as discussed extensively in the research methodology, are more appropriate organisms to use for these experiments. The ants used for the experiment are ‘Argentine’ ants (*Linepithema humile*). Initial insight from these experiments featured in an Australian Broadcasting Corporation (ABC) television segment and can be viewed online (ABC TV 2008). To study collective movement patterns under panic conditions, five scenarios of experimental trials were conducted. They are mentioned as below:

1. Ants escaping from a circular chamber with partial obstruction (a column) near the exit (30 repetitions).
2. Ants escaping from a circular chamber without partial obstruction (30 repetitions).
3. Ants escaping from a square chamber with exit at the middle of the side walls (10 repetitions)
4. Ants escaping from a square chamber with exit at the corner of the walls (10 repetitions)
5. Ants escaping from a square chamber with exit at the middle of side walls and partial obstruction (via a column) near the exit (5 repetitions)

It is to be noted here that more number of replications of the experiments reduces variability in experimental results thereby increasing their significance. As performing experiments with biological organisms is a time consuming task, tradeoffs were made between the time constraints for this study and the number of replications. However, it is expected that the number of repetitions chosen above provides the confidence level with which conclusions can be drawn about experimental factor.

In performing ant experiments, due care was taken to minimize the injuries and death of ants as much as possible. The ants were released to their natural habitat after the completion of the experiment.

4.2 Collection of ants colonies

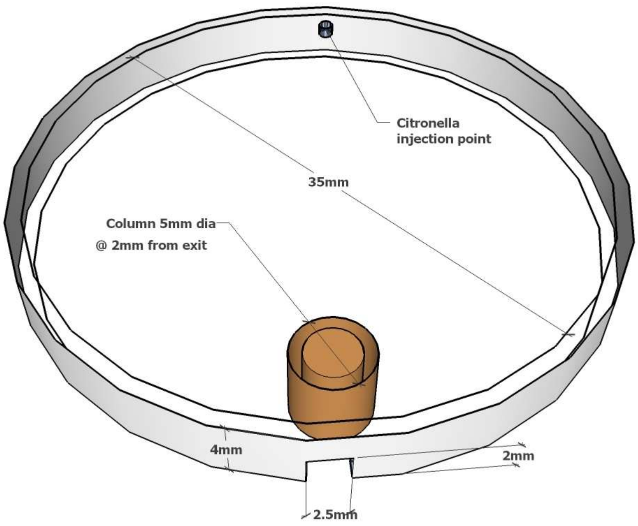
Colony fragments of Argentine ants were excavated from the grounds of Clayton Campus of Monash University (37°54′ S 145°07′E), Victoria, Australia. The colonies were collected up to a depth of 15 cm from the ground. The soil containing the ants was placed in plastic tubs. The plastic tubs had their sides coated with Fluon to prevent the ants from escaping from the tubs. The tubs were stored in a constant temperature (C-T) room to create favourable conditions for the ants. Artificial nests were kept into the tubs in the C-T room in order to attract the ants towards those nests from the soil. The artificial nests consisted of a circular chamber that was glued to a plastic base, which was itself the lid of a container holding about 300 ml of water. A small cotton wick connected the reservoir and the nest interior to draw up water and humidify the chamber. The humidity from this wick enticed the ants to nest in the apparatus. Ant food was provided regularly for the ants. Soil was occasionally removed from the tubs in order to make nesting in the soil less preferable. However, the process of collecting sufficient number of ants for the experiment via artificial nest was a time consuming task. In order to reduce the collection time for ants, in the later stage of the experiments, the ants were collected through a tool called an ‘ant extractor’. The ‘ant extractor’ was developed at School of Biological Sciences, Monash University.

The ‘ant extractor’ consisted of cylindrical PVC (polyvinyl chloride) tube that had a hole near the base. Inside the cylindrical chamber, there were four layers of circular moulds of clay tied to a rod. The moulds were soaked in water to create moist conditions inside the chamber. The cylindrical chamber was kept in the plastic tubs and the soil in the tub was dried through hot air from a heater. As the soil began drying up, the ants moved up from the soil and entered the cylindrical chamber through the hole in the bottom. Due to favourable conditions (moist environment) inside the chamber, the ants made their nest on the moulds. When the population within the artificial nest/‘ant extractor’ was stable (200-250 in number), the artificial nests/ant extractor was then transported to the laboratory for the experiment. Photographs of equipments pertaining to ant collection are presented in Appendix A.

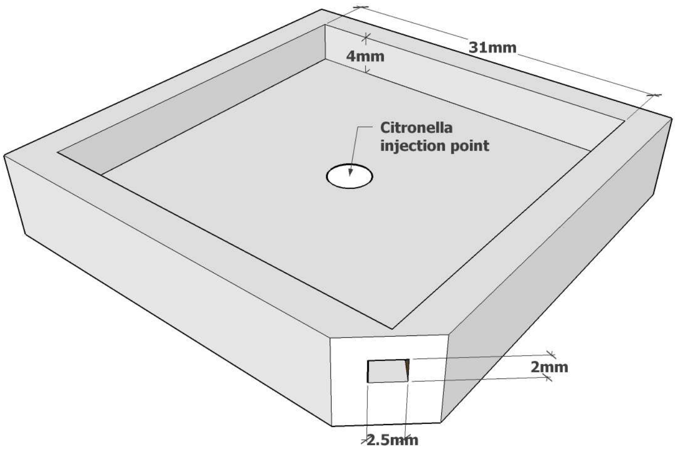
4.3 Experimental setup

Figure 4-1 shows the schematic diagram of the evacuation chambers for circular chamber and square chamber experiments. For the circular evacuation chamber, the nest was made from an upturned transparent plastic petri dish lid, 35 mm in diameter and 4 mm deep. Each nest had a single "mouse hole" entrance/exit that was 2.5 mm wide and 2.0 mm high. These dimensions allowed unimpeded passage of a single ant into or out of the nest, or somewhat encumbered passage of two ants simultaneously. The square chamber experiments used wooden chambers measuring 31mm by 31mm (an equivalent area to that of the circular chamber area). The exit width and floor-to-ceiling depth were the same as in the circular chamber experiment. The square chambers were covered with transparent Fluon coated plastic lids to prevent ants escaping out from walls. To study the effect of a partial obstruction to the exit, a circular plastic column 5 mm in diameter and 4 mm tall was placed 2 mm in front of the exit, slightly asymmetrically to the main axis of the exit. A small hole was created in the roof of the chamber to inject citronella (an insect repellent liquid) for creating panic.

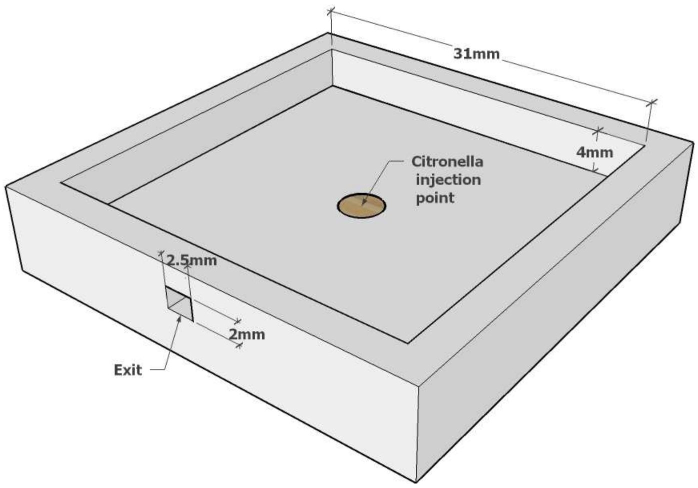
In the laboratory, ants in the artificial nests were removed into a plastic box (33x 23x12 cm) with Fluon coated interior sides. In case of 'ant extractor', the rod containing the moulds was taken out and then ants were brushed off from the moulds inside the plastic box. The evacuation chamber (for five scenarios) on which the experiment was to be conducted was then placed into the box. Each experimental trial involved a group of 200–250 ants which were sufficient to create a high density environment for the given chambers. The plastic box was left overnight in order to allow the ants to settle and occupy the evacuation chamber before conducting the experiment. Also ant food was provided in the plastic box. The evacuation chamber was humidified through the same process of creating humid condition in artificial nest during collection of ants. For square chamber experiments, a pathway made of sticky rubber attached and flushed to the base of the exit was created. The purpose of that was to make the counting of the escaped ants easier.



(a)



(b)



(c)

Figure 4-1: Schematic diagram showing evacuation chambers for circular chamber experiments (a) and square chamber experiments with corner exit (b) and middle exit (c)

4.3.1 Preliminary trials

Some preliminary trials were first conducted to confirm the symmetry breaking phenomena as previously reported (Altshuler et al. 2005). With the experiments on Cuban leaf-cutting ants, Altshuler et al. (2005) reported that their experiments with ants agree with the symmetry breaking (ineffective use of exits) by panicked crowds (Helbing et al. 2000). The motive for confirming that phenomenon with Argentine ants was to develop confidence in the appropriateness of the model organism and the experimental setup for the intended study. To study the effect of multiple exits, evacuation chambers with two exits and four exits were created with the same dimensions as mentioned for the circular chamber experiment. Three repetitions were conducted for the two-exit experiment while one repetition was conducted with four exits. It is to be noted that these preliminary trials to test symmetry breaking had certain differences to the experimental setup compared to Altshuler et al. (2005) as follows:

- The experiment uses different species of ants (Argentine ants vs. Cuban leaf cutting ants)
- The Argentine ants are encouraged to make their nest in the evacuation chambers in a natural way by themselves in the experiment. This is in contrast to Altshuler et al. (2005) where the ants were manually picked up and placed in the test chamber. Also they evacuated the chamber almost immediately following placement of Cuban leaf cutting ants.
- The density of ants considered for each experimental trial is around 200-250, which is much higher than in Altshuler et al. (2005). Altshuler et al. (2005) used only 66 Cuban leaf cutting ants for the experiment. Research shows that a high-density environment is much riskier than a low-density one (Still 2000).
- One additional experiment with four exits was also carried out to see the effect on asymmetric escape with increase in exits. Altshuler et al. (2005) performed experiment with two exits only.

In order to create panic, an attempt was made first to inject diluted ethyl acetate into the chambers using micromanipulators. However, it was noticed that diluted ethyl acetate, although highly repellent, was too toxic for the Argentine ants, leading to rapid deaths of ants. Trials were then made with the injection of 10 micro-litre of citronella liquid (an insect repellent) in the evacuation chamber, as mentioned in Altshuler et al. (2005). Ants rushed toward the exit(s) when the citronella was introduced, in a manner reminiscent of humans in a crowd panic. The smell of the citronella repelled the ants. The ants were not killed unless they came into contact with the concentrated droplets of citronella. Hence, citronella liquid was selected to create panic among Argentine ants. The experiments were recorded via digital camera. The number of ants that escaped from each exit was measured by manual counting from playback of digital video recordings. In the two-exit experiments, the average difference in exit usage was 28%, while in the four-exit experiment the relative use of two exits out of the available four exits was 74% as shown in Tables 4-1 and 4-2.

Table 4-1: Number of ants evacuating in different exits of chamber with two exits

Experiment	Total no. of ants	No. of ants evacuating at		Difference in exit usage*
		1st exit	2nd exit	
1	106 (approx.)	61	41	20 %
2	155 (approx.)	113	39	49 %
3	235 (approx.)	130	99	14 %

*Remaining ants injured or remained inside

Table 4-2: Number of ants evacuating in different exits of chamber with four exits

Experiment	Total no. of ants	No. of ants evacuating at				Relative % use of two exits out of four exits
		1st exit	2nd exit	3rd exit	4th exit	
1	145 (approx.)	59	45	21	16	74 %

Figure 4-2 shows the snapshots from the experiment with multiple exits. Preliminary experiments with two exits and four exits thus pointed to ineffective use of available exits, as predicted for humans escaping under panic (Helbing et al. 2000) and for Cuban leaf cutting ants (Altshuler et al. 2005). However, it is to be noted here that the number of repetitions performed for these preliminary experiments are few for statistical significance and are thus indicative results only.

Still (2000), with a simple calculation based on a network, reveals that network analysis as followed in building guides for crowd control needs to be updated. Still highlights that when a network offers alternatives for egress, the impact of losing some of these in an emergency has to be part of the safety calculations. This symmetry breaking phenomena is not only observed in non-human entities and pedestrian traffic but also has been a notable problem in vehicular evacuation. In mass vehicular evacuation, such as in New Orleans, unbalanced use of the available escape routes has lead to inefficient evacuation (Wolshon, 2002).

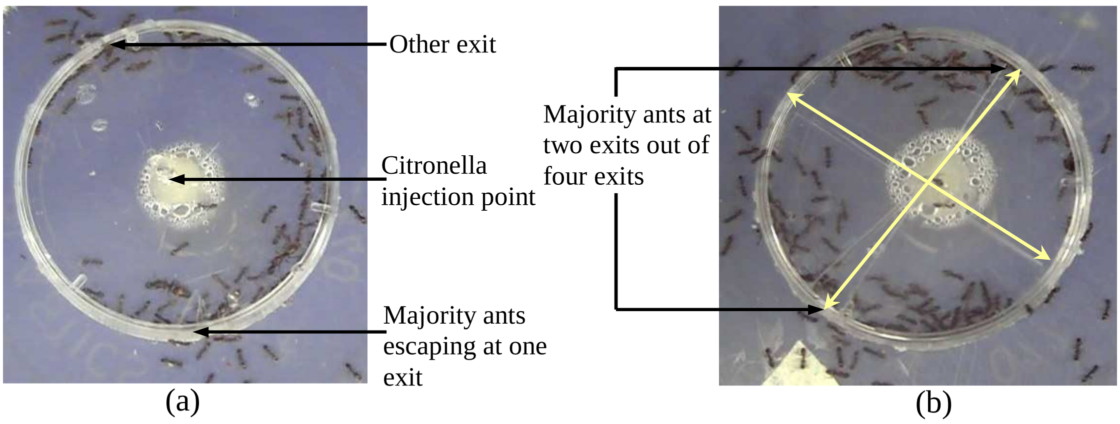


Figure 4-2: Preliminary trials on symmetry breaking phenomenon in two exits (a) and four exits (b) experiments

4.4 Experiments

The success of preliminary experiments on symmetry breaking confirmed the realism and efficacy of the experimental setup, and allowed the continuation of the intended experiments for this research study. Experiments were first performed with and without the presence of a partial obstruction (column) near the exit in the circular evacuation chamber. Thirty repetitions for each scenario (with or without the column) were conducted. After completion of these trials, the experiments with a square chamber were initiated. There was no control on the time that each trial was performed, although they were performed in the afternoon or in the evening. The injection point of citronella was at the back of the chamber for circular chambers while it was at the centre for rectangular chambers as shown in Figure 4-1 simply for convenience in performing the experiments. However, there is scope to account for variations in agents (here ants) capabilities in terms of their physical features and their proximity to the threat (here citronella) in future. The citronella was injected in a cotton wick inside the chamber and not directly among the ants. The cotton wick diffused the smell of the citronella, creating panic among ants. The evacuation chamber and the plastic base (on which the evacuation chamber was glued) were rinsed with water after filming to remove any traces of citronella in them. The evacuation chambers and plastic base were reused after a minimum of two days later to allow additional time for any smell of citronella to diffuse.

4.4.1 Observations and Measurements

The experiments were recorded through digital video. The body lengths, mass, speed and reaction time of Argentine ants were measured. The sampling for those measurements was done for 100 ants in random order. The measurements of the body lengths of the Argentine ants are shown in Table 4-3, while the mass and speed are shown in Table 4-4.

Table 4-3: Measurements of body lengths of the Argentine ants

Measurement	Head length	Head width	Thorax length	Thorax width	Abdomen Length	Abdomen Width	Total Length
Mean dimension(mm)	0.65	0.53	0.98	0.36	0.87	0.53	2.50
Standard Deviation (SD)	0.02	0.01	0.02	0.01	0.03	0.01	0.05

Table 4-4: Measurements of the mass and speed of Argentine ants

Measurement	Mean	Standard Deviation(SD)
Mass (g)	$4.8 \times 10^{(-4)}$	$4.67 \times 10^{(-5)}$
Speed (mm/s) : normal condition	3.56	1.33
Speed (mm/s) : panic condition	9.91	4.05

Figure 4-3 shows the snapshots from the experiment with circular chamber and square chamber experiments. From the video data of the experiments, the pre-evacuation time, evacuation time and number of ants that escaped was measured by manual counting from playback of digital video recordings. When panic was created, the density of ants became quite elevated near the nest exit, resulting in frequent contacts. However, they tried to avoid colliding with each other when they were very close (<1mm) or when contact actually occurred. The ants thus had restricted movement near the exit. Between 1mm to approximately 8mm inter-individual distance, the density of ants was not as great as it was near the exit. In that zone, mobility of ants was not as constrained as it was near the exit. Beyond 8mm from their nearest neighbour, the ants were attracted to the exit on a random basis. The existence of these different zones can be conceptualized as zones of attraction and repulsion, similar to what have been observed in the collective dynamics of schools and flocks (Okubo 1986). Thus, it is observed from the experiments that the repulsion zone existed at a distance less than 1mm while attraction zone existed after 1mm and up to approximately 8 mm.

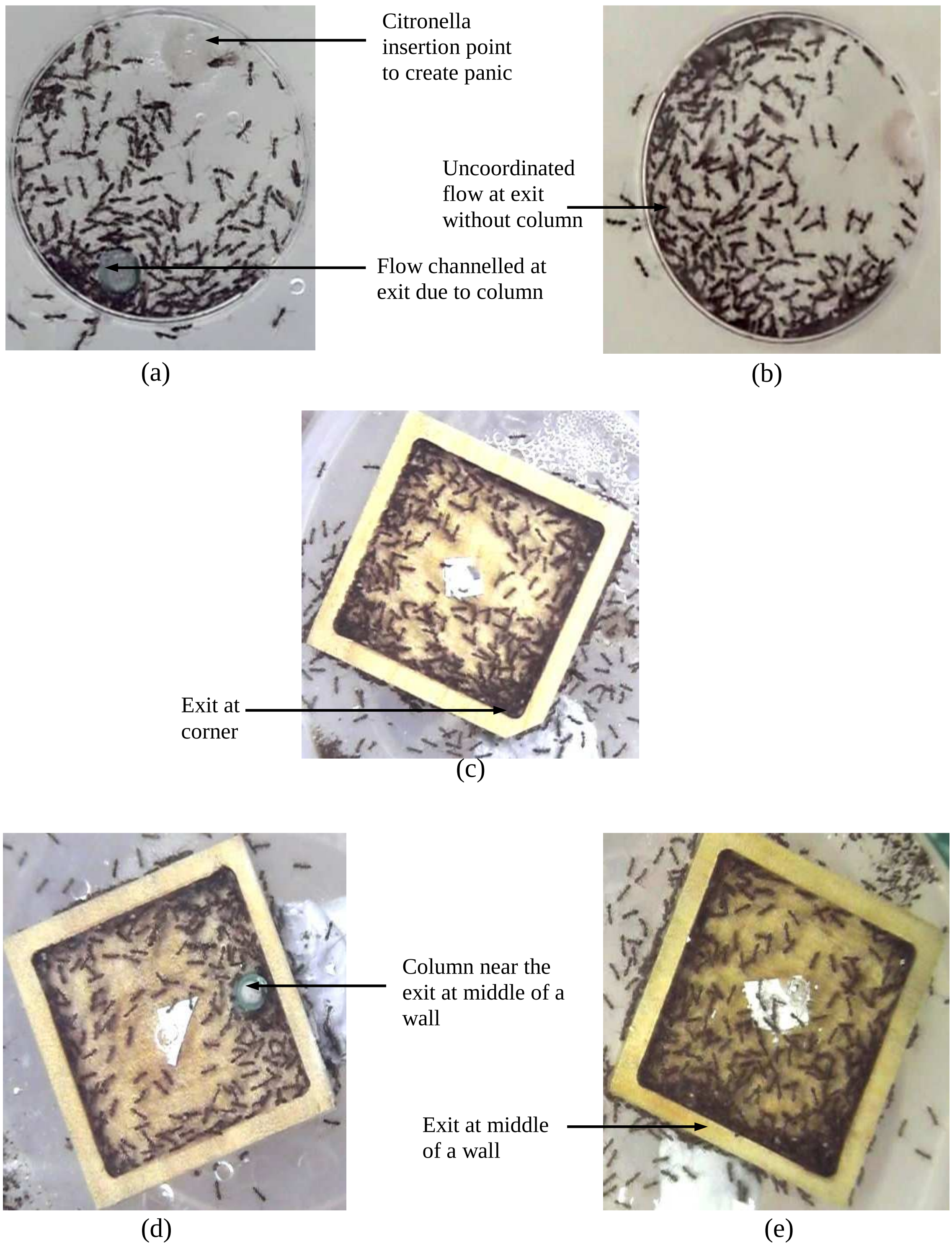


Figure 4-3: Snapshots from the experiments: circular chambers with and without the column near the exit (a & b), square chamber with exit at the corner (c), square chamber with and without the column near the exit at the middle of the side walls (d & e)

4.4.2 Results

In this section the results from the circular chamber experiments and the square chamber experiments are presented. The efficiency of the escape of ants for each set of experimental treatments was compared through the evacuation time for the first and second cohorts of 50 ants. These cohorts were considered primarily to capture the urgency of escape. It was observed from the experiments that the urgency of escape was very high usually for the first 120-150 escaped ants. Afterwards, ants preferred to remain in the nest or escape slowly. With the first and second cohorts of 50 ants, consistent observations of panic escape could be made across all replications. For every trial, the elapsed time (to the nearest second) between injection of the citronella oil and the escape of the cohorts of 50 ants was measured, as determined by playback of digital video recordings of the escape.

These data were analysed by a repeated-measures ANOVA. Like standard ANOVA, repeated measures ANOVA tests the equality of means. However, standard ANOVA in this case is not appropriate because any correlation between the repeated measures violates the ANOVA assumption of independence. Repeated measures ANOVA is used when all members of a random sample are measured under a number of different conditions. As the sample is exposed to each condition in turn, the measurement of the dependent variable is repeated. In the ant experiment, escape time for 50 ants was the dependent variable, the two experimental treatments (for e.g. with/without column) formed the between-subjects factor, and cohort sequence (the first or second group of 50 ants) was the within-subjects repeated measure. In the following sections, results from the experiments are presented.

4.4.2.1 Circular chamber experiments

Figure 4-4 shows the comparison of mean escape time (along with Standard Error (SE)) for different cohort of ants for the with/without column scenario in circular chamber experiments. Across all cohorts, mean escape time for 50 ants was 14.0 seconds when the column was present and 20.1 seconds when it was not, i.e., about 44% slower under the ostensibly more favourable conditions of an unobstructed exit.

As shown in Table 4-5, there were highly significant differences in escape times between trials with and without the partial exit obstruction. The main effect of the column was substantial. Cohorts differed significantly in their escape time (Table 4-5). Escape times in both treatments were higher for the first 50 ants than for the next 50. In any case, escape was always faster in the presence of the column, and there was no column × cohort interaction (Table 4-5, Figure 4-4).

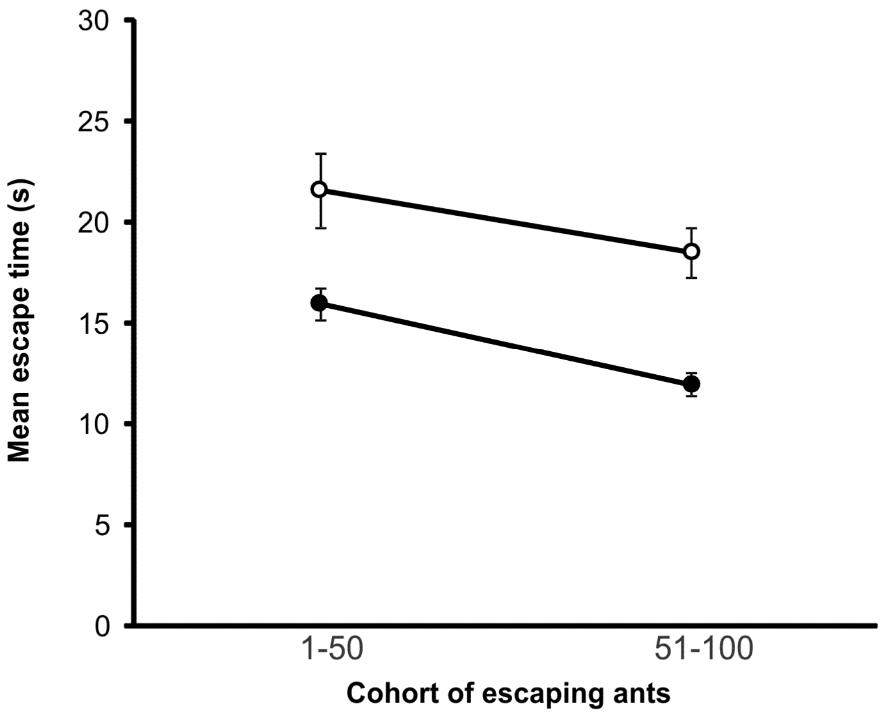


Figure 4-4: Mean escape times for the first and second cohorts of 50 ants to leave the nest under panic conditions. Open symbols indicate the absence of a column as a partial exit obstruction and closed symbols indicate presence of a column. Error bars show ±1 SE.

Table 4-5: ANOVA results for the effect of column presence / absence and cohort sequence on escape time for circular chamber experiments

Effect	df	Mean-Square	*F*	*P*
Between-subjects				
(Column presence/absence)	1	1142.4	15.71	<0.001
Error	58	72.7		
Within-subjects repeated measure				
(1st, 2nd cohort)	1	351.2	30.4	<0.001
Cohort × column treatment	1	10.7	0.9	0.340
Error	58	11.5		

The presence of a column at the exit generally enhanced the flow of panicking ants as compared to the absence of a column. The presence of a column in front of the exit channelled the traffic in a manner that did not occur with an unimpeded exit (Figure 4-3a and 4-3b). One manifestation of this channelling was that lone exits (a single individual passing through the exit hole rather than temporal overlap of two or more individuals) were more common when the column was present. Of the first 50 ants to escape in each trial, an average of 24.1 (± 5.3 SD) were lone exits when the column was present and 19.1 (± 4.4 SD) when it was absent (t_{16} = 2.17, P = 0.022, one tailed test). The net effect was that the flux of ants through the exit was improved, on average, by the presence of the partial obstruction.

4.4.2.2 Square chamber experiments

Figure 4-5 shows the comparison of mean escape time for different cohort of ants (first or second group of 50 ants) for exit at the middle of the wall and at the corner in square chamber experiments. Across all cohorts, mean escape time for 50 ants was 12.9 seconds when the exit was at the corner and 20.4 seconds when the exit was at the middle. That result in about 58 % faster evacuation due to the exit location at the corner compared to the location at the middle of the wall. As shown in Table 4-6, there were highly significant differences in evacuation times between trials with the corner and centre exit ($F_{1, 18}$ = 21.85, P < 0.001), that is, the main effect of the corner exit is significant. Cohorts differed significantly in their escape time (Table 4-6).

Escape times in both treatments were lower for the first 50 ants than for the next 50. Escape was always faster with exit located at the corner, and there was no exit × cohort interaction (Table 4-6, Figure 4-5).

The location of an exit at the corner generally reduced the evacuation time as compared to the location of an exit at the centre. One reason for this reduction in evacuation time could be the minimization of change in direction of escaping ants in the corner exit. At the centre exit, ants escaping from both side walls near the exit had to change their direction in order to evacuate. That resulted in interactions with the ants that were moving straight towards the exit. In the corner exit, the ants escaping from the side walls near the corner could pass through without much change in their original direction. This result demonstrates the role that change in direction of individual members in a crowd (during collective dynamics) can play during the escape of a crowd. This represents an important dimension of this field of research and is considered further in section 8.3 of Chapter 8.

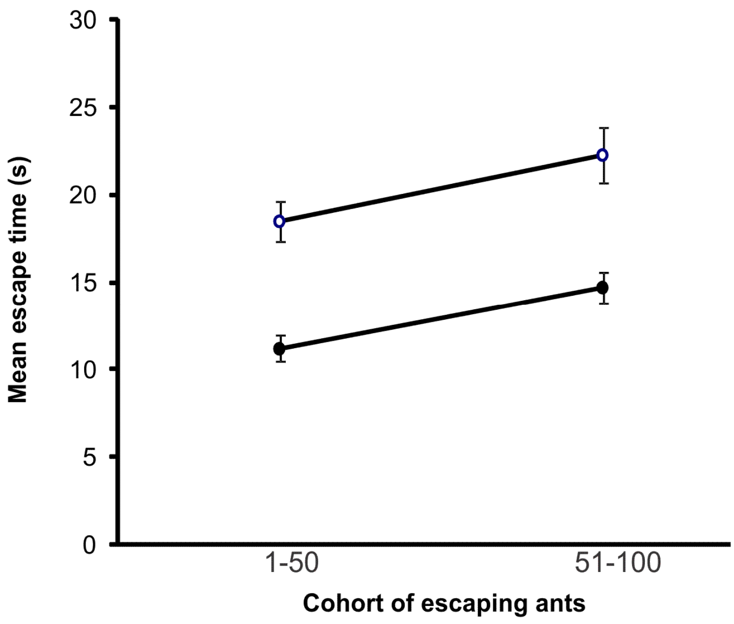


Figure 4-5: Mean escape times for the first and second cohorts of 50 ants to leave the nest under panic conditions. Open symbols indicate the exit located at the middle of the wall and closed symbols indicate the exit located at the corner. Error bars show ±1 SE.

Table 4-6: ANOVA results for the effect of exit at corner/middle and cohort sequence on escape time

Effect	df	Mean-Square	*F*	*P*
Between-subjects				
(Exit at corner / middle)	1	551.75	21.85	<0.001
Error	18	25.25		
Within-subjects repeated measure				
(1st, 2nd cohort)	1	133.66	20.97	<0.001
Cohort × Exit treatment	1	0.19	0.03	0.87
Error	18	6.38		

Figure 4-6 shows the comparison of mean escape time for the first and second cohorts of 50 ants in trials with and without a column near the exit at the middle of the wall. Across all cohorts, mean escape time for 50 ants was 13.5 seconds when the column was present near the middle exit and 20.4 seconds in the absence of column, that is, 34 % reduction in evacuation time due to the presence of the column.

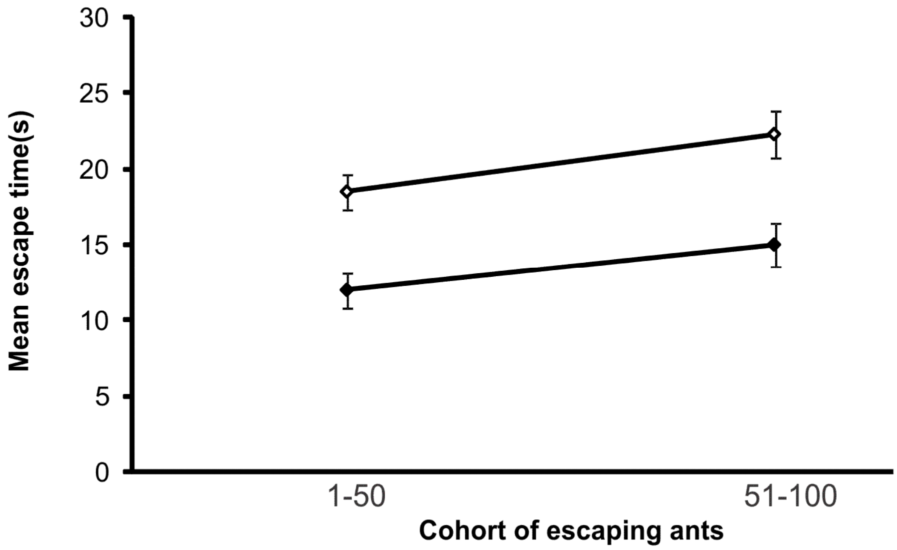


Figure 4-6: Mean escape times for the first and second cohorts of 50 ants to leave the nest under panic conditions. Open symbols indicate middle exit without column and closed symbols indicate the middle exit with column. Error bars show ±1 SE.

Although the repetitions were fewer (only 5 repetitions for column scenario), there were significant differences in evacuation times between trials with and without column near the centre exit ($F_{1, 13}$ = 9.8, P =0.008), as shown in Table 4-7. The main effect of the column is significant. Consistent with the results of the circular chambered experiment, the presence of column near the centre exit was efficacious (compared to absence of column) in the square chambered experiment as well.

Table 4-7: ANOVA results for the effect of column presence / absence near the centre exit and cohort sequence on escape time

Effect	df	Mean-Square	*F*	*P*
Between-subjects				
(Column presence/absence)	1	315.20	9.80	0.008
Error	13	32.14		
Within-subjects repeated measure				
(1^{st}, 2^{nd} cohort)	1	77.43	13.77	0.003
Cohort × column treatment	1	0.18	0.18	0.68
Error	13	5.62		

4.4.2.3 Pre-evacuation time

The reaction time (pre-evacuation time) of the ants before they start evacuating the nest was also measured. The reaction time was considered to be the time that elapsed between the injection of the citronella to the chamber and the time when ants began to evacuate the chamber (benchmarked by the escape of the first 3 ants from the chamber).

Figure 4-7 shows the distribution of the pre-evacuation times of the ants based on 90 observations. The majority of the reaction times (90%) were below 10 seconds with the average being 5.5 seconds. It was observed that the ants which were near to the citronella injection point pushed the ants that were nearby and those ants then pushed the other surrounding ants, continuing like a chain reaction until the ants began to leave the chamber. The chain-reaction mechanisms of communicating the danger conditions among ants may provide an insight into the possibility of developing such mechanisms in cases of human panic.

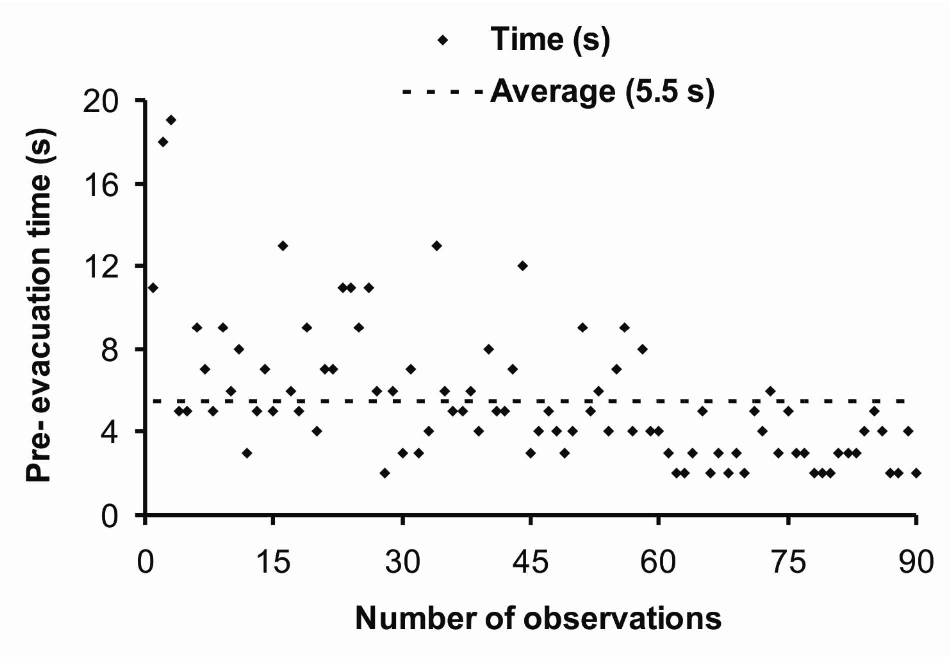


Figure 4-7: Distribution of pre-evacuation time of the ants

In human evacuation, total evacuation time consists of the sum of the pre-evacuation time and the evacuation time (to leave the exit or enclosed area). However, limited data exist on pre-evacuation times for humans. Usually consideration of pre-evacuation time is ignored (due to difficulty in estimating its value) or assumed (usually between 0 and 120 seconds) in simulation based on modellers' experience (Daamen 2007). From the ant experiment, the observations suggest that inclusion of higher pre-evacuation time (at least more than 10 seconds) is justifiable for estimation of pre-evacuation time in simulations of the human case. This is supported by the fact that even the ants, which are known to be usually co-operative and non-selfish by nature (Hölldobler & Wilson 1990), took on average 5.5 seconds to react to the event (citronella) and begin to evacuate. In one study relating to human evacuation trials (Tavares et al. 2007), pre-evacuation times were collected from the experiments and these ranged from 5 to 98 seconds with a mean pre-evacuation time of 46.7 seconds (based on two trials). That study also supports the above stated assumption of using higher pre-evacuation time based on ant experiments.

4.5 Summary

This chapter presented the experiments with Argentine ants under panic conditions to gain insight into human panic. Five different scenarios of experimental trials were attempted. These experiments reflect an original and innovative attempt to study the effect of architectural features of the escape area to the collective movement patterns of non-human entities during rapid egress. The method of collection of ant colonies and creation of artificial nests for the experiment was explained in detail. That is believed to assist other researchers in creation of such artificial nests and experimental setup for future experiments. Discussions from preliminary trials of experiments were presented before presenting the results from the five scenarios of experimental trials. The preliminary experiments assisted in arranging the suitable experimental setup for the intended study.

From the video data of the experiments, evacuation time and number of ants that escaped was measured by manual counting from playback of digital video recordings. Those data were analysed through repeated measures ANOVA. The ANOVA test revealed that the small structural adjustments in an escape area can have significant effects on the outflow of the individuals. The pre-evacuation times for the ants were also extracted. The data suggested the inclusion of higher pre-evacuation time in considering total evacuation time.

The empirical data analysed and observed from the experiments represents the key dimension of this field of research and provides the foundation for the next chapters 5, 6, 7 and 8 of this thesis. Specifically, these empirical data provide various testing and validation scenarios for the prediction model to be developed in the next chapter.

CHAPTER 5 DEVELOPMENT OF MODEL (EMSIM)

5.1 Introduction

This chapter is dedicated to the development of 2-dimensional continuous space with discrete time step updating simulation model EmSim (**Em**ergency **Sim**ulation) for collective traffic. The model is based on observations from ants experiment, previous studies on animal dynamics and collective pedestrian dynamics. As the model is required to simulate collective traffic across a size gap as large as ants and pedestrians; for consistency, non-human organisms or pedestrians are referred to as 'individuals' throughout the model development. The pedestrian crowd is treated as an 'emergent system' for model formulation. Emergent systems, also referred to as self-organized systems, arise from 'The emergence of order on a global scale through interactions on a local scale' (Charlotte 2005). Such order has been observed in flocks, herds, schools, etc., where entities with limited intelligence interact locally, which in turn leads to the emergence of group behaviour on a global scale (Charlotte 2005, Pfeil 2006). For example, an ant colony exhibits emergent order where each individual ant, following a simple rule of pheromone deposition as it travels, contributes to the establishment of a complex interactive communication system (Hölldobler & Wilson 1990). The simplicity of such interactions in various biological entities has motivated the development of the model in this research on the assumption that pedestrian crowds act as an emergent system.

Figure 5-1 shows the interdependence between individual goals, interactions among individuals, and the emergent group behaviour. How pedestrian crowds escape under emergency conditions is highly dependent on how the group goals and individual goals are constituted and coordinated in those situations. The basic philosophy is to address the complexity of human behaviour by assigning each individual (having limited information) with simple locomotion rules as those observed from collective animal dynamics, and observing the emergent group behaviour based on the local interactions of the individuals as shown in Figure 5-1. If the simulation model produces the observed emergent behaviour, such as formation of lanes, oscillations at bottlenecks, herding and pushing behaviour during emergency conditions, then that result reinforces the validity of the model.

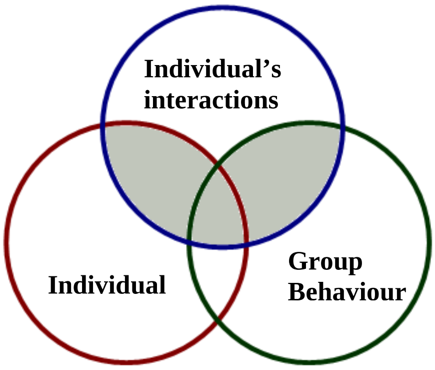


Figure 5-1: Interdependence between the individual, interactions among individuals, and emergent group behaviour.

5.2 Model formulation

Previous studies on collective animal dynamics (Okubo 1986, Matuda & Sannomiya 1985) and limited studies on collective human dynamics (Helbing et al. 2000) have been based on Newton's law of Motion. Hence it can be assumed that Newtonian mechanics can be a platform for modelling collective dynamics. Newtonian mechanics state that a temporal change of the momentum of an individual occurs in the direction of the net force $\vec{F}$ which is the product of mass (m_α) and acceleration ($\vec{a}_\alpha$) as shown below by Equations 5-1 and 5-2

$$m_\alpha \, \vec{a}_\alpha = \vec{F} \qquad (5\text{-}1)$$

$$m_\alpha \frac{d^2 x}{dt^2} = \vec{F} \qquad (5\text{-}2)$$

For a number of individuals (N), the forces ($\vec{F}_{\alpha\beta}$) acting on individual (α) from another individual (β) and from the surrounding environment ($\vec{F}_{w\alpha}$), such as number of obstacles and walls (N_w), would be

$$\vec{a}_{\alpha} = \frac{1}{m_{\alpha}}\left[\sum_{\beta=1(\alpha\neq\beta)}^{N}(\vec{F}_{\alpha\beta}) + \sum_{1}^{N_W}\vec{F}_{w\alpha}\right] \tag{5-3}$$

If one specifies the forces such as in Equation 5-3, the motion of an individual is uniquely determined as the position $\vec{x}(t)$ and velocity $\vec{v}(t)$. These could be updated in each time step (Δt) from the integration of the Newton's equation of motion as shown below by Equations 5-4 and 5-5

$$\vec{x}(t+\Delta t) = \vec{x}(t) + \vec{v}(t)\Delta t + \frac{1}{2}\vec{a}(t)\Delta t^2 \tag{5-4}$$

$$\vec{v}(t+\Delta t) = \vec{v}(t) + \frac{1}{2}\left[\vec{a}(t) + a(t+\Delta t)\right]\Delta t \tag{5-5}$$

The important issue here is to identify and represent those forces that would be able to produce the collective dynamics of the individuals under emergency situations. To understand the nature of these forces, real data of human panic under emergency conditions are required, however those data are rare. Hence experiments with Argentine ants were conducted to gain insight into human panic in Chapter 4.

5.2.1 Modelling collective forces

Based on the ants experiments described in Chapter 4, a number of forces are formulated that are important to represent the nature of collective forces. These forces, as detailed in the following sections, underlie the detailed development of the modelling framework.

5.2.1.1 Impulsive forces

Panic among ants is associated with increase in fleeing speed from 3mm/s (normal) to 9mm/s (panic) as observed in section 4.4.1 of Chapter 4. This phenomenon of increase in fleeing or desired speed is observed in other non-human organisms as well such as schools of fish and flocks of birds when exposed to frightening stimuli (Okubo 1986). An increase in desired speed (more than 5m/s and up to 10m/s) has also been associated with panic in pedestrian crowds, which can lead to effects such as the "faster is slower effect" (i.e. increase in fleeing speed actually slows down individual), "pushing / trampling", and "herding" phenomena (Helbing et al. 2000). This increase in fleeing speed could be viewed as the consequence of impulsive or motivational forces on the part of individuals to move towards a safe place or exit as quickly as possible. The impulsive acceleration resulting from these impulsive forces could be thus modelled as proportional to their fleeing or desired speed as shown below

$$\vec{a}_I \propto v_d \frac{\vec{d}(t) - \vec{p}_\alpha(t)}{\left\| \vec{d}(t) - \vec{p}_\alpha(t) \right\|} \tag{5-6}$$

Where,

$\vec{a}_I$ = impulsive acceleration

v_d = fleeing or desired speed

$\frac{\vec{d}(t) - \vec{p}_\alpha(t)}{\left\| \vec{d}(t) - \vec{p}_\alpha(t) \right\|}$ = unit vector from a particular position of an individual $\vec{p}_\alpha(t)$ towards exit $\vec{d}(t)$ at the characteristic time (t).

For accelerative equilibrium of impulsive forces and those resistive forces resisting impulsive forces, a constant, termed as relaxation time (τ^{-1}) is necessary. In particular, the use of relaxation time (τ^{-1}) is valid when the resistance force is linearly proportional to the velocity (Okubo 1980). Hence Equation 5-6 can be written as

$$\vec{a}_I = \tau^{-1} v_d \frac{\vec{d}(t) - \vec{p}_\alpha(t)}{\left\| \vec{d}(t) - \vec{p}_\alpha(t) \right\|} \tag{5-7 }$$

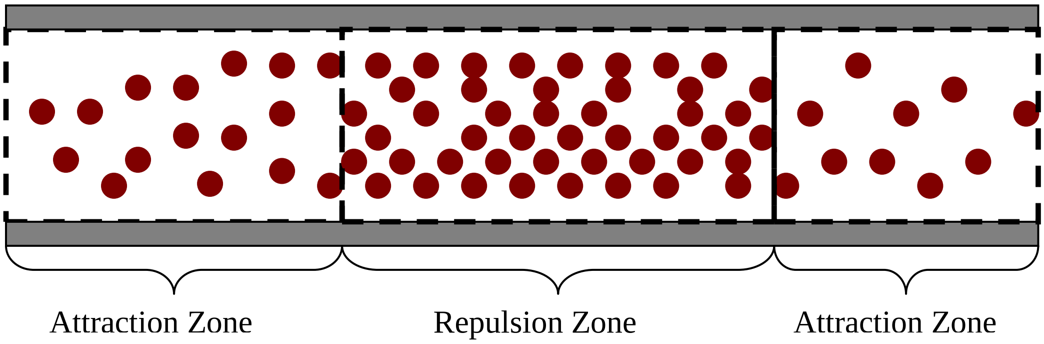
The variations in different desired speeds could lead to fluctuations in the simulation. That could be taken into account by adapting the actual velocity of each individual to a constant desired velocity for all the individuals within a certain relaxation time (τ), as mentioned in Helbing et al (2000).

5.2.1.2 Local interactive forces

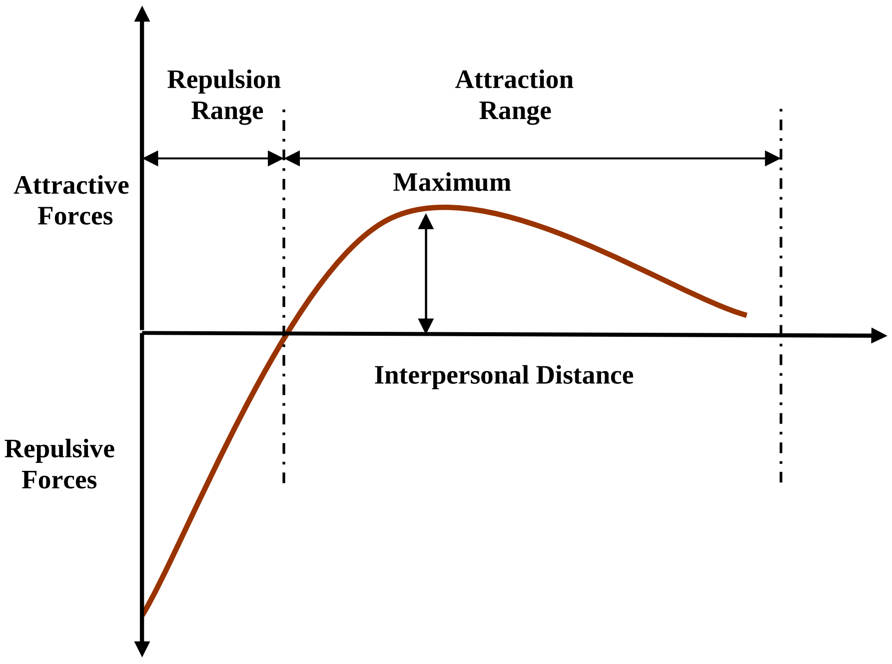
Individual have limited information and vision during emergency conditions (collective motion); i.e., they consider only the things that they can see in their immediate surroundings. Thus local interactions are important. As observed from ants experiment in Chapter 4, section 4.4.1, there was evidence of formation of attraction and repulsion zones (which was the function of inter-individual distance). The existence of these different zones is similar to what have been observed in the collective dynamics of schools and flocks. For example, the critical distance that fish in schools maintain from each other varies within 16 to 25% of their mean body length, while attractions start at a distance beyond their body length (Okubo 1986). Okubo (1986) mentions that a wave of agitation propagated through schools of fish exposed to frightening stimuli in an experiment. The formation of "shock waves" was due to a rapidly shifting zone in which the fish reacted to the actions of their neighbours by changing their own positions. The speed of the wave's propagation reached 11 to 15 m/s, which is much higher than the maximum forward speed of individual fish (about 1 m/s). Similarly, when predators attacked bird flocks, formation of a "ball" of birds has been observed along with an increase in their flight speed. At times, the flock "pulsated" (expanding and contracting in a spatial sense) as inter-bird distance varied (Okubo 1986). Kholshevnikov & Samoshin (2005) reviewed studies on pedestrian evacuation carried out by researchers in Russia and elsewhere in the world and identified the identical structures of collective pedestrian flow. They mention that the distance between people constantly changes and causes local squeezing which later on disappears and appears again. Such "pulsating" collective dynamics behaviour is similar in schools, flocks and swarms as explained above.

Assuming that individuals during panicking situations have limited information and vision (due to high crowd density and short time for egress), there appears to be striking similarities in the structure and behavioural rules of the collective dynamics of several biological organisms, such as schools, swarms, flocks, and also human groups. These behavioural rules, as observed from the ants experiments and studied from an animal dynamics perspectives (Okubo 1980, Matuda & Sannomiya 1985), can be represented conceptually as a relationship between interpersonal distance and the resulting repulsive and attractive forces, as shown in Figure 5-2(a) and 5-2 (b) and as proposed by Shiwakoti et al. (2009b, 2010a). The regulation of collective patterns of individual dynamics to perceived risk results directly from a change in interaction range (i.e. the attraction range and repulsion range as represented in Figure 5-2).

The repulsive forces depend on the proximity of individuals. The magnitude of the repulsive forces is large when interpersonal distance is small, and decrease with increasing distance until a point where the interpersonal distance exceeds the repulsion range. At that point, attractive forces begin to act on pedestrians to draw them together, until the maximum point of attraction is reached. At even greater separation, the attractive forces would start decreasing and eventually have a negligible effect. It can therefore be assumed that, as in animal dynamics, these zones of attraction and repulsion maintain the collective movements of pedestrian crowds. While the concept of repulsive forces based on interpersonal distance has been addressed previously (Helbing et al 2000), the importance of attractive forces has received limited attention in the study of the collective pedestrian motion. It is important to consider both attractive and repulsive forces to capture the "pulsating" nature of the collective movements of pedestrians. The "tendency to follow others" and "strong local interactions," as observed in the collective motion of both animals and humans, provides the foundation for realistic simulation models of the collective motion (Shiwakoti et al. 2008b, 2010a, 2010b, 2011a).



(a)



(b)

Figure 5-2: Conceptual diagram showing the existence of attractive and repulsive zone during collective dynamics (a) and nature of repulsive and attractive forces based on interactive range of interpersonal distance (b)

To be included in the model, the local interactive forces (both attractive and repulsive), as discussed above and represented conceptually in Figure 5-2, need to be mathematically represented. Inspired from behavioral rules in animal dynamics (Okubo 1980, Matuda & Sannomiya 1985), here it is assumed that local interactive forces are inversely proportional to the square of the distance between individuals, similar to Newton's law of gravitation, and given by

$$\vec{F}_L = \phi \; W(\theta_{\alpha\beta}) \left(\frac{\left[\left(X_{\alpha\beta} - r_{\alpha\beta} \right) - \lambda_R \right]}{\left[\left(X_{\alpha\beta} - r_{\alpha\beta} \right) - \lambda_R \right]^2 + \lambda^2{}_A} \right) \vec{n}_{\alpha\beta} \tag{5-8}$$

$\phi = \phi_R$ When $\left(X_{\alpha\beta} - r_{\alpha\beta} \right) < \lambda_R$ (repulsive forces)

$\phi = \phi_A$ When $\left(X_{\alpha\beta} - r_{\alpha\beta} \right) > \lambda_R$ (attractive forces)

Where,

$\vec{F}_L$ = local interactive forces (repulsive and attractive),

ϕ =constant

$X_{\alpha\beta}$ = interpersonal distance between individuals (centre to centre),

$r_{\alpha\beta} = r_\alpha + r_\beta$ =sum of radii of the circular representation of the individuals,

λ_R = repulsion distance,

λ_A = attraction distance,

$\vec{n}_{\alpha\beta}$ = normal unit vector.

$W(\theta_{\alpha\beta})$ = a weighing factor that represents the influence of the individual in front and back

The variation in repulsive and attractive forces is achieved by introducing different constants ϕ_R and ϕ_A for repulsive and attractive forces, respectively, to tune the model for pedestrian traffic. The function $W(\theta_{\alpha\beta})$ is given by

$$W(\theta_{\alpha\beta}) = 1 - \left(\frac{1 - \cos\theta_{\alpha\beta}}{2} \right)^2 \tag{5-9}$$

Where $\theta_{\alpha\beta}$ = angle between individual (α) and (β)

The weighing factor is maximum when the individual (β) is in front of individual (α) while this factor keeps on decreasing with the position of individual (β) at the side or behind the individual (α). Figure 5-3 shows the components of the interactive forces as described above while Figure 5-4 shows how the weighing factor varies as a function of the angle $\theta_{\alpha\beta}$.

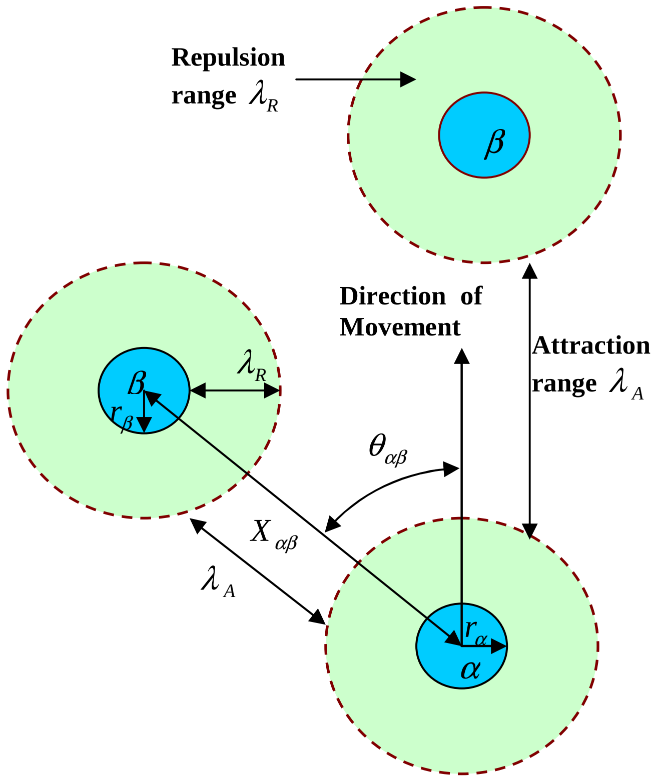


Figure 5-3: Schematic diagram showing components of local interactive forces

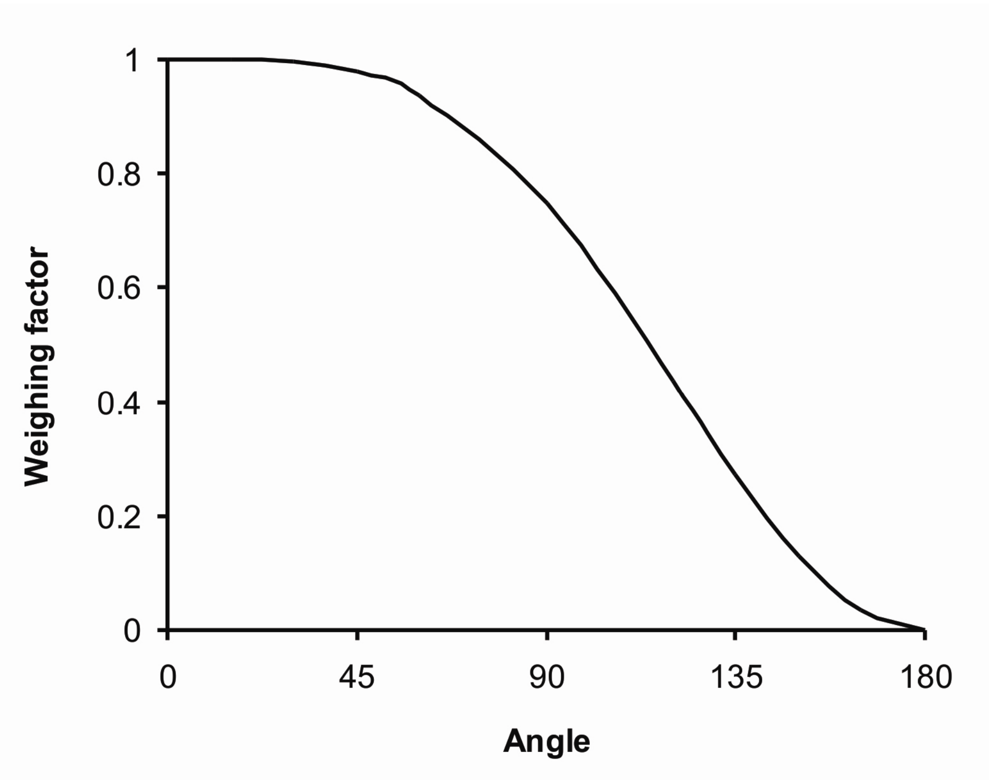


Figure 5-4: Variation of the weighing factor as the function of the angle between two individuals

5.2.1.3 Collision/pushing forces

When ants were moving at high speed, frequent collisions with mutual interactions occurred near the exit. At high density or high speed, individuals tend to come very close and sometimes push each other. In such instances, there is the possibility that individuals collide or overlap each other in the simulation. Likewise, consideration of the pushing forces is necessary to take into account additional delays incurred due to such mutual interactions. In these cases, repulsive forces alone are not enough. These collisions and overlapping phenomena also have been a notable problem in the study of rigid spherical body collisions in molecular dynamics (Rapport 1995, Bell et al. 2005). The problem is usually addressed by invoking strong normal forces as well as frictional (shearing) forces acting tangentially between the colliding particles. An analogous approach can be taken for particle-based simulation of traffic. As shown in Figure 5-5, the initial velocity (dashed arrow) gets diverted to a new direction due to a normal force ($\vec{F}_n$) and a shear force ($\vec{F}_t$).

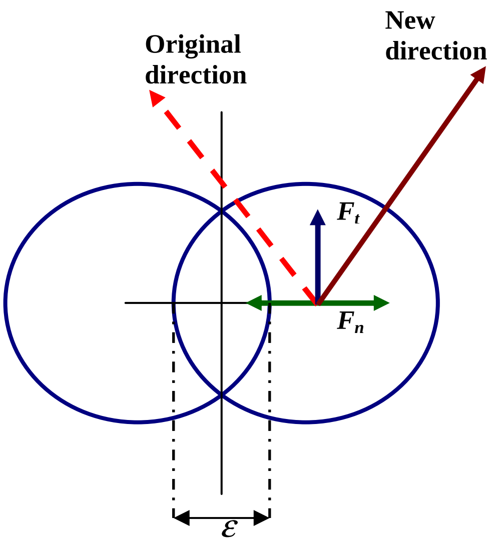


Figure 5-5: Components of pushing forces to avoid collision based on inelastic sphere collision concept of molecular dynamics

Thus, the pushing force ($\vec{F}_P$) can be represented by two components; damped linear spring force (normal force $\vec{F}_n$) and shear frictional force (tangential force $\vec{F}_t$), as shown in Equations 5-10, 5-11 and 5-12.

$$\vec{F}_n = \alpha_1 \vec{v}_{rn} + \alpha_2 \varepsilon \, \vec{n} \quad (5\text{-}10)$$

$$\vec{F}_t = \mu_1 \vec{v}_t + \mu_2 \varepsilon \, \vec{t} \quad (5\text{-}11)$$

$$\vec{F}_P = \vec{F}_n + \vec{F}_t = \alpha_1 \vec{v}_{rn} + \alpha_2 \varepsilon \, \vec{n} + \mu_1 \vec{v}_t + \mu_2 \varepsilon \, \vec{t} \quad (5\text{-}12)$$

Where,

α_1 =dampening constant,

α_2 =elastic restoration constant,

$\vec{v}_{rn}$ =relative velocity in normal direction,

ε =overlap,

$\vec{n}$ =normal unit vector,

μ_1 & μ_2 =frictional constant,

$\vec{v}_t$ = tangential relative velocity,

$\vec{t}$ = tangential unit vector.

The normal force pushes two individuals apart much like a compressed spring would do. Dissipation of the collision energy by the "spring" is determined by a damping coefficient, α_1, and the normal component of the impact velocity, $\vec{v}_{rn}$. The rebound in the normal direction $\vec{n}$ is governed by the compression ε (the overlap between the colliding bodies) and an elastic restoration coefficient α_2 that reflects the stiffness of the particles in contact. The tangential force is similarly governed by friction coefficients, μ_1 and μ_2, the tangential component of the impact velocity, $\vec{v}_t$, and the compression ε. While Helbing et al. (2000) proposed a similar approach for modelling pushing forces, however there are some differences in the Equations 5-10 and 5-11 proposed in this dissertation. The extra term $\alpha_1 \vec{v}_{rn}$ is added in Equation 5-10 to take into account the effect of relative velocity in normal direction as well. Also the term $\mu_2 \varepsilon \, \vec{t}$ considered in Equation 5-11 can accommodate the case of relative velocity at or near zero. In the absence of term $\mu_2 \varepsilon \, \vec{t}$, the frictional force would be zero if relative velocity is near or equal to zero. It is to be noted here that the model representation of these forces does not capture the "intentionality" behind pushing in a crowd but only its physical manifestation. It is intended to capture only the physical consequences of contact between elements of the crowd. Expressions similar to those for $\vec{F}_L$ and $\vec{F}_P$ hold true for repulsive forces from stationary obstacles such as walls and columns ($\vec{F}_{w\alpha}$).

5.2.1.4 Randomness

From the ants experiment described in Chapter 4, it was observed that ants movement in response to certain stimuli (here citronella) does not necessarily follow set of rules. As in animal dynamics, there were predictable responses such as *taxis* where animal demonstrates guided movement towards or away from the stimulus source (Okubo 1980). As citronella was repellent to ants, they showed negative taxis resulting movement away from stimulus source and positive taxis towards the exit. This is similar to what one can expect when a crowd of people is running away from source of danger (for e.g. a fire) towards safe place. However, in some cases, there were movements so irregular as can be regarded as a random motion, especially in the attraction zone (1mm-8mm inter-individual distance) and beyond (>8mm inter-individual distance) as observed in section 4.4.1 of Chapter 4.

The above examples of random motion such as *klinokinesis*, which involves change in the frequency and direction of movement in response to the stimulus, or *orthokinesis*, in which the speed of movement is altered could be observed in ants experiment similar to those observed in animal dynamics (Okubo 1980). The increase in fleeing speed and running towards safe place/exit as noted in section 5.2.1.1 could be viewed as the combination of positive *orthokinesis*, negative *klinokinesis* and positive taxis which result a strong tendency to aggregate toward the source of the stimulus (here safe exit). However, it has been observed that even *kinesis* is not entirely random and that the degree of response depends on the strength of the stimulus, so that the motion appears to be deterministic in a statistical sense (Okubo 1980). One can expect similar kind of *taxis* and *kinesis* during collective dynamics of pedestrian crowds as well. Thus, when considering the crowd dynamics, it is better to consider the random components besides the non-random components.

In the proposed modelling framework, the non-random components consist of forces described in section 5.2.1.1 to 5.2.1.3. The disturbances produced due to random behaviour as discussed above could, however, be result of several factors. Thus randomness could be the function of difference in speed, size, cognitive abilities, and other biological traits of the individuals as below

$$\vec{\xi} = f \ \ (\textit{speed, size, cognitive abilities, psychological state............}) \qquad (5\text{-}13)$$

Where,

$\vec{\xi}$ = fluctuations arising from randomness

For simplicity, in this dissertation, randomness in the collective dynamics is introduced by random distribution of the individuals in the simulation, different body sizes and different body masses of the individuals for each simulation run.

5.2.2 Operation of simulation model EmSim

With the collective forces modelled as described in section 5.2.1, the optimal instantaneous acceleration of the individual as mentioned in Equation 5-3 now can be written as

$$\vec{a}_{\alpha} = \vec{a}_{I} + \frac{1}{m_{\alpha}}\left[\sum_{\beta=1(\alpha\neq\beta)}^{N}\vec{F}_{\alpha\beta} + \sum_{1}^{N_w}\vec{F}_{w\alpha}\right] + \vec{\xi} \qquad (5\text{-}14)$$

Or,

$$\vec{a}_{\alpha} = \vec{a}_{I} + \frac{1}{m_{\alpha}}\left[\sum_{\beta=1(\alpha\neq\beta)}^{N}(\vec{F}_{L} + \vec{F}_{P}) + \sum_{1}^{N_w}\vec{F}_{w\alpha}\right] + \vec{\xi} \qquad (5\text{-}15)$$

It is difficult to solve Equation 5-15 analytically; hence simulation is the preferred approach. The instantaneous acceleration as determined can be updated in each small discrete time step based on the integration of the equations of motion as previously stated in section 5.2. Since the model formulated is a continuous one, the time step for the update needs to be very small to minimize the error due to assignment of discrete time steps for a continuous model. Hence, the appropriate time step need to be selected based on the trade-off between the computational time for the model and the observed visual instability during simulation run. A schematic diagram explaining the operation of the simulation model is presented in Figure 5-6.

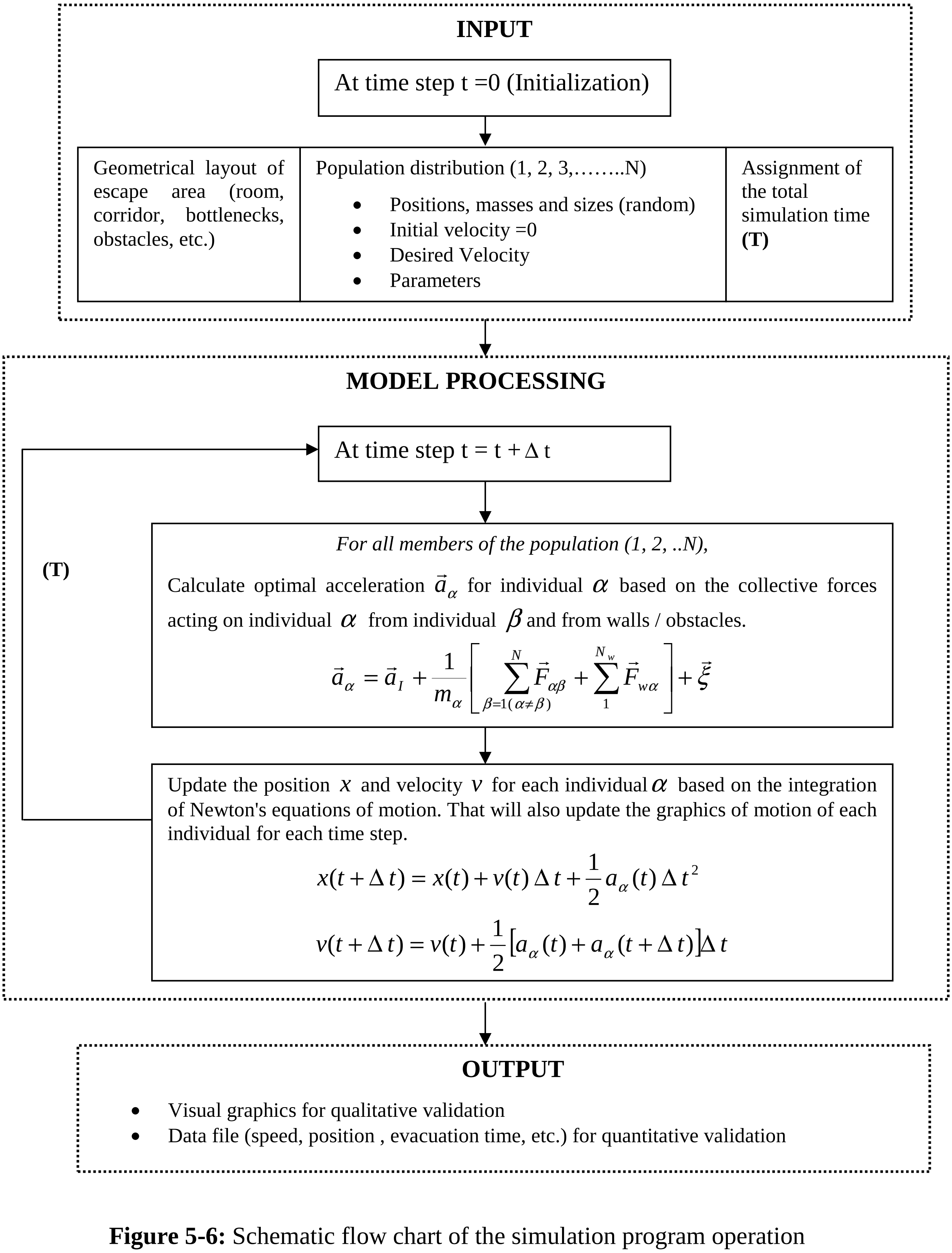


Figure 5-6: Schematic flow chart of the simulation program operation

5.3 Scaling model parameters

One can take into account the difference in magnitude of the parameters in ant traffic and pedestrian traffic through ‘scaling effects’. That is to say, if one organism was built to the same design as another, but on a different scale, the various characteristics of the original would necessarily be scaled up or down to produce a working model. The scaling of morphology, physiology, and life history with body size has interested biologists for decades (Kleiber 1932, Schmidt-Nielsen 1984, West et al. 1997, Peters 1999, Bonner 2006), but only recently has the same attention been given to the scaling properties of organismal groups, such as social insect colonies (Jun et al. 2003, Waters et al. 2010). An immediate consequence of social living is the emergence of crowd dynamics, which appear in organisms as diverse as ants (foraging trails), wildebeests (herd migrations), locusts (swarms), and humans (crowds on city footpaths). Two scaling questions might be raised about crowd dynamics. The first is how collective properties depend on the size of the group, and the second is how these attributes depend on the size of the individuals that comprise the group. The first approach has been used by Waters et al. (2010) to examine collective metabolism and behaviours such as velocity distribution in groups of the ant *Pogonomyrmex californicus* that range in size from 95 to 659 individuals. In this dissertation, the second perspective is adopted to address the crowd behaviour of humans and Argentine ants, two species for which individual body mass differs by a factor of about 1.5×10^8 (comparing an average pedestrian mass of 70kg and an average Argentine ant mass of 0.48mg).

A power formula is usually used in biology to describe the relationship (often termed an *allometric relation*) between an animal’s body mass (M) and another of its characteristics (C) (Peters 1999) i.e.

$$C = k_1 M^k \qquad (5\text{-}16)$$

Where k_1 and k are constants

The change of C with respect to M is called the scaling of that characteristic to body size. These allometric equations are usually transformed to logarithms to make it simpler to draw and interpret the variations in the rate of change of C at different values of M. It is easier to plot the data with logarithmic transformation due to the achieved linearity as shown by following equations

$$\log C = \log(k_1 M^k) \tag{5-17}$$

$$\log C = \log k_1 + k \log M \tag{5-18}$$

In biology, many aspects of locomotion follow similar power laws with respect to body mass even across a size gap as large as ants to humans. One of the relations that are commonly used are the relations that scale maximum velocity to size for each locomotory mode of swimming, running and flying as shown in Figure 5-7 (adapted from Peters 1999).

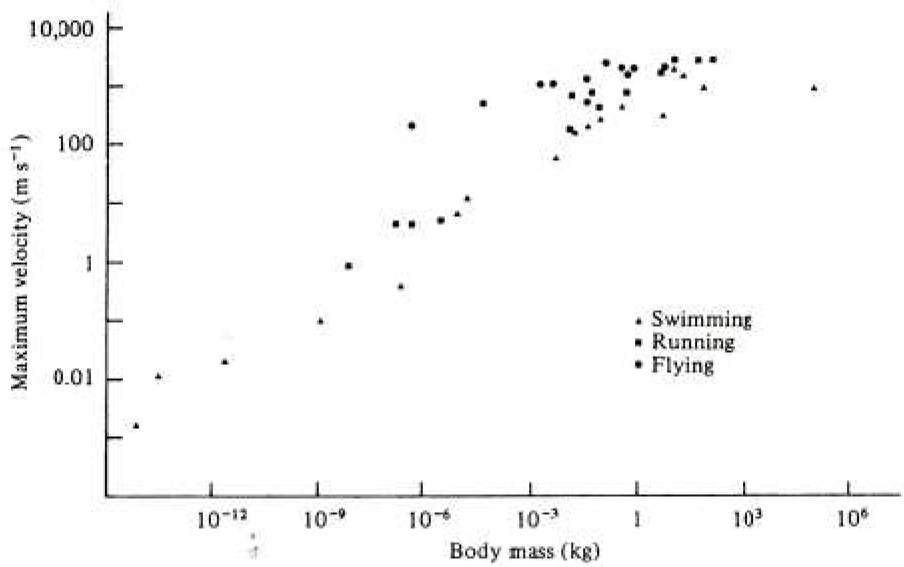


Figure 5-7: The effect of body mass (M in kg) on the maximum velocity ($V_{\max}$ m/s) of flying ($V_{\max\,(fly)} \propto M^{0.144}$), swimming ($V_{\max\,(swim)} \propto M^{0..35}$), and running ($V_{\max\,(run)} \propto M^{0..38}$), adapted from Peters (1999).

Figure 5-7 suggests, consistent with the intuition, that since larger animals usually run faster than smaller ones, then maximum speed increases with size. The scatter of data as shown in Figure 5-7 allows exceptions for particular comparisons (e.g. a cheetah can run faster than an elephant). However, the overall pattern shows a positive scaling relation of maximum speed with respect to body size. For animals of similar size, flying is the fastest while swimming is the slowest. The relation that is of interest in this dissertation is the effect of size (M) on the maximum running speed (V_{max}) as shown in Figure 5-7 which is given by

$$V_{max} \propto M^{0.38} \tag{5-19}$$

Bursts of speed over short distances in human crowd panics can reach 5–10 $m \cdot s^{-1}$ (Helbing et al. 2000). A scaling exponent of 0.38 applied to an average human pedestrian mass of 70 kg and an average Argentine ant mass of 0.48 mg implies that panic speed of the ants should reach 4–8 $mm \cdot s^{-1}$. From the experimental measurements, the average speeds of Argentine ants changed from 3 to 9 $mm \cdot s^{-1}$ during normal activity and during induced panics, close enough to accept 0.38-power scaling for the human-ant comparison. Therefore, for scaling model parameters, simple proportional scaling of the model parameters based on the body mass difference between humans and ants has been considered by using Equation 5-19. Hence, the scaling factor (S) for model parameters is proportional to $M^{0.38}$ i.e.

$$S \propto M^{0.38} \tag{5-20}$$

Or,

$$S = \gamma M^{0.38} \tag{5-21}$$

Where,

γ = constant

5.4 Summary

In this chapter, a 2-dimesnional continuous space with discrete time step updating simulation model EmSim was developed for collective dynamics. The model was based on the fundamental principle of emergent system i.e. emergence of order on a global scale through interactions on a local scale. The platform for modelling the collective dynamics was based on Newtonian mechanics.

By drawing on the strength of the three approaches, animal dynamics (and ants experiment), pedestrian dynamics and molecular dynamics, collective forces were formulated. The collective forces included following:

- impulsive forces to drive an individual towards exit /target
- local interactive forces based on repulsion and attraction zones to take into account the local interactions between individuals
- collision and pushing forces to represent the physical interactions among individuals

The formulation for the model recognises the role of both attractive and repulsive forces in maintaining the coherence of collective dynamics under panic conditions. To date, consideration of both repulsive and attractive forces has received limited attention in studies of crowd panic reported in the literature. Also the granular forces for pushing behaviour were modified to consider the case of discontinuity when the relative velocity is zero or near to zero.

With those collective forces, optimal instantaneous acceleration of each individual was obtained. The position and velocity of each individual were then updated in each time step from the integration of the Newton's equation of motion. The graphics of motion of individual were also updated with the new position. The process continued for the total simulation time assigned. The output from the simulation was the visual graphics for qualitative validation and data file (e.g. speed, position, evacuation time, etc.) for quantitative validation.

An original attempt has also been made to scale the model parameters for collective pedestrian traffic via ant traffic, based on a scaling concept commonly used in biology. With that there is scope to compare the collective movement patterns of non-human biological entities and pedestrians in order to devise sound strategies to aid evacuation. The developed model EmSim is applied to simulate ant traffic and pedestrian traffic in the next two Chapters 6 and 7 respectively. It is also applied to develop design solutions that enhance the safety of pedestrian crowds in Chapter 8.

CHAPTER 6 SIMULATION OF ANT TRAFFIC

6.1 Introduction

In this chapter, the simulation model EmSim proposed and developed in Chapter 5 is applied to simulate collective ant traffic as observed from experiments with panicking ants. The model must be appropriately calibrated and validated for ant traffic before scaling up to the human situation. Simulation was conducted with EmSim to examine the impact of:

- the presence of a column near the exit, and
- alternative exit locations (i.e. locating the exit at the corner of the walls as opposed to in the middle of a wall).

The situations indentified above replicate the scenarios presented in the ants experiment described in Chapter 4. First the model is calibrated for scenarios with and without a column being present. Then the model is validated with the independent data from the scenarios with exit at the corner or the middle of the walls. A total of 200 ants were distributed randomly at the start of each simulation. For simplicity in simulating circular chamber experiment, the experiment was simulated with a square chamber of equivalent area (31mm by 31mm) to the circular chamber used in the ants experiment.

In calibrating the model, some of the parameter values were measured and obtained from the experiment (such as desired speed, mass, size, reaction time, repulsion and attraction range) as mentioned in Section 4.4.1. Because of the difficulty in directly measuring the other parameters (such as repulsive and attractive force constants, dampening and elastic restoration constant, frictional constant), those parameters were estimated from simulation trials so as to replicate the experimental scenario. In assessing those parameters, firstly it was ensured that these different set of parameters and input variables prevent ants colliding or overlapping each other (unrealistic behaviour) in simulation. Secondly, several trial simulations were conducted to make sure that there were no extremities observed in collision and frictional effect (high rate of collision or strong static friction). Thus a trade-off analysis was conducted in estimating those parameters. Thirdly, the specific value of the parameters was assessed to minimise the error between mean and standard deviation of escape rate of ants. The values of the parameters calibrated and used for the simulation are given in Table 6-1. The time step (Δt) for the update of the simulation was 0.001 s.

Table 6-1: Value of the parameters assessed for the simulation of escape rate of ants

Experimental measurements		From estimation	
Parameters	Value	Parameters	Value
v_d (desired speed)	9 mm/s	ϕ_R (repulsive constant)	0.1 g mm^2 / s^2
τ (reaction time)	0.2s	ϕ_A (attractive constant)	2.5×10^{-4} g mm^2 / s^2
m_α (mass)	3.4×10^{-4} g to 6.2×10^{-4} g	α_1 (dampening constant)	0.01 g/s
r_α , r_β (radius)	0.5 mm to 0.6 mm	α_2 (elastic restoration constant)	8 g/ s^2
λ_R (repulsion distance)	0.5 mm	μ_1 (frictional constant)	0.06 g/s
λ_A (attraction distance)	8.0 mm	μ_2 (frictional constant)	0.06 g/ s^2

6.2 Simulation results

6.2.1 With/without column at the exit

Thirty replicates were simulated for with/without column scenarios. The same data were extracted on escape times of individual ants and headways (the time interval between the exit of successive ants) between successive ants as in the experimental trials. The exit time (to the nearest 0.04s) of the first 50 ants to leave the chamber were extracted. From these data, the cumulative time-versus-escape sequence pattern and the distribution of traffic headways were reconstructed. For determination of headways, the exit time was taken from the video frame in which the *gaster* (posterior portion of the ant's abdomen) of an escaping ant first cleared the outer wall of the chamber.

Figure 6-1a and 6-1b show the temporal pattern of escape for each trial in the two treatment groups (absence or presence of a column in front of the exit). Figure 6-1c and 6-1d show the equivalent data generated by model simulation (30 repetitions).

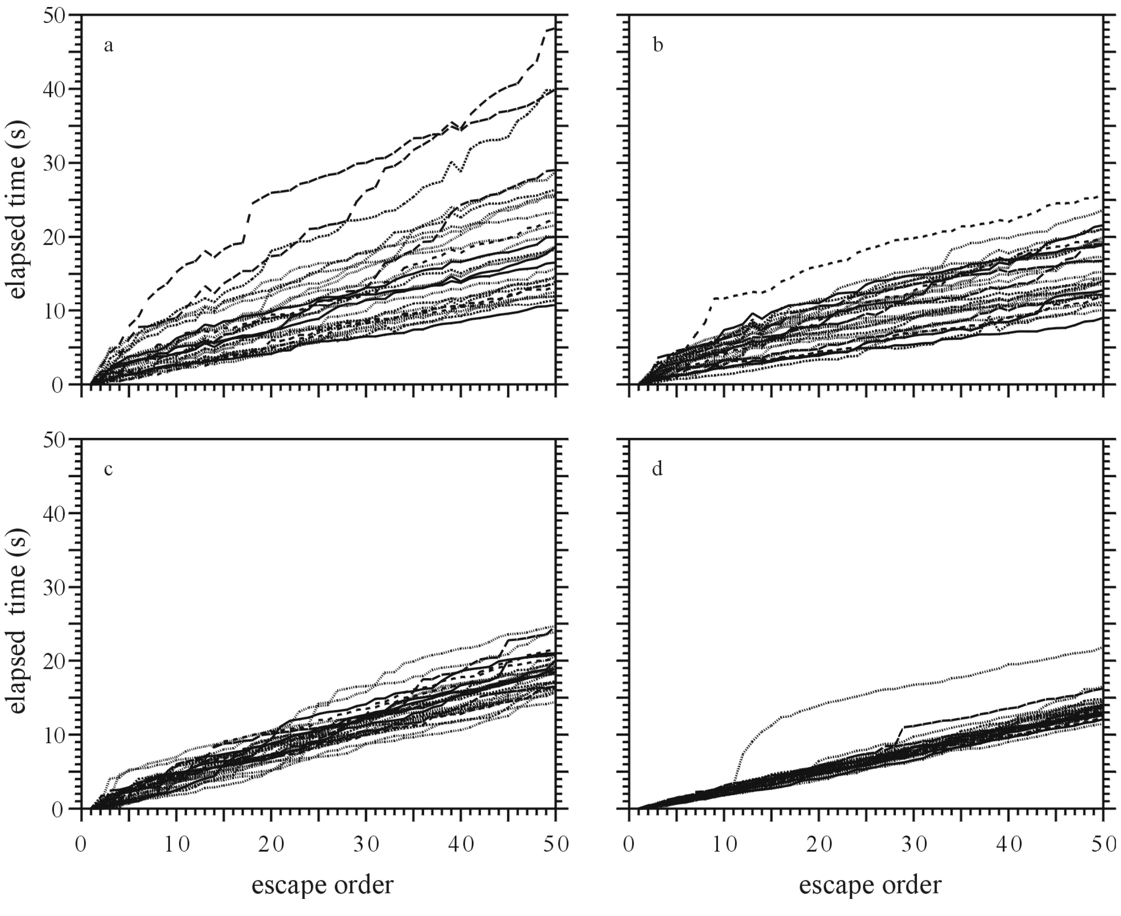


Figure 6-1: Escape pattern in experimental (a, b) and simulated (c, d) ant crowds. The horizontal axis indicates individual ants in the order they exit the chamber. The vertical axis indicates the cumulative time in seconds. Each trace shows an individual experimental trial or simulation. Results for the column-absent treatment in (a, c) and for the column-present treatment in (b, d).

With an unobstructed exit, evacuation times for the first 50 ants ranged from 10.76 to 48.20 s (mean ± s.d = 21.6 s ± 9.9 s), while in the presence of a column, evacuation times ranged from 9.00 to 25.66 s (mean ± s.d = 16.0 s ± 4.3 s). The corresponding results for the simulations were 14.41 to 27.42 s (mean ± s.d = 18.9 s ± 2.6 s) without the column, and 11.5 to 21.86 s (mean ± s.d = 13.9 s ± 1.9 s) with the column present.

Some comparisons are available by inspection of Figure 6-1. First, it is clear that the model output is quantitatively similar to real ant behaviour, certainly well within the correct order of magnitude, although variation among trials seems lower in the simulations. Second, the presence of the partially obstructing column decreases the average time needed to evacuate the first 50 ants in both real and simulated trials by 5.6 s and 5.0 s, respectively. Third, the superior escape rate with a column near the exit is, on average, established early and maintained throughout the escape sequence. Fourth, there is overlap in escape sequences between the two treatment groups (presence and absence of the column), so that the advantage due to the column is an average effect.

Levene's test confirms that the variance in evacuation time is significantly greater for the empirical than for the simulation results as observed from the P-value in Table 6-2. Given the lack of homogeneity of variances, the treatment means were compared by the nonparametric Mann-Whitney test as shown in Table 6-3. Escape times for 50 ants were significantly greater when the column was absent than when it was present for both real and simulated data as observed from the P-value in Table 6-3. In contrast, there was no significant difference between the empirical and model results for the column-present trials nor for the column-absent trials. Thus, the model output is consistent with the empirical behaviour (within the ability of the Mann-Whitney test to detect a difference), and both model and empirical tests confirmed the counterintuitive effect of a partial obstruction in enhancing the evacuation rate. If the non-homogeneity of variances is ignored, ANOVA produces qualitatively equivalent results. That is, there are significant differences in escape time between the column-present and column-absent treatments for both real and simulated results, but no significant difference between real and simulated results when comparing only the column-present results or only the column-absent results.

Table 6-2: Levene's test for homogeneity of variances

Treatment	Levene's Test
Experiment vs. simulation with no column	$F_{1,58}$ = 23.89, P <0.0001
Experiment vs. simulation with column	$F_{1,58}$ = 30.14, P <0.0001
Experiment with and without column	$F_{1,58}$ = 11.162, P =0.001
Simulation with and without column	$F_{1,58}$ = 5.237, P =0.026

Table 6-3 : Mann-Whitney Test for treatment (with/without column) means

Treatment	Mann-Whitney Test
Experiment vs. simulation with no column	U= 422, Z =0.197, P =0.84
Experiment vs. simulation with column	U= 341, Z =1.611, P =0.11
Experiment with and without column	U= 291.5, Z =2.176, P = 0.03
Simulation with and without column	U= 41, Z =6.047, P < 0.0001

What mechanism produces the column effect? Figure 6-2 shows that the distributions of headway times differ between the two column treatments. There were more short headways and fewer lengthy headways in column-present than in column-absent trials, for both the empirical and model results. Table 6-4 consolidates the headway distributions into three classes: gaps up to 0.5 s in length, gaps greater than 0.5 s up to 1 s, and gaps greater than 1 s. Differences between the outcomes with and without a column present at the exit are statistically significant for both the empirical and simulation data as shown by Chi-squared test in Table 6-4. The Chi-squared values (degree of freedom = 2), as presented in Table 6-4 test the homogeneity of frequencies between the column-present and column-absent results.

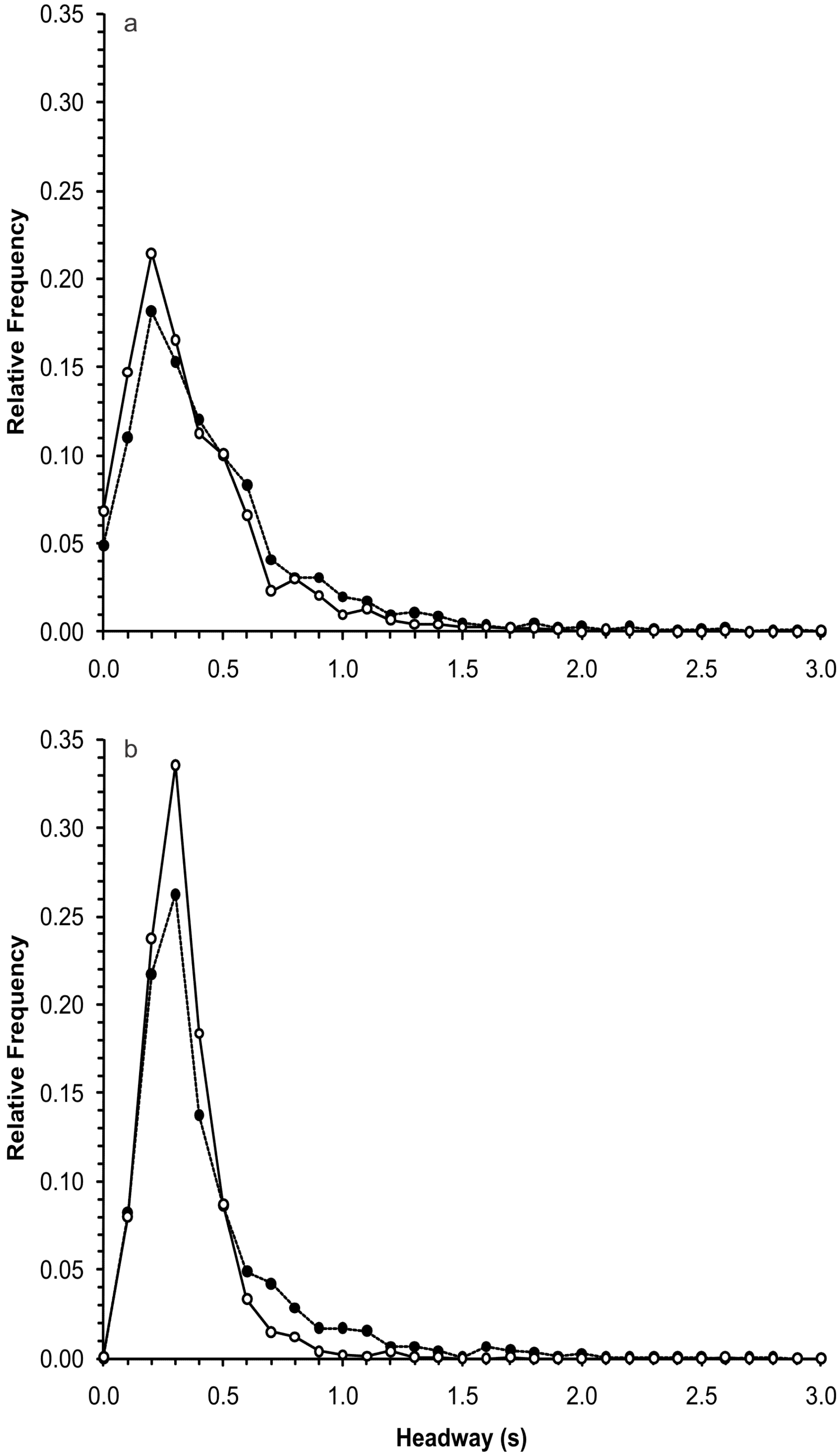


Figure 6-2: Distribution of headway time intervals in (a) experimental and (b) simulated ant crowds. Open symbols indicate the column-present treatment; closed symbol indicate the column-absent treatment.

Table 6-4: Frequency of headways in the empirical and simulation data (column present vs. column absent)

	Empirical data		Simulation data	
Headway interval, *t* (s)	column present	column absent	column present	column absent
$t \leq 0.5$	1187 (80.7%)	979 (71.3%)	1359(92.4%)	1156(78.6%)
$0.5 < t \leq 1$	219 (14.9%)	281 (20.5%)	98 (6.7%)	226 (15.4%)
$t > 1$	64 (4.4%)	112 (8.2%)	13 (0.9%)	88 (6.0%)
	χ^2 = 37.4, $P < 0.001$		χ^2 = 122.6, $P \ll 0.001$	

Figure 6-3a presents simulation snapshot showing the escape of ant traffic without a column at the exit, while Figure 6-3b shows the snapshot of ant traffic in the presence of a column. As observed from the experimental and simulation results of headway above, a partial barrier in the vicinity of an exit should reduce the frequency of long time headways (gaps during which the crowd is momentarily jammed and no exits occur) and increase the frequency of short headways (rapid succession of exits).

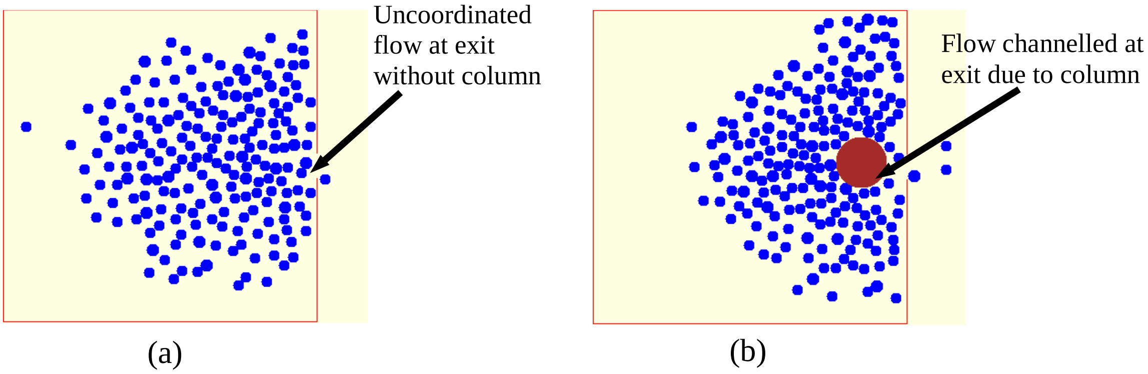


Figure 6-3: Simulation snapshots showing the escape of ants without column (a) and with column (b) near the exit

6.2.2 Corner exit vs. middle exit

After calibrating the model for with/without column scenarios, the model was then validated with corner exit/middle exit scenarios. Ten replicates were simulated for middle/corner exit scenarios and the same data were extracted on escape times of individual ants and headways between successive ants as in the experimental trials. The exit time (to the nearest 0.04s) of the first 50 ants to leave the chamber were extracted. From these data, the cumulative time-versus-escape sequence pattern and the distribution of traffic headways were reconstructed as in column/no column scenarios. Figure 6-4a and 6-4b show the temporal pattern of escape for each trial in the two treatment groups (corner or middle exit). Figure 6-4c and 6-4d show the equivalent data generated by model simulation (10 repetitions).

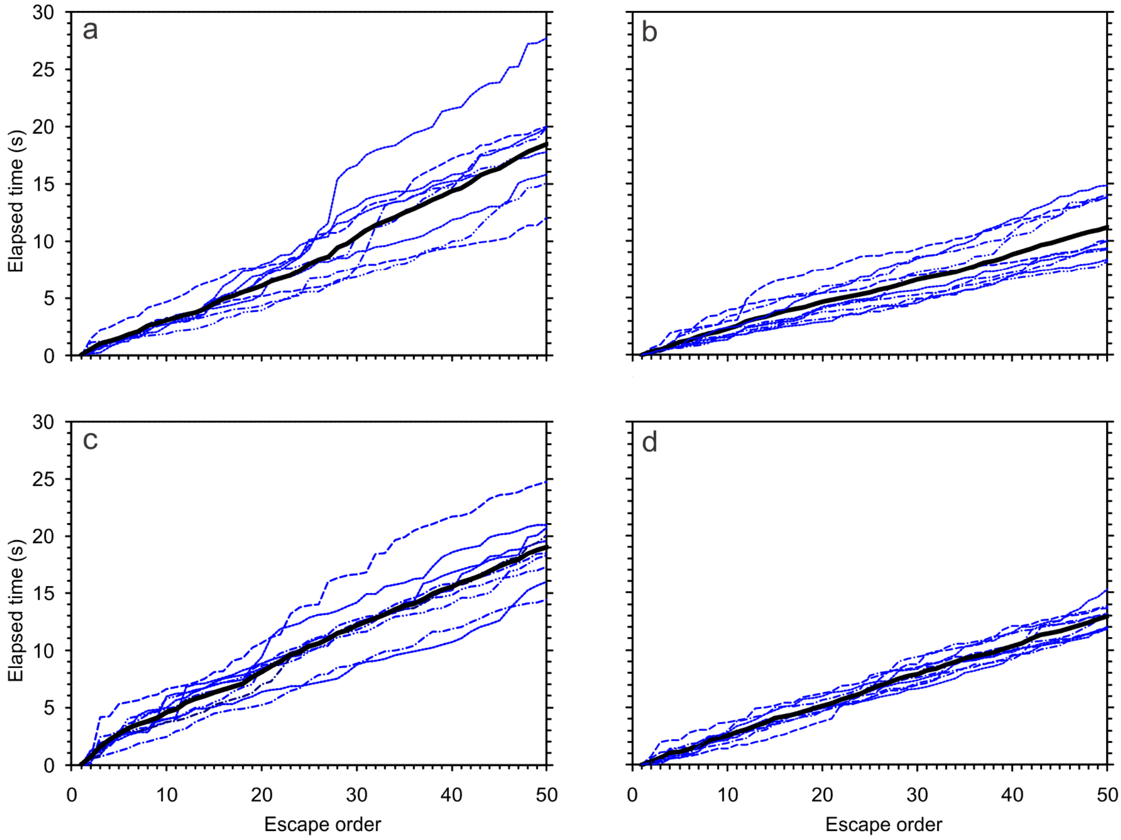


Figure 6-4: Escape pattern in experimental (a, b) and simulated (c, d) ant crowds. The horizontal axis indicates individual ants in the order they exit the chamber. The vertical axis indicates the cumulative time in seconds. Each trace shows an individual experimental trial or simulation. Heavy trace in black represents the means of 10 replicates of each condition. Results for the middle exit treatment in (a, c) and for the corner exit treatment in (b, d)

With a corner exit, evacuation times for the first 50 ants ranged from 8.24 to 14.84 s (mean ± s.d = 11.18 s ± 2.61 s), while in middle exit, evacuation times ranged from 12.0 to 27.64 s (mean ± s.d = 18.48 s ± 4.09 s). The corresponding results for the simulations were 11.83 to 15.27 s (mean ± s.d = 12.98 s ± 1.11 s) with the corner exit, and 14.41 to 24.69 s (mean ± s.d = 19.02 s ± 2.89 s) with the middle exit.

As shown in Figure 6-4, it is clear that the model output is quantitatively similar to real ant behaviour, although variation among trials seems slightly lower in the simulations. With the exit at the corner, the average time needed to evacuate the first 50 ants in both real and simulated trials decreases by 7.3 s and 6.0 s, respectively. Also there is overlap in escape sequences between the two treatment groups (exit at corner and middle), so that the advantage due to the corner exit is an average effect. The T-test reveals that there are significant differences in escape time between the corner exit and middle exit treatments for both real and simulated results, but no significant difference between real and simulated results when comparing only the corner exit results or only the middle exit results (Table 6-5).

Table 6-5: T-test for treatment (corner vs. middle exit) means

Treatment	T- test
Experiment with corner vs. middle exit	$t\ (18) = 4.748, P < 0.0001$
Simulation with corner vs. middle exit	$t\ (18) = 5.998, P < 0.0001$
Experiment vs. simulation with corner exit	$t\ (18) = 2.016, P = 0.066$
Experiment vs. simulation with middle exit	$t\ (18) = 0.324, P = 0.75$

Figure 6-5 shows that the distributions of headway times differ between the exit at corner and at middle. In both the empirical and simulation results there were more short headways and fewer long headways with the exit in the corner compared to it being in the middle of a wall.

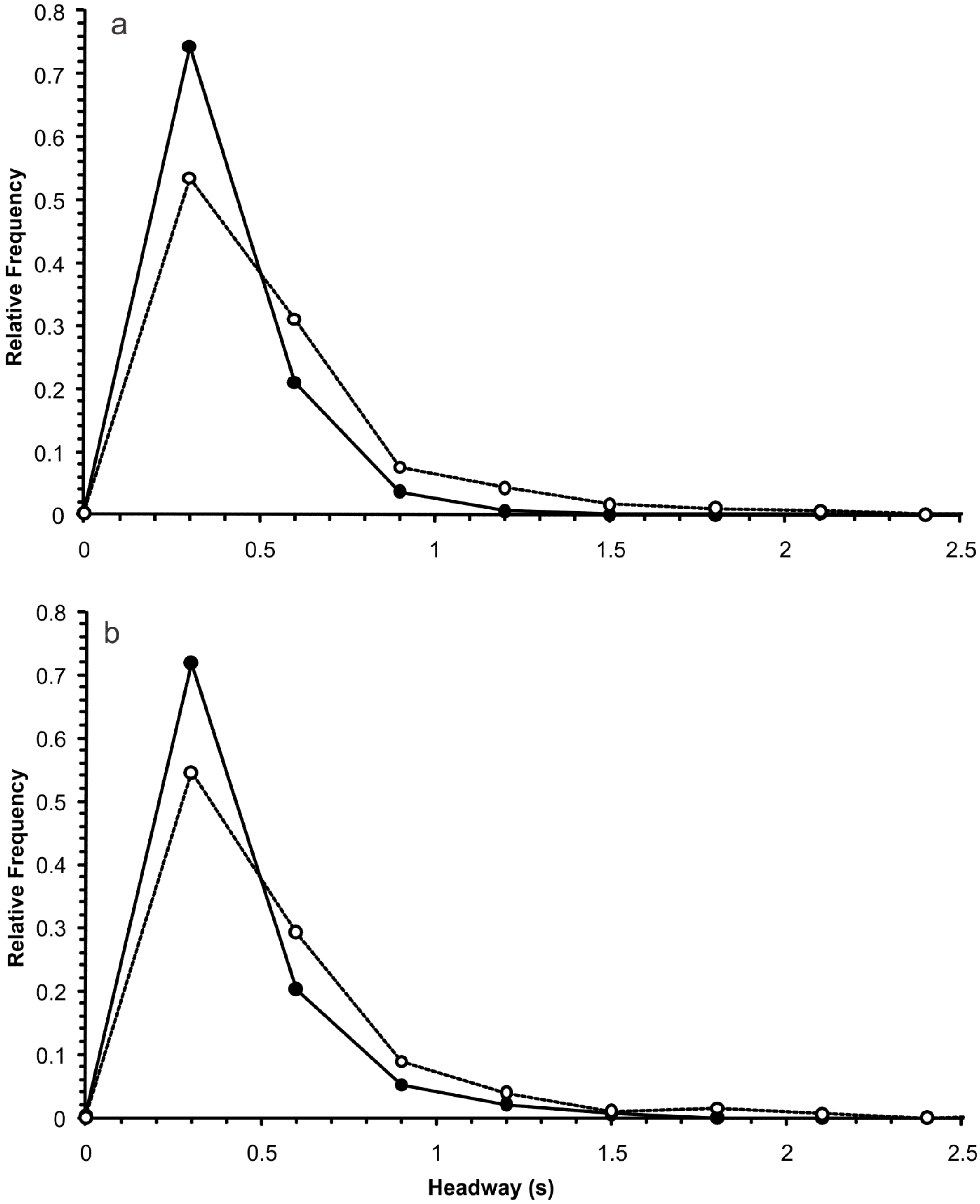


Figure 6-5: Distribution of headway time intervals in (a) experimental and (b) simulated ant crowds. Closed symbol indicate the corner exit treatment; open symbol indicate the middle exit treatment.

Table 6-6 shows the headway distributions classified into three classes: gaps up to 0.5 s in length, gaps greater than 0.5 s up to 1 s, and gaps greater than 1 s. Differences between the outcomes with the exit located at the corner and middle of the walls are statistically significant for both the empirical and simulation data as shown by Chi-squared Test in Table 6-6. Chi-squared values (degree of freedom = 2), test the homogeneity of frequencies between corner exit and middle exit results.

Table 6-6 shows that the proportion of headways less than or equal to 0.5 s is higher in the case of the corner exit (91.4% in the experiment and 90% in the simulation) compared to the case of the middle wall exit (76.5% in the experiment and 77.2 % in the simulation). In contrast, the proportion of headways greater than 0.5 s is higher in case of the middle exit (23.5% in the experiment and 22.8% in the simulation) compared to the case of the corner exit (8.6% in the experiment and 10 % in the simulation). These results suggest that the exit located at the corner reduces the frequency of long time headways and increases the frequency of short headways thereby facilitating the rapid succession of exits compared to when the opening is located in the middle of the wall.

Table 6-6: Frequency of headways in the empirical and simulation data (corner vs. middle exit)

	Empirical data		Simulation data	
Headway interval, *t* (s)	corner exit	middle exit	corner exit	middle exit
$t \leq 0.5$	448 (91.4%)	375 (76.5%)	441(90%)	378(77.2%)
$0.5 < t \leq 1$	39 (8%)	89 (18.2%)	42 (8.6%)	83 (16.9%)
$t > 1$	3 (0.6%)	26 (5.3%)	7 (1.4%)	29 (5.9%)
	$\chi^2 = 44.24, P < 0.001$		$\chi^2 = 31.74, P < 0.001$	

6.3 Summary

In this chapter, simulation was conducted with EmSim model developed in Chapter 5 to parameterize the model and replicate the scenario of experiments with panicking ants as illustrated in Chapter 4. Some of the parameter values were measured and obtained from the experiment (such as desired speed, mass, reaction time, size, repulsion and attraction range). Because of the difficulty in directly measuring the other parameters (such as repulsive and attractive force constants, dampening and elastic restoration constant, frictional constant), those parameters were estimated from simulation trials so as to replicate the experimental scenario.

First the model was calibrated for scenarios with and without a column being present near the exit. Then the model was validated with the independent data from the scenarios with exit at the corner or the middle of the wall. The model correctly predicted the empirical flow rates for ants. In addition, the distribution of time headways between successive ants in the escape sequence was similar in both the simulation model results and the empirical data.

The next chapter extends application of the EmSim model to pedestrian traffic. This involves the application of the scaling concept derived in Section 5.3. Successful prediction of collective movement in both humans and Argentine ants through parameter re-scaling would suggest that the model captures something fundamental about the dynamics of self-driven particles in crowds despite variation in size, manner of locomotion, cognitive abilities, and other biological traits.

CHAPTER 7 SIMULATION OF COLLECTIVE PEDESTRIAN TRAFFIC

7.1 Introduction

With the successful calibration and validation of the EmSim model for ant traffic in Chapter 6, the model is scaled up to simulate collective dynamics of pedestrians in this chapter. The model parameters re-scaling are conducted through scaling concept derived in Section 5.3. The motive for this was to test the robustness of the model with respect to differences in the size, speed, and other biological details of the panicking individuals. There is scope within such a test to compare the collective movement patterns of biological entities and pedestrians in order to devise sound strategies to aid evacuation.

EmSim was used to study pedestrian traffic for panic conditions as well as for normal (non-panic evacuation) conditions. For panic conditions, the model was validated with the experimental scenarios as described for ant traffic but scaled up for the human scenario. For normal (non-panic) conditions, the model was validated with experimental data on pedestrian traffic; specifically the comparison of headway distribution in uni-directional traffic, the comparison of speed distribution and lanes formation in bi-directional traffic and the comparison of outflow in bottlenecks with various widths. Parameter values in the model were either taken from the available empirical data on pedestrian traffic (e.g. mass, size, speed) or *allometrically* scaled up from the ant values based on the body mass difference (as explained in Section 5.3) where direct measurement of parameter values was not possible (for example, repulsive force constant ϕ_R = 2500 kg m^2, elastic restoration constant α_2 = 1.7×10^5 kg/s^2). The sensitivity analysis of the model parameters will be discussed later in section 7.4.

7.2 Collective dynamics under emergency /panic conditions

The panic scenario was simulated to examine the effect of two situations:

- the presence or absence of a column near the exit of a room, and
- the relative effectiveness of locating the exit at the middle of the walls as opposed to at the corner.

In the simulation, 200 pedestrians were distributed randomly in a room of 15m by 15m and were allowed to escape through a single door width of 1.2m. For the column trial, a 1.5 diameter column was placed slightly asymmetrically near the exit at a distance of 0.5 m from the exit. The desired velocity of 5m/s corresponded to the fleeing velocity under panic conditions reported in the literature (Helbing et al. 2000). Randomness in the simulation was introduced via a distribution of different locations of individuals, different body sizes and masses. Ten trials were carried out for each simulation scenario.

7.2.1 With/without column scenario

The average flow was 1.63 ped./s (SD= ± 0.09) without column while it was 2.12 ped./s (SD= ± 0.10) when the column was present. That represents an increase in efficiency of escape by 30% when the column is present. The flow was significantly greater when the column was present than when it was absent as determined by a t-test, with p-value (<0.0001) being less than 0.05. Figure 7-1 compares the flow based on 10 simulation trials for the column / no column scenarios. It can be seen from Figure 7-1 that consistent with the experiments with panicking ants, the presence of a partial obstruction such as column near the exit generally increases the flow of the people compared to the absence of column. Figure 7-2 shows typical curves of escape rate for the simulation scenarios of with/without column. It can be observed that the difference in evacuation time with and without the column increases as time elapses and the cumulative number of evacuated pedestrians increases.

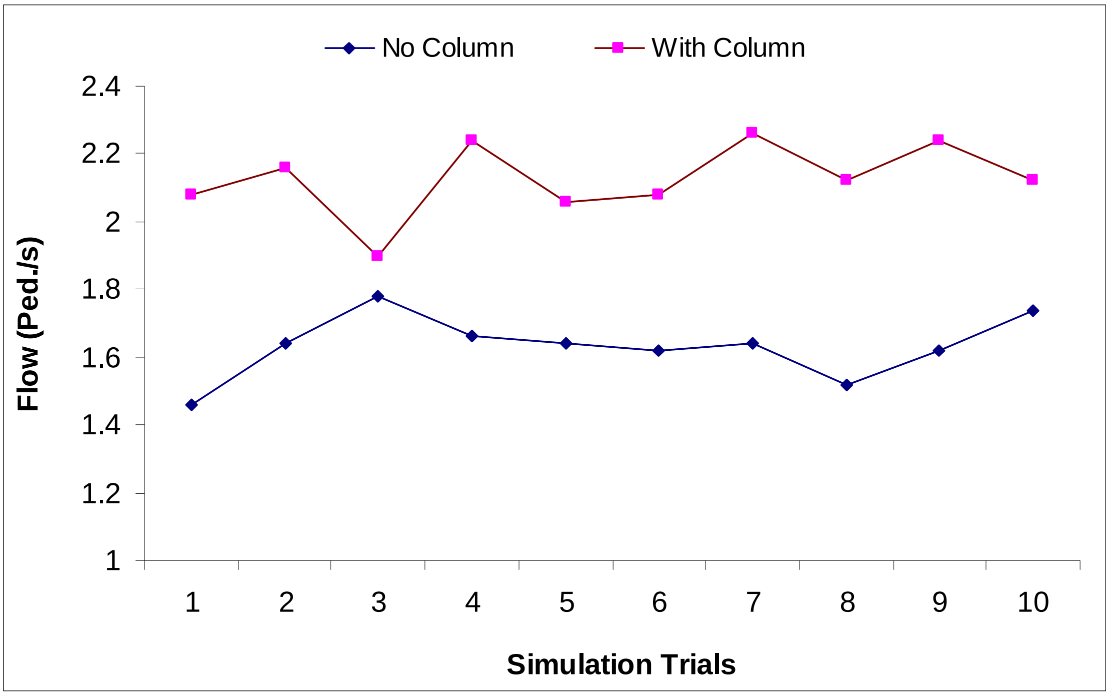


Figure 7-1: Comparsion of flow for with/without column scenario

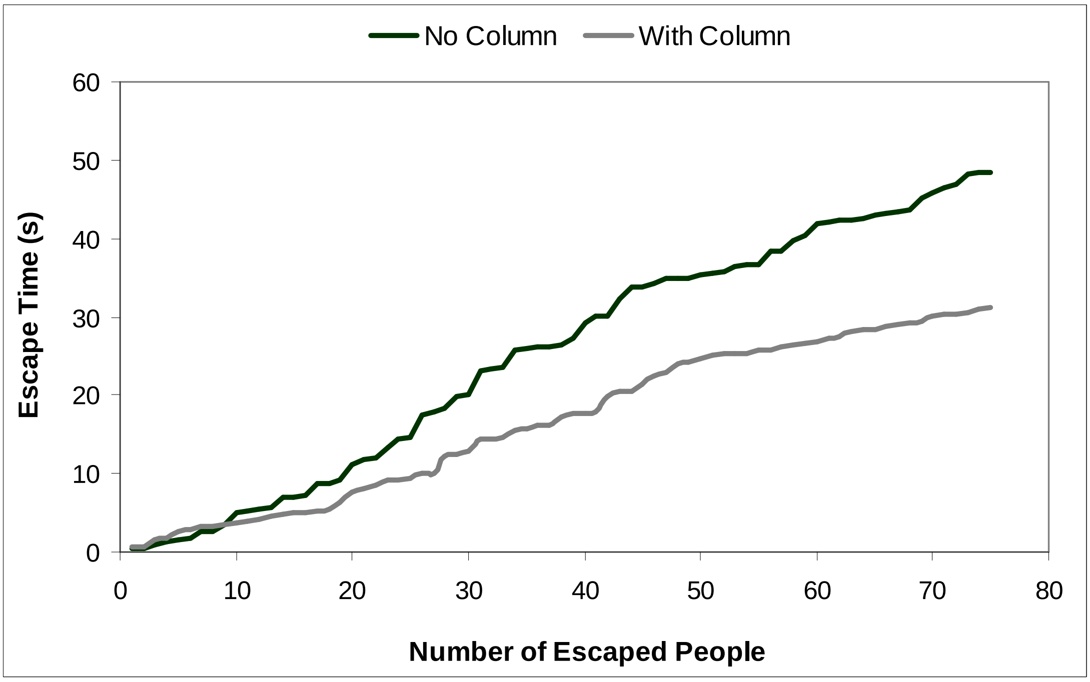
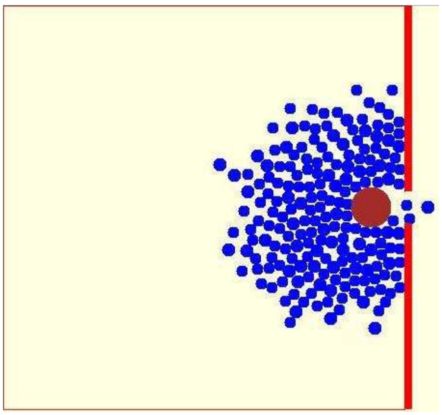
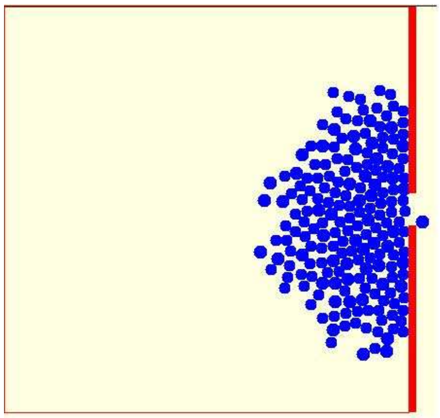


Figure 7-2: Typical escape rate curves for with and without column scenario for pedestrian traffic showing the similarities of trend as observed in ants experiment

Figure 7-2 shows that the curve is more regular for the scenario with column than for the one without a column, suggesting that the irregularity observed when the column is absent is due to the halt periods in the simulation, i.e., the time lapse during which no pedestrian manages to pass through exit. This may occur because there are more frequent strong local interactions and pushing behaviour when there is no column present to moderate the flow. During emergency egress, the presence of such strong local interactions could slow people to impact on their chance of survival. Figure 7-3 shows the simulation snapshots for the escape of pedestrians for the with/without column scenarios. It is evident that the barrier absorbs physical pressures from a dense crowd and helps disrupt transiently “frozen” crowd configurations near the exit that momentarily prevent egress. This may help to prevent trampling and crushing by distributing the tremendous pressure generated at the exit.



(a)



(b)

Figure 7-3: Simulation snapshots showing the escape of people with column near the exit (a) and without column (b).

7.2.2 Corner exit vs. exit in the middle of the wall

The average flow was 3.01 ped./s (SD= ± 0.11) with corner exit. However, it was 1.63 ped./s (SD= ± 0.09) with middle exit (as mentioned in without the column scenario in section 7.2.1) resulting in more than 85% increase in outflow. The flow was significantly greater when the exit was located at the corner than when it was located at the middle of the walls (p-value for the t-test <0.0001 being less than 0.05).

Figure 7-4 compares the flow based on 10 simulation trials for scenarios where the exit is at corner and at in the middle of the wall. It can be seen from Figure 7-4 that consistent with the experiments from panicking ants (72% efficient in outflow for ants); the corner exit was predicted to be more efficient (85%) for the outflow of pedestrians compared to the middle exit. Figure 7-5 shows the simulation snapshots for the escape of pedestrians with the exit located at the corner. As explained in Section 4.2.2.2, this increase in flow rate with corner exit could be due to the minimization of change in direction of escaping individuals in the corner exit. This will be further examined in section 8.3 of Chapter 8.

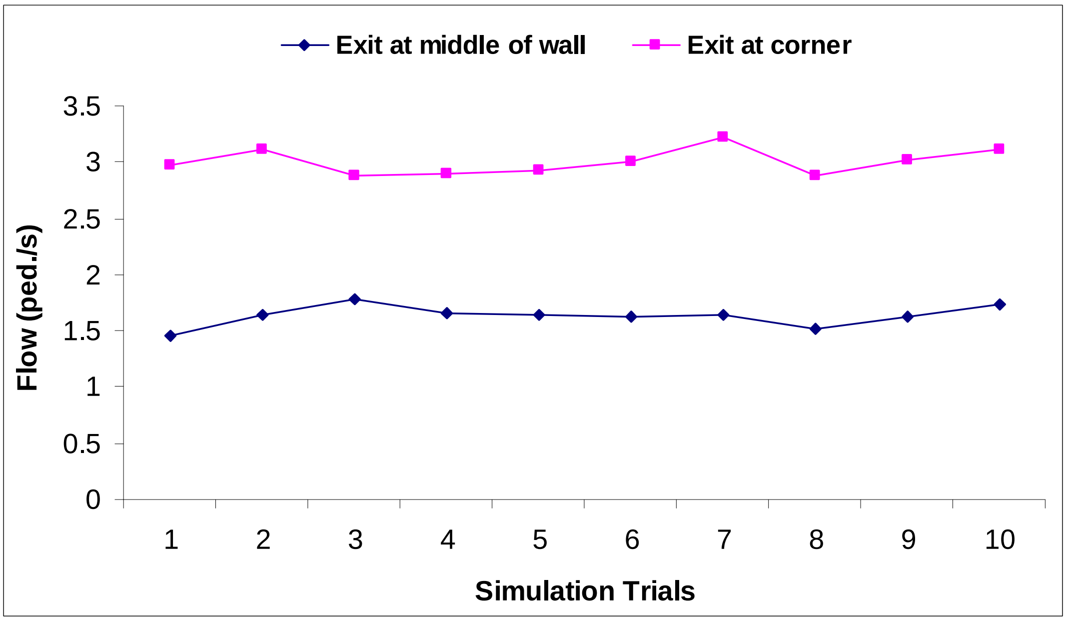


Figure 7-4: Comparsion of flow with exit at the corner and the exit at the middle of the wall

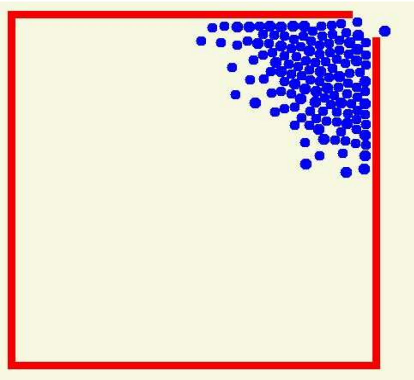


Figure 7-5: Simulation snapshots showing the escape of people with exit located at the corner

7.2.3 Corner exit with column

With the column located near the corner exit, the average outflow of pedestrians varied with the horizontal offset of the column from the exit as shown in Figure 7-6. Contrary to the result for the scenario where the column was near an exit in the middle of the wall (Section 7.2.1), having a column offset 0.5m from the corner exit did not improve the flow of pedestrians. In that case, the average outflow was substantially lower (2.7 ped./s) than when the column was absent (3.01 ped./s) at corner exit as shown in Figure 7-6. However for horizontal offsets between 0.6m and 0.8m, the average flow rate was more than when the column was absent and peaked at a 0.7m horizontal offset (3.71 ped./s). When the column was offset more than 0.8m, the flow rate was less than when the column was absent.

The above result suggests that the performance of these partial obstructions near the exit depends on the architectural layout of the escape area. The performance of these partial obstructions seems to depend on the size and location of the obstruction. The effect of location and size of the obstruction will be further discussed in more detail in Section 8.2 of Chapter 8.

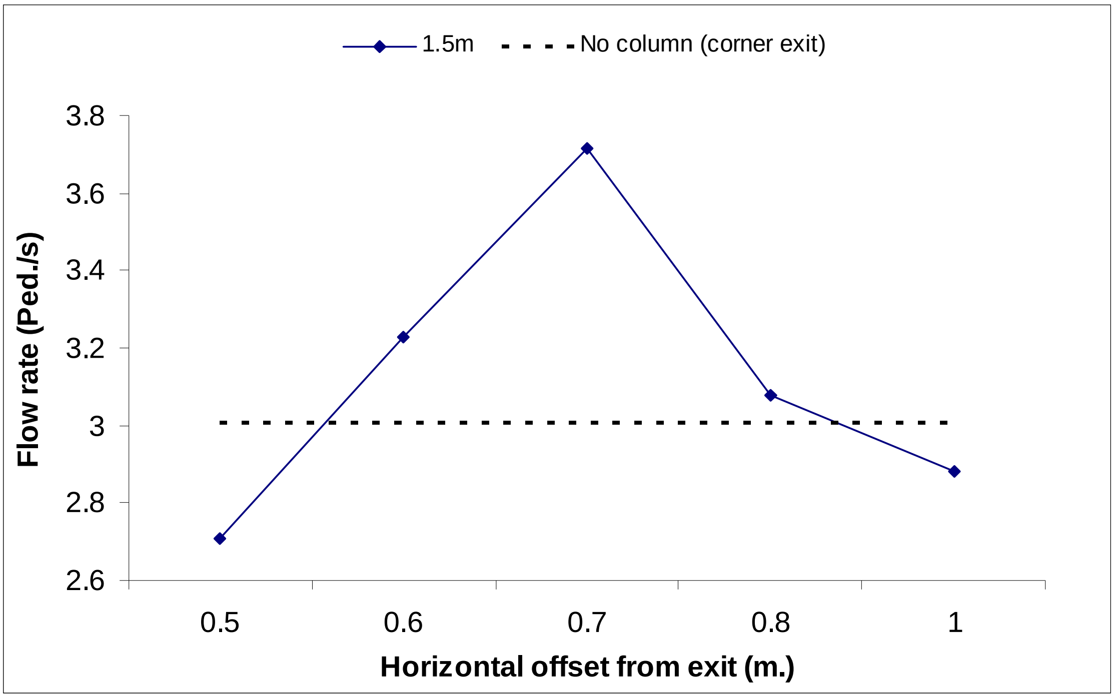


Figure 7-6: Comparison of flow rate with column located at different horizontal offset from the corner exit.

7.3 Collective dynamics under non-panic conditions

EmSim was used to study collective pedestrian dynamics under non-panic conditions. The ability of the model to replicate a normal evacuation process was assessed based on the comparison of the simulation results with those obtained from a real-life experiment involving human subjects. The real-life experiments focused on pedestrian flow through bottlenecks (uni-direction) and corridors (uni-direction and bi-direction). The bottleneck experiments were conducted by researchers at the University of Duisburg-Essen (Kretz 2007). The experiments with uni-directional and bi-directional movement in a corridor were conducted by the researchers at the Institute of Industrial Science, University of Tokyo, Japan (Asano et al. 2009). Video files and the data of the experiments were provided by those researchers to enable to compare those experimental results with the simulation results obtained in this thesis.

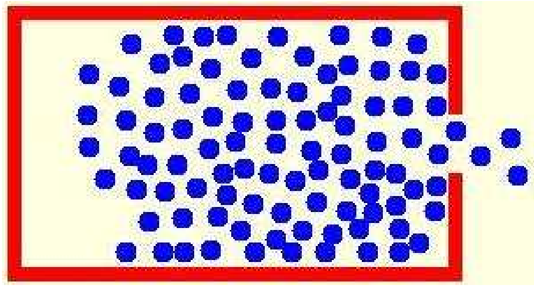
As the simulation was performed for normal conditions, the frictional/pushing forces were not considered i.e. μ_1 and $\mu_2 = 0$. For bottlenecks and bi-directional traffic, the desired speed was assigned to be 1m/s corresponding to the free velocities for leaving a room under normal conditions (Helbing et al. 2000). In the case of uni-directional traffic, the desired speed of the pedestrians was assigned to be 0.6m/s, corresponding to the observed speed under relaxed conditions (Helbing et al. 2000).

7.3.1 Flow through bottlenecks

Bottlenecks are critical points for crowd egress. The ability to estimate the capacity of such critical points provides an important input for the design and evaluation of pedestrian facilities with respect to safety. EmSim was used to study pedestrian traffic for normal evacuation process in the case of a bottleneck of various widths. The experiments (Kretz 2007) involved a uni-direction movement of 100 pedestrians passing through a bottleneck of various widths; 80 cm, 100 cm and 120 cm. The bottleneck was formed by two cabinets with a height of two meters and a depth of 40 centimetres. The pedestrians were confined in an area approximately 9 m deep and 4m wide. The pedestrian movement through the bottleneck was recorded by a video camera mounted above the bottleneck.

Figure 7-7 shows the snapshot from the experiment and corresponding simulation. Figure 7-8 compares the flow obtained from the simulation with that from the experiment for the various bottleneck widths. In reality and in the model, flow is sensitive to the egress width. As intuition would suggest, wider bottlenecks allow greater flow. It is not intuitive, however, what the pattern of this increase should be. There is disagreement in the literature over whether to expect a linear or step-function increase (Kretz 2007).

(a)



(b)

Figure 7-7: Snapshots showing the experimental setup for bottleneck experiments (a) and corresponding simulation setup (b).

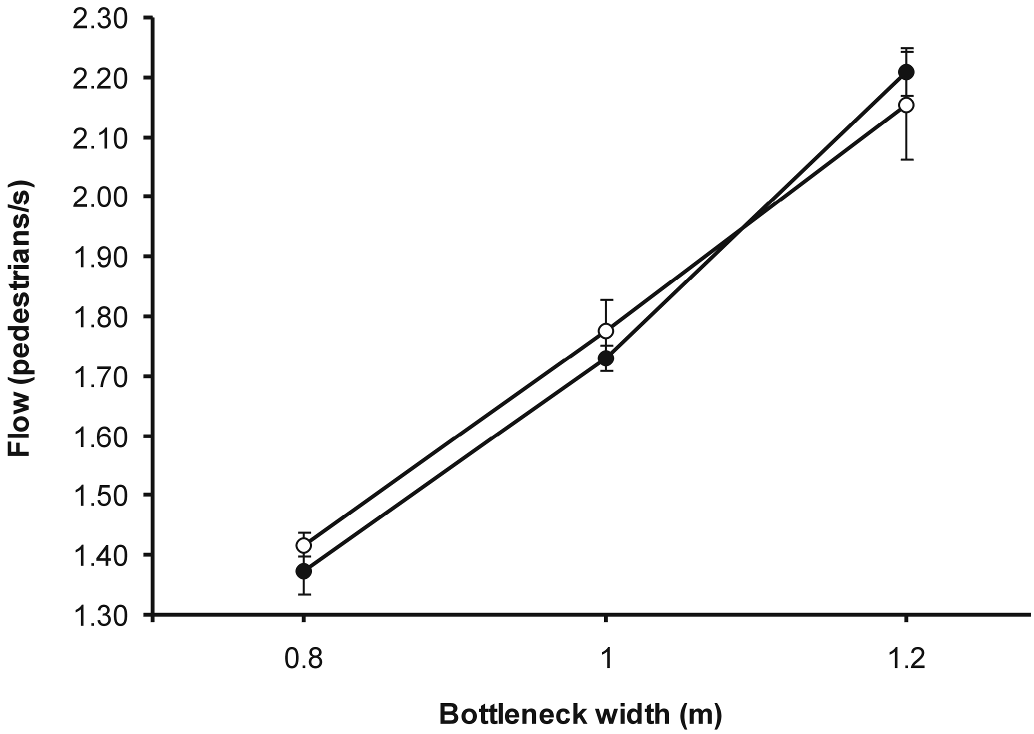


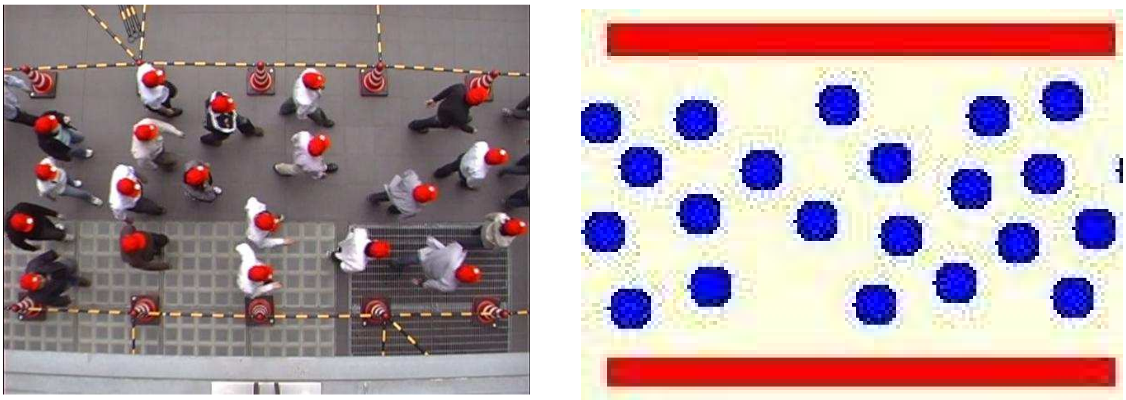
Figure 7-8: Empirical and simulated flow rates of humans through corridor bottlenecks at three widths. Open symbols, empirical results; filled symbols, EmSim results. Error bars show ± 1 S.E.

In both the model and the experiment, flow rate followed a roughly linear increase with bottleneck width over the range of three widths studied. The analysis of variance showed a highly significant effect of width ($F_{2,12}$ = 118, P < 0.0001) but no difference between empirical and simulated data ($F_{1,12}$ = 0.07, P = 0.795) and no interaction effect between the factors ($F_{1,12}$ = 0.66, P = 0.54). Also if we compare the flow through 1.2 m bottleneck from experiment (2.15 ped./s, Figure 7-8) to that from the simulation for panic conditions with no column scenario (1.63 ped./s, Figure 7-1), it can be observed that as expected, the flow under panic condition is much less (32% less) than under non-panic condition for the same bottleneck width of 1.2m.

7.3.2 Uni-directional traffic

Unidirectional flow is the most common characteristic of pedestrian flow in an evacuation, when pedestrians herd towards an exit through a corridor. The width of the corridor and the number of pedestrians determines the evacuation rate. With an increase in the number of pedestrians and/or a decrease in the width of the corridor, the collective motion of pedestrians is constrained, resulting in the reduction of the exit flow rate.

The experiment consisted of constrained unidirectional pedestrian movement under normal conditions (Asano et al. 2009). In the experiment, 92 participants moved through a narrow corridor 3 m wide. The pedestrian movement in a test area of 5m by 3m was recorded by a video camera mounted above the test area. The initial and final 6 pedestrians were not considered for data extraction, in order to exclude any initialization effects. The flow and the headway distribution were extracted at the downstream end of the test area for 80 pedestrians. The same physical layout was also used as a configuration for the simulation mode. Comparisons were made between the observed flow rate and headway distribution from the simulation and the corresponding values from the experiment. Figure 7-9 shows the snap shots of experiment and the simulation which illustrate the relatively uniform distribution of pedestrians across the width of the corridor.



(a) (b)

Figure 7-9: Snapshot showing unidirectional experiment (a) and corresponding simulation (b)

Figure 7-10 shows the comparison of headway as extracted from the experiment and simulation. It shows that the simulation is able to predict the headways satisfactorily.

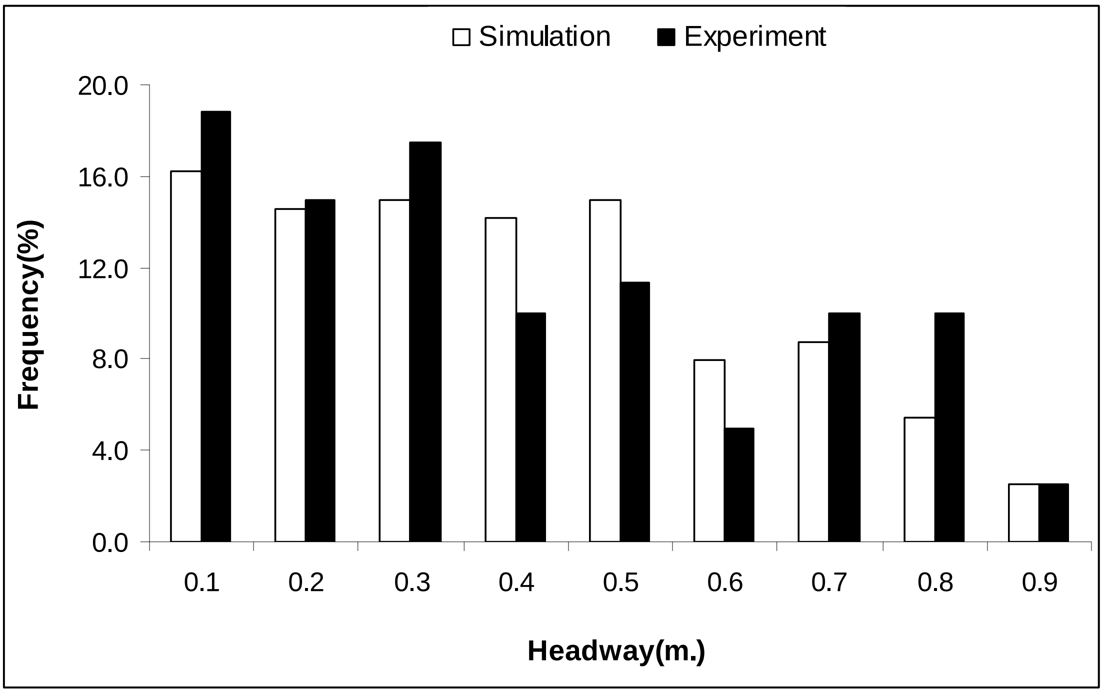


Figure 7-10: Comparison of unidirectional traffic headway distribution from the experiment and the simulation

Figure 7-10 shows that the headway is distributed over a wide range (0.1m to 0.9m) in both the experiment and the simulation, with the average headway being 0.35m in the experiment and 0.36m in the simulation. As the corridor width reduces, the range of the headway distribution can be expected to reduce with more regular time gaps (maximum more pronounced), due to a greater number of interactions in the narrower corridor. The flow rate as measured from the experiment was 2.85 pedestrians / second, while the average flow rate from simulation was 2.84 pedestrians / second. The close agreement between those values provides evidence of the model's capacity to accurately predict the flow rate.

7.3.3 Bi-directional traffic

Bidirectional flow is important in high density crowds (Still 2000). It is also relevant in emergency situations when both rescuers and the victims have to use the same path during evacuation. Previous studies have noted that, under bidirectional flow, self-organized lanes form as pedestrians use the available space effectively and minimize interactions (Daamen & Hoogendoorn 2003). The number of lanes in bidirectional traffic depends on the density of people and the width of the corridor. Models dealing with pedestrian dynamics should be able to produce this phenomenon.

The experiment involved bidirectional movement of pedestrians through a corridor 3 m wide and 5 m long (Asano et al. 2009). Pedestrian movement was recorded by a video camera mounted above the test corridor. A total of 93 pedestrians passed through, 47 in one direction and 46 in the other. Data from the experiment was used to validate the simulation model ability to analyse bidirectional pedestrian flows. The simulation model was validated qualitatively, with trajectory data, and validated quantitatively, with speed distribution data.

The formation of lanes can be observed in the corridor experiment, as shown in Figure 7-11a. The dark (red) caps represent pedestrians passing from left to right while light (white) caps represent pedestrians passing from right to left. The major flow in each direction passes in a self-organized lane in the middle part of the corridor while minor flows occur primarily on the sides of the corridor. Figure 7-11b shows a snapshot from the simulation in which the formation of lanes can be observed. Filled circle represent movement from left to right while empty circle represents movement from right to left. Figures 7-11c and 7-11d show trajectories from the experiment and from the simulation model respectively. It can be seen that the simulation is able to produce the formation of lanes in bidirectional traffic as observed in the experiment. Figures 7-11e and 7-11f show the speed distribution from both the experiment and the simulation along with the average and standard deviation of the speed for bidirectional traffic.

The speed distribution from the simulation closely matches the speed distribution observed in the experiment. In the experiment, individuals at the edges moved faster than those in the middle; however, it can be seen that the overall average speed in each direction is almost equal when the flow is nearly equal (47 and 46 pedestrians) in each direction. While the desired speed was assigned to be 1.0 m/s in the model, the average speeds achieved in the simulation were 0.78m/s in one direction and 0.84 m/s in the other. This difference between the actual and desired speeds reflects the ability of the model to capture the constrained movement of pedestrians in self-organized lanes. It is to be noted here that the model capability of representing the wide range of speed distribution as in experimental data is limited due to the assignment of same desired speed for all pedestrians. However, it is the ability of the model to reproduce the formation of self-organized lanes in bi-directional movement that is important for the study of collective dynamics.

Such bidirectional traffic is important not only in pedestrian traffic but also in ant traffic. Based on an analysis of the traffic dynamics of leaf-cutting ants (*Atta cephalotes*), Burd et al. (2002) suggested that bidirectional traffic enhances total flow rates by breaking up clusters of slow, laden ants that would otherwise impede overtaking. This phenomenon has also been observed in pedestrian traffic where bidirectional high-density crowds flow through each other with relative ease (also known as the finger effect) (Still 2000).

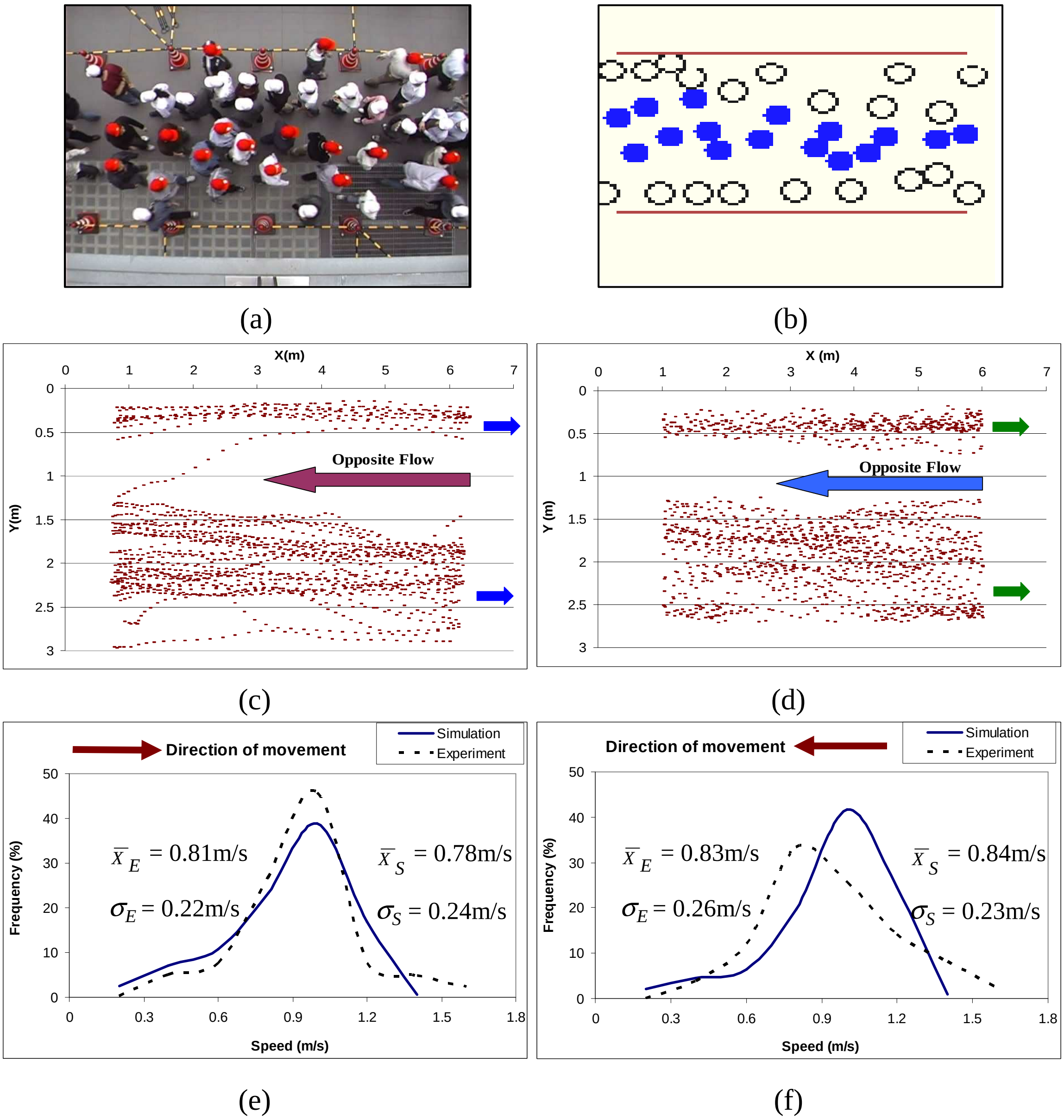


Figure 7-11 : Bidirectional traffic experiment (a), simulation snapshot showing formation of lanes in bidirectional traffic (b), trajectories data showing formation of lanes in experiment (c), trajectories data showing formation of lanes in simulation (d) and speed distribution comparison from experiment and simulation for each direction (e, f).

7.4 Sensitivity analysis

Sensitivity analysis is the systematic examination of the response of a simulation model to changes of the model's parameters (Kleijnen 1999). In this section, local sensitivity analysis will be used to provide an insight into how the simulation output changes when one or more parameters are changed. The analysis considers small perturbations from a reference set of parameters. The approach is to vary one parameter at a time, with all other parameters kept constant (Ellner & Guckenheimer, 2006). The sensitivity coefficient (S_i) of output "*X*" to parameter "p_i" is defined as the percentage change in "*X*" relative to the percentage change in "p_i", for a small change in "p_i". Usually, 5% or 10% changes are used with a centred difference estimate of the response (Ellner & Guckenheimer, 2006). Thus S_i for 10% change, is calculated as

$$S_i = \frac{\text{fractional change in output}}{\text{fractional change in parameter}} = \frac{X(1.10\,p_i) - X(0.9\,p_i)}{0.2 \times X(p_i)} \tag{7-1}$$

Because of the absence of further knowledge on the interpretation of the sensitivity coefficient for the robustness of a model, it has been suggested that the absolute value of the sensitivity coefficient should desirably be less than 1 (Reeves & Fraser 2009). That implies that any fractional change in the input will correspond to a smaller fractional change in the output. Conversely, if the absolute value is greater than 1, small fluctuations in the input will be amplified in the output (Reeves & Fraser 2009). Also the bigger the absolute value of sensitivity coefficient, the more sensitive is the given parameter (Wang et. al. 2008).

Equation 7-1 was used to determine the sensitivity of flow rate (*X*) with respect to the parameters of the EmSim model. A 10% changes in "p_i" was considered for each parameter. A standard test scenario of 200 pedestrians escaping from a room of 15m by 15m through a 1.2m door width was considered for the analysis. The desired speed of the pedestrians was assigned as 5m/s. Table 7-1 presents the sensitivity of different model parameters. It can be seen that the model is robust to parameter variations. Even with 10% change in parameter variations, the sensitivity coefficient is less than 1 for all the model parameters. Also high values of the frictional constant and the relaxation/reaction time (near to 1) suggest that these two parameters are more sensitive than the other parameters of the model.

Table 7-1: Local sensitivity analysis of model parameters

Parameter (p_i)	**S_i (absolute)**
Frictional constant (μ_1 & μ_2)	0.87
Relaxation/ reaction time (τ)	0.86
Elastic restoration constant (α_2)	0.34
Repulsive force constant (ϕ_R)	0.17
Repulsion distance (λ_R)	0.15
Attractive force constant (ϕ_A)	0.05
Attraction distance (λ_A)	0.04

7.5 Summary

In this chapter, the EmSim model was validated for the ability of the model to predict pedestrian traffic for panic conditions as well as for normal (non-panic) conditions. Parameter values in the model were either taken from the available empirical data on pedestrian traffic or *allometrically* scaled up from the ant values based on the body mass difference as described in Section 5.3. For panic conditions, the model was validated with the experimental scenarios as described for ant traffic in Chapters 4 and 6 but scaled up for the human subject scenarios. Under normal, non-panic conditions, the model was validated with experimental data on pedestrian traffic. Specifically, the comparison of headway distribution was made in uni-directional traffic while the comparison of speed distribution and lanes formation were made in bi-directional traffic. Comparison was also made with the outflow through bottlenecks of various widths. It was demonstrated that the model can successfully describe human pedestrian traffic under both normal and emergency conditions. That confirmed the capability of the model in accommodating both non-panic and panic conditions within the same modelling framework. Results from Chapter 6 and this chapter demonstrate that the model correctly predicts the empirical flow rates for both organisms (ants and human). This consistency suggests that there are fundamental features of crowd behavior that transcend the biological idiosyncrasies of the organisms involved.

In this study, only local sensitivity analysis was conducted. This 'one-at-a-time' approach may leave out possible interactions between input parameters i.e. whether the effect of one factor depends on the level of one or more parameters. Hence, there would be a merit in undertaking a global sensitivity analysis, which would consider simultaneous changes in multiple parameters (Ellner & Guckenheimer, 2006), as part of future research. Nevertheless, the local sensitivity analysis performed above revealed that the model is robust with respect to individual parameter variations.

As research on crowd panic is a continuously challenging process, it is possible that development of future algorithms and models of pedestrian traffic will increasingly rely on insight from the study of social insects and other social animals. In the next chapter, the EmSim model is used to examine design solutions which have the potential to enhance the safety of pedestrian crowds.

CHAPTER 8 DEVELOPMENT OF DESIGN SOLUTIONS

8.1 Introduction

The experimental and simulation results from the panicking ants experiments (as explained in Chapters 4 and 6) as well as the simulation results from the escape of panicked pedestrians (as explained in Chapter 7) showed how the collective movement patterns of the organisms are affected by the layout or the geometrical structure of the escape area. Detailed analysis of microscopic effects (i.e. behavioural variations) would be a potentially valuable additional perspective to aid in devising solutions that are efficacious and improve the safety of the crowd. Insight into microscopic variations would assist in enhancing understanding of what properties of panic are inherent to the physical nature of the crowds, and what properties depend on the idiosyncratic details.

External factors (such as presence of police or an evacuation team) are also important in emergency or panic situations, however, in this study the worst case has been considered, when the influence of external organisers or evacuation teams is absent. There have been several cases of crowd disasters with minimal or no influence of evacuation support, as well as a failure of communication systems (Chertkoff & Kushigian 1999). Hence, in such situations, the solutions need to arise from the crowd and the immediate environment to which they are exposed. The immediate environment that the crowd is interacting with that moment when a flight response is required are the individuals within the crowd and the layout or the geometrical structure through which they need to escape. By making appropriate architectural adjustments within the escape area, there is the possibility of changing the collective movement patterns in a way that enhances the safety of the crowd. In that way, we are actually generating the design solutions from the crowd themselves. Hence, the solution for preventing crowd disasters may lie within the crowd.

The following sections, draw on the simulation tool and the empirical experiments (with non-human organisms) to examine how those tools can enhance understanding about the development of safe design solutions for panic escape. Focus will be made to study four relevant scenarios:

- Effect of location and size of obstacles to the escape rate
- Consequence of turning movements to the escape rate
- Optimization of flow within an escape area
- Effect of body sizes on the escape rate

8.2 Effect of location and size of obstacles to the escape rate

In Chapter 7, it was observed that similar to ants experiment, the placement of a partial obstruction such as column near the exit facilitated the flow of the people. However, several important points need to be considered when designing such solutions. For example, does the efficiency of the partial obstruction depend on its location i.e. the horizontal offset from the exit? Is the size of the obstacle also important? This section examines the effect of location and size of obstacles (column) for the escape of pedestrians. In Section 7.2.1, simulation was conducted with / without a partial obstruction (a column of 1.5m diameter) located at a horizontal distance of 0.5m from the exit. In this section, the same simulation scenario as in Section 7.2.1 is repeated but with different horizontal offsets (0.6m, 0.7m, 0.8m and 1m) from the exit and also with different sizes of the column (1m diameter, 1.5m diameter and 2m).

Figure 8-1 shows the average flow rate for different horizontal offsets from the exit and for different size of the column. Also a reference dotted line is drawn representing the average flow of pedestrians without any obstruction near the exit. Figure 8-1 highlights that the presence of a partial obstruction like a column near the exit is effective only for some horizontal offsets and some column diameters. In the case of the largest offsets, the presence of a column actually decreases the flow of the people. Several combinations of horizontal offset and column diameter enhance the outflow compared to when the column is absent. Figure 8-1 also shows that the maximum flow rate could be different for different combinations of column size and horizontal offset. For example, the maximum flow rate for either a 1.5m or 2m diameter column occurs when there is a 0.5m horizontal offset while for a 1 m diameter column the optimum offset is 0.6m. Among all the combination of horizontal offset and the column diameter, the 2m diameter column located at 0.5m horizontal offset creates the maximum flow as shown in Figure 8-1.

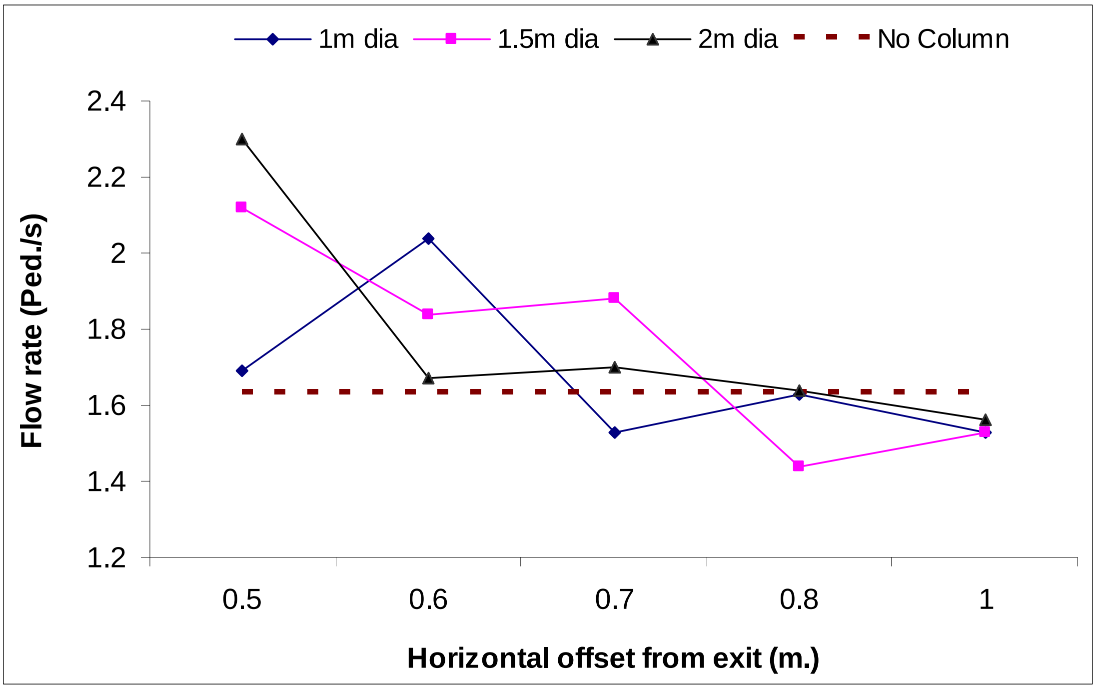


Figure 8-1: Comparison of flow rate for different horizontal offsets and for different sizes of column

The simulation results highlighted that the presence of partial obstructions such as a column near the exit do not always increase the flow of the people compared to when the column is absent. The effectiveness of the obstruction depends on its location (relative to the exit) and its size. The general trend from this simulation suggests that the column should be placed as close as to the exit as possible without creating any additional space (horizontal offsets) between the exit and column for the pedestrians. The creation of such additional spaces in front of column may provide opportunities for strong interactions and pushing behaviour among pedestrians in that space resulting in a reduction of the outflow. If there is no such additional space, then that is more conducive to the production of channelled flow of the people (with minimization of interactions) from the two sides of the column as shown in simulation snapshots of Figure 7-3, Chapter 7. The role of horizontal offset (of the partial obstruction) for other architectural layout of the escape area will be discussed more in section 8.4 on optimisation of flow within an escape area.

8.3 Consequence of turning movements to the escape rate

From the experiments with panicking ants in Chapter 4, it was observed that the presence of column at the exit channelled the ant flow and generally increased the evacuation efficiency. One manifestation of that channelling was that lone exits (a single individual passing through the exit hole rather than temporal overlap of two or more individuals) were more common when the column was present. The qualitative examination of video data reveals that the existence of more lone exits due to the presence of a column was the result of minimization of the physical interactions resulting from the turning movement near the exit.

In the experiment, it could be observed that the ants escaping from the side walls had to turn in order to exit while those ants moving relatively straight towards the exit did not have to turn. The existence of those two different directional movement patterns near the exit could be the primary reason for interactions and pushing behaviour. The net effect of that was pronounced in the case of no partial obstruction near the exit resulting in interactions and temporal overlap between two or move individuals as observed from the analysis of the video data.

Figure 8-2a shows the schematic diagram of interactions of ants moving from side walls (indicated by bundle of arrows in two small circles) and those moving relatively straight towards the exit (indicated by bundle of arrows without two small circles) In contrast, with a column present near the exit, those different directional movement patterns were minimised resulting in more lone exits as shown in Figure 8-2b.

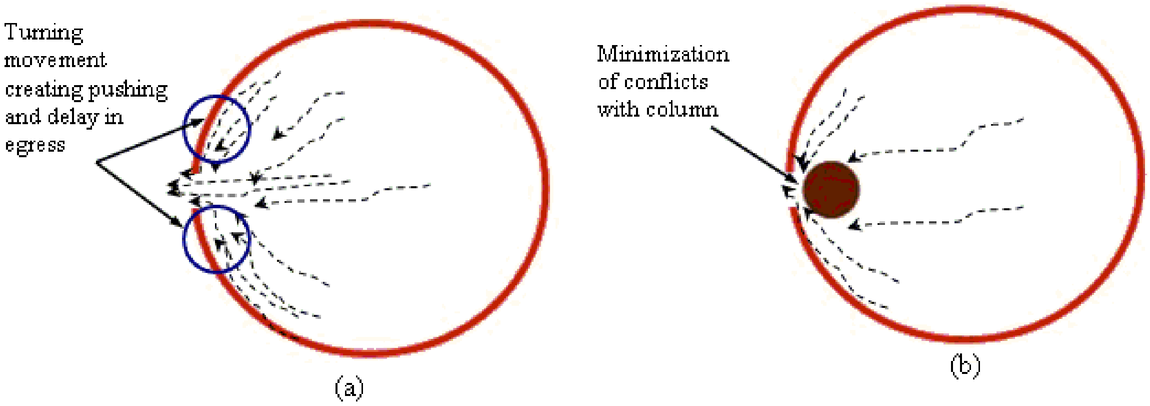
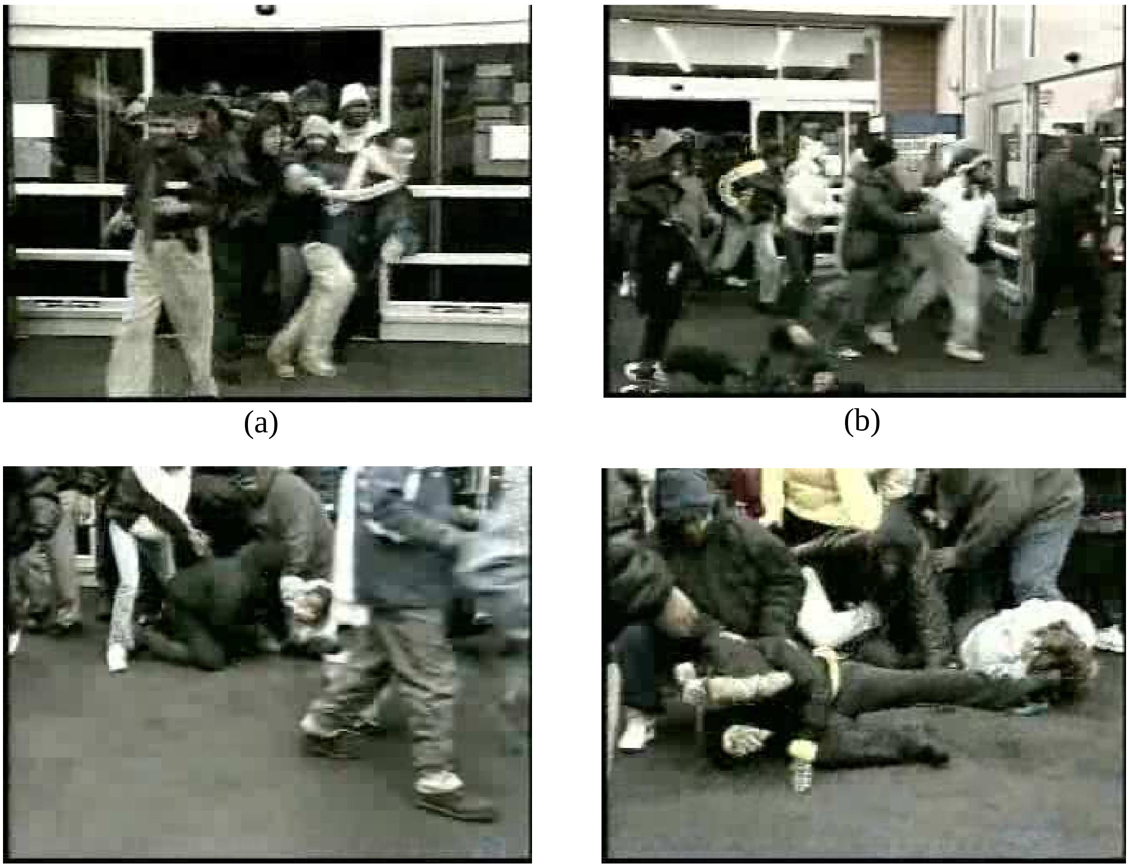


Figure 8-2: Schematic diagrams showing the movement patterns of ants without column near the exit (a) and with column near the exit (b).

The interactions produced by different directional movements during collective dynamics can have major implications during pedestrian crowd stampedes. In 2005, several people were trampled and injured when frenzied shoppers rushed inside a Wal-Mart to buy a just released consumer electronic product on “Black Friday” following the American Thanksgiving holiday (Youtube video 2009). The Friday following Thanksgiving is traditionally the first day of Christmas shopping in the United States and consequently large crowds are usually anticipated. In 2008, a man was killed while several people were injured when frenzied shoppers rushed inside a Wal-Mart (NY Daily News 2009).

Analysis of a rare short video segment (of 26 seconds duration) of the 2005 Wal-Mart incident available online (Youtube video 2009) shows how sudden changes in direction of the movement of crowd lead to trampling. Initially the crowd of people waited impatiently outside the door to enter the store. As soon as the door opened, one could see the incoming rush of people attempting to turn at an angle of 45–60 degrees towards a second internal doorway. In the process, those waiting outside the first door were competing with each other to enter the store, and individuals on the sides of that door were competing more strongly with the people who were moving straight from the back of the crowd. Because the flow had to turn at an angle instead of moving straight ahead once they entered the store, people were pushed off their trajectories and lost control of their movement. As a result, several people fell to the ground and were injured. This could have lead to fatalities had there been a larger crowd. Figure 8-3 shows snapshots of the incident showing the sequence of events leading to the stampede.



(a) (b)

(c) (d)

Figure 8-3: Wal-Mart stampede: Impatient crowd waiting to enter (a), crowd turning towards another angled adjacent entrance (b), trampling of people on the ground due to people being pushed off from their trajectories and losing control of their movement (c and d) (video source: Youtube video 2009).

Both qualitative and quantitative studies seldom address the above stated phenomenon of turning movements specifically for emergency/panic situations (Shiwakoti et al. 2011b). The examples from the panicking ant experiments and the video footage of a human crowd stampede highlight the necessity of understanding the consequences of turning movements during panic escape. It is necessary to avoid sharp turns in stairs or corridors or at egress points when large numbers of people are exiting from an escape area.

To illustrate the importance of avoidance of turning movement and sharp turns, simulation was conducted with EmSim for a crowd of people escaping from an exit / bottleneck for the following scenarios:

- Crowd of people escaping from a bottleneck with a corridor after the bottleneck located at different angles (the situation reflects a similar scenario to that from the store stampede described above)
- Crowd of people escaping from an exit with/without a column near the exit with the exit at the middle of the wall (as considered in the ants experiment)
- Crowd of people escaping from an exit at the corner (as considered in the ants experiment)
- Crowd of people escaping from a funnel shaped exit

8.3.1 Angled escape route

For the angled escape route scenario, a simulated crowd of pedestrians was generated in an area of 10m by 8m with a bottleneck of 2m width. Upon exiting the room, people then had to pass through a corridor. Four cases were considered based on different angled configurations for the layout of the corridor as shown in Figure 8-4. In each case the corridor was the same length (10 m) and width (2 m). In the first case, the corridor was straight, 10m in length and 2 m in width. In second case, the straight corridor continued for 5m and then a connecting corridor was placed at an angle of 45 degree. The total length and width of the corridor was equivalent to that of the first case. Similarly, the corridor was placed at an angle of 60 degree and 90 degree with equivalent length and width as that of 45 degree for third and fourth cases respectively. The simulation was conducted with different numbers of people (200, 250 and 350) for each case. The outflow of the people at the fixed downstream end of the corridor was measured for each case. When the pedestrians in the simulation passed through the straight corridor, the collective movement was uniform in nature. In contrast, when the pedestrians passed through the angled corridor, congestion was observed at the turning junction, creating delay in egress, as shown in Figure 8-4. That congestion could be the result of strong interactions and pushing behaviour due to the turning movements, similar to those observed from the video data of the store stampede.

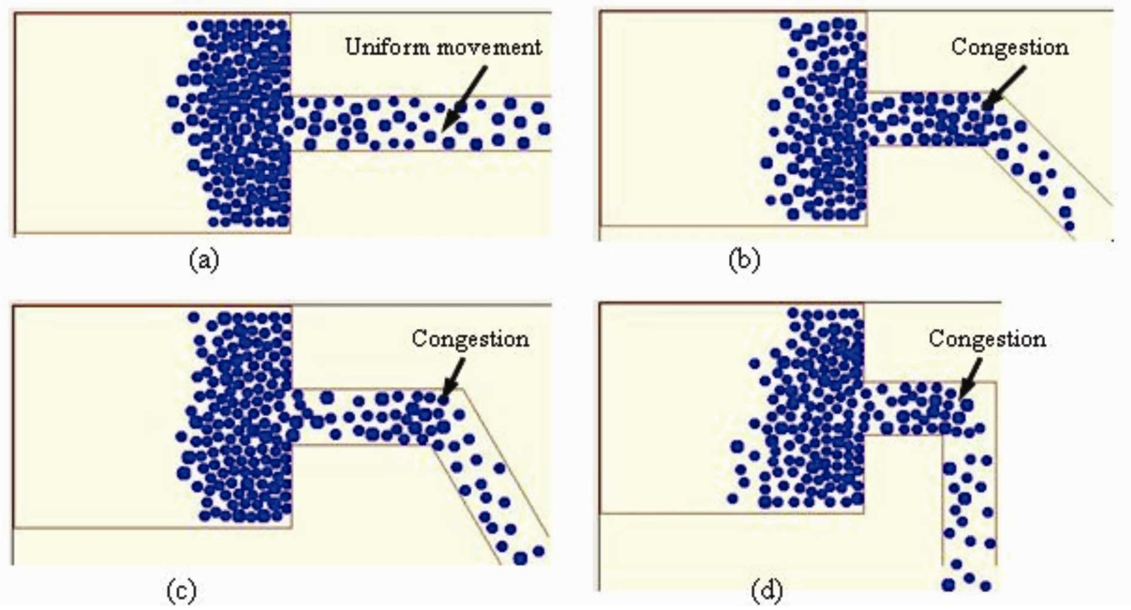


Figure 8-4: Snapshots of simulation for pedestrian escaping through different angled corridor: straight (0 degree) corridor (a), 45 degree corridor (b), 60 degree corridor (c) and 90 degree corridor (d).

Figure 8-5 shows the comparison of the average flow rate of pedestrians for different densities and the turning angle, based on 10 simulation trials for each scenario. The straight corridor (turning angle =0) is the most effective compared to other options. There is decrease in flow rate with 45, 60 and 90 degree turns compared to that of a straight corridor. With the increase in pedestrian density from 200 to 350, that difference in flow rate is more pronounced. For example, the straight corridor is 50% more efficient than the 90 degree turn for the density of 350 pedestrians compared to 18% more efficient when the density is 200 pedestrians. This suggests that the effect of turning movement is important particularly at high crowd density. It is also interesting to note in Figure 8-5 that there is an increase in the exit flow of pedestrians for a 60 degree turn angle compared to the 45 and 90 options. Of the three turn angle options considered here, the 90 degree turn is the most inefficient.

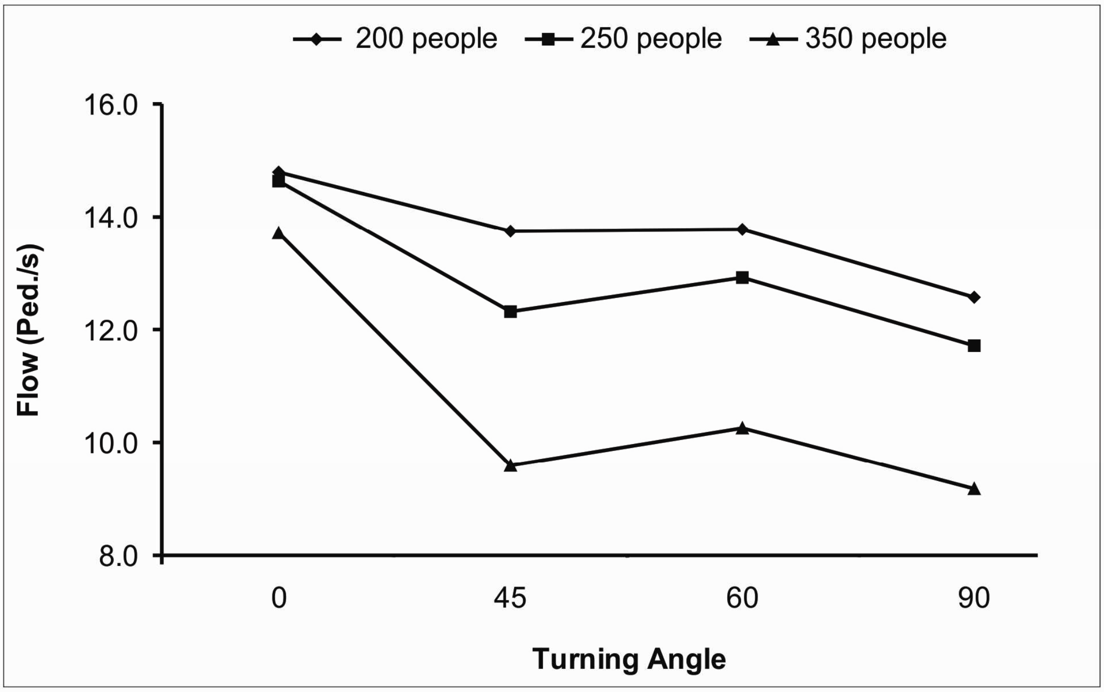


Figure 8-5: Comparison of flow of pedestrians for different density and turning angle

The increase in flow of pedestrians with a 60 degree turn highlights that perhaps the flow of people does not always decrease proportionately with an increase in the turning angle. There could be some turning angles which are more suited or beneficial for collective traffic than others. This certainly appears to be the case for traffic on ant trails. Ants in many species create bifurcating trail networks, and the ability of ants to negotiate the path depends on the bifurcation angles. Jackson et al. (2004) demonstrated that foraging *Monomorium pharaonis* ants adaptively reoriented their direction of motion most successfully along paths with 60° bifurcation angles. For example, the rate of correct to incorrect reorientations was approximately five times greater with angles of 60° than with angles of 120°. Laboratory colonies of *Monomorium pharaonis* ants allowed to forage for two hours produced trail bifurcations with an average angle of 53° (s.d. = 15°) (Jackson et al. 2004), and field colonies of another ant species, *Messor barbarus*, produced mean trail branching angles of 43.6° on open surfaces and 60.9° through vegetative cover (Acosta et al. 1993). These preferences for particular trail angles have not yet been related to flow rates on the trails, but it seems likely that there may be optimal angles for maximizing flow.

The flexibility on the choice of turning angles can have implications in situations when it is not possible to have straight corridor due to design and/or space restrictions. More research on those aspects is necessary, however. Nonetheless, the general trend from the simulation shows that the flow of pedestrian is reduced with turning movements compared to straight movements due to more strong interactions and pushing behaviour in turning scenarios.

8.3.2 With/Without partial obstruction near the exit with exit at the middle of the walls

In section 7.2.1, it was observed that consistent with the experiments from panicking ants, the simulation model predicted an increase in the evacuation rate of the pedestrians with a column near the exit compared to when the column is absent. When the graphics of simulation run were examined closely, it was observed that the pedestrians who were trying to escape from the side walls had to turn in order to get out from the exit. In that process, they compete with pedestrians that were moving straight towards the exit creating delay in egress.

The existence of the two different directional movement patterns (straight and turning) near the exit was dominant in case of people escaping where there was no partial obstruction (column) near the exit (Figure 8-6a). However, as shown in Figure 8-6b, with the presence of column near the exit, conflicts between turning and straight movements were minimised resulting in efficient outflow of the pedestrians; similar to that observed for ants as explained in Section 8.3.

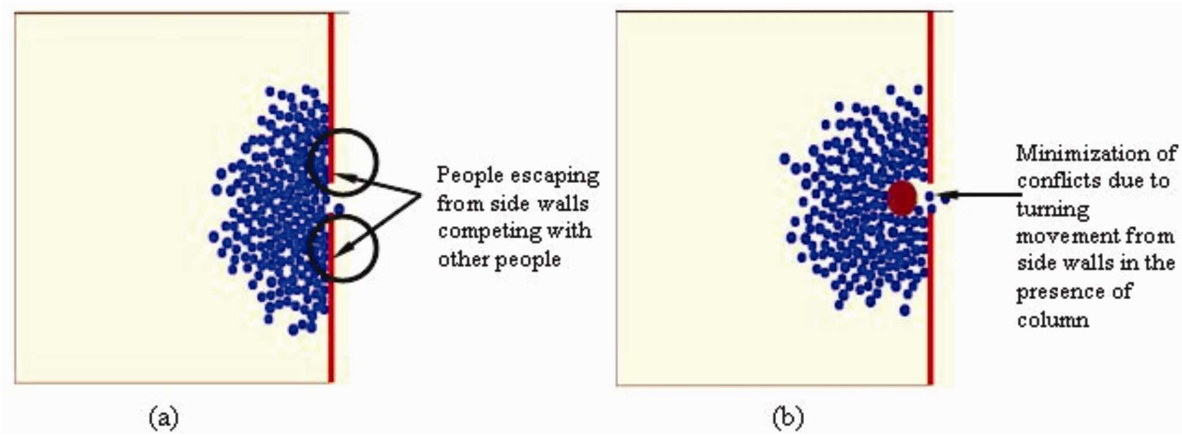


Figure 8-6: Simulation snapshots showing escape of people in absence of column near the exit (a) and presence of column near the exit (b) similar to ants experiment

8.3.3 Exit at the corner

In the case of an exit located at the corner (as considered in Section 7.2.2), it was observed that the corner exit was more efficient than the exit at the middle of the wall. When the graphics of simulation run was examined, it was observed that the pedestrians exiting at the corner had freedom to escape without much change in their original direction. The pedestrians exiting through the exit located at the middle of the side wall, as mentioned above in Section 8.3.2, had to compete with the pedestrians who needed to change their directions in order to get out of the exit. This is best illustrated by Figure 8-7 where it can be seen that the collective movement at the corner takes a form of efficient escape channel (similar to a cone-shaped channel) facilitating the outflow (with minimum change in direction of exiting people). However, the collective movement at the middle exit is affected by the movement at the sides of the wall where change in direction of flow occurs.

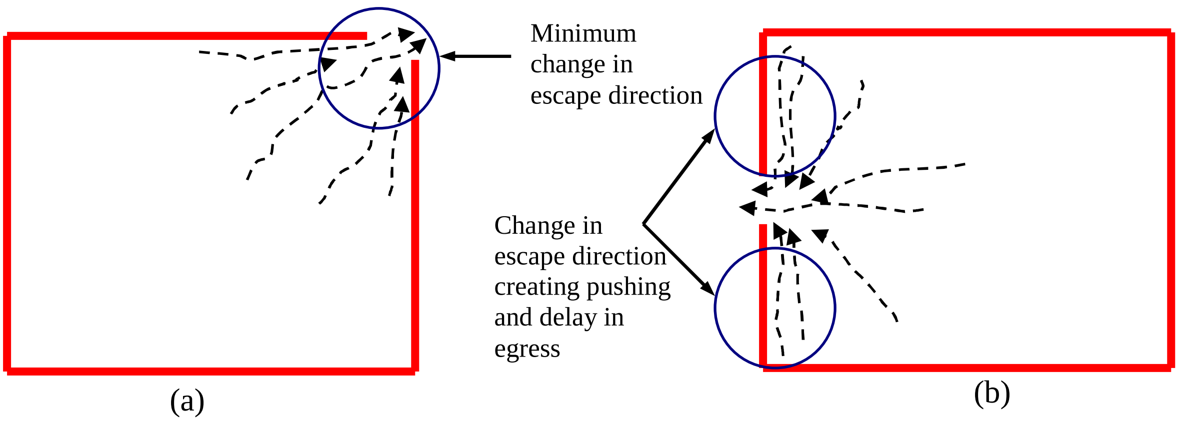


Figure 8-7: Schematic representation of the role of escape direction in corner exit (a) and middle exit (b)

8.3.4 Funnel shaped exit

Building off the previous results, a further simulation was conducted using the same room area (15m by 15m) with a funnel shaped exit on the side wall. Creation of the funnel design involved truncating the ineffective area on either side of the middle of the wall exit as shown in Figure 8-8a. That design, minimizes the changes in escape direction of the pedestrians at the exit as shown in Figure 8-8a. Figure 8-8b shows the corresponding simulation for the funnel shaped egress point.

Comparisons of the escape flow rate for the conventional side exit and the funnel shaped exit are shown in Figure 8-9. The average escape flow increases from 1.63 ped./s with the conventional side exit (Section 7.2.1) to 2.72 ped./s with the funnel design. The escape flow in the truncated side wall case is also much higher than for the case of a partial obstruction near the exit (2.12 ped./s as observed in section 7.2.1). These variations observed in the outflow within a same layout of the escape area suggests that there could be several options for small adjustments of structural features that can produce the optimum outflow for the given escape area. This is further examined in the next section.

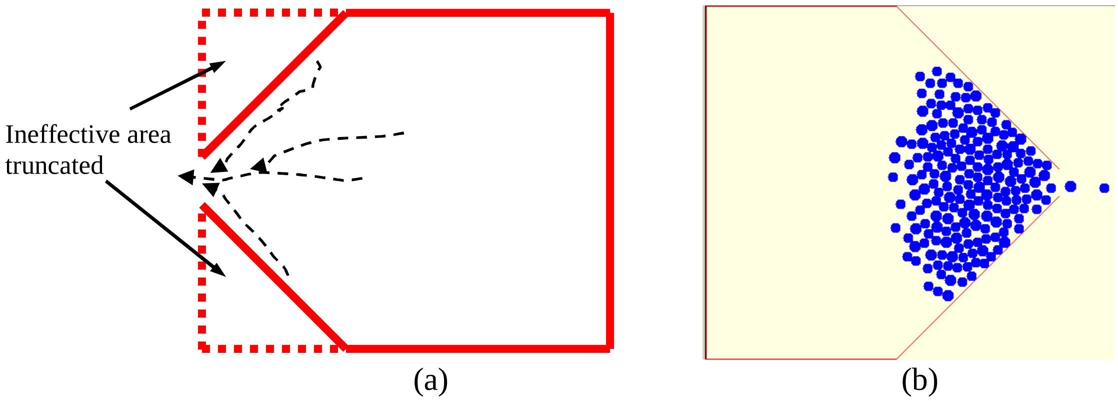


Figure 8-8: Diagram showing the formation of funnel shaped exit due to truncation of ineffective area (a) and corresponding simulation for funnel shaped exit (b)

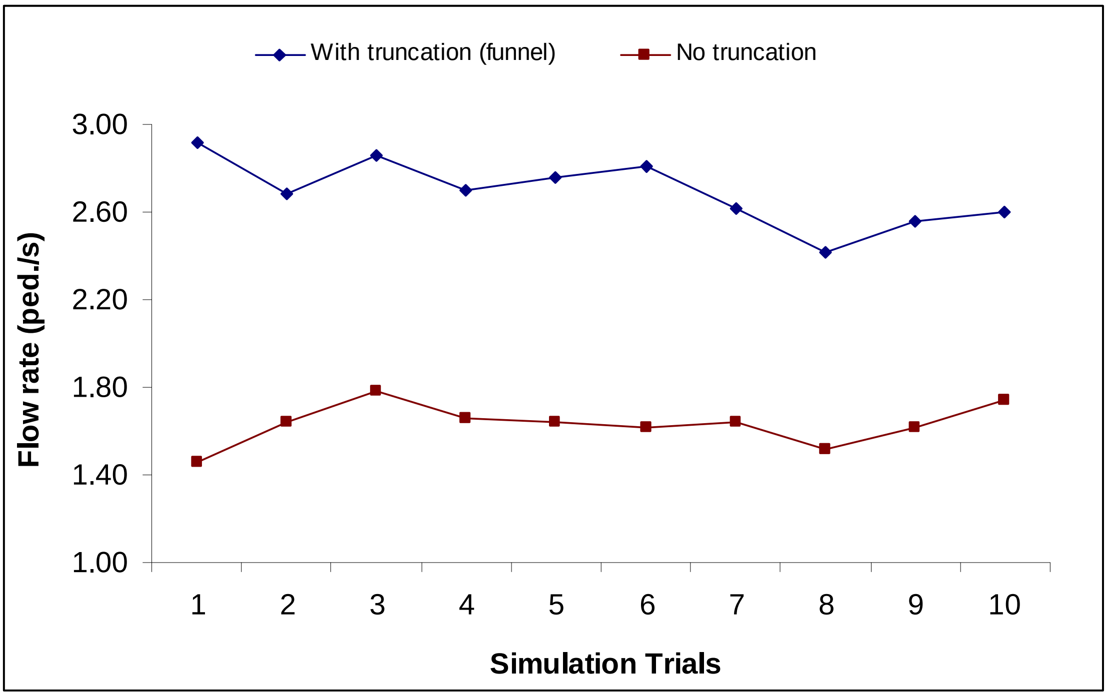


Figure 8-9: Comparison of the outflow rate for funnel shaped exit (with truncation) and exit at the middle of the wall (no truncation)

8.4 Optimization of outflow within an escape area

The preceding analysis suggests that there are several options for architectural /structural adjustments that optimise the escape flow within a same layout of the escape area. In this section, results from the simulations conducted for different scenarios (as described in previous sections), are used to demonstrate how an optimum design can be achieved within a given escape area.

The escape rates of people are compared for a standard case: 200 pedestrians escaping from a room (15m by 15m) with egress door width of 1.2m and with a desired speed of 5 m/s. These dimensions of the room and desired speed are consistent for most of the simulations conducted for pedestrian traffic in this study and hence it will be easier to compare the outflow for the same escape area and simulation conditions. The simulation results are then compared for following cases:

- Case 1: Pedestrians escaping with egress point at the middle of the walls
- Case 2: Pedestrians escaping with egress point at the corner of the walls
- Case 3: Pedestrians escaping with funnel shaped egress point
- Case 4: Pedestrians escaping with egress point at the middle of the walls and with a partial obstruction (column) present near the egress point
- Case 5: Pedestrians escaping with egress point at the corner of the walls and with a partial obstruction (column) present near the egress point
- Case 6: Pedestrians escaping through a funnel shaped egress point and a partial obstruction (column) present near the egress point

Table 8-1 shows the comparison of the average outflow rate for the different cases mentioned above. From the table, it can be observed that for the different cases considered, case 5 produces the maximum outflow of pedestrians. The results for case 5 highlight that the maximum escape flow of 3.71 ped./s occurs when the exit is at the corner and a column of 1.5 m diameter is located at 0.7m horizontal offset. That is followed by a maximum outflow rate of 3.25 ped./s for a funnel shaped exit with a column of 1.5 m diameter located at a 1m horizontal offset.

The results in Table 8-1 also highlight that the trend of an increase in outflow when the column is present is different for the funnel shaped exit as compared to the exit at middle or the corner of the room. For example, for the cases of a corner and middle exit (with column), the flow rate peaks at a certain horizontal offset and then starts decreasing. With the exit located at middle of the wall, the maximum escape flow occurs for a 0.5m horizontal offset and then the flow decreases. Similar results are seen for the case where the exit is located at the corner where the peak flow is observed for a 0.7m horizontal offset and then a drop in the escape rate occurs for larger offsets. The trend described above is different in the case of the funnel shaped exit with a column present (case 6). In that case, the escape flow continues to increase up to a 1m horizontal offset. Additional simulation runs were conducted with horizontal offset above 1m, specifically at 1.2 m and 1.5 m for case 6 (Note those results are not shown in Table 8-1). It was observed that the outflow actually peaked at a 1.2m horizontal offset with the flow rate of 4.24 ped/s and then decreased to 3.31 ped./s for the 1.5 m horizontal offset case.

Table 8-1: Comparison of average outflow for the considered six cases

Scenarios	Average flow rate (ped./s) with no column	Average flow rate (ped./s) with column (1.5m dia.) *Horizontal offset (m.)*				
		0.5	0.6	0.7	0.8	1
Case 1: Exit at middle	1.63	n/a	n/a	n/a	n/a	n/a
Case 2: Exit at Corner	3.01	n/a	n/a	n/a	n/a	n/a
Case 3: Funnel shaped exit	2.72	n/a	n/a	n/a	n/a	n/a
Case 4: Exit at middle with column	n/a	2.12	1.84	1.88	1.44	1.54
Case 5: Exit at corner with column	n/a	2.70	3.22	3.71	3.08	2.88
Case 6: Funnel shaped exit with column	n/a	1.10	1.34	1.83	1.83	3.25

Note: n/a = not applicable

The observed peak flow rate of 4.24 ped./s highlights that with the small architectural adjustments, it is possible improve the escape flow of the pedestrians by more than 2.5 times compared to the outflow from the standard case (1.63 ped./s) of pedestrians exiting from a room with exit at the middle of the walls. Therefore, the case of funnel shaped exit with 1.5 m diameter column located at 1.2m horizontal offset produced the maximum escape flow rate based of all the cases considered above. This result also qualifies the conclusion that the effectiveness of a partial obstruction near the exit in fact depends on the size of the obstruction and the architectural layout of the escape area. It is not necessary that putting a partial obstruction as near to the exit as possible will improve the outflow as stated in Section 8.2 for the case of an exit at the middle of the wall. This section has thus demonstrated that with the given layout of the escape area, one can adjust the architectural elements to optimise the maximum outflow through the egress point.

8.5 Effect of body sizes on the escape rate

In the Hillsborough crowd disaster, most of the victims were teenagers and children who were either crushed to death or severely injured (BBC News Service 2007, Bennett 2000). This disaster highlights the value of greater insight into the relationship between crushability and body size in high density crowds. The effect of body size in crushability is not only important to human crowds but has been examined in the context of non-human organisms. For example, crushability is known to depend on body size in sheep. Lambs/weaners (small sheep in large mobs) are more likely to get squashed and crushed than larger sheep, even when the mob is of equal size. Thus, a pen full of lambs with fewer sheep is safer than the same sized pen of lambs accompanied by more sheep (Casey & Hamilton 1990). The need for consideration and research on body sizes of pedestrians in high density environments, particularly during ingress and egress periods, has been highlighted by Still (2000).

In order to study the effect of body sizes on the escape rate, simulations have been conducted where there is variability in the body sizes of the entities seeking to escape.

The body size of pedestrians is reflected through the distribution of shoulder widths which is represented in the simulation model by the diameter of a circle for each entity. The distribution of the shoulder widths of the pedestrians are usually in the range of 0.4m to 0.6m (Pheasant & Haslegrave 2006). Hence to conduct the simulation, at first 200 persons with distribution of body sizes between 0.4m to 0.5m escaping from a 15m by 15m room through 1.2m door width was considered. Then another series of simulations were conducted with composition of different percentages of body sizes between 0.5m to 0.6m within the previous population (of size range of 0.4m to 0.5m). The percentages of 0.5m to 0.6m body sizes considered among the previous 200 pedestrians were 0%, 15%, 30%, 45%, 80% and 100% respectively. Thus, there were 6 groups of pedestrian with different body sizes as shown in Table 8-2.

Table 8-2: Distribution of different percentages of body size among six groups

Group	Percentage of people with body size between 0.4m to 0.5m	Percentage of people with body size between 0.5m to 0.6m
1	100%	0%
2	85%	15%
3	70%	30%
4	55%	45%
5	20%	80%
6	0%	100%

Ten simulation trials were conducted for each scenario. Figure 8-10 shows the comparison of the flow rate for different body sizes group. It can be seen that when the larger sized pedestrians are introduced (group 2 to 6), the flow rate is decreased compared to smaller sized pedestrians (group 1). The figure shows that the flow rate of people with a distribution of body sizes of people between 0.4m to 0.5m (group 1) is much higher than those with a mix of people with body sizes between 0.5m to 0.6m (groups 2 to 6). For example, the average flow rate of pedestrians for group 1 was 1.63 ped./s while for group 6, it decreased to 0.89 ped./s. Thus the pedestrian mix in group 1 is 83% more efficient than group 6 in terms of outflow.

The simulation results highlight the impact of heterogeneity of the body sizes under emergency or high-density environments. Similar to the example of separation of lambs/weaners in large mobs of sheep as mentioned above, it is advisable to divide the heterogeneous mix of people in the crowd to make it more homogenous in terms of body sizes, especially in mass gatherings such as stadiums or concerts. One can for example assign the designated place for parents and children, youths /teenagers, adults and elderly people in such mass venues to prevent the likelihood of crushing.

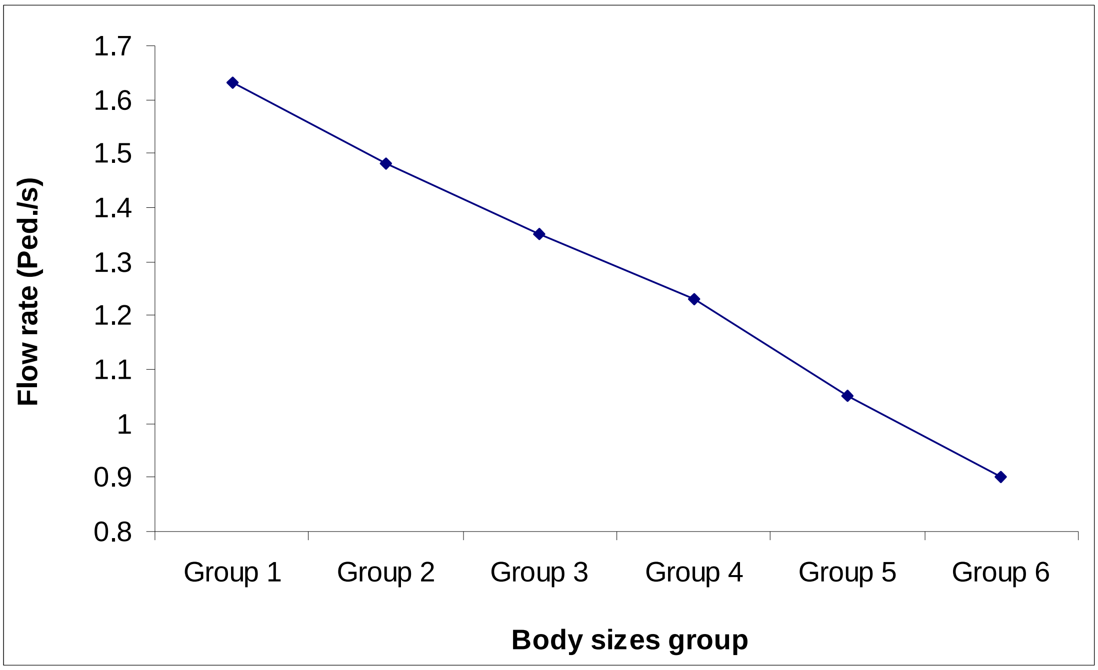


Figure 8-10: Comparison of flow rate of pedestrians for different body sizes group.

8.6 Summary

Modelling and empirical study of pedestrian behaviour under emergency conditions is crucial to assist planners and managers of emergency response. It is particularly relevant in current era of rapid urbanization where the design of major spaces of transport interchange, sporting events and mass religious activity is imperative. In this chapter, the effectiveness of different design solutions to improve the escape outflow of people was examined using insight from the simulation model and the ants experiment. The cases examined in this chapter demonstrate the potential to develop practical design solutions to enhance crowd mobility and safety. A combination of qualitative and quantitative analysis has provided insight into the effects of heterogeneity of body sizes, differing decisions about the size and location of partial obstructions near an exit and the consequences of turning movements on the escape rate. It was shown that by making heterogeneous mix of people in the crowd more homogenous in terms of body sizes, a substantial improvement in the escape outflow (as much as 83%) can be achieved. It also minimises the risk of crushing.

It was concluded that the effectiveness of a partial obstruction near the exit depends on the size of the obstruction and the architectural layout of the escape area. It is not always necessary that putting a partial obstruction as near to the exit as possible will improve the outflow. Careful design of small structural features can have large potential effects on pedestrian traffic outflow. An increase in the escape outflow of pedestrians by more than 2.5 times compared to the escape outflow in a standard situation can be achieved with small architectural adjustment in a given escape area.

It was noted that when there is sudden change in direction of the movement of individuals moving at a high speed in a crowd, that could lead to delay in egress as well as trampling and stampede. An analysis of video data of an in-store stampede showed the consistency with the observations from the ants experiment. Experimental study of crowds under panic / emergency conditions for such scenarios is dangerous with investigation hampered by ethical and safety concerns. However, with the empirical data from panicking ants and a simulation model developed in this study, the capability to study a variety of scenarios, potential problems, their consequences, and the outcome and effect of turning movements during collective dynamics was demonstrated.

The importance of egress design and crowd control is growing given the global trends of mass urbanization, mega-events, terrorism and natural disasters. Some of the design solutions developed in this chapter demonstrate the potentiality of the proposed framework to enhance crowd control.

CHAPTER 9 CONCLUSIONS

9.1 Introduction

This chapter presents the main findings of the study in relation to the aims (stated in Chapter 1) and objectives (stated in Chapter 3). Emphasis is also placed on the usefulness of findings to the researchers and practitioners engaged in the analysis and assessment of safety precautions for collective dynamics of pedestrian crowds under emergency or panic conditions. This dissertation adopted an innovative approach involving integration of insights and methodologies from biology and traffic engineering to advance the use of non-human organisms in the development of a pedestrian traffic model capable of handling emergency conditions. The specific contributions from this thesis are mentioned below with the relevant chapter number/s noted in parenthesis.

- New knowledge on the viability of using non-human organisms in studying crowd panic (Chapter 4)
- A simulation model/tool for studying crowd dynamics under panic and non-panic conditions (Chapter 5, 6 and 7)
- Insight into how microscopic layout changes affect the escape flow rate (Chapter 8)

The following sections present the conclusions from this research. The conclusions are discussed in the context of the contributions as mentioned above.

9.2 Contributions

9.2.1 New knowledge on the viability of using non-human organisms in studying crowd panic

The paucity of data on incidents involving human panic has hindered the study of crowd panic and restricted progress in modelling this behaviour in the past. This situation also raises questions about the reliability of the predictions of the few models that exist in literature. In this dissertation, new knowledge was presented in which empirical contributions from non-human organisms could illuminate the behaviour of pedestrian crowds under emergency conditions to compensate for the scarcity of data on incidents of human panic. Although few studies existed in the literature that showed the potential of non-human biological organisms in the study of collective traffic, there was a lack of knowledge on how and to what extent could the study of the collective dynamics of non-human biological organisms be applied to the study of human crowd panic. In this study, large potential effects from the adjustments of small structural features of the escape area were demonstrated via experiments with panicking Argentine ants. These experiments reflect an original attempt to study the effect of geometrical structures on the collective movement patterns of non-human entities during rapid egress and then translate those results to the study of human panic. This has advanced knowledge of the consequences of different patterns of collective human dynamics by using non-human entities to compensate for the scarcity of data on incidents of human panic.

The model organism approach is commonplace in medical research but not in engineering, yet as shown in this study, it has enormous potential to provide insight and theoretical understanding of crowd panic. It will help us understand what properties of panic are inherent to the physical nature of crowds, and what properties depend on the idiosyncratic details. Also in biology, little attention has been given to the study of the effect of nest design elements on collective movements of social insects. Social insect colonies face a number of threats that may require rapid movement. These movements are often described qualitatively and anecdotally, but there has been little in the way of quantitative or experimental tests of nest evacuation. The experiments reported here thus addresses those gaps on study of alarm traffic in social insects as well, by drawing attention to the wider issue of the relationship between nest architecture and internal traffic under alarm conditions. It is expected that these novel experimental studies will appeal to a broad audience, including researchers interested in social insects, nest architecture, self-organization and traffic dynamics and engineering.

In this study, an effective approach was also demonstrated for collecting ants and creating an artificial nest under natural conditions which could then be used in panic experiments. The proven effectiveness of that approach represents an advancement in knowledge for researchers involved in the creation of such artificial nests and experimental setup for future experiments. A range of findings from the experiments with Argentine ants were found to be relevant to the study of crowd panic. Those findings included:

1. Contrary to expectations, the presence of a partial obstruction near an exit generally increases the evacuation rate. That was demonstrated by the experiments where the escape rates of ants were compared for cases where a column (obstruction) was either present or absent near the exit. The presence of column reduced the evacuation time by around 31%. The presence of a column in front of the exit channelled the traffic in a manner that did not occur with an unimpeded exit. One manifestation of this channelling was that lone exits (a single individual passing through the exit rather than temporal overlap of two or more individuals) were more common when the column was present. The net effect was that the flux of ants through the exit was improved, on average, by the presence of the partial obstruction. The experimental results were consistent with the mathematical prediction. Such experiments showed the enormous potential for testing combinations of different architectural adjustments to enhance the safety of the crowd.

2. The experiments with the exit at the middle of the walls and the exit at the corner showed that the corner exit is more efficient than the middle exit. The evacuation rate was 58% higher with the corner exit compared to the middle exit. One reason for this reduction in evacuation time was observed to be the minimization of change in direction of escaping ants in the corner exit design. For the centre exit, ants escaping from both side walls near the exit had to change their direction in order to evacuate. That resulted in interactions with the ants that were moving straight towards the exit. In the corner exit, the ants escaping from the side walls near the corner could pass through without much change in their original direction.

These results highlighted the consequences of turning movements in a panicking crowd.

3 From ants experiment, the observations suggest that consideration of higher pre-evacuation time (at least more than 10 seconds) is justifiable for simulation in human case. In human evacuation, total evacuation time consists of sum of the pre-evacuation time and the evacuation time to leave the exit or enclosed area. However, limited data exists on pre-evacuation times for humans. Usually it is ignored due to difficulty in estimating its value or assumed (usually between 0 and 120 seconds) in simulation based on modellers' experience. The suggestion for inclusion of higher pre-evacuation time is supported by the fact that even for ants, who are known usually to be co-operative and non-selfish by nature, took on average 5.5 seconds to react to the event (citronella) and began to evacuate.

4. Preliminary experiments with multiple exits confirmed the previous findings on symmetry breaking phenomenon (i.e. the ineffective use of available exits) among panicking individuals. The phenomenon was observed with the different species of ant and density in this thesis (compared to the previous reported experiments in the literature).

9.2.2 A simulation model/tool for studying crowd dynamics under panic and non-panic condition

This thesis developed a simulation model EmSim for studying collective traffic based on empirical experiments with panicking Argentine ants, animal dynamics, molecular dynamics and pedestrian dynamics. The contributions from the development of the simulation model that are relevant to the study of crowd panic are summarized below:

1. It was shown that principles of the collective animal dynamics and molecular dynamics (to some extent) are applicable for modelling collective pedestrian dynamics. The existence of general rules for dissimilar agents may indicate that

collective dynamics are emergent systems where entities with limited intelligence interact locally to produce emergent group behaviour on a global scale.

2. Emphasis was given to the development of model which considered the role of both attractive and repulsive forces under panic condition to maintain the coherence of collective dynamics; something which has received little attention in the past. Also the granular forces for pushing behaviour were modified to consider the case of discontinuity when the relative velocity is zero or near to zero. The proposed model also provided insight into the minimal interactions or physical mechanisms required for the emergence of collective dynamics and the nature of those underlying mechanisms through experiments with panicking ants. The model's robustness was demonstrated by comparing its ability to simulate the collective traffic of panicking ants as well as collective human traffic. Despite the difference in speed, size and other biological details of the panicking individuals, the model proved capable of explaining the collective dynamics of both ant traffic and pedestrian traffic. This consistency suggests that there are fundamental features of crowd behavior that transcend the biological idiosyncrasies of the organisms involved and that there is possibility of developing a generic model that could explain the fundamental principles of collective dynamics of two different entities. It has also showed that such method provides a very effective approach toward systemization in fields where there is not enough information about the underlying process.

3. The scaling concept derived from biology was a first attempt to scale the model parameters with respect to body mass difference across a size gap from ants to humans. With this framework, there is scope to compare directly the collective movement patterns of non-human biological entities and pedestrians in order to devise sound strategies to aid evacuation. The effectiveness of the proposed modelling framework was calibrated and validated through simulation of panicking ant traffic as observed from the experiment and then scaling those up for the human situation. The local sensitivity analysis revealed that the model is robust with respect to parameter variations. The simulation results also showed

consistency with the observed data (under non panic condition) from the experiment with pedestrian traffic. Thus, the model indicated its capability of accommodating both non-panic and panic conditions within the same modelling framework for pedestrian traffic.

9.2.3 Insight on how microscopic variations affect the escape flow rate

This study has provided insight into the importance of microscopic features (within a crowd and the space within which it interacts) in designing solutions that are efficacious and contribute to enhance the crowd safety. Results from the panicking ants experiments demonstrated that microscopic features within a panicking crowd can have large impacts on the escape flow rate. This could be crucial for crowd safety. In the absence or failure of external emergency managers (such as the police or an evacuation team), the immediate environment that a crowd is interacting in at that moment are the individuals within the crowd and the layout or the geometrical structure through which they need to escape. In such worst cases, by making appropriate architectural adjustments within the escape area, there is the possibility of changing the collective movement patterns in a way that enhances the safety of the crowd. In that way, we are actually generating the design solutions from the crowd themselves. Hence, the solution for preventing crowd disasters may lie within the crowd.

To demonstrate the impact of microscopic variations to the escape flow rate, simulation was conducted for different relevant scenarios. The findings from the simulation are summarized below:

1. The examples from the panicking ants experiments and the video footage of an in-store human crowd stampede highlighted the need to better understand the consequences of turning movements during panic escape. It was identified that the existence of two different directional movement patterns near the exit (straight and turning movements) could be the primary reason for the strong interactions and

pushing behaviour at the exit. The simulation results also illustrated the adverse impact of changes in directional movement during collective pedestrian dynamics. Higher evacuation flows can be achieved by avoiding sharp turns in stairs or corridors or at egress points when large numbers of people are exiting from an enclosed area. It was also highlighted that there could be some turning angles which are more suited or beneficial for collective pedestrian traffic than others as have been reported in the literature for the case of traffic on ant trails.

Experimental study of pedestrian crowds under panic/emergency conditions for such scenarios is dangerous with investigation hampered by ethical and safety concerns. However, with the empirical data from panicking ants and a simulation model developed in this study, the capability to study a variety of scenarios, potential problems, their consequences, and the outcome and effect of turning movements during collective dynamics was demonstrated. With such a tool, one can develop several evacuation strategies and design solutions that can prevent trampling and stampede when large numbers of people are escaping from confined spaces and the egress paths having abrupt changes in directions.

2. The simulation results highlighted that inserting carefully designed partial obstructions, such as a column, near the exit may increase the outflow of the people compared when the partial obstruction is absent. However, it was noted that the performance of these partial obstructions depends on their size and location relative to the exit with some design configurations resulting in less flow than was the case with an un-obstructed exit. It was demonstrated that with a given layout (fixed area) of the escape area, adjustment of the architectural elements can be conducted to optimise the maximum outflow through the egress point. It was shown that with such small adjustments of architectural features, an increase in the outflow of pedestrians by more than double (compared to standard case) can be achieved within the given layout of the escape area.

3. It was observed that the heterogeneity of body sizes can influence the escape flow rate and hence the safety of people in the crowd. The simulation results showed

that it is necessary to consider the heterogeneity of the body sizes in emergency situations or cases of high-density crowds. It is advisable to divide the heterogeneous mix of people in the crowd to make it more homogenous in terms of body sizes, especially in mass gatherings such as stadiums. One can for example, if possible, assign the designated place for parents and children, youths /teenagers, adults and elderly people in such mass venues to prevent the risk of crushing. It was also shown that by making the crowd more homogenous in terms of body sizes, a substantial improvement in the escape outflow (as much as 83%) can be achieved.

9.3 Future research

1. This research demonstrated that there is scope to use non-human biological entities to study crowd behaviour under panic conditions. However, the taxonomic differences between the non-human biological organisms and pedestrian should not be ignored and the results should be interpreted based on that particular context or study. In this dissertation, an attempt was made to develop a generic model that could capture something fundamental about the dynamics of self-driven particles in panicked crowds despite variation in size, manner of locomotion, cognitive abilities, and other biological traits. In the future, there is need to further explore the physical and behavioural similarities and dissimilarities among these different entities and how they may help to develop the capability to model the crowd panic.

2. The experiments with biological organisms could be performed for more complex situations such as at intersections. Intersections form a regular part of any street network, and, in particular, intersections near public spaces attract huge crowds during special events. For example, huge crowd congregate at the Flinders Street/Swanston Street intersection in Melbourne on New Year’s Eve. Intersections also serve as refugee points during natural disasters like earthquakes and fires or terrorist attacks. It is imperative for event managers to assess flow

management of crowds during outdoor events and to be aware of ways to control the crowd if emergency situations occur. A preliminary attempt to use ants for studying crowd panic at intersections is described in Appendix B. Using an alternative empirical system like ants or other biological agents can boost the reliability of models predictions. These biological entities are not human, but at least living creatures are, literally, more life-like than equations, and may be expected to behave and interact with complexities that may not be fully captured in mathematical models.

3. In this study, the simulation model provided insight into the magnitude of the interactions or physical mechanisms required for the emergence of collective dynamics and the nature of those underlying mechanisms. With that, in the future, there is the possibility of incorporation of other detailed individual microscopic characteristics (e.g. age, gender, variation in walking speed, socio-psychological factors) and some decision making capabilities for more realistic predictions. Although, it might not be possible to represent all the complex socio-psychological factors associated with panic in a model, an attempt should be made to represent the dominant factors.

4. There would be merit in extending the local sensitivity analysis conducted here which did not examine interactions between input parameters i.e. whether the effect of one factor depends on the level of one or more parameters. Hence, a global sensitivity analysis, which considers simultaneous changes in multiple parameters, could be performed in future research.

5. In this study, scaling was treated with regards to body size/mass and maximum speed as a large number of empirically based relationships describe biological rates as simple function of body size. It would be useful, however, in the future to study other scaling attributes and factors (e.g. agility, balancing etc.) and how they relate to the panic escape.

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APPENDIX A

Photographs of the equipments

Photo 1: Fluon coated plastic tubs for ant collection

Photo 2: Ant extractor showing cylindrical PVC chamber with hole near the base (left) and four layers of circular moulds (right)

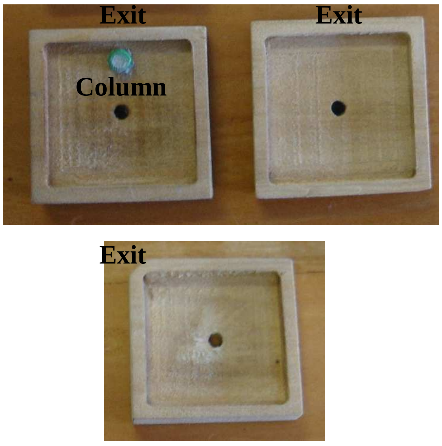

Photo 3: Wooden square chambers for the experiments. The top pair is the chambers with a column near the middle exit and without a column (near the middle exit) respectively. The bottom is the chamber with corner exit.

Photo 4: Setup of circular chambers on the top of container holding water for humidification. The circular chamber and the container are placed inside the Fluon coated plastic box.

Photo 5: Ants making nest on the humidified circular chamber

APPENDIX B

Preliminary attempt to study panic at intersection

B.1 Introduction

There is potential to use ants to simulate pedestrian crowds in an intersection during panic. Intersections form a regular part of any street network, and, in particular, intersections near public spaces attract huge crowds during special events. Intersections also serve as refugee points during disasters like earthquake, fire, or terrorist attacks. Outdoor scenarios such as at intersection can be quite different to indoor scenarios in terms of the extent (scale) and layout of infrastructure, the number of exits (limited in indoor scenarios), and variation in walking speed . It is imperative for event managers to assess flow management of crowds during outdoor events and to be aware of ways to control the crowd if emergency situations arise. Pedestrian traffic at intersections has not been well addressed in the literature to date, particularly with regard to panic traffic. At intersections, according to Helbing et al. (2002), one is confronted with various alternating collective patterns of motion of a temporal and unstable nature. Phases during which the intersection is crossed in the "vertical" or "horizontal" direction alternate with phases of temporary roundabout traffic as shown in Figure B.1 (a). When two pedestrian streams cross, evidence of a 'banding' phenomenon where 'bands' of people are observed moving in the same direction as shown in Figure B.1 (b) has been reported in the literature (Helbing et al 2002, Hughes 2003).

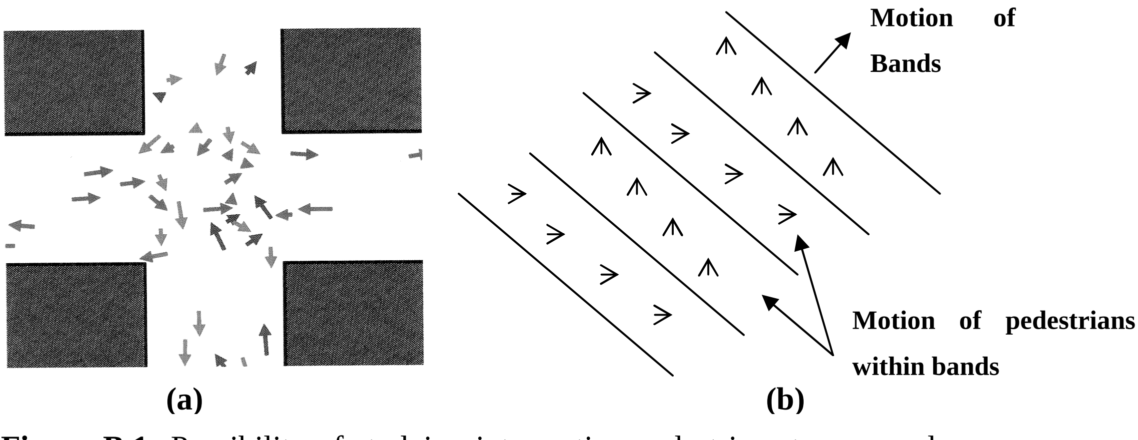

Figure B.1 Possibility of studying intersecting pedestrian streams under emergency conditions through experiment with panicking ants: temporal roundabout traffic in intersecting pedestrian streams (a) (Helbing et al. 2002), 'bands' formation with two crossing pedestrians (b) (Hughes 2003*)*.

B.2 Preliminary Trials and Results

Some preliminary experimental trials to study crowd panic at intersection were carried out in later stage of this dissertation. But due to time constraints in this study, only preliminary observations were possible. The experimental setup consisted of a four-legged intersection created via wooden chambers as shown in Figure B.2. The dimension of each leg of intersection was as below:

Length = 35mm

Breadth= 7mm

Depth = 4mm

Figure B.2 Experimental setup for intersection study

Preliminary results show that ants enhance their escape patterns by minimizing the mutual interactions at the central part of the intersection as shown in Figure B.3 below. They tend to distribute towards the nearby intersection leg instead of crossing each other at the central portion of the intersection. However, further experiments and analysis are necessary to understand their peculiar way of avoiding the conflicts and integrating it into pedestrian traffic model.

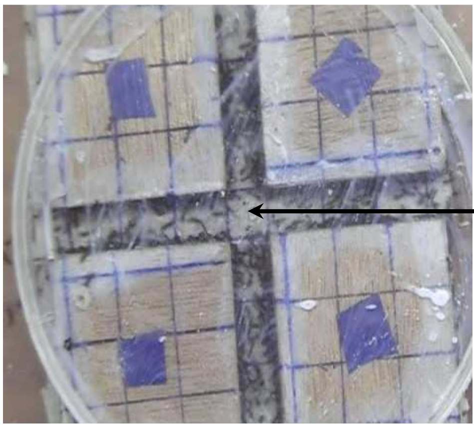

Figure B.3 Preliminary experiments showing organization of ant traffic at intersection under panic conditions

B.3 Conclusion

The preliminary results suggest there is potential within such experiments to illuminate how pedestrian traffic at intersections becomes organized under emergency/panic conditions. Experiments should address the following questions in future:

- Do ants form bands similar to those described for human crowds in crossing flows? How do the ants behave under panic in crossing flows? How do they overcome conflict in direction of two streams? Observations could provide useful information for developing strategies for efficient flow of pedestrians, and may also provide valuable input for model development and prediction.
- Are any substantial improvements in traffic flow achieved by placing barriers in the intersection? The concept is similar to indoor situations where putting obstacles at exits breaks up the pressure generated by panicked crowds.