PILGRIM CROWD DYNAMICS

by

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Dedication

To my Parents, Wife

and

Children (Saud, Sultan, Sarah and Khalid)

Acknowledgments

In the Name of Allah, the Most Beneficent, the Most Merciful

I am deeply indebted to several individuals who have assisted to make this study a successful and worthwhile venture.

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Abstract

Among the steady progression of disasters worldwide lie the numerous instances of fatality where crowds gather. The scale of these is particularly high at the Hajj in Makkah, where there are exceptionally high numbers of pedestrians in a number of confined areas and, depending on the time of year, all in searing heat.

In order to reduce the likelihood of repetition in the future, the present thesis involved firstly determining the characteristics of the pedestrians attending the Hajj, and then collecting speed, flow and density data by observing them walking along one of the busiest roads between the Holy Mosque and the other holy sites, Ajyad Street. These were analyzed against various models from the literature including those of Greenshield, Weidmann and Greenberg, and it was found that none of these fitted convincingly, mostly because pilgrims do not walk at the maximum speeds that the crowd density allows. This thesis proposes the use instead of a maximum possible speed model based on a linear relationship between speed and density i.e.

$$u \leq 1.75\,(1 - k/5.47)$$

where u is speed (m/s) and k is density (people/m^2). It then goes on demonstrate with a simulation model that on increase of 50% in traffic with the current layout would result in severe overcrowding. This however could be avoided relatively easily by combination of changing the directions of flow and the geometry of the road.

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Chapter 1
Introduction

1.1 Introduction

The Hajj is an Islamic pilgrimage where millions of pilgrims gather together in specific areas of Makkah to perform spatial and temporal rituals. This meeting can result in extreme overcrowding, as all pilgrims wish to perform the same rituals simultaneously. The security and comfort of Hajj participants has become a principal concern **.**In January 2006, a ‘Stoning of the Devil’ (Jamarat) ritual took place on Jamarat Bridge in Mina, eight kilometers from the Holy Mosque (Al-Masjid Al-Haram) in Makkah, Saudi Arabia. Approximately 346 pilgrims were killed and 289 others injured during a stampede there.

Sacred places like Arafat, Muzdalifah and Mina are located twenty-two, thirteen, and eight kilometres from the Holy Mosque, respectively. Setting up for the Hajj involves spatial and ritual preparations, as well as coordinating the movements of huge numbers of people and the services they will require during the pilgrimage. More than 3 million people travel from over 150 countries to participate in the Hajj; it is one of the largest pre-arranged holy tours in existence. The number of visitors to the Hajj and Umrah has increased yearly, while the most recent census shows a population increase in the city of Makkah.

More than three million Muslim pilgrims perform the Hajj every year during the Dul-Hija, the twelfth lunar Arabic month. Hajj activities begin on the ninth day and terminate on the twelfth day of this month. The increase in Muslim population means that the number of pilgrims performing the Hajj is also increasing every year. The Hajj pilgrimage to Makkah consists of compulsory rituals performed in the city and suburbs of Makkah in sacred areas and at specific times from the 8^{th} to the 12^{th} day of the pilgrimage month (Dul-Hija). These rituals are performed in sacred places, such as the Holy Mosque in Makkah city and the holy areas (Masha'ir) in Mina, Mouzdalifah, and Arafat. Pilgrims stay in Mina during the 10^{th} to the 12^{th} day of the pilgrimage month, with the 13^{th} is an optional day for the Jamarat. Most pilgrims go to the Holy Mosque in Makkah on the 10^{th} day to perform the Tawaf (Alifadha). This causes particular days of the pilgrimage month to become extremely crowded with millions of pilgrims performing these religious rituals. As the time and space of the events cannot be changed, overcrowding often results in serious accidents (Saudi Civil Defence,2010) .

With the number of pilgrims increasing every year, the pilgrimage authorities are making efforts to ensure the safety of the crowds. Recently, researchers (AlGadhi et al., 2002) have suggested making constructional improvements to the geometry of the holy sites (Al-Abideen, 2005), organisation of the streets (Al-Bosta, 2006), and have made new developments in pilgrim crowd control (Halabi, 2006).

Rather than using the Gregorian calendar common in Western countries, the Islamic calendar uses Hijri years. To distinguish between them, “H” will denote a Hijri year, and “G” will be used to indicate a Gregorian year.

The pilgrimage season inevitably means large gatherings of people will perform set rituals at the same time; this has led to several fatal incidents in past years. One of the primary sources of danger is cross-traffic in dense areas. Pilgrims finishing their activities struggle to exit, while new arrivals struggle to enter. This type of traffic creates unpredictable movement patterns which can easily cause falls, leading to injuries or fatalities. On some occasions approximately three million people come to Makkah within a single day. This can occur during Umrah, a religious visit to Makkah that can be performed at any time of the year but is especially common during the holy month of Ramadan. Such a high number of people simultaneously visiting a specific geographical area dramatically increase the risk of disaster. The average number of visiting individuals is approximately 500,000 per month (Ministry of Hajj, 2000).

The large number of people occupying the Holy Mosque can easily lead to overcrowding since some of the ritual activities can only be performed within the Holy Mosque and in a specific sequence. This is illustrated in Figure 1-1, where pilgrims are crowded around the Holy Mosque area in Makkah during the 10th day of the Hajj, 2009.

Figure 1-1 Pilgrim crowd at the Holy Mosque Plaza during the 10th day of Hajj, 2009

This seasonal overcrowding can lead to disasters similar to those that have already occurred. Table 1-1 shows the number of fatalities, and causes of death, for pilgrims from 1990 to 2006 in Makkah during pilgrimage times.

According to Saudi Civil Defense (2006), several fatal incidents have occurred during the Hajj season. The majority of fatalities during the Hajj in Makkah between 1990 and 2006 were from scrambling and falling. In 2006, 340 pilgrims died in a stampede during the Stoning of the Devil ritual at the Jamarat in Mina. In 2004, 251 pilgrims died in a stampede at Jamarat. In 2003, 14 people were crushed to death when pilgrims were returning from Jamarat. In 2001, 35 pilgrims were killed in the crowd at Jamarat. In 1998, 118 pilgrims were crushed to death when a panic arose after a number of people felt during the stoning ritual. In 1997, approximately 340 pilgrims died after a fire in the pilgrims' tents in Mina. In 1994, 270 pilgrims had been killed in a stampede during the stoning ritual. In 1990, 1,426 pilgrims were killed in a stampede in an overcrowded tunnel leading to the Holy Mosque.

Table 1-1 Pilgrim crowd disasters from 1990 to 2006 (Saudi Civil Defence, 2010

Year	No. of Deaths	Reason
2006	345	Scrambling and Falling
2004	251	Scrambling and Falling
2003	14	Scrambling and Falling
2001	35	Scrambling and Falling
1998	118	Scrambling and Falling
1997	340	Fire
1994	270	Scrambling and Falling
1990	1426	Scrambling and Falling

By far the worst disaster was in 1990, and fire was responsible for a relatively small percentage of deaths. The figures highlight how unpredictable crowd disasters in Makkah have been and how important it is for the government of Saudi Arabia to find a sustainable solution to the problem of pilgrim overcrowding.

1.2 Research problem

The Hajj is performed in specific holy places, such as the Holy Mosque, Mina, Muzdalifah, and Arafat. All of these places are located in the geographical territory of Honored Makkah spread over an 802 km^2 area. Unfortunately, as illustrated in Table 1-1, there have been large numbers of pilgrim fatalities in some years. Due to the unique importance of this religious ritual, the government of Saudi Arabia has revisited its safety plans for pilgrims. The most recent research has focused on crowd dynamics at Mina during the Jamarat ritual (Kaysi et al, 2012) and inside the Holy Mosque (Zafar et al, 2011) which complements this study on the Holy Mosque outside Area—the next pilgrim destination after Mina. This location was selected because a solution to overcrowding in Mina could lead to increased crowd-related risks in the Holy Mosque Area. In order to analyse crowd dynamics of pilgrims during the Hajj in this location, this study will investigate the pilgrim dynamics characteristics, focusing especially on Ajyad Street, one of the main crowded streets, used by pedestrian pilgrim arrivals from Mina to the Holy Mosque.

1.3 Research questions

This research will attempt to answer the following key questions:

1. What factors are involved in pilgrim crowd dynamics during the Hajj and what is the extent of the problem on Ajyad Street, and how could a 50% increase in traffic be accommodated?
2. What are the impacts of crowd dynamics management on the pilgrims' movement during the Hajj?
3. How do the speeds, densities and flow rates of Hajj crowds compare with values in the general literature of pedestrian crowd dynamics?

1.4 Research aim and objectives

The main aim of this study was to develop an understanding of pilgrim crowd dynamics in one particular area during the Hajj. However, there are broader objectives that should be addressed:

1. Describe crowd dynamics management in the context of the Hajj.
2. Conduct primary research concerning Hajj activities.
3. Investigate and identify an appropriate method for collecting crowd dynamics data.
4. Collect and analyse crowd dynamics characteristics (speed, density and flow etc.).
5. Develop a simulation model for pilgrim flow within the area selected for investigation.
6. Validate the simulation model of pilgrim crowd dynamics using data collected from Ajyad Street.
7. Conduct 'what if' analyses using the simulation model to investigate the consequences of an increase in traffic and suggest an appropriate course of action.
8. Synthesise and integrate research outcomes and propose recommendations.

1.5 Research outline

Chapter 1: includes an introduction; it provides an overview of the study and background information for the subsequent chapters of the thesis.

Chapter 2: presents a literature review for this study. It describes trends in the literature of relevant research fields; details various issues related to pedestrian crowd dynamics including theory, applicability, and modelling; and it reviews pedestrian crowd dynamics data collection methods.

Chapter 3: gives details about the Holy city of Makkah in the context of Hajj and the pilgrimage.

Chapter 4: describes the details of the research method and its issues. It also describes the data collection instruments, and presents the actual data collected.

Chapter 5: provides a comprehensive analysis of the pilgrim crowd dynamics data and identifies the best model for pilgrim crowd dynamics.

Chapter 6: discusses the validation of the simulation model using data collected from Ajyad Street, and describes some what-if analyses conducted so as to investigate the feasibility of some physical changes to Ajyad Street.

Chapter 7: highlights conclusions drawn from the findings of the study**.**

Chapter 2
Literature Review

2.1 Introduction

Crowd dynamics is a discipline that analyses the administration and movement of pedestrians in massed locations depending on variable circumstances. Still (2000) defined it to be "the study of the how and where crowds form and move above the critical density of more than one person per square metre". Contemporary studies dealing with crowd dynamics are largely focused on disasters caused by overcrowding, with emergency evacuations as the principal cause for people being trampled or crushed. The factors surrounding crowd dynamics will be explored by evaluating human group management and by considering the design for smart spaces. Among others, individuals in the fields of architecture, civil planning and event management need to be made aware of the factors which can reduce crushing and overcrowding. By effectively implementing certain techniques and applications, space utility, design and traffic flow may proactively reduce the chances of injury or loss of life during unexpected conditions or events.

2.2 Crowd psychology

Psychology and engineering are both involved in crowd behaviour studies. The concept of a psychological environment is important to approaching crowd dynamics as it considers the association between people (pedestrians) and their physical and social settings (Sime, 1995).

In one study, Fruin (1987) analysed the association between various factors such as individual space, speed of progress, current and community adequacy. He found that by implementing the level of service with respect to pedestrian movement, individuals are able to progress at a dissimilar pace and in dissimilar trends based upon the situation.

Treuille et al.(2006a) established three governing psychological factors that influence crowd movement:

1. Every person attempts to reach a geographical objective

2. People tend to change their walking speed based upon various circumstances

3. People prefer to avoid walking too close to each other.

Travers and Milgram (1969) proposed a conventional understanding of groups; they perceived them as a gathering of human beings with a few commonly held general practices and did not establish smaller subsets of people within the group. Turner et al. (1987) McPhail (1991) and Reicher (2001) described a number of groups within a crowd. This kind of study has not been completely neglected by the scientific community who identify that a 'physical' group may be made up of more than one 'psychological' crowd or group. This study has considered a fairly small element of molded crowd dynamics. If an individual cooperates with a crowd as part of a group, then it may be suitable to enlarge group analysis at the inter-individual level.

Taking a different approach, Aveni (1977) regularly questioned members of the public at American football games where he considered sub-groups of people within a larger group. The results indicated that only some of the people in this group were actually themselves, thus the majority were not secluded, unspecified individuals. A later study across a variety of group events ,(Reicher, 1984), supports this conclusion. Findings indicate that (a) many people in crowd events are not anonymous but rather known to each other; (b) large crowds such as those at sporting events are sometimes made up of opposing factions who act and move collectively against other groups in the crowd as a whole (Stott et al, 2007); and (c) the extent to which people in a crowd operate and behave as individuals versus as in sub-groups or collectively varies over time and place (Stott and Drury, 2000).

These examinations obviously have implications for the reproduction of group performance. In order to accurately simulate crowd movement through computer programming, two inter-related levels of analysis are required, one for individuals and one for groups.

2.3 Crowd Disasters Worldwide

Many tragedies have occurred in crowded situations worldwide over the last few years (e.g Illyas et al. 2013, Okoti et al. 2014). For example in 1986, 96 people lost their lives as a result of stampeding at a football match at Hillsborough Stadium in Sheffield, UK (Elliott and Smith, 1993). Then in 2005, USA Apple notepads were reduced in price at Richmond Virginia resulting in a violent stampede of 5,500 people through a single entrance (MSNBC, 2005).

In 2005, 258 people lost their lives due to overcrowding at a Hindu religious festival in India (Okoli and Nnorom, 2007); some other past tragedies in India are mentioned by Chatterjee (2007). However comparison with the numbers cited by Prabakaran et al.(2011) indicated how such gathering are on a smaller scale than the Hajj. By using crowd simulation models, such accidents and incidents can be reduced or prevented. In addition, these models would be useful in understanding and preventing terrorist attacks in high density areas.

2.4 Modelling and Simulation Technologies

Crowd dynamics simulations include representations of group progress, communication with the public and objective locations. Crowd dynamics is considered to be an important factor when designing venues for which crowd management will be a critical factor, including large arenas, railway stations and passageways.

The modelling and simulation technologies used to examine crowd dynamics are rapidly developing and advancing. Musse & Thalmann (2001) and Petty et al. (2004) have developed and established various simulation architectures. Researchers such as Petty et al (2004), Pan et al. (2005) and Bandini et al. (2007) have also determined several simulation tools. Grillon et al. (2009) and Paris et al. (2006) alongside Shao & Terzopoulos (2005) have even developed virtual environments for crowd simulations.[1]

Different modelling techniques for crowd behaviour have been developed for different approaches, such as flow-based models or agent-based models. Researchers have considered physical, social and psychological aspects in examining and evaluating behavioural features of a crowd.

Models examining crowds may also include other crowd features, such as appearance, poses, movement patterns or coordinated positions of individuals. At the same time, other models may examine social behaviours of crowds which may be impacted by other factors, such as the start time of an event.

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[1] A large number of researchers have worked to develop the simulation model for examining crowd behaviour in a different way including: Helbing et al., 2000; Hughes, 2003; Batty et al., 2003; Sung et al., 2004; Pelechano et al., 2008; and Arentze and Timmermans, 2009.

Crowd simulation and modelling are utilized in several fields, such as military model, security production, architectural plans and digital distraction. Crowd simulation has been used in real time strategic military training by simulating civilian behaviour and combat actions during peacekeeping operations. By grouping individuals and examining their behaviour in a virtual environment we are able to determine risks or failures in various circumstances, and enable the development of safe architectural designs. Software like Massive Software (2009) and AI implant (Presagis, 2009) were designed to animate crowds in digital entertainment.

Though there are various studies that deal with crowd modelling and simulation, the field is still developing and is one that requires the study of many complicated factors. Hence the crowd technologies and simulations are to be provided with the comprehensive survey techniques and approaches.

2.5 Crowd Modelling Approaches

The crowd modelling approach defines the overall simulation technique that in turn controls the performance of the simulated individuals in the crowd. The following section describes three modelling approaches with various modelling granularities. The crowd can be considered as a single entity or as collection of both homogenous or heterogeneous entities and their subsequent interactions.

2.5.1 Flow-based Approach

In the flow-based approach the crowd is considered a continuous flow of fluid. Examples of this type of approach are EVACNET (Kisko and Francis, 1985), and Flow Tiles Techniques (Chenney, 2004). The characteristics of individuals are avoided in this approach, they often consider for the feature of flow-based models. This approach can be used to evaluate the flow of movement (e.g. an evacuation) of very large and dense crowds.

2.5.2 Entity-based Approach

In the entity-based approach individuals are considered sets of entities with common features. In particle system models, individuals in a crowd are considered particles in the physical world. In entity-based approach models, global or local laws are identified as influencing the movements of entities. These laws are established to make predictions using relevant factors such as social, physical or psychological variables that influence the individuals' movements within the crowd.

2.5.3 Agent-based Approach

In the agent-based approach, individuals are considered to be intelligent autonomous agents. Agents are capable of adapting to the simulated world, which involves variable events as part of a complex dynamic environment. Agents are provided with rules regarding the decision making process and are able to make their decisions based on set requirements derived from local information or behavioural factors. Increased computing power has led to a sophisticated level of crowd modelling and simulation using the agent-based approach (Crooks et al., 2008).

2.6 Modelling and Simulation of Short-term Phenomena

2.6.1 Large Crowds

When modelling crowds in the thousands, the flow-based approach is effective because this reduces computational times. In the flow-based approach, the participants are treated as a whole and not on an individual or group basis. The environmental impacts with respect to crowd movement are determined by vector fields while time differential equations are used to represent crowd movement.

Hypotheses and statistical assumptions need to be identified in order to establish the field vectors and differential equations. Hughes (2003) stated that the intelligence of crowd flow is being considered in recent research dealing with the flow-based approach. Researchers differentiate between crowd flow and classical fluid models by considering the reasoning capabilities of the crowd. According to the observations of behavioural sciences, pedestrian movement capability is understood using “thinking fluid” research. Crowd movement is the major focus of the flow-based model while other factors are largely eliminated.

The building evacuation program (EVACNET4) is an application developed specifically for the flow-based approach and was developed by Kisko (1985) and his colleagues at the University of Florida. The users are provided with tools to develop a simulation model for complex building evacuations. The environment has been considered in a network representation that includes nodes and arcs.

The capacity of the node can be determined from the number of participants occupying the region and the passage for the flow of the participants is determined by the arcs. The capacity of the arc can be predicted from the number of humans passing through the passage in a set period of time. The traversal time may be defined as the time taken for the occupants to move through the passages. A flow-based model based on EVACNET4 (Kisko and Francis, 1985) was significant in identifying the specialized algorithm used for solving linear encoding problems with a complex framework.

While considering architectures and building types, EVACNET4 is proven to provide greater flexibility. The behavioural aspects of the crowd are not examined by EVACNET4 when it is considered a flow-based approach. EVACNET4 greatly simplifies crowd movement in flow-based approaches, like those developed by Hughes (2003) . In this approach the differential equations and vector fields are not implemented, making it a much simpler process of implementation where the speed of the crowd is considered a piece wise constant.

2.6.2 Small-to-Medium Crowds

Most of the research and development studies that deal with crowd modelling and simulation are short-term occurrences involving small-to-medium-size crowds ranging from tens to hundreds of individuals. The study can be classified into two further sections using the approaches in crowd modelling: entity-based approaches and agent-based approaches. In the entity-based approach, crowd dynamics are determined by incorporating physical factors and using physics. The flow-based approach uses the latest technologies in computer science and engineering. In entity-based models the individuals are treated as particles or objects in the crowd, whereas the individuals in agent-based models are individual agents capable of making their own decisions based on human behavioural factors.

2.7 Crowd Dynamics Simulation Models

There are significant differences between the entity-based model and the agent-based model. The differences are becoming increasingly unclear e.g. Braun et al. (2005), but fundamentally the entities (in the former) tend to act as “dumb particles” whereas agents (in the latter) behave according to prescribed rules.

Various models of evaluating crowds utilizing cellular automata, fluid models, social factors and agent-based models are examined and evaluated by Zheng et al. (2009). The aspects related to groups and individuals are examined by the models. Shi et al.(2009) examined crowd behaviour by combining Computational Fluid Dynamics models of fire and agent-based evaluation processes. So as to model the covered arena used in the Beijing Olympics. It was concluded from the study that the system can reflect group characteristics by conducting evacuation.

The behavioural features of a crowd at a railway station in China were observed by Fang et al. (2008). Crowd speed is determined to be in association with front-back interpersonal openings and character incentives. Spieser & Davison (2009) proposed a hypothesis to illustrate how reliable data combined with a queuing group can increase communication between controlling agents. To measure the impact of human factors on ship design, Deere et al. (2009) described the information using the maritime EXODUS model, which includes sub-models such as hazard and movement.

Data obtained from large building evacuation attempts are compared with the evacuation model (EXODUS) of (Gwynne et al., 2005) evacuation model. In the study both qualitative and quantitative agreement are achieved. It has been determined that most of the models did not validate their data. Data from interviews and observations were obtained from the group behaviour of crowds and contribute to the realism of the model (Filippidis et al., 2006). The effects of alcohol on the behaviour of the crowd are determined by the particle crowd model (Moore et al., 2008).

An engineering approach to crowd dynamics is to model people as particles. Psychological factors (such as panicking) are deemed to be significant, while social interaction (herding) is of less importance. Practically speaking, movements of individuals are related to the movements of the group. The sum of an individual's motion is functionally similar to Newtonian particles like phase transformation, cluster formation and the occurrence of domain walls (Nishinari et al., 2006). Several attempts have been made to model crowds using macroscopic fluid models (Helbing, 1991); (Thompson and Marchant, 1995). Physical forces are used to evaluate the fluid flow. The crowds are not considered to be satisfying Newton's third law (of action and reaction); instead the flow is assumed to be influenced by psychological elements.

2.8 Pedestrian Movement Simulations

This section focuses on the movement of pedestrians in an urban area using simulation techniques. In many cases the examination can be done in an activity scheduling model, an evacuation model or a route choice model, the differences between these being summarised neatly by Hoogendoorn and Bovy (2004). Zheng et al.(2009) proposed a complete review of the evacuation model but they do not completely focus on transport-related studies. An array of modelling techniques are available and vary from macroscopic (flow based) to microscopic (agent or entity based) models using constant time periods, isolated time periods or an occasion-based evolution.

Even though microscopic models are derived from literature reviews or analytical information, re-creation policies are mainly dependent on the vital kinetics or passage course hypothesis. Due to the stochastic character of most of the models, model driven rules are rarely used. Models are often macroscopic and always dependent on the passage course or queuing hypothesis with fluid referred to the continuum procedure.

By contrast Griffiths and Hunt (1991), utilized a macroscopic method for pedestrian movement in cities on the basis of a vehicular passage level. Mitchell and MacGregor Smith (2001) developed the analytical methodology for processing the performance of a group of people based on examining pedestrian queuing networks. Hughes (2002) projected the continuum theory for the movement of pedestrians in a crowd, in which the crowd is considered as a whole unit and is considered to perform reasonably in order to achieve its immediate goal. Huang et al. (2009) reformulated Hughes' model and showed that the “pedestrian route choice strategy in (it) satisfies the …. principle in which a pedestrian chooses a route to minimize the instantaneous travel cost to the destination”.

The fundamental traffic flow diagram for pedestrian crowds was standardized by Dammen et al. (2005). The proposed diagram describes the disaggregation of a crowd in traffic. Most of the existing pedestrian models are related to the microscopic model. The initial macroscopic and microscopic models depend on ‘cellular automata.’ In these, pedestrian movement is modelled as a network of cells. The rules in this model define the state of cells which are dependent on the vicinity of the cell and where the position of the cell can be updated by using a transition matrix.

In 1985, Gipps & Marksjö proposed a re-creation tool to examine the movement of perambulators both inside and outside of the structures using a set of rules. The method was selected solely on the perception of the transitional destination. The pedestrian trip itself contained transitional decision making nodes and these nodes were related to either intermediate trip points or objects across the trip. However the tool was not tested against any macroscopic observations.

Borgers et al. (1986) established a stochastic tool that considers the movement and selection of a path by pedestrians in city centres and shopping areas. Modelled rules were formed using the findings of pre-existing literature and studies. Various aspects were determined during the study, including the total number of shops in each trip, the types of freights, the series of goods being purchased, and the location of the shops. The route was selected based upon the utility of the functional objective characteristics. These characteristics can be examined through multinomial logic sub-models but, in its initial form, did not include effects such as agglomerations and competitions.

The microscopic evacuation simulation tool EVACISM was developed by Poon, (1994). It models evacuation dynamics by (1) modelling pedestrian facilities as a network of a walkway section and (2) modelling the network of pedestrian flow as a queuing network process where individuals are separate objects interacting with each other in different ways. Based on a conditional probabilities sequence, there is an assumption of an event based on the Markovian evacuation process. However it had yet to be integrated with a fire model.

Considering the bi-directional pedestrian walkway, Blue & Adler (2001) modelled three factors: (1) separated flows, which are similar to two unidirectional flows; (2) interspersed flow, where pedestrians prefer to walk in a group rather than shaping different directional flow lanes; and (3) active path-shaping, where individuals are able to interact with each other but no fixed lanes exist. The behavioural features of individual pedestrians are modelled using mobile automatons. In this model, characteristics are understood as self-governing entities by establishing limited rules. The characteristics of individual pedestrians, like side stepping, variable improvement and temporary stand-offs, are examined by the model of cellular automata. The rules are described in admirable detail.

Burstedde et al. (2001) established a different stochastic approach for estimating bi-directional floods through cellular machines. Under these circumstances, dynamic grids are based on the static grids of pedestrians. The static grid determines pedestrian walking space rather than examining the travel time or presence of pedestrians but, the mathematical formulations seem overly complicated.

At the same time, the dynamic grid includes the presence of pedestrians and includes its own coefficient of decay and diffusion. The interaction among pedestrians is commonly modelled by a dynamic grid. The modifications of static grids are based on probabilistic changes within a network.

A bi-directional pedestrian flow micro-simulation tool was developed by Weifeng et al. (2003). The system has been developed with the following considerations: during low population, individuals are considered to have free movement; when the population increases, individuals are self-motivated to make use of other lanes; when there is a rapid increase in population, all lanes can be combined into two large lanes. The model also enables certain basic behavioural characteristics like lane changing and backward movement. A simulation model with respect to bi-directional pedestrian flow at crosswalks was developed by Lee & Lam (2008) . The model mainly considers the development of rules and equations of the simulation tools from previous studies. The model was developed to provide information about pedestrian crosswalks at signalized regions.

The micro-simulation model DRACULA was developed to evaluate movements of individual pedestrians at crosswalks and vehicles on highways (Liu et al., 2000). The model also evaluated interactions between individual pedestrians. Another purpose for the model was to establish and develop pedestrians responses to signal control strategies. Pedestrians can be classified into law-abiding and opportunistic. Each type of pedestrian is programmed with its own set of routes through a pathway grid of links and nodes.

Dissimilar perambulators follow different crossing rules. Based on default probabilities, drivers and pedestrians individually reach decisions.

A Marcovian model of pedestrian movement based on four different states was developed by Wakim et al. (2004). The four states that were included in the model are standing, walking, jogging and running. The main concern for the model was to evaluate the risks of a vehicle-pedestrian collision during road crossing situations.

Pedestrian behavioural characteristics can be evaluated by means of the multi-agent system developed by Dijkstra & Timmermans (2002) . The virtual network, as well as certain aspects of the independent agents within the virtual network (behaviour, beliefs and intentions), are determined in the model by means of a cellular automata. A multi-agent model that operates in cellular space was developed by Batty & Jiang (1999). The model described the global pattern to be the consequences of optimistic comment and examined the restricted activities of perambulators, but the simulations therein are fictional (rather than read) and demonstrations (rather than validations).

Based on the conditions, the PEDFLOW re-creation tool for examining perambulator groups was developed Kukla et al. (2001). In this model, the operation of agents may include:

1. Direction determination
2. Observation
3. Parameterization of observation
4. Rule evaluation and movement

The "shortest path rule" was adapted by the direction of determination, whereas the parameterisation and evaluation make use of different ordered options for distance, speed and direction. The interaction between different pedestrian agents is enabled at a certain level. The basic rules of the model are achieved by video recordings obtained from short road sections of city centres.

In order to examine the space allocated for pedestrians, Teknomo (2006) implemented a multi-agent re-creation tool. In this model, it has been determined that the assumptions made in relation to space and pedestrian flow at the macroscopic level cannot be reproduced consistently. By improving the interaction process among pedestrians movement quality can be improved. Findings were obtained by using the simple multi-agent tool of kinematics (i.e. acceleration/deceleration) and physics (i.e. forward or repulsive forces).

One of the main determinants of pedestrian walking behaviour is mental stress (Osaragi, 2004). Mental stress can be defined as a correlation between the shortest path measure and perception of the environment. Other factors caused by pedestrian behaviour are irregular aspects such as pursuing behaviour, halting to avoid collision, foreseeing collisions and overtaking. Mental stress was quantified by means of a non-linear regression, while occasional factors are quantified via linear regressions. In order to examine this factor, video recordings were implemented in a railway station. In order to examine the comfort and efficiency of space occupied by pedestrians, a multi-agent simulation tool was used.

A multi-agent simulation tool was also used by Kitazawa & Batty (2004) to examine the shortest path rule and maximum utility of pedestrians in shopping areas. Every agent activation cycle includes four stages: (1) collecting information and comparing it with that of the previous cycle; (2) using marketing data similar to a neutral network algorithm to determine the features of locations that attract pedestrians; (3) based on time factors, an optimal route is selected; and (4) local movement is based on obstacle eliminations. At the third stage, the optimization can be made based upon the mixed logit model which can be further processed by establishing travelling salesman algorithms.

In the research conducted by Hoogendoorn (2004), pedestrians are treated as adaptive controllers in order to reduce costs associated with walking. Based on the physical and control models, a multi-agent system was developed. General physical and frictional forces are included in the physical model, while various costs like drifting, proximity and acceleration are included in the control model. Along with these factors, behavioural features of pedestrians (e.g. impatience) are also considered. Certain macroscopic characteristics, like bottleneck circumstances and dynamic lane formation in evacuations related to the pedestrian flow, are also examined in the model.

A probabilistic model that examines the behaviour of pedestrian flow based on discrete choice analysis was developed by Antonini et al.(2006). Pedestrian behaviour was based on three factors: (1) speed, including same speed, acceleration and deceleration; (2) radial direction, including eleven alternatives; and (3) number of pedestrians present in the current simulations. From examining the cross nested logit and mixed logit models, it has been determined that utility functions yielded are similar to each other. Models were standardized with the help of a series of videos of pedestrian movement through the entrance of the metro station in Lausanne, Switzerland. Utilizing a similar framework, Robin et al.(2009) developed a model based on unconstrained and constrained circumstances. The model was designed based on leader-follower and collision reduction assumptions. The data on uncontrolled and controlled experimental conditions were used to validate the models. However, a simulation framework in association with this model has not been established.

Airault et al. (2004) conducted research on the interaction process among pedestrians during traffic. The movement of pedestrians is considered to be on virtual lanes in the microscopic traffic simulation tool ARCHISIM, and also examines the management of obstacles. According to the model, pedestrians conclude that traffic is one of the obstacles. While considering pedestrian and vehicle interactions, the options considered by pedestrians are deceleration and deviation, while vehicles only consider deceleration. Research conducted by Doniec (2008) examines a simulation tool for modelling pedestrian movement at intersections and roundabouts.

Research on a hierarchical model that models pedestrian walking behaviour in urban areas have been developed by Guad et al. (2008).The research adapts a multi-level multi-agent simulation tool that examines various interactions and attractions among pedestrians walking in urban areas and also enables the transition from a macroscopic to a microscopic level. The objective of the study was to examine the system design, processes, performance and results of the simulation, with respect to the behaviour of pedestrians.

This and the micro-simulation techniques mentioned above are established and are known as multi-agent model methods, but their weaknesses is in computational speed and in losing sight of the “big picture” offered by macroscopic models.

2.9 Behavioural Factors

Various aspects that influence and characterize crowd dynamics are position and speed of individuals, various social responsibilities among individuals and the emotional features of individuals. A crowd model can consider various behavioural features of individuals depending upon the objectives and requirements of the model (Singh et al. 2009). Therefore, the factors can be categorized as physical, social or psychological.

Physical Factors: The external tangible features of an individual, such as position, movement, speed, appearance and gesture are considered physical factors. These factors are used to determine the impact of an individual’s movements on the movements of the entire crowd. While designing a crowd model, these factors are considered as basic in the decision making processes (Adrien et al. 2006b).

Social factors: Different social aspects, such as culture, social norms, family relations and leadership, are considered to be intangible factors. Computational models that involve social factors are generally influenced by social theories and observations derived from various sociological studies. The crowd behaviour model conducted by Kaminka & Fridman (2006) involved social comparison theory. In order to evaluate certain social behaviours of individuals, Pan et al. (2005) adapted a multi-agent based framework.

Psychological Factors: It has been demonstrated that psychological aspects, such as the emotional features of individuals, significantly influence the decision-making process. Due to the complex nature of these psychological factors, they have not been extensively examined.The theories that consider psychological factors are considered to be undeveloped. Based on appraisal theory, a framework for representing emotion has been developed by Gratch & Marsella (2004).

2.10 Social Force Model

Helbing & Molnar (1995a) established a model that takes social force in account. It satisfied forces of physical contact under stressful circumstances (Helbing et al., 2000 , Helbing et al. 2001). Gas-kinetic models are used to examine social force and pedestrian flow, Helbing (1992). Self-motivation and other driving forces are included in the model. For instance, people may interact with society based on given societal rules. Each individual has their own particular velocity and direction, which is adapted as necessary. Individuals in a crowd try to avoid colliding with other people and also the environmental margins. An individual's velocity may change because of social forces, or social interactions, rather than physical factors. Social forces may include the environment, other individuals and the internal states of those individuals.

Social forces are important to consider when examining traffic flow and movement in crowded areas. Strangers may exert a repelling effect while friends or interesting things in a shop window may attract us. Despite the crowd being in the way, individuals prefer to move forward along a path rather than be diverted toward a less direct route.

2.11 Pilgrim Crowd Dynamics Management in Hajj

It is essential to design a plan that accommodates both residents and pilgrims. Kaysi et al. (2012) explained that the Center of Research Excellence in Hajj and Omrah at Umm Al Qura University requested SETS (Systems Equipment Telecommunication Services Company) to design a toolkit that offers information about a plan “for the metropolitan modification for the betterment of pilgrims.” By using a simulation program to model pedestrian behaviour, planners can observe predicted movement and usage patterns in the area and leverage that information to reduce crowd density.

Detailed studies of pilgrim crowd simulations have been conducted around the stoning ritual problem; some of them use continuum-based models for crowd dynamics. In a study by Johansson et al.(2008), researchers examined the measurement process and relevant safety features of speed-density and flow-density diagrams using video data. While it is extremely challenging to accurately study high-density populations using video data, accuracy can be increased and some difficulties overcome, depending on the relevant variables.

For example, Al-Bosta (2006) recorded pilgrims crossing the Jamarat Bridge in Mina, eight kilometers from the Holy Mosque in Makkah, Saudi Arabia. Hughes (2003) demonstrated that a digital model of Al-Masjid Al-Haram (the Grand Mosque) can be used in educational sessions and crowd replications by using 3D digital modelling. A crowd simulation structure uses a multi-agent system and presents fewer effort goals. The algorithm used for this structure is provided by Hughes (2003) where he describes the ongoing effort to plan a digital model of the core area of Makkah.

Crowd replication engines can simulate tens to hundreds of thousands of pilgrims in real time. Replication engines also allow for direct control of crowd movements to analyse the effects of architectural modifications or revised evacuation plans. Such a system could be used to supply engaging tutorials on the Hajj or the Umrah and to aid decision-makers in solving logistical and organizational challenges related to overcrowding.

In 2009 , Narain conducted a study on pilgrim crowds at the Al-Masjid al Haram (the Holy Mosque) and Arafat, twenty two kilometers from the Holy Mosque in Makkah, Saudi Arabia as high-density crowds, and developed a continuum-based approach for crowd dynamics simulation, based on collision avoidance between the agents and deal with crowds as set of discrete agents with a continuous presentation .

Hughes (2003) points to other factors that influence pedestrian movement and states that the difficulties inherent in separate simulations may be avoided by using a continuum formulation. This study models the movement of crowds as a continuum, using equations specially derived for this purpose. However, this method is more appropriate for medium-density crowds where individuals are less tightly packed and unlikely to collide with other pedestrians. In this analysis a sample is given in which the theory has been used to provide likely assistance in the Hajj. Guy et al (2010) proposed an innovative algorithm to produce energy-efficient trajectories for crowed simulations. The model calculated a biomechanically energy-efficient trajectory for everyone in a multi-agent re-creation using the condition of “least effort” for the simulation agents.

The importance of pilgrim planning during the Tawaf has been studied by Zafar (2011). The Tawaf is an Islamic custom performed by Muslims when they visit Al-Masjid al Haram (the Holy Mosque). The Al-Masjid al-Haram envelops the Kaaba, which is the place to which Muslims around the world turn towards while performing regular prayers. This mosque, the largest in the world, is considered Islam's holiest place. Throughout the Tawaf, Muslim pilgrims circumambulate the Kaaba seven times in a counter-clockwise direction, while in supplication to God. The Tawaf is carried out both during the Umrah and the Hajj. Executing the Hajj is one of the five pillars of Islam and each Muslim aspires to visit Makkah at least once in his or her life. Once a year, more than two million Muslims carry out the Hajj. While the Hajj has various levels and occurs over several days, all pilgrims move through the various stages of the Hajj on the same day and this results in very high crowd densities during the Tawaf. Throughout Hajj, or the last few days of Ramadam, as many as 35,000 pilgrims execute Tawaf at the same time in the Mataf area in the Al-Masjid al Haram. With such an enormous population present, it is important to model crowd behaviours and movements. Such modelling may aid in developing potential crowd management techniques and ultimately increase security at the site. However, the Tawaf has various properties that make modelling it particularly difficult:

1. *Heterogeneous Population:* Pilgrims may travel for different reasons, such as entering or exiting the Mataf area, rotating the Kabaa or pausing to pray. Crowd density over Mataf varies considerably and has been as high as eight people per square meter near the Kabaa (Curtis et al. 2011). This density severely limits the progress of the pilgrims within this zone.

2. *Varying Speed of the pilgrim:* In Mataf these differ depending on various factors such as distance from the Kaaba, distance to various features on the ground such as Maqam Ibrahim or congestion caused by other people.

3. *Complex Motion Flows:* Various group streams have been observed and monitored during the Tawaf. Pilgrims may attempt to stand still to kiss the Black Stone at the corner of the Kaaba, circumambulate the Kaaba, try to move orthogonally into the circular flow toward the Kaaba or move outwards towards the exit (thus inhibiting the circumambulating pilgrims).

Zafar et al. (2011) developed a system that models the movement of individual agents in the large packed level performing the Tawaf. The agent-based model, in combination with a finite state machine (FSM), can be used to model the pilgrims' purpose, while a geometric, local collision-avoidance algorithm (LCA, which computes collision free velocities with respect to neighbouring agents as per Van der Berg et al, (2011) can be used to manage communication among the agents.

The FSM programs particular activities, calculating a single behaviour vector comprised of pre-agent properties such as preferred velocity. The collision-avoidance algorithm uses behaviour vectors in combination with physical agent states in order to map a collision-free route. They can use various criteria for modification among the various states based on agent properties, including spatial, stochastic and temporal conditions.

The above system would allow us to reproduce the crowds of heterogeneous individuals present at the Tawaf accurately. Favoured speed and highest speed vary based on the age and gender of the model agent (men travel more quickly than women and youths travel more quickly than older individuals). For each pilgrim of modelled by the FSM, the characteristics of the agent can vary, making the immediate goal of an agent independent of its neighbour's goal, while different constraints limit the manner in which a particular agent can achieve its goal(s). For instance, certain pilgrims desire to approach the Kabba, while others prefer to avoid this particularly dense region. It is possible to measure collective behaviour (e.g. velocity and density) from this model, as well as calculate the total number of pilgrims that can complete the Tawaf per hour and their average completion times.

There have been some attempts at managing crowd flow in ceremonies like the Tawaf and Hajj. S.Al-Gadhi et al (1990) demonstrated that with the aid of continuum models, it is possible to manage crowd movement in the Jamarat area of the Hajj. Al-Gadhi et al. (2002) investigated pilgrim crowd bi-directional speed in Jamarat. Mulyana & Gunawan (2010) explained that it is possible to simulate crowd flow using agent-based simulations, as was done with a simulation of the Tawaf using 500 agents. Using SimWalk, a commercial modelling application, Zainuddin et al.(2009) performed crowd flow simulations of the Tawaf using over 1,000 agents. Samady et al.(2010) used a combination of cellular automaton (CA) techniques and discrete-event simulators to execute a large crowd simulation of the Tawaf. There have been other studies on crowd management in the Mataf area in Al-Masjid al Haram. To enhance security and manage greater numbers of pilgrims at the Tawaf, (Akl, 1997) designed a powerful spiral movement pathway in his 1997 study. Using GPS devices Koshak and Fouda (2008) identified the tracks of pilgrims performing the Tawaf in the Hajj, the flow rates and levels of service within different areas and times of Mataf at Al-Masjid al Haram (The Grand Mosque). But of course measuring such flows is far from straightforward, as demonstrated in the next chapter.

2.12 Summary of Findings

Taken as a whole, the literature of crowd dynamics seems to be divided between macroscopic approaches (i.e. based upon likening the flow of people to that of fluids) and microscopic ones (in which people are countered individually, usually as automatons). Fundamental diagrams of the type standardised by Daamen et al., (2005) provide excellent linkage between speeds, densities and flows, and have the potential to be used in the validations of experimental data. This is demonstrated in Chapter 5.

Advance software exists in the commercial market for the simulation of crowd movements. The most promosing that is available is based on the so-called “social force model” but its use to date has been for studying commuters at railway stations and shoppers in malls but not huge crowds at mega-events. Furthermore the methodology of validating such models is less than fully developed so confidence in any results is limited; this is one of the gaps addressed by this research.

The many tragedies worldwide arising from stampedes in crowds have prompted extensive research into crowd behaviour under conditions of panic etc, but these have been studies of much smaller gatherings than the Hajj. There is thus an obvious need for specific work directed to at reducing the likelihood of casualties at this unique event.

Chapter 3 Makkah and the Hajj

3.1 General background to the City of Makkah

Makkah is the place to which, according to the teachings of the Islamic faith, every able-bodied Muslim should journey at least once in their life to perform the Hajj (pilgrimage).

3.1.1 Religious significance

Makkah is the one place every Muslim must visit at least once in their life to perform the Hajj. Makkah is the focus of all the great religious rituals of Islam. In every other city more than one religion is embraced by its inhabitants except in Makkah and Al-Madinah, where Islam is the only religion. Every Muslim, wherever they are in the world, must turn their face towards it in prayer. Moreover, Muslims believe that one prayer made in the Holy Mosque in Makkah is equivalent to 100,000 prayers in any other mosque. Entering the mosque with Ihram is a must for those who are going to perform Hajj or Umrah, and the ritual baths are obligatory. Makkah has been a sanctified and secure place since before Islam. Allah, the almighty, said in the Holy Quran:

"*for the protection of the Quraish, the (Quraish) caravans to set forth safe in winter (to the south) and in summer (to the north without any fear), so let them worship (Allah) the Lord of this House (the Ka'bah in Makkah), (He) who has fed them against hunger, and has made them safe from fear."* [106:1-4] (1990).

3.1.2 Historical significance

According to Muslim belief, the importance of Makkah can be seen from early history. Allah selected this isolated and lonely place in the middle of the barren foothills of the Arabian peninsula as the new residence for the prophet Abraham's family, his wife Hagar and his son Ishmael, peace be upon him (PBUH), eventually to become the cradle of His heavenly Islamic message to humanity and the centre of the Islamic religion for all the Muslim nations of the world. The history books indicate that Makkah was a pilgrimage city before Islam; according to Abdullah Ibn AzZobair, the companion of the Prophet Mohammad (PBUH): "Seven hundred thousand of the Children of Israel performed Hajj at this House. They took off their shoes at Tane'm and then entered."

It is not like any other Arabian city. Abdullah Ibn Abbas, the companion of Prophet Mohammad (PBUH) quoted the Prophet as saying, "Allah has made Makkah a sanctuary (a sacred place) and it was a sanctuary before me and will be so after me. It was made legal for me (to fight in it) for a few hours of the day. No-one is allowed to uproot its thorny shrubs, or to cut its trees, or to chase its game, or to pick up its fallen things except a person who announces it publicly."

3.1.3 Location

Makkah is located in the west of Saudi Arabia around 75 km from the Red Sea, and is situated in the Ibraham valley in the foothills of the Alsarawat chain of mountains at 277 m above sea level. The geographic coordinates of Makkah are: latitude: 21°25′36″ N and longitude: 39°49′33″ E. Figure 3-1 illustrates the physiographic map of Makkah.

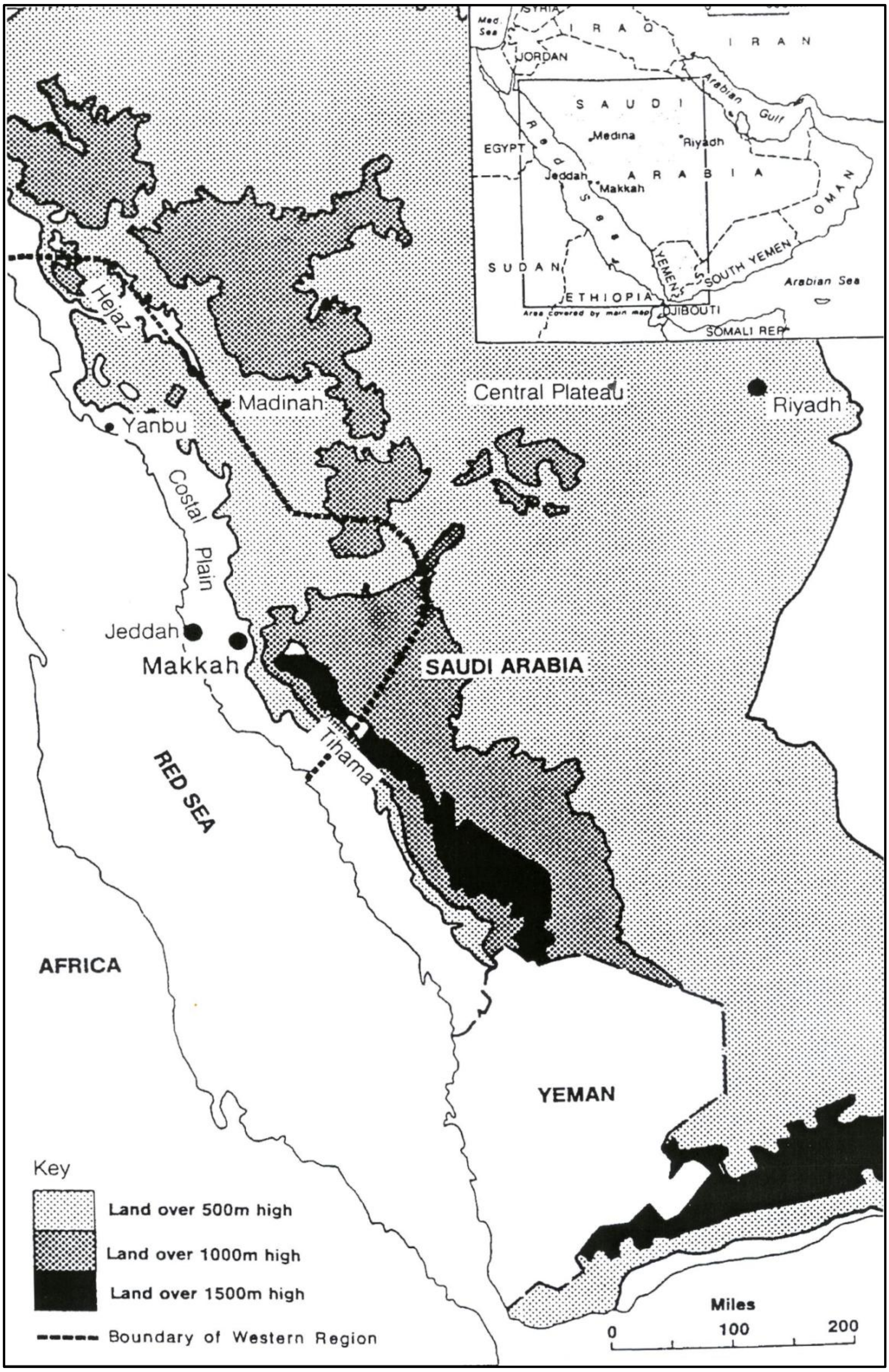

Figure 3-1 Physiographic Map of Makkah

3.1.4 Climate

Makkah lies in the hot tropical zone. The weather varies from being hot and dry during summer and warm in winter. The lowest temperatures in 2009 were registered in December (12.4° C) and in January (11°C). June and July of that year registered the highest temperatures with a peak of 48° C. The intensive heat in Makkah occurs partly because the surrounding hills create a wind-free zone. The average yearly temperature is around 31° C. Its relative closeness to the Red Sea and the surrounding Hijaz escarpment modifies Makkah's climate further, resulting in low relative humidity; humidity in Makkah varies from 45% to 53% and is inversely related to the temperature. However, short periods of higher humidity also occur in the summer. Rainfall is scarce, occurring during the winter months with an annual average of less than 100 mm. Rainfall commonly results in flooding, particularly on the low-lying sandy plains. Runoff is also high and can be dramatic within the valley, though most of the water permeates underground. Makkah is located in a valley surrounded by mountains, with prevailing north and North West winds. The dangers posed by floods, heat, humidity etc. have serious implications for the conditions experienced by pilgrims at the Holy Mosque site and these can influence crowd behaviour. As the time of the pilgrimage is based on the Islamic lunar calendar, the dates shift from year to year, meaning that the Hajj takes place during the summer in some years (e.g. 1986, 1989 and 1991), and the winter in other years (e.g. 1975, 2005 and 2006).Figure 3-2 and Figure 3-3 shows an example of how the timing of Hajj and typical temperature vary from season to season in different years, (PME, 2013).

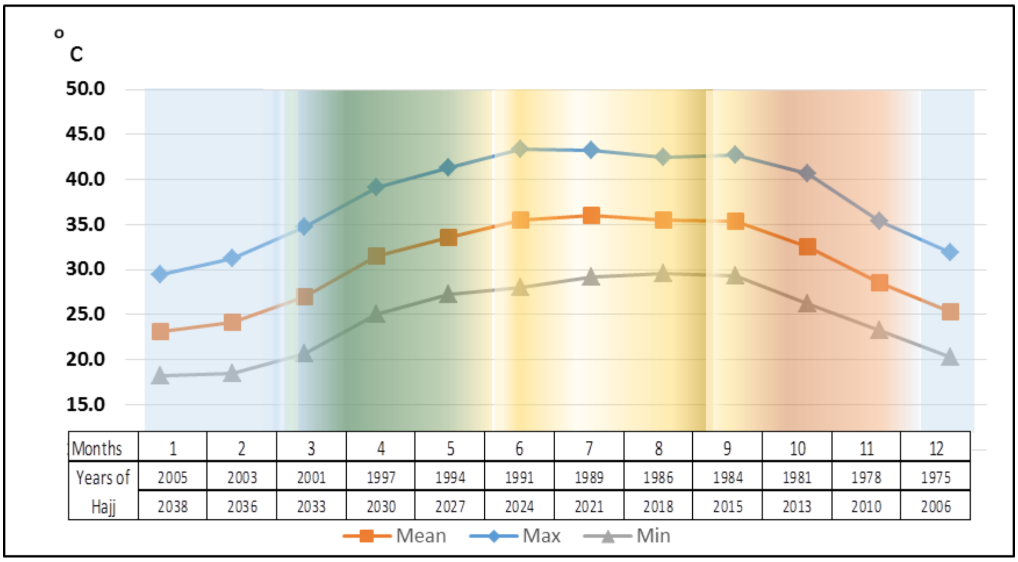

Figure 3-2 Monthly (G) temperature vs. Hajj seasons (PME,2013)

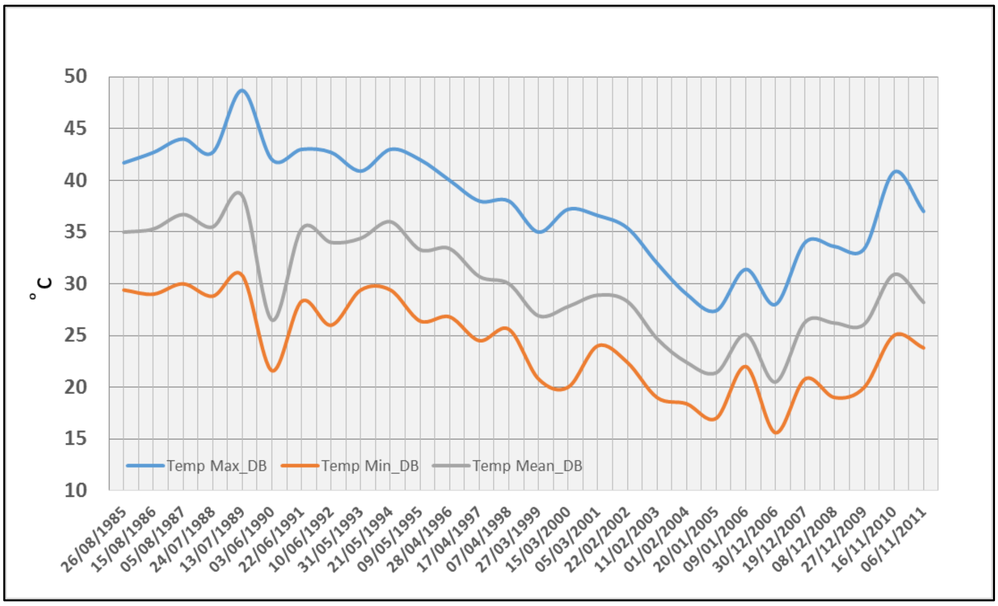

Figure 3-3 Air temperature in the 10th day of Hajj seasons (1985-2011) (PME,2013)

3.1.5 The Impact of the Weather on Pilgrim Activities

A few studies have been conducted on the impact of the weather on pedestrian movements although the results vary; some indicate that winter increases pedestrian speed while other studies find the opposite. A study conducted in Japan by Muraleetharan et al. (2005) shows that pedestrian speeds increase during winter and that this is due to a preference for walking rather than cycling. In another study, Guo et al. (2013) found that weather changes influence the routes chosen by pedestrians, with the amount of cycling increasing during good weather and being reduced during bad. Lam et al.(2000) revealed that in Hong Kong high temperatures cause pedestrians to walk faster. In contrast, Clifton and Livi (2005) showed that 40% of pedestrians reduced their speed in bad weather. The way in which the weather affects pilgrims varies according the timing of the pilgrimage. For example, Figure 3-4 illustrates the incidence of sunstroke and heat exhaustion incidents during pilgrimages between 1985 and 2010. This shows a sharp increase in the years during which the pilgrimage is performed in summer (Statistics of Saudi Ministry of Health, 2013) as might be expected.

Long-term hourly observations (1985-2011) of Makkah weather data obtained from the Saudi Presidency of Meteorology and Environment (PME 2013) and plotted in Figure 3-3, show significant variations in weather conditions .These changes have a significant impact on the health and movement of pilgrims. Saudi Ministry of Health statistics (2010) reveal a correlation between the incidence rate of sunstroke and heat exhaustion among pilgrims and the weather. Figure 3-2 illustrates the number of incidents in relation to the Hajj seasons, where the majorities of these incidents happened during the high temperature days. The fluctuation in the weather temperature in Makkah during the summer is a significant factor affecting pilgrim movement. It should be added to the other factors causing tiredness and fatigue, namely travel difficulties, performing religious rituals on foot, crowd congestion causing lack of air movement, the fact that many pilgrims are not used to hot weather, stress as result of walking for several kilometres, especially during the daytime, traffic jams and carbon emissions from public transport, and the lack of air conditioning in many vehicles.

In his study Elghazouny (1988) suggested that sunstroke was responsible for about 28% of pilgrim deaths during summer, and that the elderly and women were more likely to die of suffocation due to congestion during the stoning ritual.

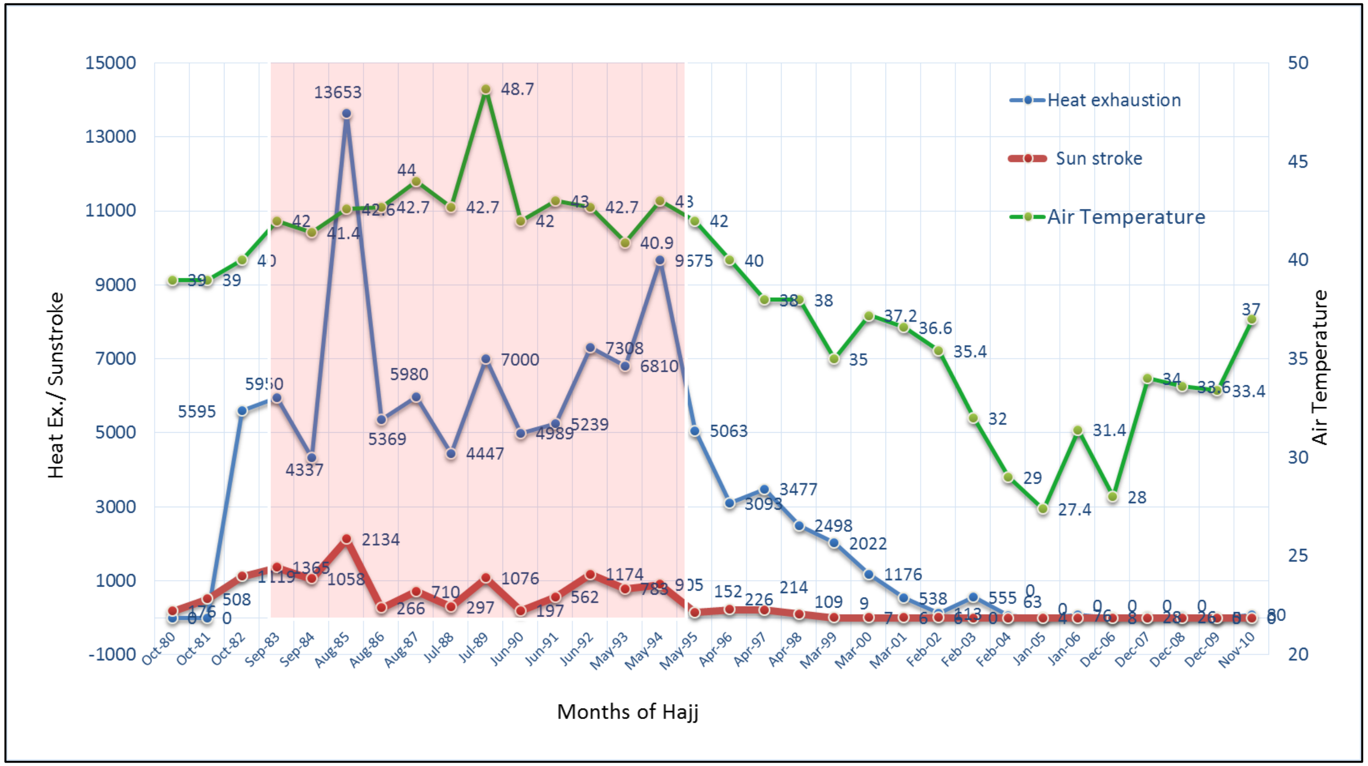

Figure 3-4 Incidents of sunstroke and heat exhaustion during Hajj (1980-2010)

3.2 The Hajj, Pilgrimage to Makkah

The pilgrimage in Makkah consists of a number of rituals performed over a five days period starting from the eighth day of Thul-Hijjah, the twelfth month of the Hijri (Islamic) year and terminating on the thirteenth day of the month (Ministry of Hajj, 2010).

3.2.1 Hajj rituals and the Holy sites

The pilgrimage lasts five days during which pilgrims must visit four designated holy sites to perform specific rituals called the acts of Hajj (Ministry of Hajj, 2011). Figure 3-6 illustrates the Holy sites of Makkah where the pilgrimage rituals are performed as follows:

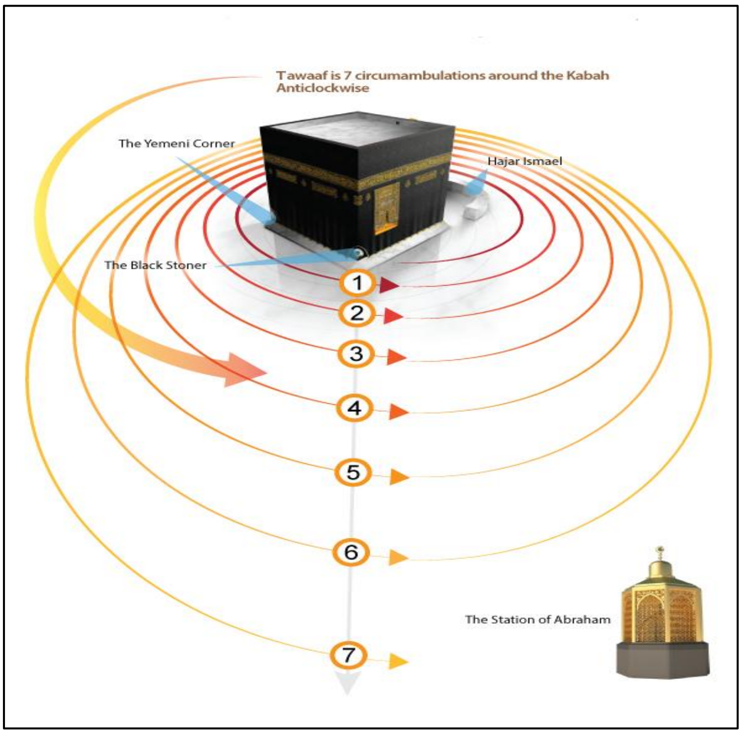

Figure 3-5 Tawaf consists of seven circumambulations around Kaabah

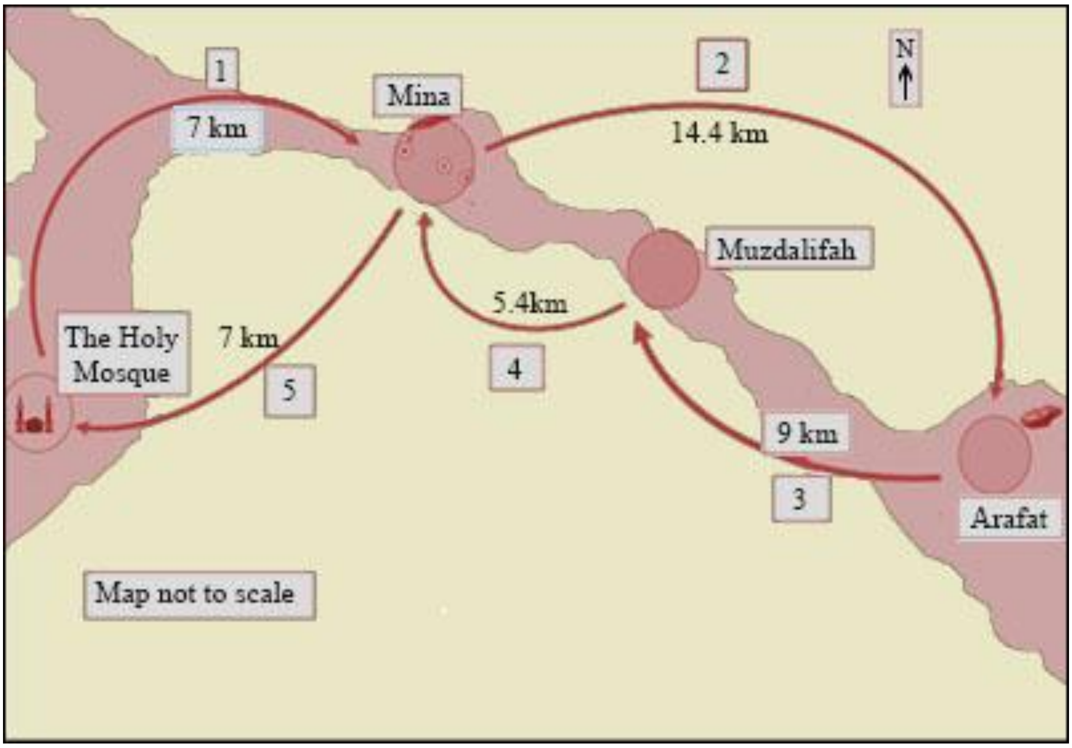

Figure 3-6 Hajj ritual sites (not to scale)

1. Al-Masjid Al-Haram, the Holy Mosque where the Holy Ka'aba is situated and Tawaf rituals are performed. Pilgrims must circumambulate seven consecutive times as shown in Figure 3-5, and perform the ritual of Sa'ee between the two hills of Al-Safa and Al-Marwa.
2. Mina is a valley located about 7 km south east of the Holy Mosque where the road leads to Arafat from the east end of the valley. The area of Mina is about 812 hectares of which more than half is flat land situated in the foothills of the southern and northern mountains. On the eight day of Hajj, and to prepare for pilgrimage; pilgrims head to Mina in the first instance as it is the starting point for the other holy destinations and they spend at least three days and four nights there.

3. Arafat is located in the south east of Makkah, around 22 km away from the Holy Mosque and covers an area of 20 square kilometres. Pilgrims spend the entire ninth day of Hajj here from morning to night to perform the Alwuguf (staying) in Arafat ritual, worshipping God and saying Dhohor and Asr prayers in Masjid Mamerah (Mosque). They begin journeying to Muzdalifah immediately after sunset on their way back to Mina.
4. Muzdalifah is the next destination after Arafat and is located before Mina where pilgrims say Maghrib and Isha'a prayers. Pilgrims stay overnight and start heading back to Mina at the beginning of the next day (the tenth day of Hajj).
5. From Mina, and after stoning the biggest devil (at Jamarat), pilgrims continue their journey back to the Holy Mosque to perform Tawaf rituals in the 10^{th} day of Hajj.

3.2.2 Demography of Pilgrims

During the Hajj, the population of Makkah grows significantly, reaching four to five times its normal population level. Pilgrim numbers are given in Figure 3-7.

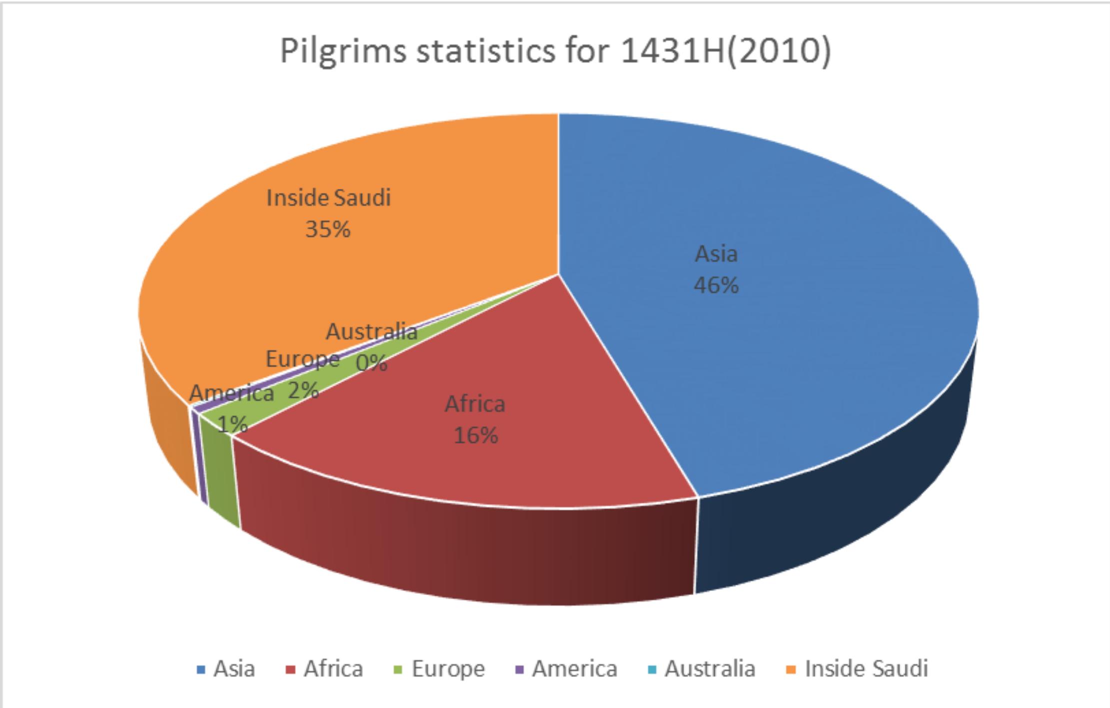

Figure 3-7 Foreign pilgrim demographics, 2010

3.2.3 Crowd incidents during Hajj

Pilgrimages at Makkah have witnessed a number of crowd disasters as a consequence of overcrowding during the rituals. Table 3-1 and Figure 3-8 document crowd incidents for the period 1978 to 2008 (Saudi Civil Defence,(2010b).

Table 3-1 Crowd Stampede (1987-2008)

Year	Casualties	Deaths
1987	1	1
1988	17	2
1989	29	3
1990	11	1424
1991	5	5
1992	5	3
1993	36	0
1994	109	274
1995	12	6
1996	79	27
1997	83	27
1998	482	125
1999	26	9
2000	33	7
2001	33	4
2002	30	1
2003	33	19
2004	273	254
2005	51	6
2006 (Jan)	462	441
2006 (Dec)	26	5
2007	19	2
2008	54	7

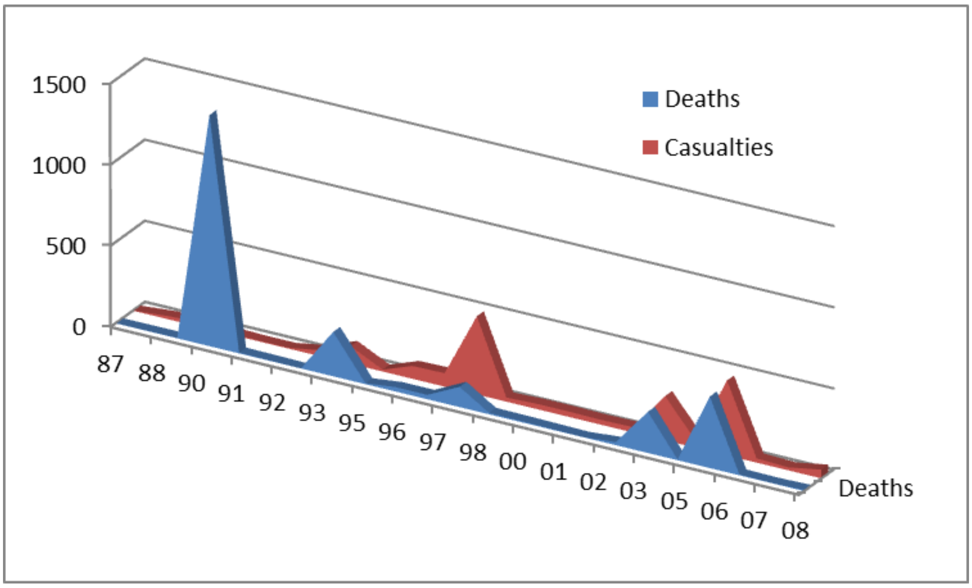

Figure 3-8 Crowd incidents during Hajj (1987-2008)

Chapter 4Research Methodology

4.1 Introduction

This chapter discusses issues related to research design and data collection methods used to conduct research in this study. The issues are addressed after considering the basic research objectives, relevant research questions, and appropriate simulation software. This chapter includes a brief literature review of available research designs and methods, data collection methods, phases of fieldwork, the procedures and problems encountered in specific phases of the fieldwork, as well as the actual data collected. Measurements of densities, velocities, and flow rates are needed to understand the pilgrims' movements during the Hajj.

4.2 Choice of Study Area

On the morning of the 10th day of the pilgrimage month, most pilgrims come to Makkah from Mina. They are supposed to remain at Mina from the 10th to the 12th or may stay one extra day, until the 13th of Dhul-Hijja, to participate in the Stoning of the Devil ritual (Jamarat). During each of these days, pilgrims come to the Holy Mosque at Makkah either to perform the Tawaf or to pray. One major cause of incidents is cross-traffic in highly dense areas. Pilgrims finishing their activities are struggling to leave the space, while arrivals are struggling to enter. This type of traffic creates an unpredictable movement pattern which easily results in falls, causing bodily injuries or even fatalities.

To collect data, cameras would be set up at a particular site of interest, and video footage analysed, giving parameters that would be fed into a simulation model, so that, the simulated results would be contrasted with the data observed from the field.

4.3 Data Collection Plan

Two data collection activities were performed to collect the necessary information. In the pilot study (2009), diagnostic measurements of the crowd (during the Hajj) were collected using a still camera. This was to aid in determining the most critical places in the vicinity of the Holy Mosque that affect pilgrim dynamics as shown in Figure 4-2 and described in section 3.7. Based on the primary data collected, one of the main roads leading to the Holy Mosque and the Holy Mosque plaza were chosen for the full case study with the objective of alleviating the problem of overcrowding.

This data will support an in-depth investigation of the characteristics of pilgrim crowd dynamics. The following factors would be determined:

1. Pilgrim flow rate, speed, and density at one of the main roads leading to the Holy Mosque.
2. Movement patterns of pilgrims (e.g. unidirectional, bi-directional, and multi-directional pedestrian flow).
3. Pilgrim density at the plaza of the Holy Mosque.
4. High-density areas in front of the gates of the Holy Mosque.

4.4 Data Collection Equipment

The Saudi Ministry of the Interior supported this work by providing a video recording crew, as well as the required instruments and tools, such as HD video cameras, HR still cameras, laptops, and software. The data collection equipment included:

1. High-definition video cameras

Sony model HDR-XR105 high-definition digital video camcorders were used. This model records up to 33 hours of Full HD 1920 x 1080 quality footage at a high bit-rate using an advanced Video Coding High Definition AVCHD format and Exmor CMOS sensor for brilliant picture quality. It also uses a high sensitivity and low noise high-speed image processor (BIONZ) for enhanced image quality and responsive performance. It has a Carl Zeiss Vario-Tessar lens with 10x optical zoom/120x digital zoom. The camera has 'Steady Shot' image stabilization to provide a clearer video and still pictures when shooting handheld. It has a D-Range Optimizer with Auto Backlight Correction that adjusts exposure and contrast for evenly-exposed backlit shots and a four megapixel still photo capability.

2. High resolution professional still camera

- High resolution Nikon D 300 camera,12.3 megapixel DX format CMOS sensor
- ISO 200-3200 (6400 with boost)
- Auto Focus sensor (51-point, 15 cross-type, more vertical coverage)
- Auto-focus calibration (fine-tuning)
- Custom image parameters to support brightness as well as contrast

- Six frames per second continuous shooting
- Zoom lens, AF-S DX NIKKOR,18-200mm f/3.5-5.6G ED VR II, 11x zoom versatility, ED glass superiority, and VR II image stabilization for sharp image
- Wide angle lens, SIGMA 10-20mm F4-5.6 EX DC, Ultra- wide-angle zoom, with 2x zoom ratio and variable angle-of-view from 99 degrees at 12 mm to 61 degrees at 24 mm.

4.5 Data Collection Methods

Both quantitative and qualitative research methods were used to study, analyse, and discuss pilgrim crowd dynamics at chosen sites. A combination of these methods enabled the study of crowd movements from different perspectives. These methods included:

1. Visual inspection of the video recordings and high resolution still images to understand the general mechanisms of how pilgrims interact (e.g. how they tend to over-take each other, organise themselves into lanes, and physically interact with each other), as well as pilgrim crowd trajectories, movement types, and the overcrowding of certain areas.
2. Manually counting of fundamental pilgrim dynamics characteristics, including speed, density, and flow.

Footage was processed using AVS software to obtain crowd dynamics characteristics. The software is based on breaking down each video data into consecutive frames, to provide the movement speed for each individual along with the crowd's overall movement. Groups of individuals (pilgrims) would then be studied as a case study to investigate movement characteristics with respect to place, time, and day.

4.6 Field Study Phases

Originally, the field studies were going to be conducted during two Hajj seasons (2009 and 2010). However, two unforeseen factors led to changes in the field study schedule- swine flu in 2009, and the early completion of the Government's "Masha'ar Train" transportation project in 2010. Threats of swine flu decreased the number of pilgrims by 4% compared with the previous year, as some foreign countries restricted their people from travelling to Makkah during the 2009 Hajj. In contrast, the number of pilgrims increased by 17 % in the 2010 Hajj season, as per Figure 4-1 (Saudi Ministry of Planning, 2010) , reflecting a steady increase in the number of Muslims permitted to attend and perform Hajj.

In 2010 the Saudi government introduced a new transportation system in Makkah. The new train operated at around 33% of its expected capacity of 500,000 pilgrims (Ministry_of_Municipal_and_Rural_Affairs_, 2010). The train would reduce traffic congestion by replacing thousands of buses that shuttle pilgrims between holy sites (outside of the Holy Mosque area); by 2011 the train was expected to operate at full capacity. Trains were introduced as part of the government's plan for safer and more sustainable pilgrim transportation. This dramatic change in transportation during the Hajj may transfer overcrowding to the Holy Mosque area.

Data collection during two Hajj seasons ensures the validity and relevance of the data. Pedestrian studies are largely based on surveillance and video recordings for accuracy, multiple analyses, as well as time saving and efficiency. The above data collection methods have been selected to improve pilgrim crowd dynamics during the Hajj and to provide new insights into the field of study.

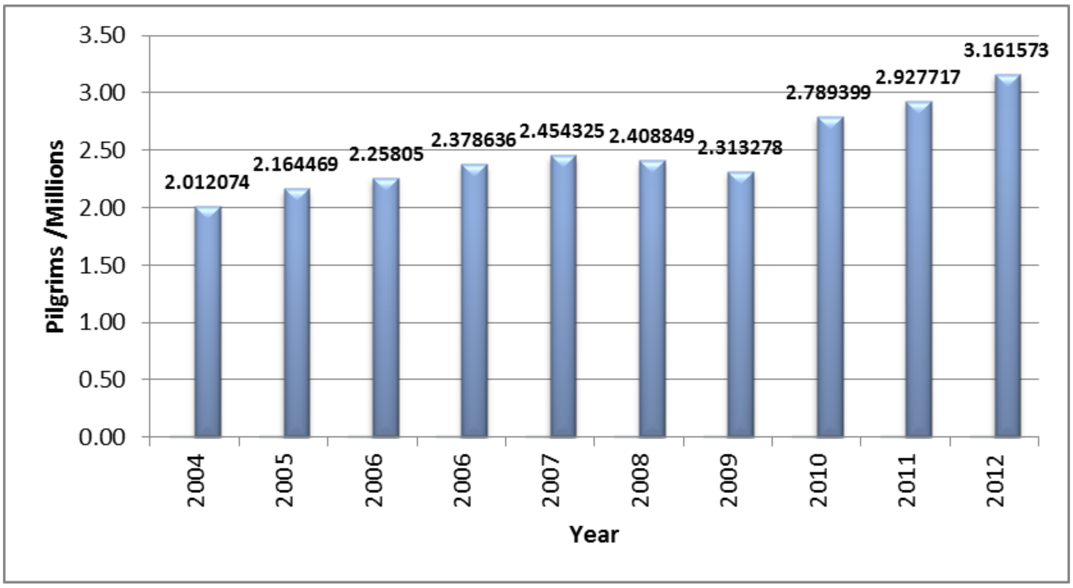

Figure 4-1 Pilgrim numbers from 2004 to 2012

4.7 Pilot Field Study

The pilot study took place between November 30th and December 30th of 2009. The data collected during this field trip included statistical data about the Hajj, such as pilgrim demography, digital maps, Hajj crowd safety standard information, and still images which predict overcrowding spots and pilgrim movement types.

Observation sites are six locations, two in the Ajyad Street area, two along the southern plaza of the Holy Mosque, one at King Abdulaziz Gate, and one at King Fahad Gate Figure 4-2.

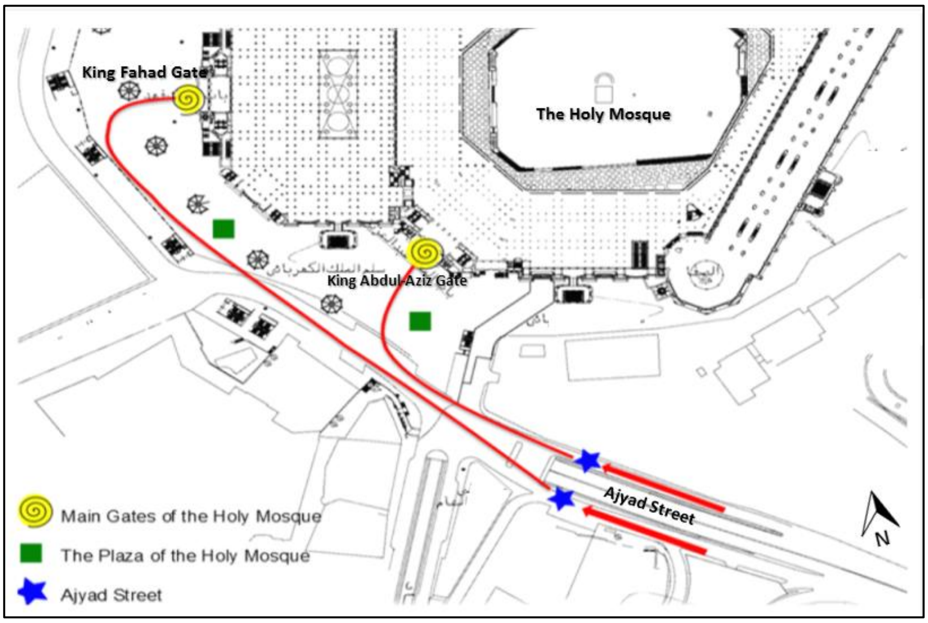

Figure 4-2 Observation sites at Ajyad Street and the Holy Mosque Plaza

Photographing the Holy Mosque area during the 2009 Hajj ensured a full picture and comprehensive understanding of pilgrim crowd dynamics and Hajj activities. High resolution pictures from inside the Holy Mosque were taken where Tawaf and Saa'i rituals were to be performed from the 10th to the 13th days of Hajj. The Tawaf ritual reaches its peak during the 10th day of Hajj, as illustrated in Figure 4-3, and due to the high-density inside the Holy Mosque at this time, some pilgrims perform the Tawaf on the second floor terrace and on the top floor of the Holy Mosque, as shown in Figure 4-4.

Figure 4-3 Tawaf ritual during the 10th day of the Hajj

Figure 4-4 Tawaf ritual on the roof of the Holy Mosque

In addition to taking exterior photographs of the Holy Mosque, the following areas were also photographed: southern plaza including main gates of the Holy Mosque Figure 4-5, King Abdulaziz's Gate Figure 4-6, and King Fahad Gate Figure 4-7. The importance of these two gates, due to the majority of pilgrims preferences of using these gates to enter the Mosque. 45% of pilgrims preferred using King Abdulaziz Gate, and 11% preferred using King Fahad Gate, Halabi, (2006).

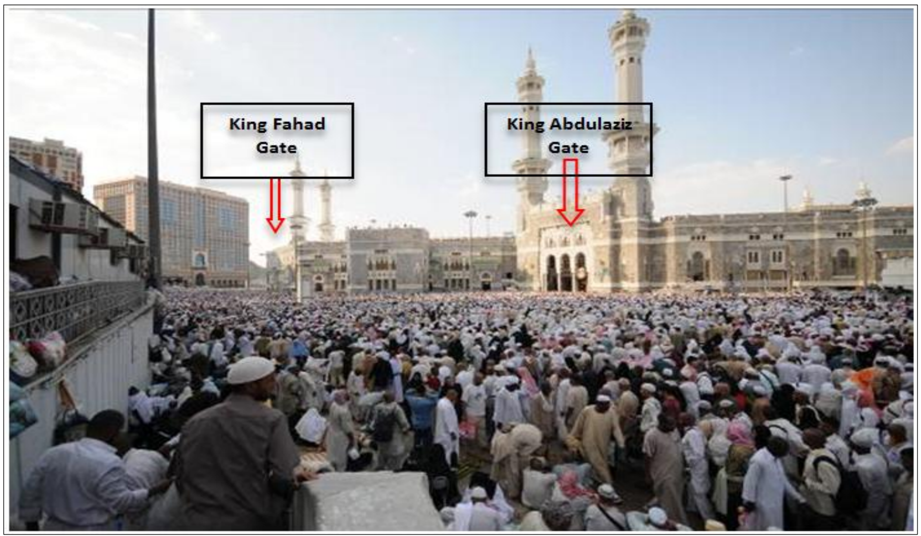

Figure 4-5 The Holy Mosque plaza and main gates

Figure 4-6 Asr prayer, in front of King Abdulaziz Gate

Figure 4-7 Asr prayer, in front of King Fahad Gate

Figure 4-8, showing a top view of the Holy Mosque plaza, indicates pilgrims during the Hajj entering the high-density plaza from Ajyad Street. Overcrowding in the plaza occurred during prayer times Figure 4-9.

In the pilot study of data collection, Ajyad Street was observed during the 10th to 13th day of the Hajj in 2009. Indeed, Ajyad Street is one of the most pedestrian crowded streets during the pilgrimage season in Makkah. All this suggested the choice of Ajyad Street as the area for the study.

Figure 4-8 Pilgrim crowds in the Holy Mosque plaza

Figure 4-9 Pilgrim influxe to the Holy Mosque plaza from Ajyad Street

4.8 Field Study

This field study took place between November 3rd and December 29th, 2010. This field study focused on the collection of pilgrim crowd dynamics characteristics data at Ajyad Street from the 10th to the 12th of the Hajj month (17th to 19th November, 2010).

4.8.1 The Study Area

Ajyad Street is approximately 500 meters long, located at the end of King Abdulaziz Street. It is considered to be one of the main streets in Makkah, since it connects Mina with the Holy Mosque, as shown in Figure 4-10. Pedestrian pilgrims use Ajyad Street during the 10th to 13th days of the Hajj to reach the Holy Mosque, to perform the rituals of Tawaf and Saii.

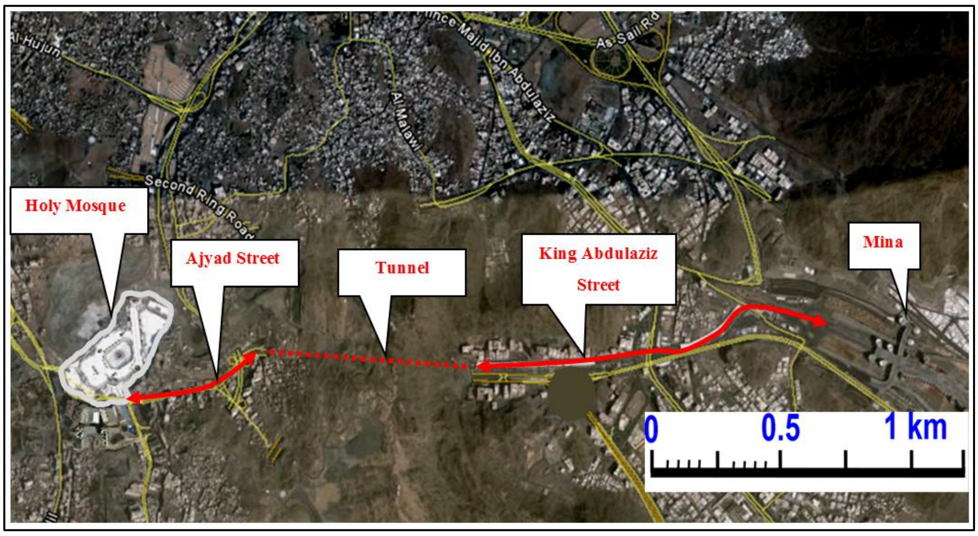

Figure 4-10 Map of Ajyad and King Abdulaziz Street

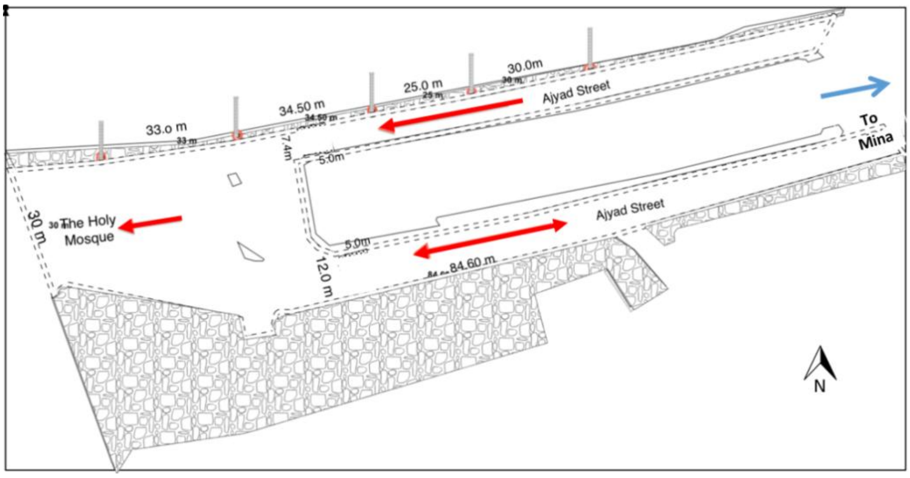

Figure 4-11 Ajyad Street Map

Ajyad Street is divided into two walkway paths that are separated from motor vehicle traffic, and constructed for pedestrian pilgrims as shown in Figure 4-11. We call these two walkways, “Ajyad 1” and “Ajyad 2”, 7.4 m and 12m respectively in width, with length of around 200 meters. They accommodate the highest volumes of pedestrian pilgrims in their trip to and from the Holy Mosque in the 10th day of the Hajj as shown in Figure 4-12. Note that Ajyad1 is “one-way” i.e. outbound (towards the Holy Mosque) Ajyad2 is both inbound and outbound.

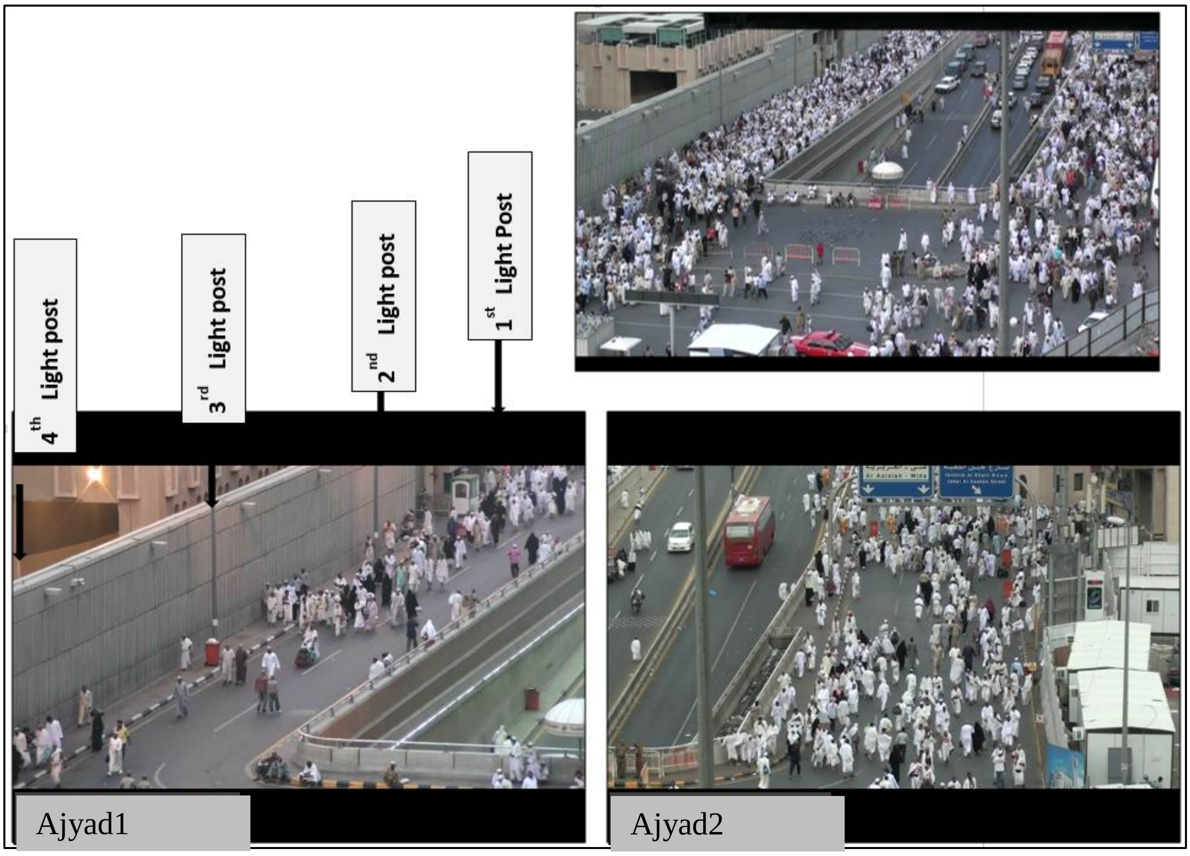

Figure 4-12 Tunnel dividing Ajyad Street into two walkways, Ajyad1 and Ajyad2

4.8.2 Data Collection Times and Procedure

Pilgrim crowd dynamics data were collected during pilgrimage time, during which Ajyad Street and the plaza of the Holy Mosque experienced variable crowd intensity. The dates and times assigned for collecting the data over 12 hours on the 8th to the 12th days of Hajj 8-10 /12/1431 H (15-19 /11/2010 G) are listed in Table 4-1. Table 4-2 shows prayer times for Makkah on the 8th to the 12th of the Hajj month.

Table 4-1 Dates and times assigned for collecting the data

Location	Date	Start	Duration	End	Camera
Ajyad1	10/12 (H)	07:30:00	12 hours	19:30:00	Cam-One
Ajyad2	10/12 (H)	07:30:00	12 hours	19:30:00	Cam-Two
Plaza (King Abdulaziz gate)	08-12/12 (H)	07:30:00	12 hours	19:30:00	Cam-Three
Plaza (King Fahad Gate)	08-12/12 (H)	07:30:00	12 hours	19:30:00	Cam-Four

Table 4-2 Prayer times for Makkah

DATE		PRAYERS				
Hijri	Gregorian	Fajr (Dawn)	Dhuhr (Noon)	Asr (Afternoon)	Maghrib (Sunset)	Isha (Night)
8	4	05:08	12:05	03:19	05:44	07:14
9	5	05:08	12:05	03:19	05:43	07:13
10	6	05:09	12:05	03:19	05:43	07:13
11	7	05:09	12:05	03:18	05:42	07:12
12	8	05:10	12:05	03:18	05:42	07:12

To collect the pilgrims' crowd dynamics data, buildings and towers with a wide and clear view of the Ajyad Street and the Holy Mosque plaza were chosen. Four high-definition video cameras with high quality and clear video recordings were fitted to record a particular angle of the street. Zoom lenses recorded the entire data collection area. Two video cameras were fitted with a wide-angle-view towards Ajyad Street and the other two cameras with wide angle views covered the entire plaza (including King Abdulaziz and King Fahad Gates) as shown in Figure 4-12. In addition, high-resolution photographic techniques were used to collect data for the study of movement types and overcrowding spots. High-quality video recorders were used to record pilgrim crowd dynamics at the microscopic and macroscopic levels. The collected data was used to measure the fundamental characteristics of pilgrims' speed, density, and flow.

4.8.3 Study Site

Two pilgrim flow areas were marked off on Ajyad Street, consisting of two rectangles outlining the Ajyad1 and Ajyad2 walkways width [with a length of 40 meters and 39.5 meters respectively along the streets]. Figure 4-13 shows Ajyad1 focused window (7.4x40) meters, and Figure 4-14 shows Ajyad 2 Street focused window of (12x39.5) meters. These two windows were selected at the end of Ajyad Street from which crowds enter and leave the plaza of the Holy Mosque. The data collected on the 10th day are reported and analysed in chapter 5.

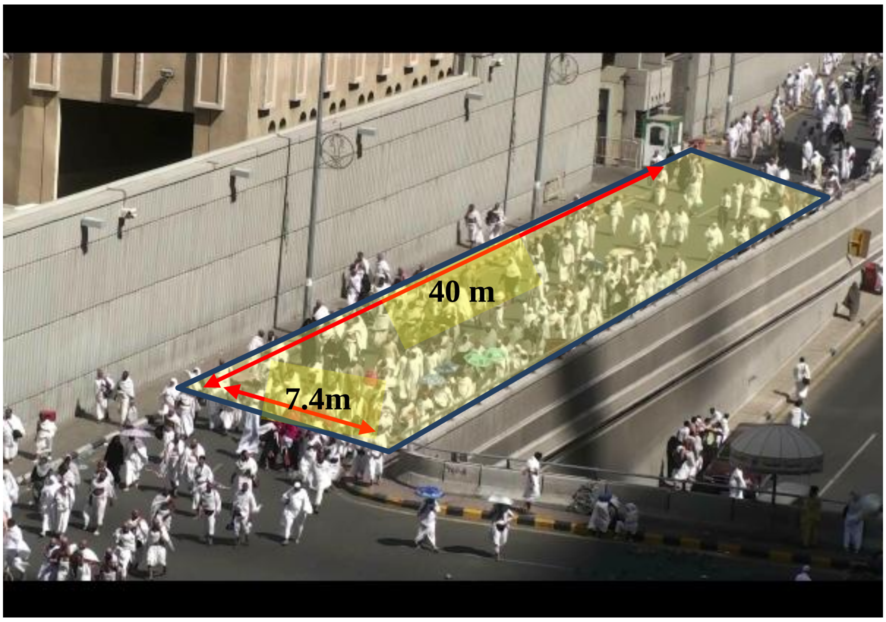

Figure 4-13 Ajyad1 Street study area

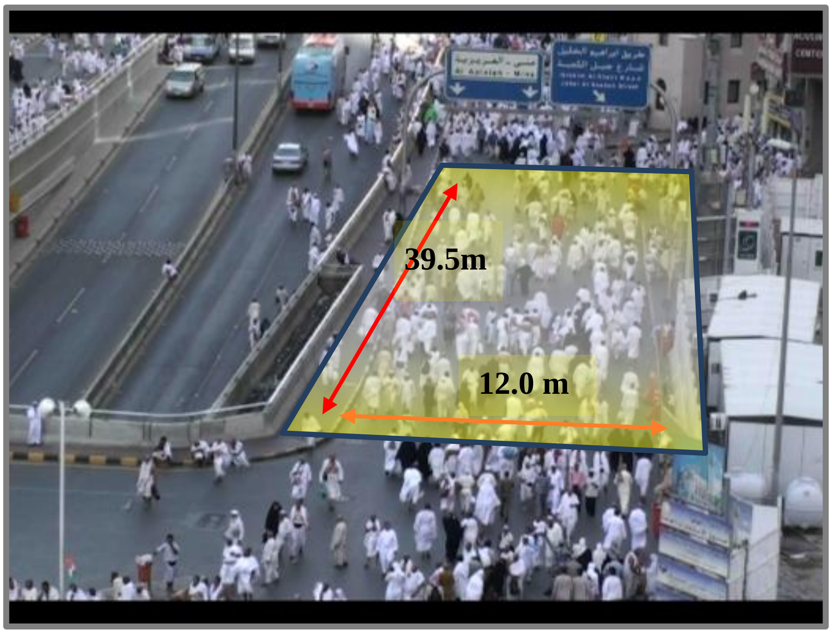

Figure 4-14 Ajyad2 Street study area

Rather than, the approach employed would be to mark off rectangular "windows" on each walkway (Ajyad1 and Ajyad2) and estimate:

1. Flow rate: by counting the number of pilgrims passing out of the windows in 1 minute intervals every 10 minutes. (HCM, 2000) ;

2. Speed: by averaging the times taken by 3 pilgrims to travel the length of the window. i.e. space mean speed rather than time mean speed according to Gerlough and Huber (1976).

3. Density: by counting the number of pilgrims within the window divided by the window area, expressed as pedestrian per square meter. (HCM, 2000)

Chapter 5: Data Collection and Analysis

5.1 Introduction

This chapter covers the extracting of figures from video recordings filmed at the study area location on Ajyad Street. These figures were analysed to extract the required variables: speed, flow and density. An individual pedestrian tracking method was used. Many frame-by-frame snapshots of the video recordings were examined at five-second intervals to measure the walking speeds of individual pilgrims; each process measures the distance travelled over 30 seconds, calculates every interval speed and then calculates the average speed for all selected samples.

Thereafter, calculations of speeds and densities were made according to the readings. Figures illustrating values and tendencies of variations were plotted, accompanied by brief comments. A discussion and analysis of the data illustrated in the Figures and Tables follows the presentation of the calculations to provide a thorough understanding of the characteristics of the pedestrian pilgrim dynamics

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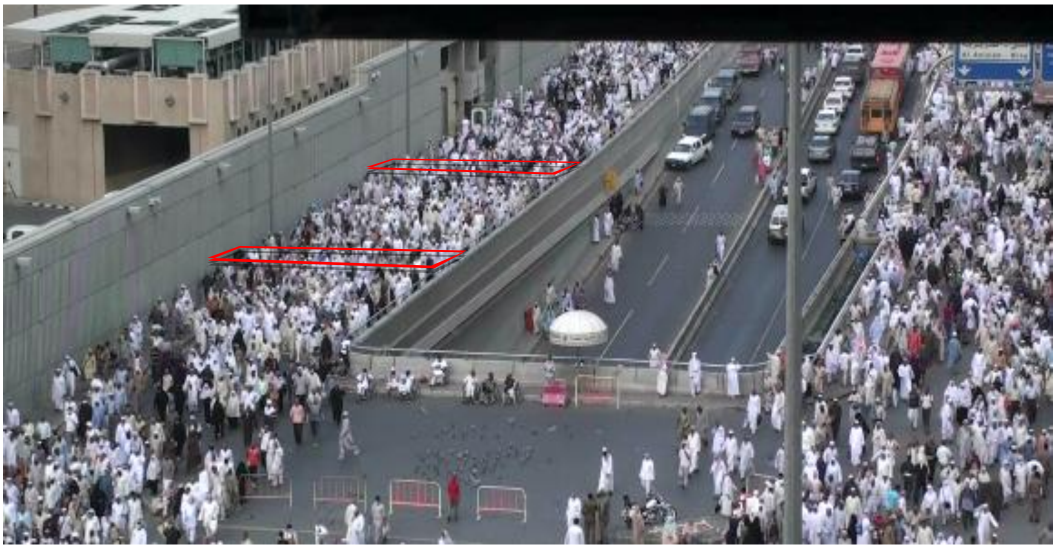


Figure 5-1 Segmentation of the pilgrim flows

Figure 5-1 illustrates, in red, two segments of 1.5 m × 7.5 m of pilgrim flows on Ajyad1, including a maximum of 28 pilgrims, moving 1.5 m at 1.03 m/s in a time of (1.5) / (1.03) = 1.48 s, giving a rate of flow of ((28 * 60) / 1.48) / 7.4 = 153.4 p/min/m.

The pedestrian density to some extent can defines as homogeneous distribution of pedestrian mass, and this can be true for small areas but in the case of Ajyad Street, the pilgrim density over the time is varies from high density sub-areas to totally empty sub-areas. This was treated by dividing large areas into a segment of smaller sub-areas, and measuring density in each of these segments. The hourly speeds, flow rates and densities observed at the two study areas (in the three directions shown in Figure 4-12) are given in Table 5-1 and discussed in detail in sections 5.2 and 5.3.

Table 5-1 Hourly observed Pilgrim flows at Ajyad Streets

	Ajyad1					Ajyad2 Outbound					Ajyad2 Inbound				
Time	speed m/s	Density p/m2	Flow p/s/m	Flow p/min/m	capacity m²/p	speed m/s	Density p/m2	Flow p/s/m	Flow p/min/m	capacity m²/p	speed m/s	Density p/m2	Flow p/s/m	Flow p/min/m	capacity m²/p
07:30:00	1.33	0.63	0.84	50.45	1.59	0.91	1.39	1.26	75.89	0.72	1.05	1.06	1.11	66.76	0.94
08:30:00	1.09	2.34	2.56	153.32	0.43	0.81	1.44	1.17	69.98	0.69	0.76	0.83	0.64	38.24	1.20
09:30:00	1.2	0.9	1.08	64.86	1.11	0.89	2.06	1.83	110.00	0.49	0.87	0.67	0.58	34.67	1.49
10:30:00	0.92	1.53	1.41	84.82	0.65	0.71	2.89	2.05	123.11	0.35	0.74	0.72	0.53	31.89	1.39
11:30:00	1.0	1.98	1.98	118.92	0.51	0.81	2.33	1.89	113.24	0.43	0.81	0.56	0.45	27.08	1.79
12:30:00	0.84	2.25	1.89	113.14	0.44	0.65	3.44	2.24	134.16	0.29	0.6	0.28	0.17	10.0	3.57
13:30:00	0.95	1.62	1.54	92.18	0.62	0.8	1.89	1.51	90.72	0.53	0.89	0.72	0.64	38.41	1.39
14:30:00	0.82	1.89	1.55	92.87	0.53	1.03	1.89	1.95	116.80	0.53	0.87	0.78	0.67	40.44	1.28
15:30:00	1.38	0.9	1.25	74.84	1.11	0.83	3.22	2.67	160.36	0.31	0.81	2.78	2.26	135.42	0.36
16:30:00	0.97	2.34	2.28	136.74	0.43	0.74	1.78	1.32	79.03	0.56	0.74	1.44	1.06	63.77	0.69
17:30:00	1.13	1.8	2.03	121.62	0.56	0.85	1.17	0.99	59.67	0.85	1.03	1.89	1.94	116.32	0.53
18:30:00	1.33	0.72	0.96	57.66	1.39	0.65	1.78	1.16	69.42	0.56	0.65	1.56	1.01	60.67	0.64
19:30:00	1.29	1.08	1.39	83.4	0.93	0.91	1.06	0.96	57.88	0.94	0.98	1.0	0.98	58.5	1.00

5.2 Pilgrim dynamics on Ajyad1

5.2.1 Time-based Speed and Density

Figure 5-2 shows that speed (m/s) and density (p/m²) of pilgrims vary with prayer times (Table 5-2), which seems to be the main factor affecting all of the rates, and suggests an inverse relation of speeds with density values lower than the critical crowd point: the higher the speed, the lower the density. The prayer times seems to have a significant effect on the speed–density relationship, where higher densities were noted at prayer calling times. The higher flows of incoming pilgrims increased the density and lowered the optimal speed of movement; if pilgrims find a space with a lower density path, they immediately increase their speed, thereby decreasing the density, as shown in the intervals from 08:30 to 09:00; 15:00 to 15:35; 17:30 to17:45; and after 19:30. Additionally, the decrease of density after 10:00 produced a clear decrease in speeds until 12:30. This phenomenon was repeated from 13:00 to 15:00 and from 15:40 to 17:30.

Table 5-2 Prayer Times for Makkah, on 10th day of Hajj month 1431H (2010)

Day Hijri	Day Gregorian	Fajr (Dawn Prayer)	Dhuhr (Noon Prayer)	Asr (Afternoon Prayer)	Maghrib (Sunset Prayer)	Isha (Night Prayer)
10/12	16/9	05:09	12:05	15:19	17:43	19:13

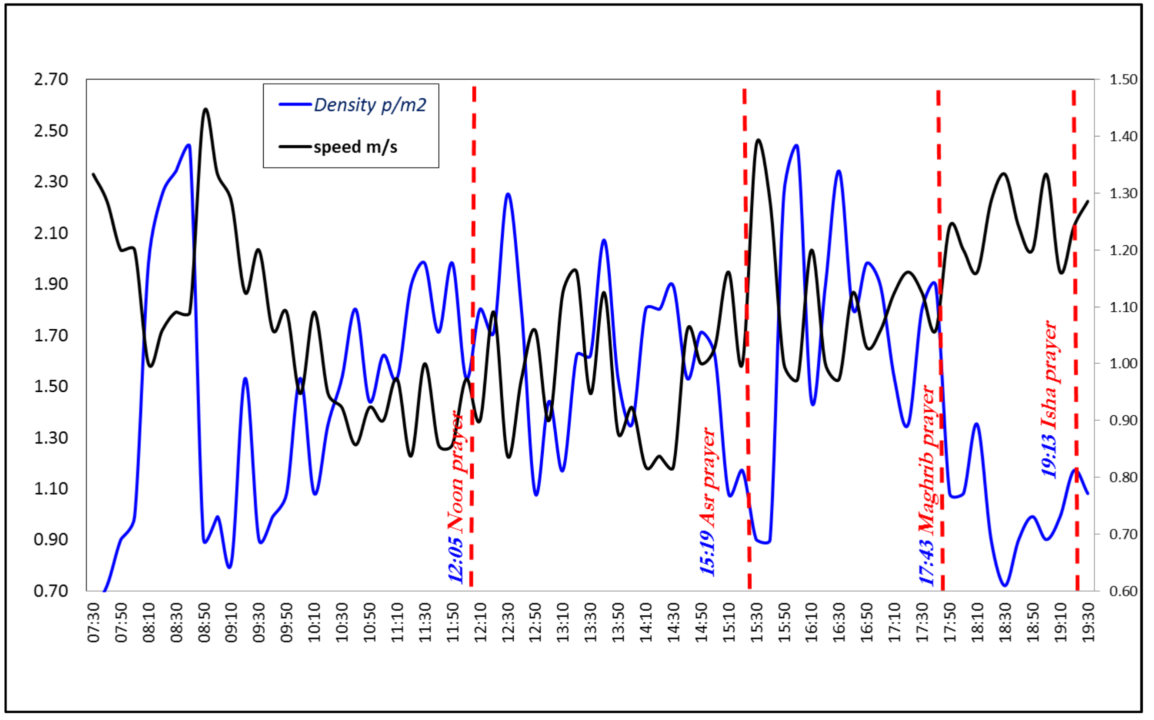


Figure 5-2 Detailed pilgrim speeds and densities on Ajyad1

The maximum pilgrim densities were found at 8:00, 12:30, 16:00 and 16:30. The first peak shows that the density increased at 8:00 causing speeds to decrease to the minimum at 12:30, at which time, the speed increased with the decrease of density until 13:00. Then, a new density increase interval began, reducing speeds until 15:00 when the speeds rose again, lowering density until 16:00. Density rose again until 17:50 then decreased again to the end of the day. This reflects the mentality of pilgrims and their motives for going to the mosque at certain times.

The black line in Figure 5-2 shows pilgrims' walking speeds at timed intervals over a 12-hour period. Rapid walking speeds were noted at the beginning of the day due to the arrival of pilgrims from Mena, after spending last night in Muzdalifah and throwing the biggest devil statue in Mena in their way to the central area of Makkah, to perform the compulsory ritual of Tawaf and Saa'i in the Holy Mosque. At this time, the crowds reached their highest density.

5.2.2 Time-based (Outbound) Flow Rates on Ajyad 1

Figure 5-3 illustrates sharp increasing in flow on Ajyad1 at 8 am, then variation over the rest of the day. The prayer times showed a significant decrease in pilgrim flow.

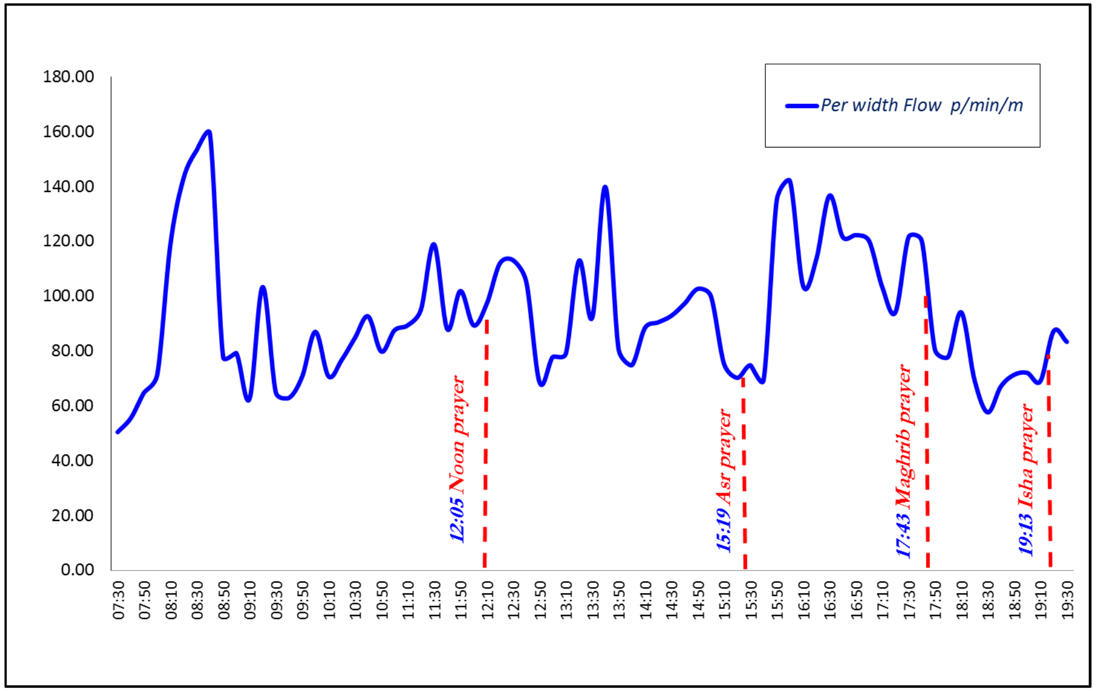


Figure 5-3 Pilgrim flow rate at Ajyad 1

5.3 Pilgrims dynamics on Ajyad2

5.3.1 Outbound time-based Speed and Density

Figure 5-4 illustrates lower and steadier pilgrim speed values in the outbound flow when compared with the pilgrim speeds on Ajyad1. It also shows a more turbulent line of density and higher values, which are due to the bi-directional movement on Ajyad2, giving a maximum of 3.2 p/m^2 at 15:50. However, the effect of density on speed and vice versa similar to that shown on Ajyad1. The prayer times showed a significant effect on the speed–density relationship, where higher densities were noted at prayer calling times.

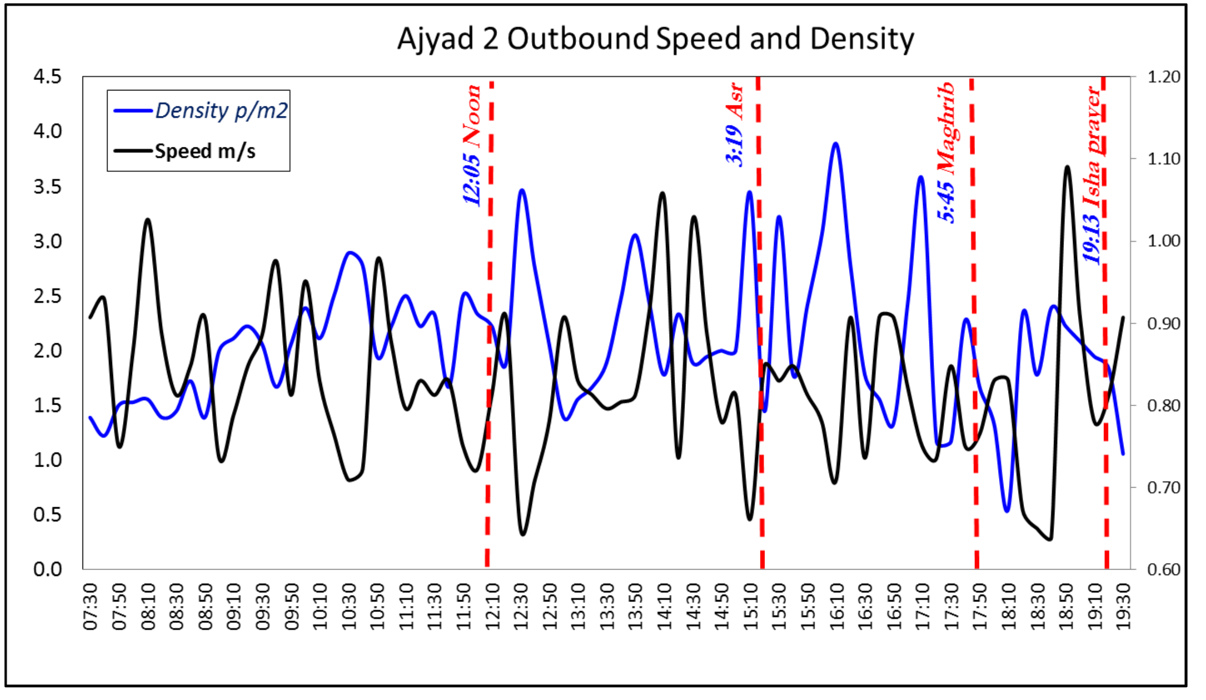


Figure 5-4 Pilgrim speeds and densities at Ajyad2 outbound

5.3.2 Inbound time-based Speed and Density

Figure 5-5 shows that the inbound flows have slightly higher speeds than the outbound flows; the density curve is identical to the outbound density in Figure 5-4, because they both contain the same number of pilgrims within the counting segment of the street.

Moreover, Figure 5-5 shows significant differences between the morning and afternoon periods. At about 15:00, most of the pilgrim dynamics is inbound, the returning pilgrims (from the Holy Mosque back to Mina through Ajyad Street) just using Ajyad2 Street rather than Ajyad1 Street , causing a maximum density of 3.2 p/m^2 at 16:00, until the end of the day.

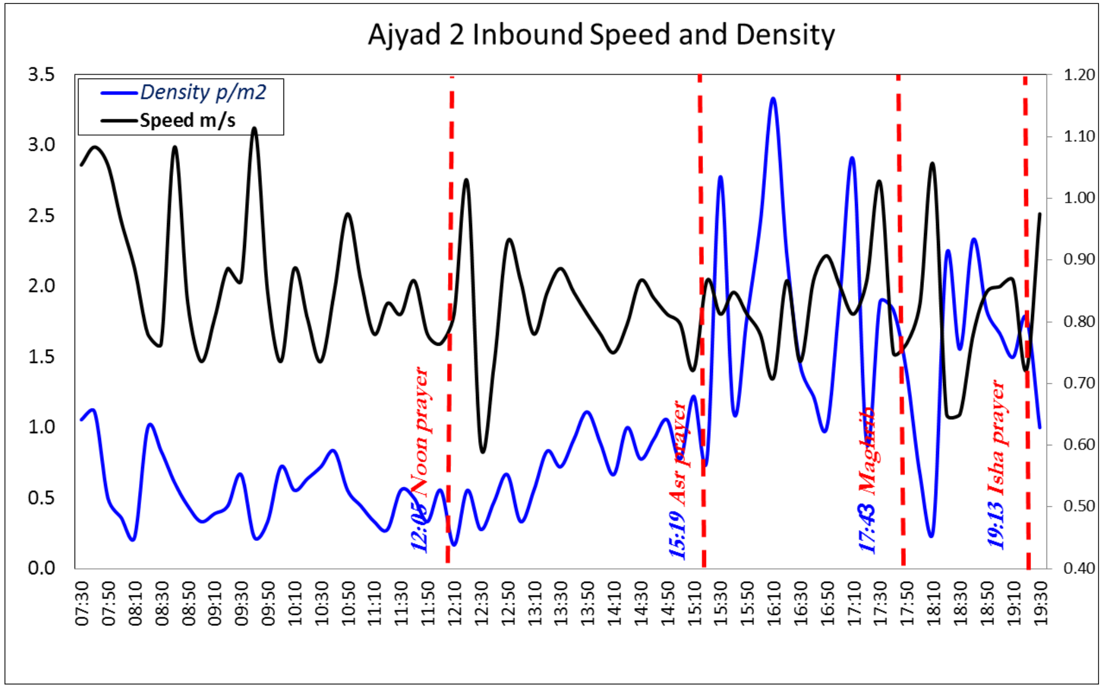


Figure 5-5 Pilgrim speeds and densities on Ajyad2 inbound

5.3.3 Time – based bi-directional Flow Rates on Ajyad 2

Figure 5-6 illustrates the variations in bi-directional pilgrim flow on Ajyad2, which are the expected product of non-uniformity in the flow of pilgrims. The variation appears to be much more complicated than on Ajyad1 because of the bi-directional movements of the pilgrims; this variation can be seen through the sharp changes in readings around the point from which we took the recording segments. These increases in values occur in both directions on Ajyad2 during the afternoon, just as they do on Ajyad 1 during the Maghrib and Isha prayer time. as concluded from the comparison between the outbound and inbound flows, a rational relationship could not be determined between the flows, except that both of these bi-directional flows are reducing each other throughout the day, which consequently produces a problem in crowd movement, which in turn requires separation of the bi-directional movement to ensure free pilgrim movement in both directions.

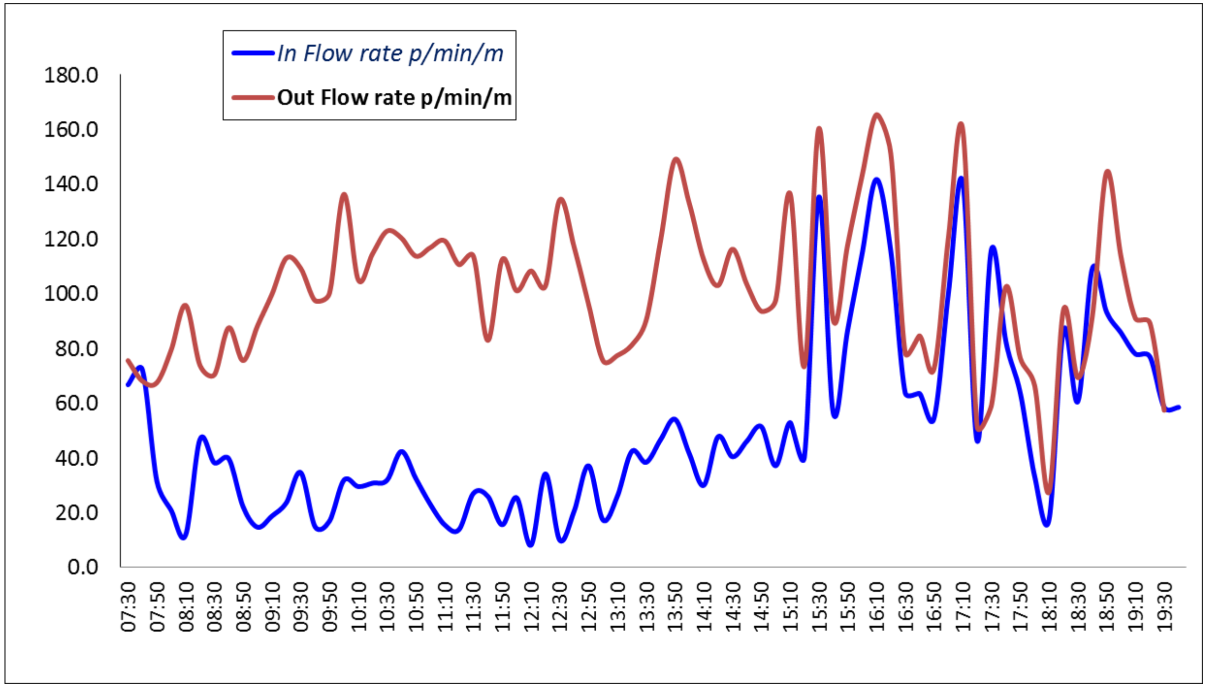


Figure 5-6 Outbound and inbound pilgrim flow on Ajyad2 Street

5.4 Relationships between Speeds, Densities and Flows

Pedestrian macroscopic flow models represent how the behaviour of one parameter of flow changes with respect to another. Several studies for pedestrian movement in a plane were reviewed for the purpose of suggesting the best fit model for pilgrim flow relationships; Hankin (Hankin and Wright, 1958), Helbing (Helbing et al., 2007), Mori and Tsukaguchi (Mori and Tsukaguchi, 1987), Navin and Wheeler (Navin and Wheeler, 1969), Oeding (Oeding, 1963), Older (Older, 1968), Predtechenskii and Milinskii (Predtechenskii and Milinskiĭ, 1978), Seyfried (Seyfried et al., 2005), and Weidmann (1993). Greenberg's (Greenberg, 1959) and Weidmann (1993) models are widely referenced in pedestrian dynamics studies.

Table 5-3 Typical characteristics of Pedestrian dynamics from the literature

Reference	Country	Type	Free Speed m/s	Density p/m²	Flow p/min/m
Oeding (1963)	Germany	Mixed traffic	1.5	3.98	89.4
Older (1968)	Britain	Shoppers	1.31	3.89	76.54
Navin & Wheeler (1969)	USA	Students	1.63	2.7	65.79
Fruin (1970)	USA	Commuter	1.36	3.99	81.2
Tanaboriboon et al.(1986)	Singapore	Mixed traffic	1.23	4.83	89.24
Tanaboriboon et al. (1991)	Thailand	Mixed traffic	1.21	5.55	101.05
Yu ((1993))	China	Mixed traffic	1.26	5.1	95.97
Gerilla (1995)	Philippines	Mixed traffic	1.39	3.6	74.94

To describe pedestrian pilgrim dynamics here the calculated observable basic quantities (speed u, density k and flow q) were used. These quantities are linked by the flow equation $q = k\,u$, the empirical relation between speed and density $u - k$, or the relation between flow and speed $q - u$. Table 5-3 illustrate the pedestrian characteristics of several references.

5.4.1 Greenshield Model

The pedestrian fundamental diagram (HCM (2000), Weidmann (1993), Seyfried et al. (2005) is a graph of speed and density of the pedestrians. The speed and density are dependent upon each other. If the density is high, the distance between pedestrian tends to be smaller and the speed is reduced. If the speed-density relationship is assumed to be linear, as per Greenshield et al. (1935), i.e.

$$\boldsymbol{u} = \boldsymbol{u_f}\,(\mathbf{1} - \frac{\boldsymbol{k}}{\boldsymbol{k_m}}) \quad \text{...5-1}$$

where u is speed (m/s), $\boldsymbol{u_f}$ is the free speed[2], k is density (people/m^2) and $\boldsymbol{k_m}$ is the maximum (jamming) density.

Then, by definition,

$$\boldsymbol{q} = ku \quad \text{... 5-2}$$

where $\boldsymbol{q}$ denotes flow (people/m/s)

The relationship between flow rate $\boldsymbol{q}$ and speed $\boldsymbol{u}$ can then be derived as

$$\boldsymbol{q} = \boldsymbol{k_m}\,.\,\boldsymbol{u} - \left(\frac{k_m}{u_f}\right)u^2 \quad \text{................................. 5-3}$$

---

[2] Free speed is the (maximum) speed at which pedestrian will walk when free from interference from others.

Alternatively,

$$q = k\,u$$

$$= k\,u_f\,(1 - \frac{k}{k_m})$$

$$q = u_f k - \frac{u_f}{k_m}\,k^2 \qquad \text{……………………………………5-4}$$

Table 5-4 Pilgrims Speed-Density relations (Greenshield model)

	SPEED – DENSITY (GREENSHIELD MODEL)	95% confidence intervals				R^2 %	Statistically Significant at 95%	Strength of Association
		Intercept	Slope	u_f	k_m			
Ajyad1	u_1 = 1.40653 – 0.221638 k_1	1.40653 (1.317,1.496)	-0.221638 (-0.279,-0.164)	1.41	6.34‡	45.30	0.1152	Moderate
Ajyad2 Outbound	u_2 = 0.957773 – 0.063318 k_2	0.957773 (0.888,1.028)	-0.063318 (-0.0958,-0.0309)	0.96	15.78	17.50	0.0869	v.week
Ajyad2 Inbound	u_3 = 0.878375 – 0.035787 k_3	0.878375 (0.837,0.920)	-0.035787 (-0.0699,-0.0017)	0.88	27.94	5.80	0.1017	v.week

‡ $\frac{u_f}{k_m} = 0.221638 \Rightarrow k_m = \frac{1.40653}{0.221638} = 6.34$

Table 5-5 Pilgrims Flow - Density relations (Greenshield model)

	FLOW – DENSITY (GREENSHIELD MODEL)	95% confidence intervals				R^2 %	Statistically Significant at 95%	Strength of Association
		Slope1	Slope2	u_f	k_m			
Ajyad1	q_1 = 1.254 k_1- 0.131845 ${k_1}^2$	(1.1319,1.3696)	(-0.19548,-0.0682)	1.254	$\left(\frac{1.254}{0.1318}\right)$ = 9.52	98.96	0.1794	Strong
Ajyad2 Outbound	q_2 = 0.9778 k_2- 0.07217 ${k_2}^2$	(0.9049,1.0509)	(-0.1010,-0.0433)	0.9778	13.55	98.74	0.1814	Strong
Ajyad2 Inbound	q_3 = 0.886 k_3- 0.04062 ${k_3}^2$	(0.8343,0.9376)	(-0.0650,-0.0161)	0.886	21.81	98.90	0.1054	Strong

5.4.2 Weidmann's Model

On the macroscopic level, and according to Weidmann (1993), we assume that the pedestrian density–speed relation ($k - u$), the so-called fundamental diagram, is defined as

$$u(k) = u_{\mathrm{f}}\left\{1 - exp\left[-\gamma\left(\frac{1}{k} - \frac{1}{k_m}\right)\right]\right\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{5-5}$$

$$u(k) = 1.34\left\{1 - exp\left[-1.913\left(\frac{1}{k} - \frac{1}{5.4}\right)\right]\right\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{5-6}$$

where u_{f} (= 1.34 m/s) is the free walking speed, γ (=1.913) is a "synthetic model parameter without direct phenomenological meaning" [4] (Bruno and Venuti, 2008), and k_m is as above.

The Weidmann model was fitted to our data (from Ajyad Street) using least square, resulting in the estimates of u_{f} , k_{m} and ϒ, listed in Table 5-6 . The values of u_{f} and ϒ compare favourably with those found by Weidmann himself but those for k_{m} do not.

[4] Bruno and Venuti hence suggest that Weidmann's Model is merely a good fit to the data rather than having any clear physical (or explanatory) basis.

Figure 5-7 Pilgrims Speed-Density relationship (Weidmann Model)

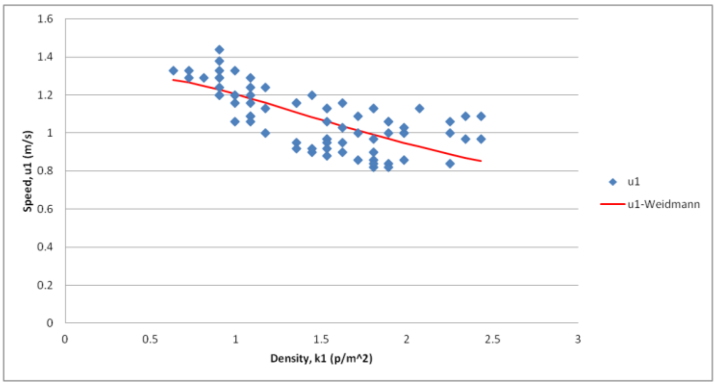
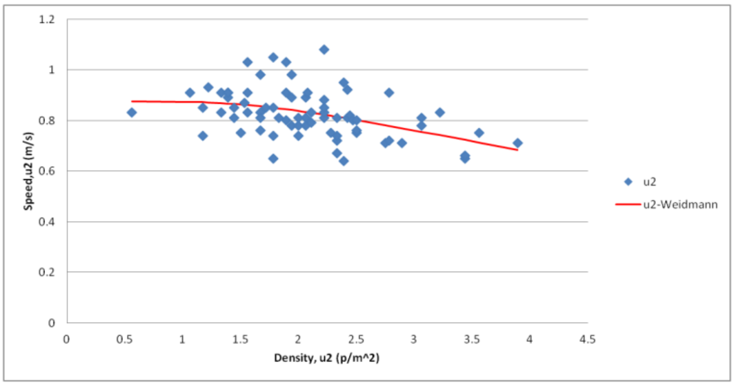
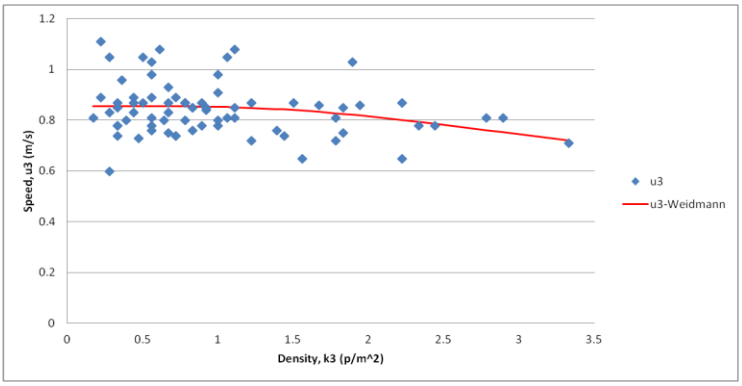
<table>
<tr><td></td><td>Weidmann Model</td></tr>
<tr><td>Ajyad1, Speed (u_1)- Density (k_1)</td><td>
</td></tr>
<tr><td>Ajyad2 Out, Speed (u_2)- Density (k_2)</td><td>
</td></tr>
<tr><td>Ajyad2 In, Speed (u_3)- Density (k_3)</td><td>
</td></tr>
</table>

Table 5-6 Estimates of u_f, k_m and Υ from Weidmann Model

	u_f	Υ	k_m
Ajyad 1	1.302	2.58	9496
Ajyad 2 Outbound	0.879	6.81	28.8
Ajyad 2 Inbound	0.853	7.33	20.47

5.4.3 Greenberg Model

In order to compare the different models, which explain the relationship between the dependent an independent variables, we apply Greenberg's model to fit our data.

In this model (5-7) , the speed–density function is given by

$$u(k) = u_f \, ln\left(\frac{k_m}{k}\right) \ldots\ldots \text{5-7}$$

or

$$k\,(u) = k_m e^{-u/u_f} \ldots\ldots \text{5-8}$$

and hence,

$$q = uk \quad , \quad q(k) = k\,u_f \ln\left(\frac{k_m}{k}\right) \ldots\ldots \text{5-9}$$

$$q\,(u) = u\,k_m e^{-u/u_f} \ldots\ldots \text{5-10}$$

Linear regression was then be applied using

$$u = u_f \ln k_m - u_f \ln k \ldots\ldots \text{5-11}$$

$$q = u_f k \ \ln k_m - u_f \ k \ \ln k \ldots\ldots \text{5-12}$$

$$\ln q - \ln\ u = \ln\ k_m - \frac{u}{u_f} \quad \text{..............................5-13}$$

For Ajyad 1, as listed in Table 5-7

$$u_f = 0.332516 \quad \text{..5-14}$$

with 95% confidence intervals (0.257,0.408)

$$u_f\ \ln k_m = 1.1919 \text{..5-15}$$

with 95% confidence intervals (1.155,1.227)

$$\Rightarrow \ln k_m = \frac{1.1919}{0.332516} = 3.584$$

$$k_m = 35.94 \text{..5-16}$$

with 95% confidence intervals (16.96 , 118.42)

Similarly for flow – density for Ajyad 1; (Table 5-8) :

$$u_f\ \ln\ k_m = 1.14957$$

$$u_f = 0.23909$$

$$\Rightarrow \quad \ln\ k_m = 1.14957/0.23909$$

$$k_m = e^{1.14957/0.23909} = 122.49$$

And for flow – speed for Ajyad 1 (Figure 5-9)

$$\ln k_m = 2.0369$$

with 95% confidence intervals (1.649638,2.424162)

$$k_m = 7.66$$

$$u_f = 1/1.57394 = 0.63534$$

Table 5-7, Table 5-8 and Table 5-9 summarise the complete set of estimations, in which the strength of the associations are categorised ($0 \leq R^2 \leq 0.19$) as very weak, ($0.2 \leq R^2 \leq 0.39$) as weak, ($0.4 \leq R^2 \leq 0.59$) as moderate, ($0.6 \leq R^2 \leq 0.79$) as strong and ($0.8 \leq R^2 \leq 1.0$) as very strong correlation (Evans, 1996) but these are rather arbitrary limits.

Table 5-7 Pilgrims Speed-Density relations (Greenberg's model)

	SPEED – DENSITY (GREENBERG'S MODEL)	95% confidence intervals*				R^2 %	Statistically Significant at 95%	Strength of Association
		Intercept	Slope	u_f	k_m			
Ajyad1	$u_1 = 1.19109 - 0.332516 \ln k_1 \Rightarrow$ $u_1 = 0.332516 \ln\left(\frac{35.94}{k_1}\right)$	(1.155,1.227)	(-0.257,-0.408)	(0.257,0.408)	(16.96,118.42)	52.33	Yes	Moderate
Ajyad2 Outbound	$u_2 = 0.901057 – 0.109436 \ln k_2 \Rightarrow$ $u_2 = 0.109436 \ln\left(\frac{3765.528}{k_2}\right)$	(-0.852,-0.9497)	(-0.044,-0.174)	N/A**	N/A **	13.71	Yes	Very weak
Ajyad2 Inbound	$u_3 = 0.835245 - 0.0323863 \ln k_3 \Rightarrow$ $u_3 = 0.0323863 \ln\left(\frac{1.586}{k_3}\right)$	(-0.810,-0.860)	(0.003,-0.067)	N/A **	N/A **	4.56	No	Very weak

* Confidence intervals obtained via Data Analysis (Regression) tool in MS Excel (not available via Statgraphics)
** Not estimated due to very weak strength of correlation.

Table 5-8 Pilgrims Flow - Density relations (Greenberg's model)

	FLOW – DENSITY (GREENBERG'S MODEL)	95% confidence intervals				R^2 %	Statistically Significant at 95%	Strength of Association
		Slope1[6]	Slope2[7]	u_f	k_m			
Ajyad1	$q_1 = 1.14957\ k_1 - 0.239093\ k_1 ln\ k_1 \Rightarrow$ $q_1 = 0.239093\ k_1 ln\ \left(\frac{122.49}{k_1}\right)$	(1.0929,1.206)	(-0.3343,-0.14386)	(0.1438,0.3343)	(26.283,4377.6)	98.85	Yes	Very strong
Ajyad2 Outbound	$q_2 = 0.943676\ k_2 - 0.166392\ k_2 ln\ k_2 \Rightarrow$ $q_2 = 0.166392\ k_2 ln\ \left(\frac{290.44}{k_2}\right)$	(0.8811,1.006)	(-0.2358,-0.0969)	(0.0969,0.2358)	(41.902,32341.)	98.93	Yes	Very strong
Ajyad2 Inbound	$q_3 = 0.84011\ k_3 - 0.0600293\ k_3 ln\ k_3 \Rightarrow$ $q_3 = 0.0600293\ k_3 ln\ \left(\frac{1196605.204}{k_3}\right)$	(0.8103,0.8698)	(-0.0993,-0.0206)	(0.0206,0.0993)	(3498.6, $2.17\text{x}10^{18}$)	98.87	Yes	Very strong

[6] Slope1 = $u_f\ ln\ k_m$
[7] Slope2 = u_f

Table 5-9 Pilgrims Flow - Speed relations (Greenberg's model)

	FLOW–SPEED (GREENBERG'S MODEL)	95% confidence intervals				R^2 %	Statistically Significant at 95%	Strength of Association
		Intercept	Slope	u_f	k_m			
Ajyad1	$ln\ q_1 - ln\ u_1 = 2.0369 – 1.57394\ u_1 \Rightarrow$ $q_1 = 7.6698\ u_1\ ln\left(\frac{-u_1}{4.8256}\right)$	(1.6496,2.4241)	(-1.9293,-1.2184)	(0.520,0.820)	(5.205,11.292)	52.33	Yes	Moderate
Ajyad2 Outbound	$ln\ q_2 - ln\ u_2 = 1.71454 – 1.25349\ u_2 \Rightarrow$ $q_2 = 5.554\ u_2\ ln\left(\frac{-u_2}{3.502}\right)$	(1.0954,2.3336)	(-1.9974,-0.5095)	N/A	N/A	13.71	Yes	Very weak
Ajyad2 Inbound	$ln\ q_3 - ln\ u_3 = 0.964109 – 1.40903\ u_3 \Rightarrow$ $q_3 = 2.262\ u_3 ln\left(\frac{-u_3}{4.0919}\right)$	(-0.33014,2.2583)	(-2.9338,0.1157)	N/A	N/A	4.56	No	Very weak

Figure 5-8 Pilgrims Speed-Density relationship

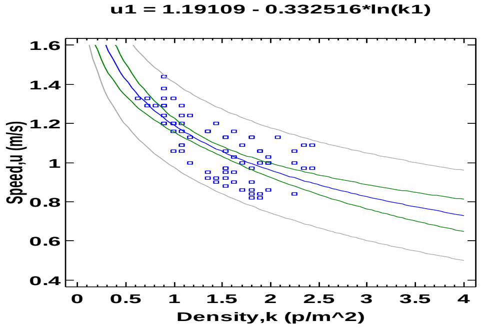
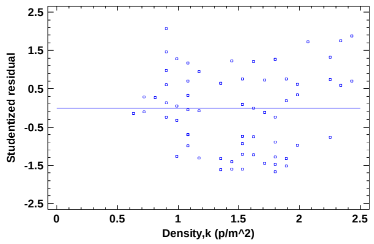
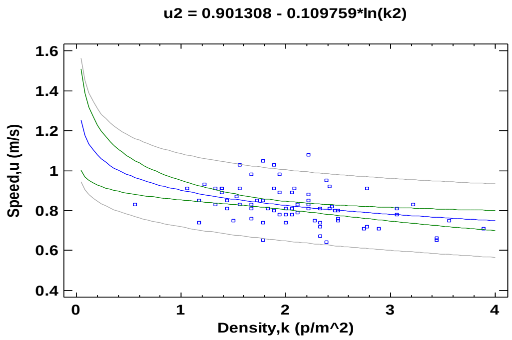
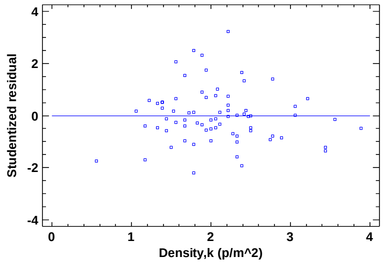
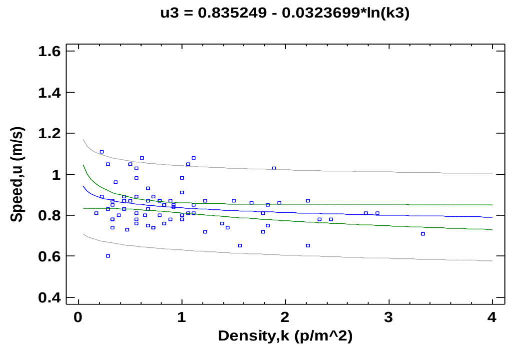
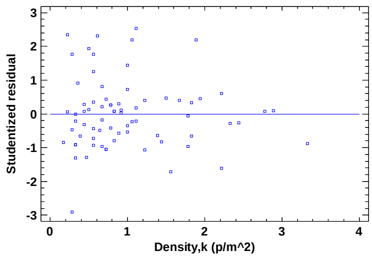
Relation-ship	Greenberg Model	Residual Plot
Ajyad1,Speed (u1)- Density (k1)		
Ajyad2 Out, Speed (u2)- Density		
Ajyad2 In, Speed (u3)- Density (k3)		

Figure 5-9 Pilgrims Flow-Density relationship

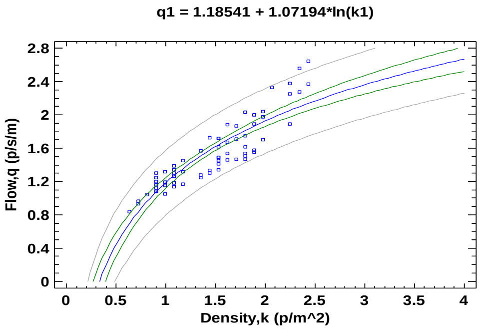
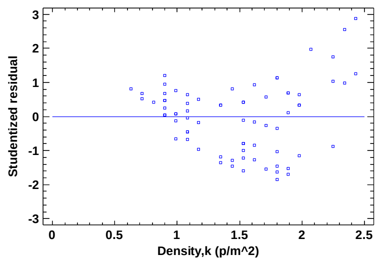
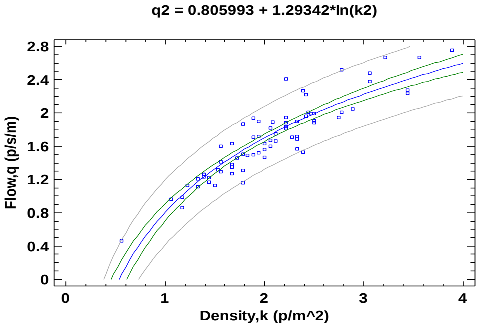
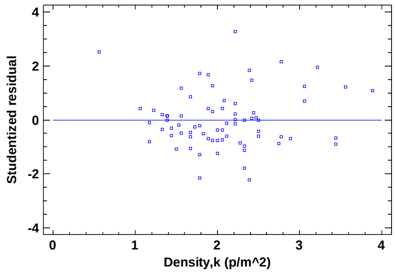
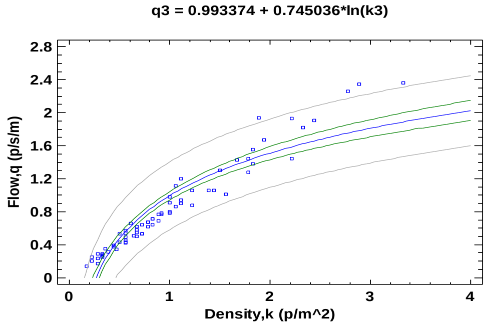
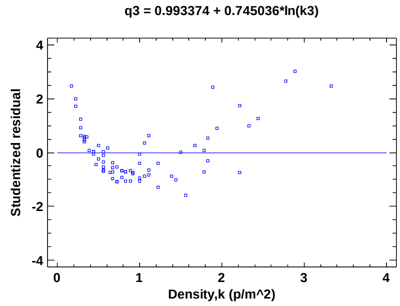
Relation-ship	Greenberg Model	Residual Plot
Ajyad1,Flow (q1)- Density (k1)		
Ajyad2 ,Flow (u2)- Density (k1)		
Ajyad2 In, Flow (q3)-		

Figure 5-10 Pilgrims Flow-Capacity relationship

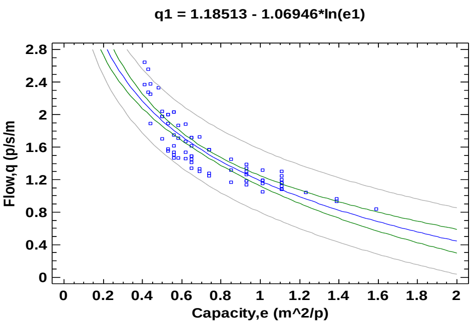
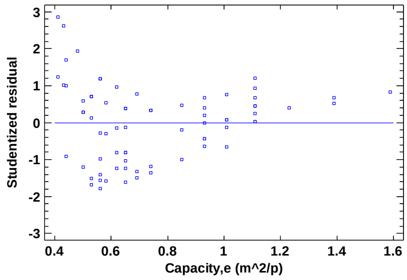
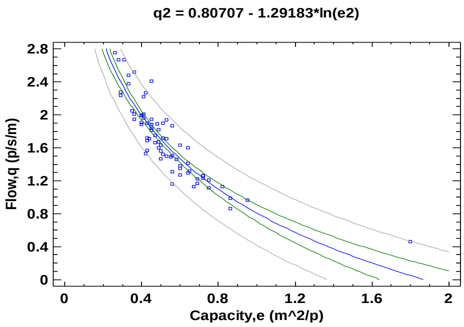
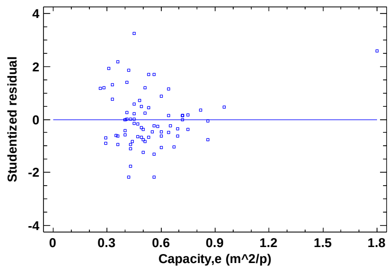
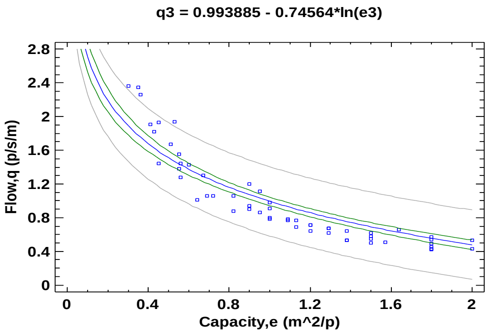
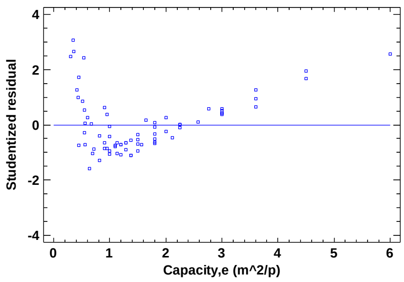
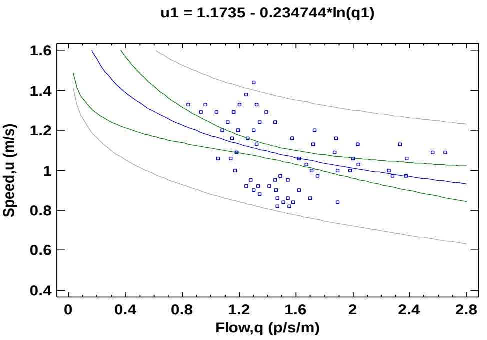
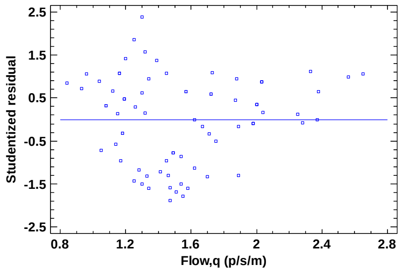
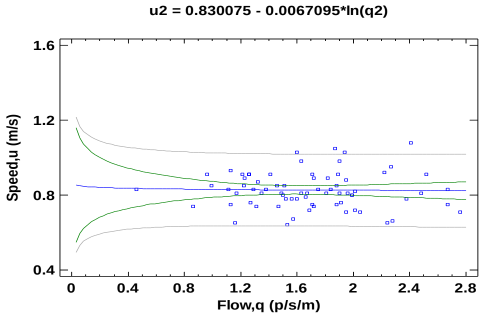
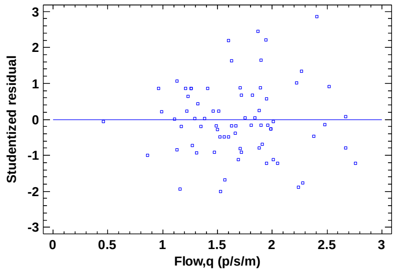
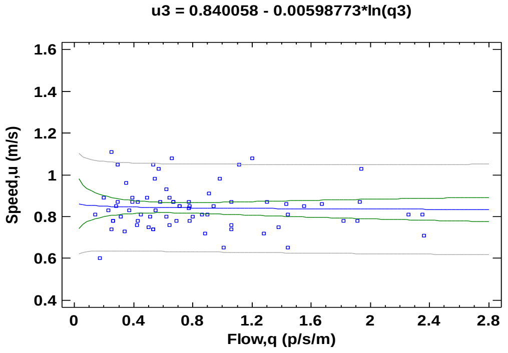
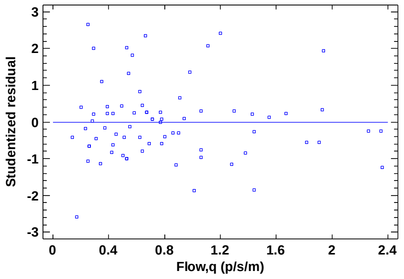
<table>
<tr><th>Relation-ship</th><th>Greenberg Model</th><th>Residual Plot</th></tr>
<tr><td>Ajyad1, Flow (q1) – Capacity (e1)</td><td>
</td><td>
</td></tr>
<tr><td>Ajyad2Out, Flow (q2) –</td><td>
</td><td>
</td></tr>
<tr><td>Ajyad2 In, Flow (q3) –Capacity (e3)</td><td>
</td><td>
</td></tr>
</table>

Figure 5-11 Pilgrims Speed - Flow relationship

<table>
<tr><th>Relation-ship</th><th>Greenberg Model</th><th>Residual Plot</th></tr>
<tr><td>Ajyad1,Speed (u1)- Flow (q1)</td><td>
</td><td>
</td></tr>
<tr><td>Ajyad2 Out, Speed (u2)-</td><td>
</td><td>
</td></tr>
<tr><td>Ajyad2 In, Speed (u3)- Flow (q3)</td><td>
</td><td>
</td></tr>
</table>

5.4.4 Estimation of Free Speed and Maximum Density

The estimated of u_f and k_m using the three models (Greenshield, Weidmann and Greenberg) are summarized in Table 5-10. Those using the Greenberg model may be immediately dismissed on the basis of the hopelessly unrealistic estimations of k_m . Those using the Weidmann and Greenshield models are at least of the right order when compared with the values quoted in the literature in Table 5-3.

Table 5-10 Estimation of u_f and k_m from Greenshield, Weidmann and Greenberg models

		Free Speed u_f (ms^{-1})			Maximum Density k_m $(people/m^2)$		
		Ajyad1	Ajyad2 Out	Ajyad2 In	Ajyad1	Ajyad2 Out	Ajyad2 In
Greenshield	Speed-Density	1.41	0.96	0.88	4.51	15.78[§§]	27.94[§§]
	Flow-Density	1.25	0.98	0.89	9.52	13.55[§§]	21.81[§§]
Weidmann	Speed-Density	1.302	0.879	0.853	9496[§§]	28.8[§§]	20.47
Greenberg	Speed-Density	(0.26,0.41)[§§]	-[***]	-[***]	(16.96,1184)	-[***]	-[***]
	Flow-Density	(0.14,0.33)[§§]	(0.10,0.24)	(0.02,0.099)	(26.3,4377)[§§]	(41.9,32341)[§§]	-[***]

[§§] For completeness only. Estimate of u_f unrealistically low, and k_m unrealistically high.
[***] Not estimated due to very weak correlation.

5.5 Alternative Estimation of Pilgrims Flow Characteristics

Given the limited success of fitting the Greenberg model to the Ajyad Street data as described above, it was decided also to explore the relationships between speed, density, flow and capacity, using linear, logarithmic, exponential, power and polynomial models, including goodness of fit based on observed data plots and ANOVA statistical parameters. It was of course recognised that none of these had any known physical basis but success might suggest something completely new. The developed relationships are given in Table 5-11.

Table 5-11 Pilgrims flow relations for alternative statistical models

Relations		Model equation	Correlation	R^2 %	P-Value	Std Dev of Residuals	Mean Absolute Error	Statistically Significant at 95%	Strength of Association
Speed-Density	Ajyad1	u_1 = sqrt(0.479839 + 0.935243/ k_1)	0.7616	58.01	0.0000	0.221568	0.186432	Yes	Moderate
	Ajyad2 Out	u_2 = 1/(1.12224 + 0.0222265* k_2^2)	0.4598	21.14	0.0000	0.124654	0.09507	Yes	Weak
	Ajyad2 In	u_3 = exp (-0.157924 - 0.0139764* k_3^2)	-0.2438	5.946	0.0376	0.118652	0.0886095	Yes	Very Weak
Flow-Density	Ajyad1	q_1 = exp (-0.342032 + 0.504347*k_1)	0.925954	85.7391	0.0000	0.0974126	0.0825524	Yes	Very Strong
	Ajyad2Out	$q_2 = 1/(0.0437275 + 1.12929 * k_2)$	0.962739	92.686	0.0000	0.06697	0.050227	Yes	Very Strong
	Ajyad2 In	q_3 = exp(-0.188064 + 0.960271*ln k_3)	0.984248	96.874	0.0000	0.119307	0.0895377	Yes	Very Strong
Flow-Capacity	Ajyad1	$q1 = 1/(0.850666 + 0.476304 * \ln e1)$	0.928764	86.2602	0.0000	0.0646297	0.0550111	Yes	Very Strong
	Ajyad2Out	$q_2 = 1/(0.0471373 + 1.12261 * e2)$	0.963543	92.8415	0.0000	0.0662653	0.0495508	Yes	Very Strong
	Ajyad2 In	$q3 = exp(-0.1874 - 0.961071 * \ln e3)$	-0.984173	96.8597	0.0000	0.11959	0.0895494	Yes	Very Strong
Speed-Flow	Ajyad1	$u1 = \mathrm{sqrt}(0.569959 + 0.895561/q1)$	0.456648	20.8527	0.0000	0.30421	0.249911	Yes	Weak
	Ajyad2Out	$u_2 = 1/(1.20749 + 0.00580187 * q2\hat{}2)$	0.0661352	0.43738	0.5783	0.14089	0.107116	No	Very Weak
	Ajyad2 In	$u3 = 0.850391 - 0.00805806 * q3\hat{}2$	-0.100898	1.01804	0.3957	0.104303	0.0767168	No	Very Weak

Units: u [m/s], k [p/m²], q [p/min/m] and e [m²/p]

5.5.1 Speed - Density relationships

Table 5-11 shows the results of fitting the first three models linking speed and density as plotted in Figure 5-12 , the outer pair of curves on the fitted models being the prediction limits for new observations, the inner ones being the 95% confidence limits of the fitted line and the residual plots being the standardised differences between the actual data and the fitted lines. The three models were:

1. A squared-Y reciprocal-X model to describe the relationship between u_1 and k_1,
2. A reciprocal-Y squared-X model to describe the relationship between u_2 and k_2, and
3. A logarithmic-Y squared-X model to describe the relationship between u_3 and k_3.

From the goodness of fit statistics, it was found that the best model linking speed and density to be a squared-Y reciprocal-X on Ajyad1. Since all three of the P-values were less than 0.05, there are statistically significant relationships between each pair of variables at the 95.0% confidence level although the strengths of the three associations are only moderate, weak and very weak respectively.

5.5.2 Flow – Density relationships

Figure 5-13 shows the results of fitting the second three models linking flow and density, i.e:

1. A logarithmic-Y linear-X model to describe the relationship between q_1 and k_1,
2. A reciprocal-Y linear-X model to describe the relationship between q_2 and k_2, and

3. A logarithmic-Y logarithmic-X model to describe the relationship between q_3 and k_3 .

All three relationships can be seen to be statistically significant relationship at the 95.0% confidence level with very strong association.

5.5.3 Flow – Capacity relationships

The third set of three models linking flow and capacity listed in Figure 5-14 shows the results of fitting:

1. A reciprocal-Y logarithmic -X model to describe the relationship between Flow q_1 and Capacity e_1,
2. A reciprocal-Y linear-X model to describe the relationship between q_2 and e_2, and
3. A logarithmic-Y logarithmic-X model to describe the relationship between q_3 and e_3.

All three relationships can be seen to be statistically significant relationship at the 95.0% confidence level with very strong association.

5.5.4 Speed - Flow relationship

Table 5-11 shows the results of fitting of the fourth set of models linking speed and flow as plotted in Figure 5-15:

1. A squared-Y reciprocal-X model to describe the relationship between u_1 and q_1,

2. A reciprocal-Y squared-X model to describe the relationship between u_2 and q_2, and

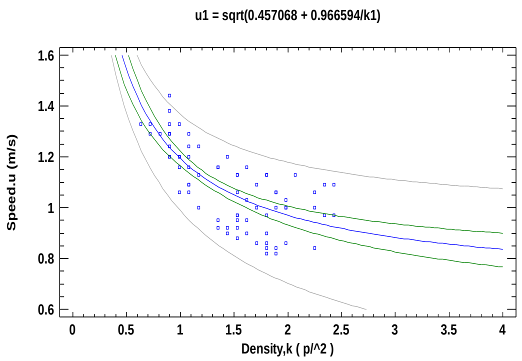
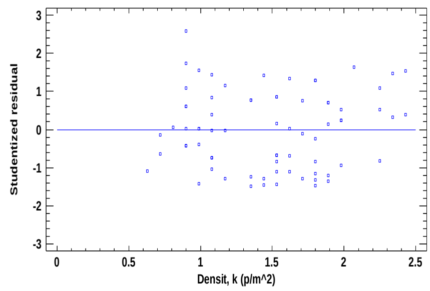
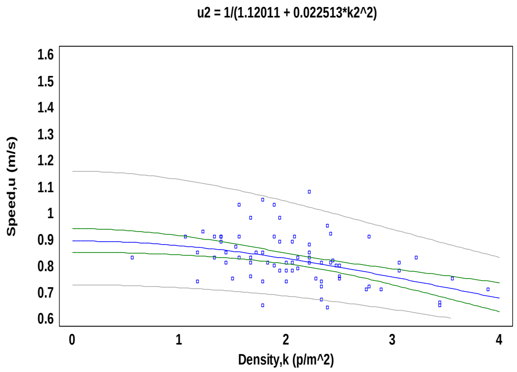
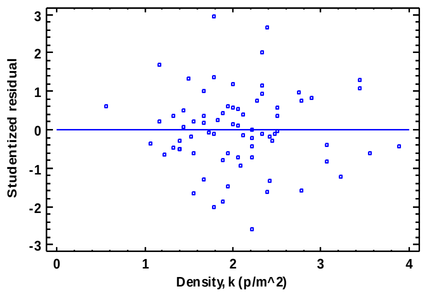
3. A squared –X model to describe the relationship between u_3 and k_3.

From the goodness of fit statistics, the best model linking speed and flow was found to be a squared-Y reciprocal-X on Ajyad1. There are statistically significant relationships between u_1 and q_1 at the 95.0% confidence, but not between either u_2 and q_2 or u_3 and k_3.

5.5.5 Results of Parameters Estimations

The models listed in Table 5-11 were found to have the highest correlations, but the results were less than satisfactory overall. Even though the correlations between both Speed-Density and Speed – Flow were generally low and, although those for Flow – Density and Flow- Capacity were generally high, there was a little consistency at all between the models themselves. For example the form and parameters values of the three Flow-Density relationships were dissimilar as were those of the three Flow-Capacity ones. Furthermore, the data points were found to be highly scattered around the best fit curve in each case. The pilgrims flow relationships developed in this study are different from the literature for Hong Kong, (1995) and the United States (Virkler and Elayadath, 1994) due to the particular nature of pilgrim movements.

Figure 5-12 Pilgrims Speed-Density relationship

<table>
<tr><th>Relation-ship</th><th>Fitted Model</th><th>Residual Plot</th></tr>
<tr><td>Ajyad1,Speed (u1)- Density (k1)</td><td>
</td><td>
</td></tr>
<tr><td>Ajyad2 Out, Speed (u2)- Density</td><td>
</td><td>
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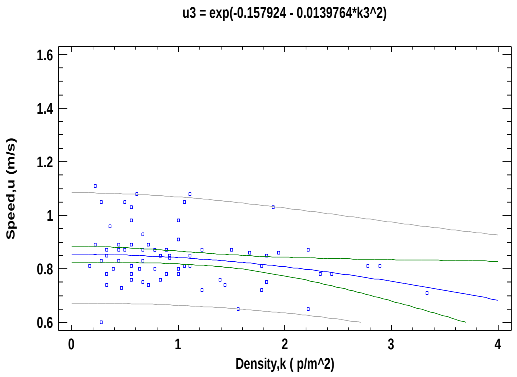
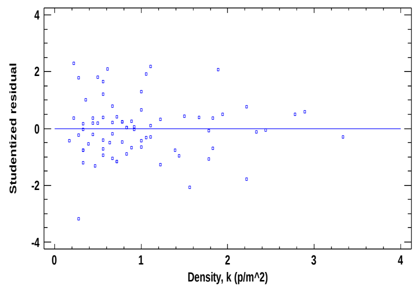
<tr><td>Ajyad2 In, Speed (u3)- Density</td><td>
</td><td>
</td></tr>
</table>

Figure 5-13 Pilgrims Flow-Density relationship

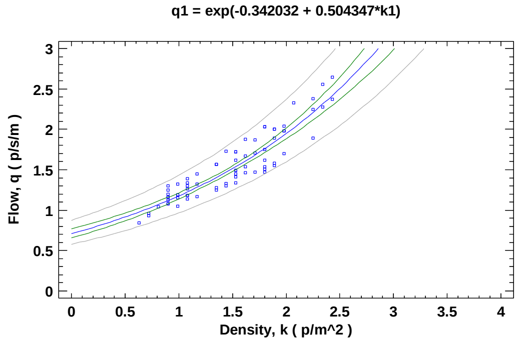
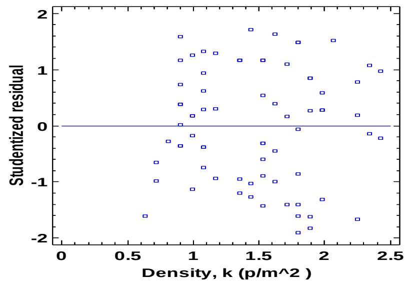
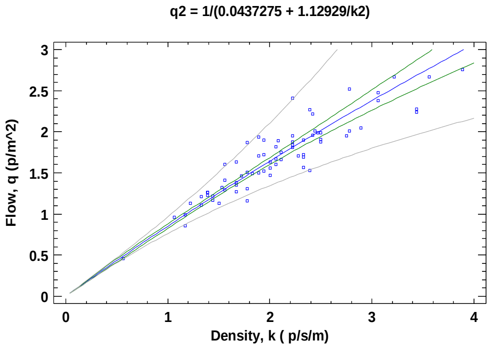
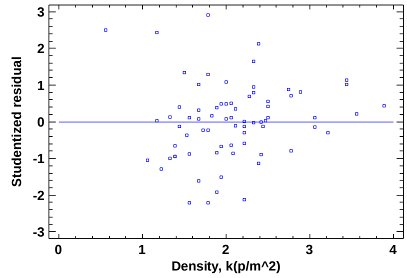
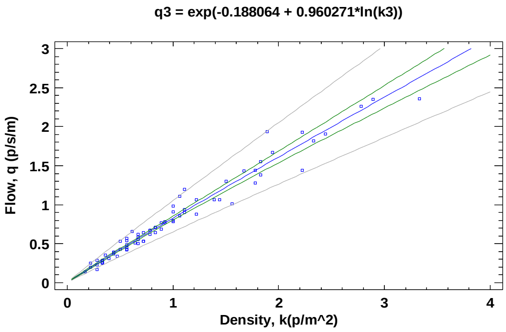
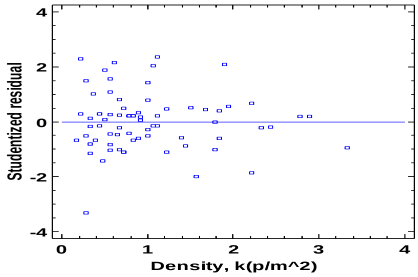
Relation-ship	**Fitted Model**	**Residual Plot**
Ajyad1,Flow (q1)- Density (k1)		
Ajyad2 ,Flow (q2)- Density		
Ajyad2 ln, Flow (q3)-Density (k3)		

Figure 5-14 Pilgrims Flow-Capacity relationship

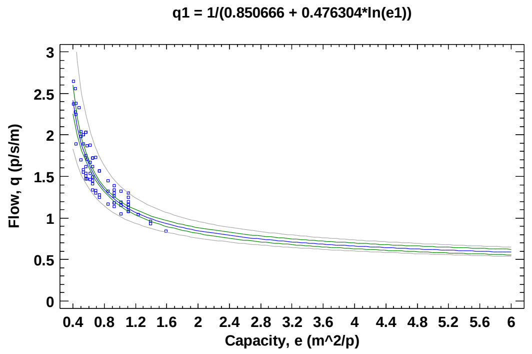
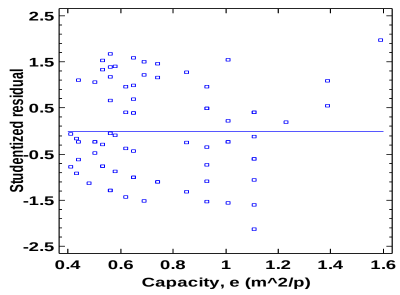
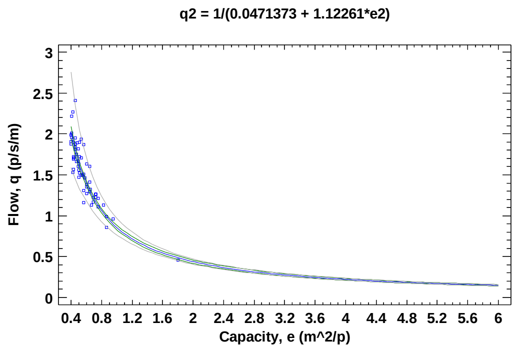
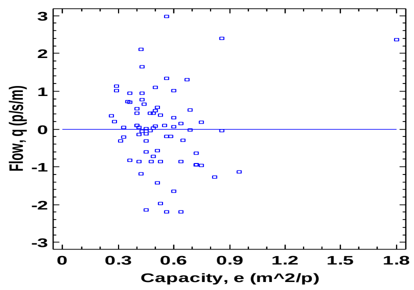
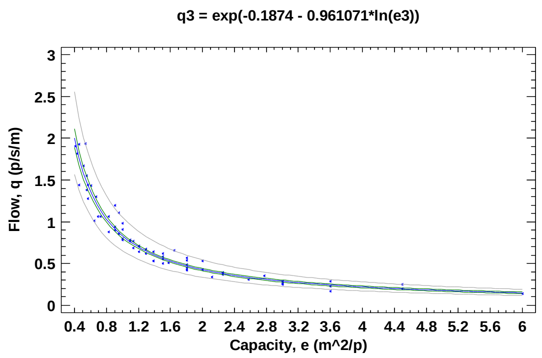
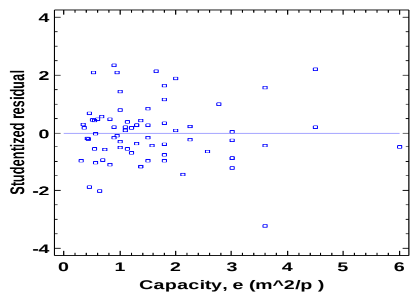
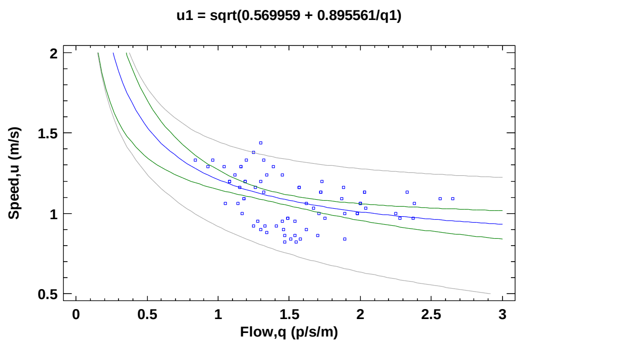
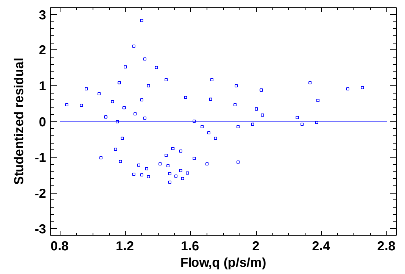
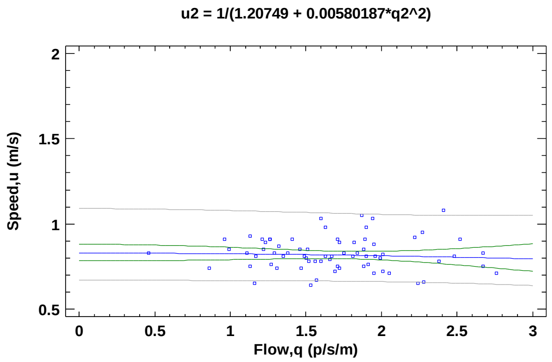
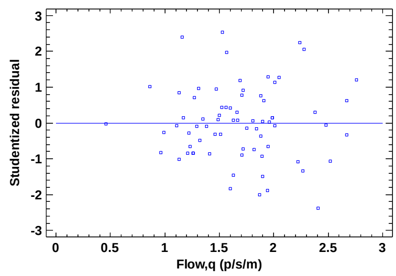
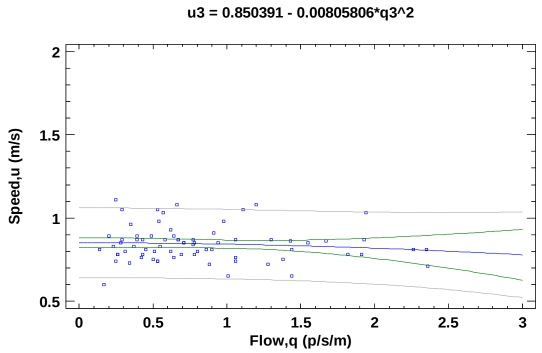
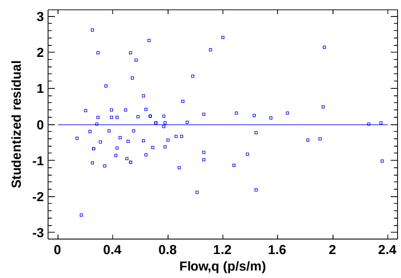
Relationship	Fitted Model	Residual Plot
Ajyad1, Flow (q1) – Capacity (e1)		
Ajyad2Out, Flow (q2)–Capacity (e2)		
Ajyad2 In, Flow (q3) –Capacity (e3)		

Figure 5-15 Pilgrims Speed - Flow relationship

<table>
<tr><th>Relation-ship</th><th>Fitted Model</th><th>Residual Plot</th></tr>
<tr><td>Ajyad1,Speed (u1) - Flow (q1)</td><td>
</td><td>
</td></tr>
<tr><td>Ajyad2 Out, Speed (u2)- Flow (q2)</td><td>
</td><td>
</td></tr>
<tr><td>Ajyad2 In, Speed (u3)- Flow (q3)</td><td>
</td><td>
</td></tr>
</table>

5.6 Maximum possible Speed Model

The various models described above may be seen to fit the data with regression coefficients between 90% and 4%. The scatter is such as to suggest that pilgrims are not simply all walking as fast as the density allows; some of them do, but, others are perfectly happy to proceed more slowly. For any given density there will be a variation in speed between the maximum possible at that density and zero. Rather than aiming to fit models through the "middle "of the data, it seems appropriate instead to enclose them from above. Figure 5-16 thus shows the speed – density data from Ajyad Street enclosed by models of the form of the Weidmann and Greenberg models but with parameters chosen so as to envelop the data in this way i.e., by minimizing the sum-squared distances of the data points below the curves; for the former, assuming u_0 = 1.5, γ = 3.6 and the same value of k_m= as found for the latter. Neither of the fits is completely satisfactory because of the lack of data at high densities. The Greenshield model is simpler and unlike the other two has at least some theoretical basis and hence

$$u \leq 1.64\ (1 - k/6.34) \quad \text{5-17}$$

the vital aspect being the presence of the "less than or equal to" sign. As shown in Figure 5-17 this represents a line parallel to the line of best fit in Table 5-4 but intercepting the u axis at $u_m = 1.64$ i.e. so as to enclose the Ajyad Street data from above with slope -0.221638 (= - 6.34/1.40653). Note the deficiency of the Weidmann model in predicting the extremes of the observed data.

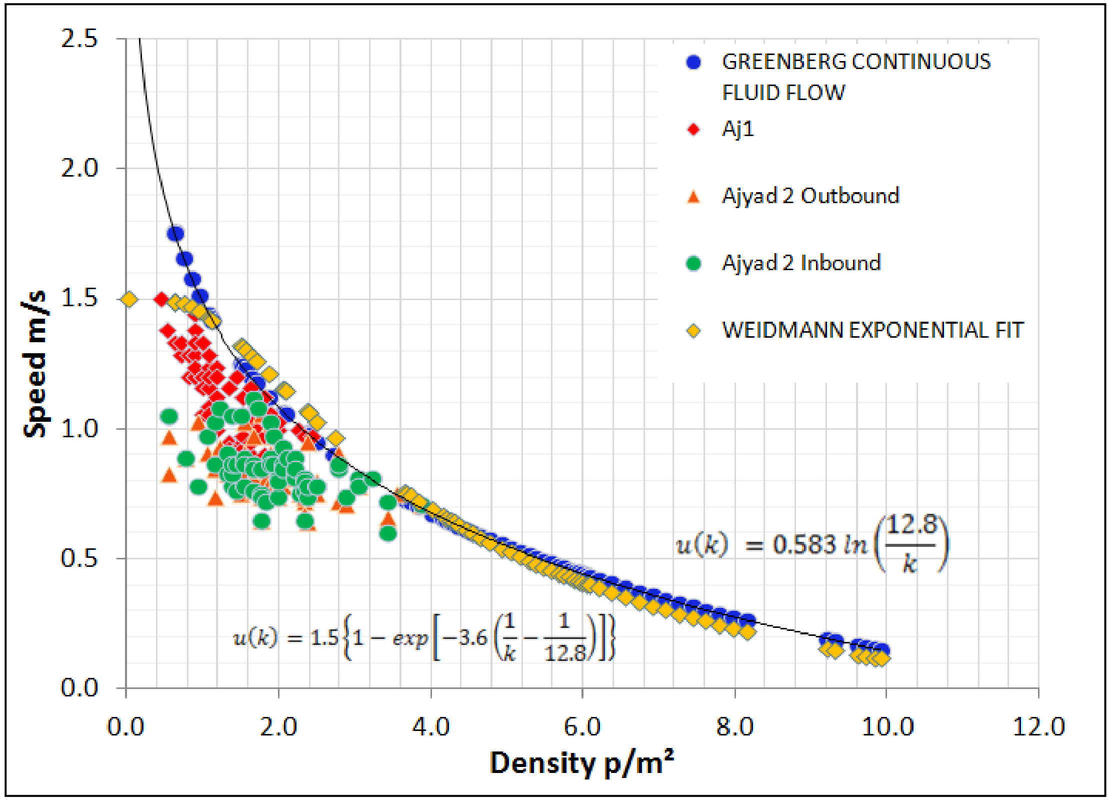


Figure 5-16 Speed–density data enclosed by the form of Weidmann and Greenberg models

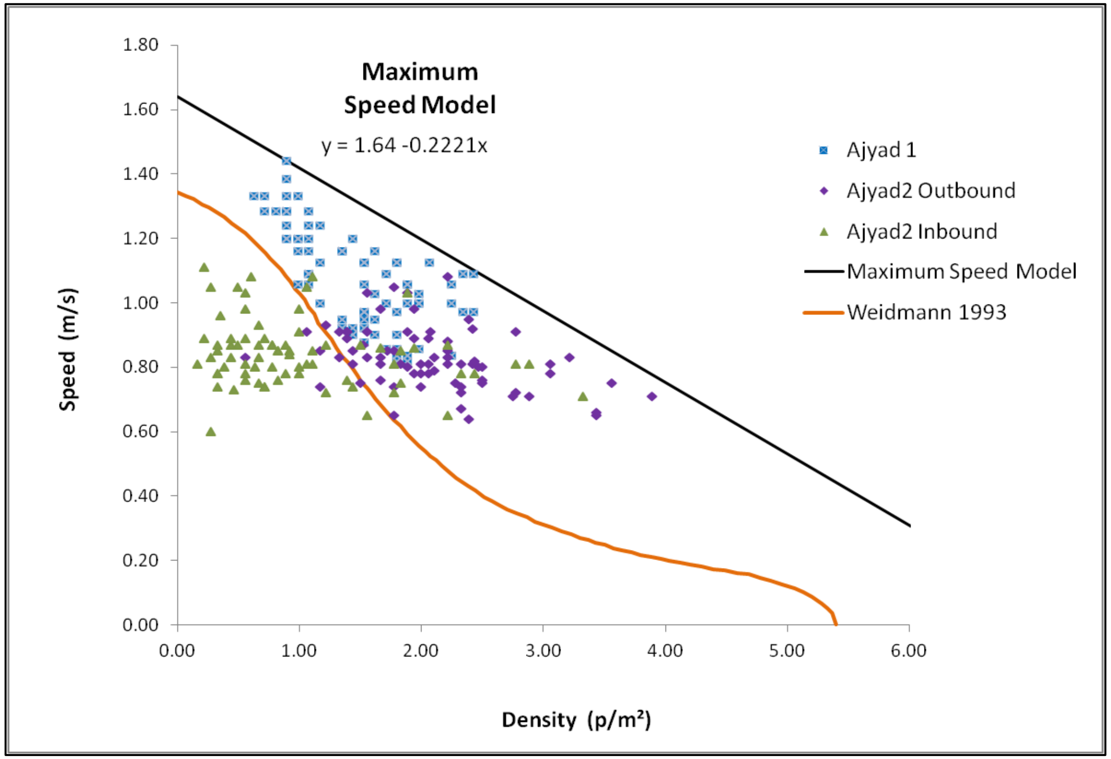


Figure 5-17 Maximum Speed Model applied to observed data

5.7 Discussion

The findings of the pilgrim dynamics data analysis in the current study may be compared with previous studies of pedestrian crowd dynamics in Figure 5-18. It will be seen that almost all but three of the data points from the literature fall below the Maximum Speed model proposed in section 5-6 and that, again, the Weidmann model is deficient in that it underestimates the maximum possible speeds. These observations lead to the final graph, Figure 5-19 into which the data from Ajyad Street has been added and the parameters of the Maximum Speed Model have been adjusted (intercept 1.75 and slope -0.32) so as to enclose both sets of data from above. Even though the Ajyad Street data is restricted to relatively low density, they are clearly consistent with those from the literature. Crowd dynamics at the Hajj may well be unique - with three million people moving in the same direction simultaneously towards one destination, the Holy Mosque, using a limited number of streets as conduits - but the same model fits the observed data and that from the literature alike i.e.

$$u \leq 1.75\,(1 - k/5.47) \quad \text{……………………………………… 5-18}$$

Some pedestrian dynamics studies were conducted on pilgrims performing Tawaf circumambulation inside the Holy Mosque, reviewed in detail in Chapter 2 (the literature review), but none of these studies were conducted on the pilgrims in the central area of Makkah during their moving towards the Holy Mosque.

In our study, a large amount of data was recorded, extracted and calculated for pilgrims traversing Ajyad Street on the main day of the Hajj event—the tenth day. These pilgrim dynamics readings, taken throughout the day, were analysed, plotted and the results were summarized in Figures and diagrams, providing clear relationships among several variables surrounding pedestrians participating in the Hajj event. These were actual physical relationships between variables such as speed, density, flow, capacity and time. Consequently, it was possible to determine mathematical relations representing the trend lines for each, which, in fact, did not provide the maximum and minimum readings, but represent the trend and tendency of the various curves with good accuracy and show the maximum and minimum average readings. As a result, pilgrims flow relationships were developed and characteristic values estimated. It is detected that the speed- density relationship were of (Squared-Y reciprocal-X form on the Ajyad1 walkway (uni-directional flow) and Reciprocal -Y squared -X form on Ajyad2 (Outbound and Inbound) walkways.

The free speeds in Makkah at Ajyad Street found more fluctuated and clearly vary with certain times. Moreover, this variation is due to certain religious and spiritual factors and correlated to the prayer times (as detailed in chapter 5).

The pilgrims found to keep higher buffer space on Ajyad Street resulting in relaxed walking. Even at very high density, the pedestrians adjust to the space available without causing body-to-body contact as indicated in Figure 5-14. This suggest that the study area in Ajyad Street is the first point from which pilgrims visually can see their destination (the Holy Mosque), this has a positive psychological impact reflected on pilgrims relaxation, and the way in which they walk and behave when arriving at this point.

The free speed at Ajyad 2 Street is not affected by the bidirectional flow as long as the flow is low. As the flow increases, the speed under bidirectional flow is found to be higher than that in unidirectional flow. The opposite behaviour is observed under congested conditions or at high density values. The pedestrians under bidirectional flow show adjusting behaviour accommodating the fellow pedestrians within the space available but without body-to-body contact was visualized. Some behavioural phenomena are observed, one is related to the psychology behaviour, where pilgrims - according to the teachings of Islam during the pilgrimage- are not deliberately crowding and harassment of others, but gives them a greater chance in the movement. In addition to a social behaviour, termed as ‘grouping’, and other at sides of the Ajyad Street termed as ‘avoiding overcrowding ’.

The findings suggest adopting different flow characteristics for pilgrims pedestrian facilities. The results of this study can be used as input to the development of dynamic continuum models which can help in understanding the pilgrims movements and behaviour during pilgrimage in spatio-temporal domain. It also indicates towards certain unsymmetrical behaviour of the pedestrians especially under bidirectional flow, as well as, under restricted conditions. It would be unsurprising if these findings could not be generalised to other similar events. However such mega events are hard to find because as many as 1 million pilgrims might be expected to use Ajyad Street on the tenth day of the Hajj. There are some similarities with sporting or cultural events but on different scales and over different time frames.

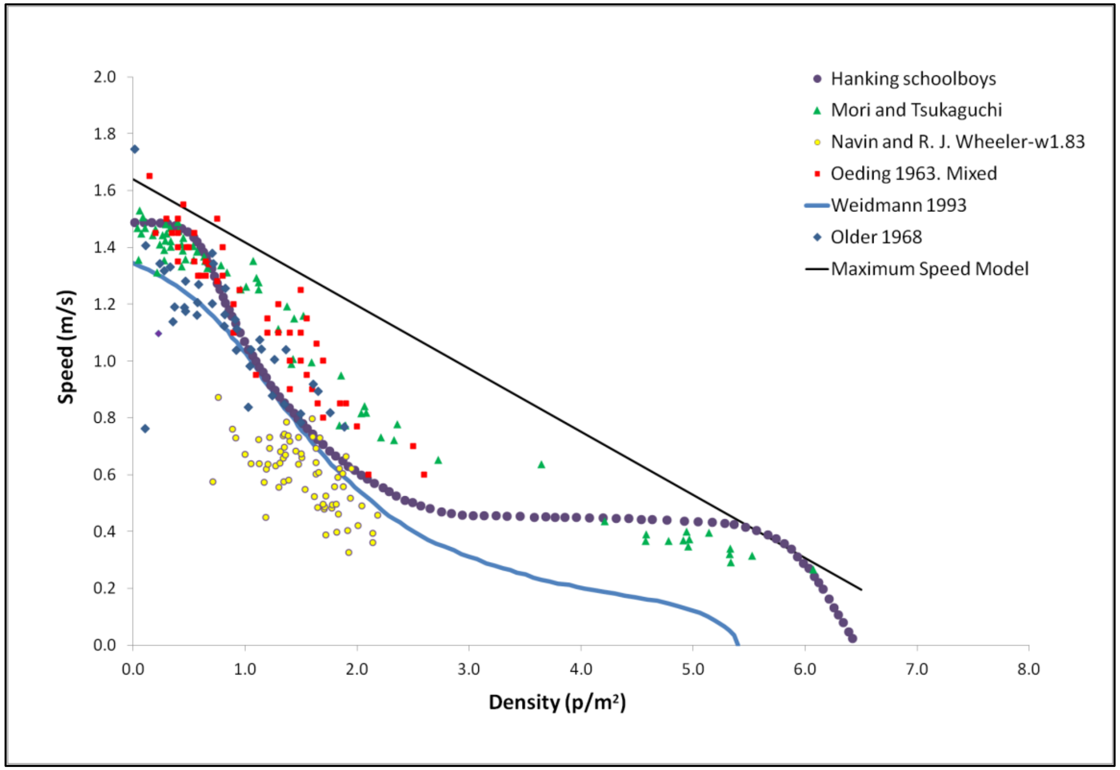


Figure 5-18 Maximum Speed Model applied to literature data

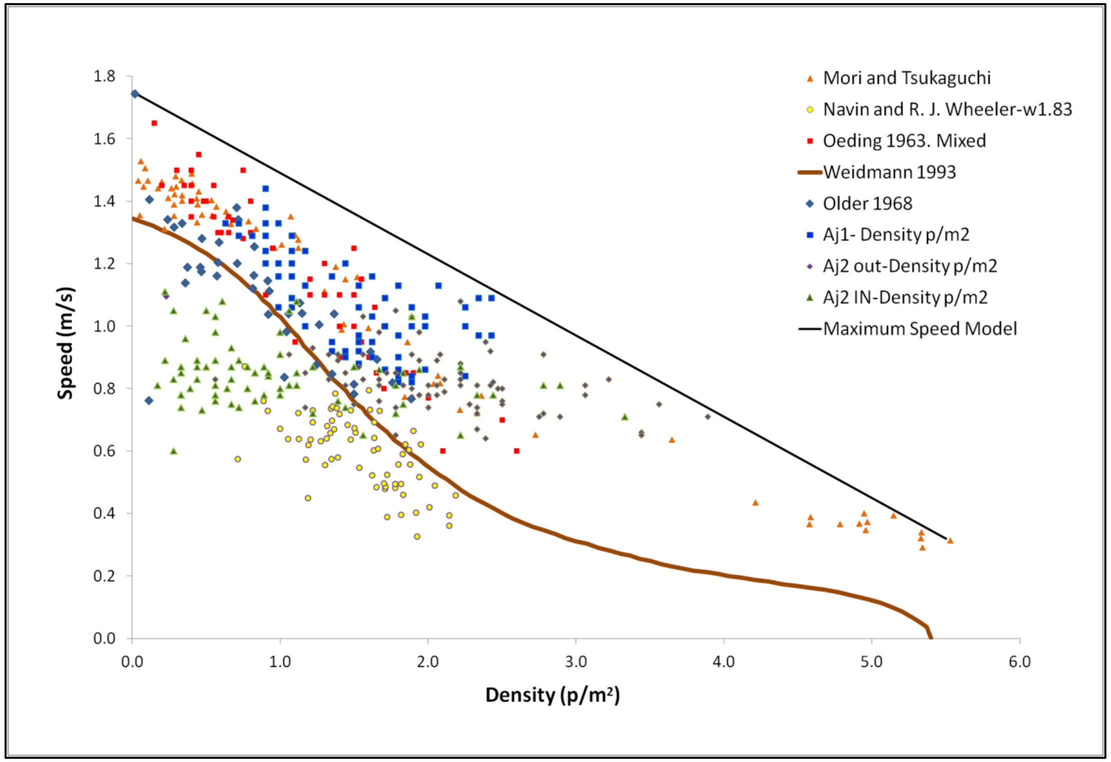


Figure 5-19 Maximum Speed Model applied to observed and literature data

Chapter 6
Simulation

6.1 Introduction

The Hajj pilgrimage to Makkah consists of compulsory rituals performed in the city of Makkah, and the holy sites laid in the suburban of Makkah at specific times from the 8^{th} to the 12^{th} day of the pilgrimage month (Dul-Hija). These rituals performed in the sacred places of: the holy mosque (Al-Haram) in Makkah city and the holy areas of (Masha'ir) in Mina, Mouzdalifah, and Arafat. The pilgrims stay in Mina during the days of the 10th to the 12th of the pilgrimage month, and some of them stay for the 13th as an optional day, to stone the devil (Jamarat) during these days. Most of the pilgrims go to the Holy Mosque in Makkah in particular the 10th day, to perform Tawaf (Alifadha). This is showing why these particular days of the pilgrimage month become crowded with millions of pilgrims performing their religious rituals with constraints of time and space to the extent that some serious incidents occur (Saudi Civil Defense, 2010). The number of pilgrims is increasing every year, where the pilgrimage authorities spending more effort to ensure the safety of pilgrim crowds. Recent research (AlGadhi et al., 2002), suggest constructural improvements in the geometry of the holy sites (Al-Abideen, 2005). and new developments in pilgrims crowd control (Halabi, 2006), and organization of the streets (Al-Bosta, 2006).

6.2 Social Force Model and VISSIM

Without theories and experimentation the simulation can never be carried out meaningfully and used for the investigation of proposed improvements. The Social Force Model introduced by Helbing et al.(1995b) considers as one of the most deliberated models for pedestrian dynamics. In the Social Force Model, the dynamics of pedestrians subject to forces. These forces considered as internal motivations that make the individual pedestrian to move in a certain path or direction, the force, F, that acting on a pedestrian consists of four terms:

$$F = F_{\text{driving}} + F_{\text{wall}} + F_{\text{social}} + F_{\text{noise}} \quad \text{6-1}$$

where F_{driving} is the driving force to the desired direction , F_{wall} is the force from walls, F_{social} is the forces between pedestrians and F_{noise} is the random force term employed and prevent stops at bottlenecks.

The most important motivation for a pedestrian to move is the desire to reach a certain destination as shortly and as easy as possible. Nevertheless, there are some essential factors in the Social Force Model, which influence the pedestrian’s path and speed towards reaching the destination. Another important factor is to keep the distance to objects, obstacles, or other pedestrians. In addition to the attractive effects of the motion, which can make the pedestrian slow down shortly, stop or turn left or right. Because of the internal motivations and forces, pedestrians form self- organized tracks in the same direction once meeting an opposing flow (Laufer and Planner, 2008). As for the formulation of the social force model, the forces acting on pedestrian *i* and determine its acceleration defined by:

$$\mathrm{f}_i(t) = m_i \frac{dv_i(t)}{dt} = m_i \mathrm{a}_i(t)$$

$$= \mathrm{f}_i^0(t) + \sum_{j(\neq 1)} \mathrm{f}_{ij}(t) + \sum_w \mathrm{f}_{iw}(t) + \sum_a \mathrm{f}_{ia}(t) + \sum_g \mathrm{f}_{ig}(t) + \xi_i(t) \qquad \text{6-2}$$

where $f_i(t)$ denotes the sum of all forces on pedestrian *i* hence, represents its acceleration $\mathrm{a}_i(t)$ at time t ; $\mathrm{f}_i^0(t)$ represents the force in direction of the pedestrian' next target; $\mathrm{f}_{ij}(t)$is the force exerted by pedestrian *j* on pedestrian *i ;* $\mathrm{f}_{iw}(t)$ represents the force exerted by object *w* (doors, walls, obstacles, etc.) on pedestrian *i* ; $\mathrm{f}_{ia}(t)$ and $\mathrm{f}_{ig}(t)$ denote the forces resulting from attracting elements (shop windows, large video screens, etc.) or pedestrian groups; and $\xi_i(t)$ denotes the noise term.

6.3 Simulation Model and Validation

The social force model is in fact what underlies the VISSIM software, which was then used to model the situation on Ajyad Street during the Hajj. VISSIM is a microscopic simulation tool for modelling multimodal traffic and pedestrian flows using social force model (Kretz et al., 2008). widely used by researchers, planners, and engineers for simulating pedestrian traffic, calibrated and validated by (Kretz et al., 2008).

Figure 6-1 shows the layout and dimensions of Ajyad Street, Figure 6-2 shows it imported into VISSIM.

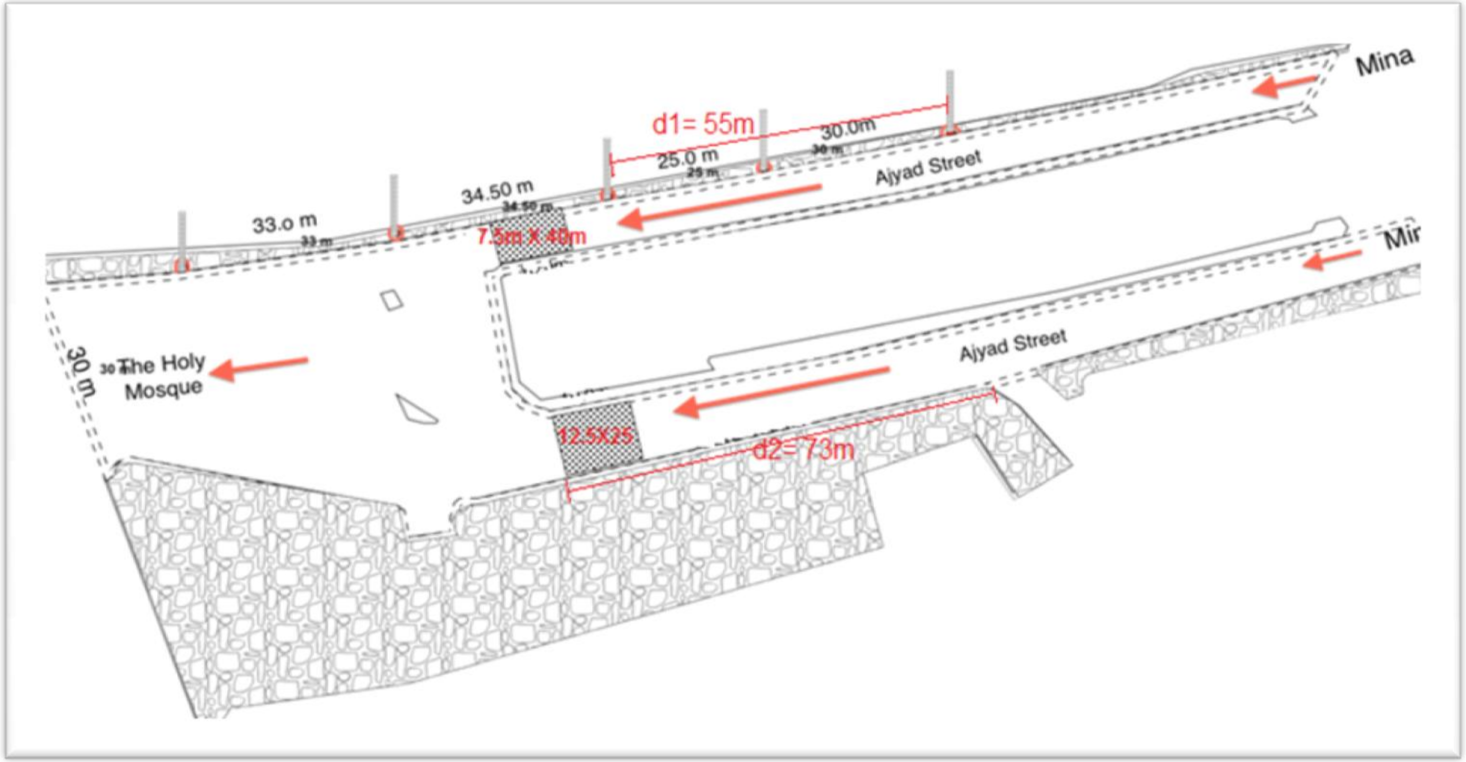


Figure 6-1 Layout of Ajyad Street

The simulations were then conducted consisting of multiple runs with each run of 43800 seconds (12 hours 10 minutes) with pilgrim speed and flow input to Ajyad1, Ajyad2 (outbound) and Ajyad2 (inbound) as given in Figure 5-2, Figure 5-3, Figure 5-4 and Figure 5-5 respectively e.g. 560 p/min at 1.33 m/s (4.79 km/h) going west from Mina towards the Holy Mosque along Ajyad1 during the first 600 seconds (10 minutes) of the simulation. Figure 6-3 is an aerial snapshot of the study area under the above conditions.

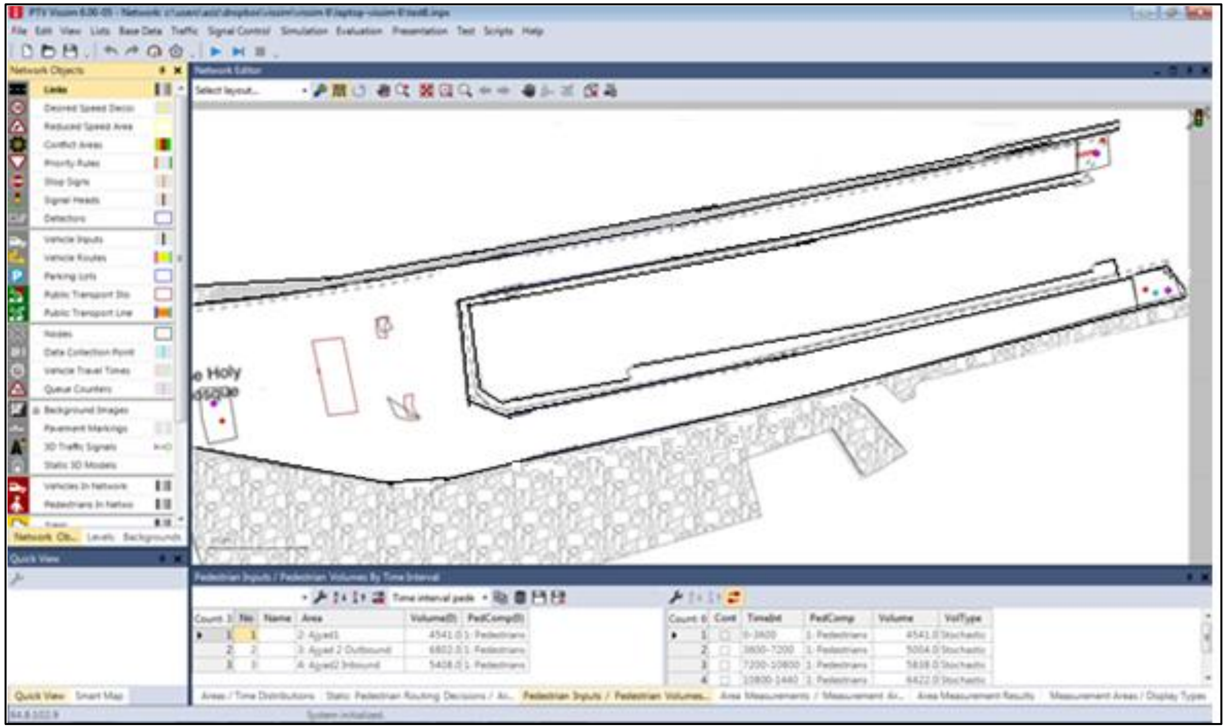


Figure 6-2 A snapshot of VISSIM interface

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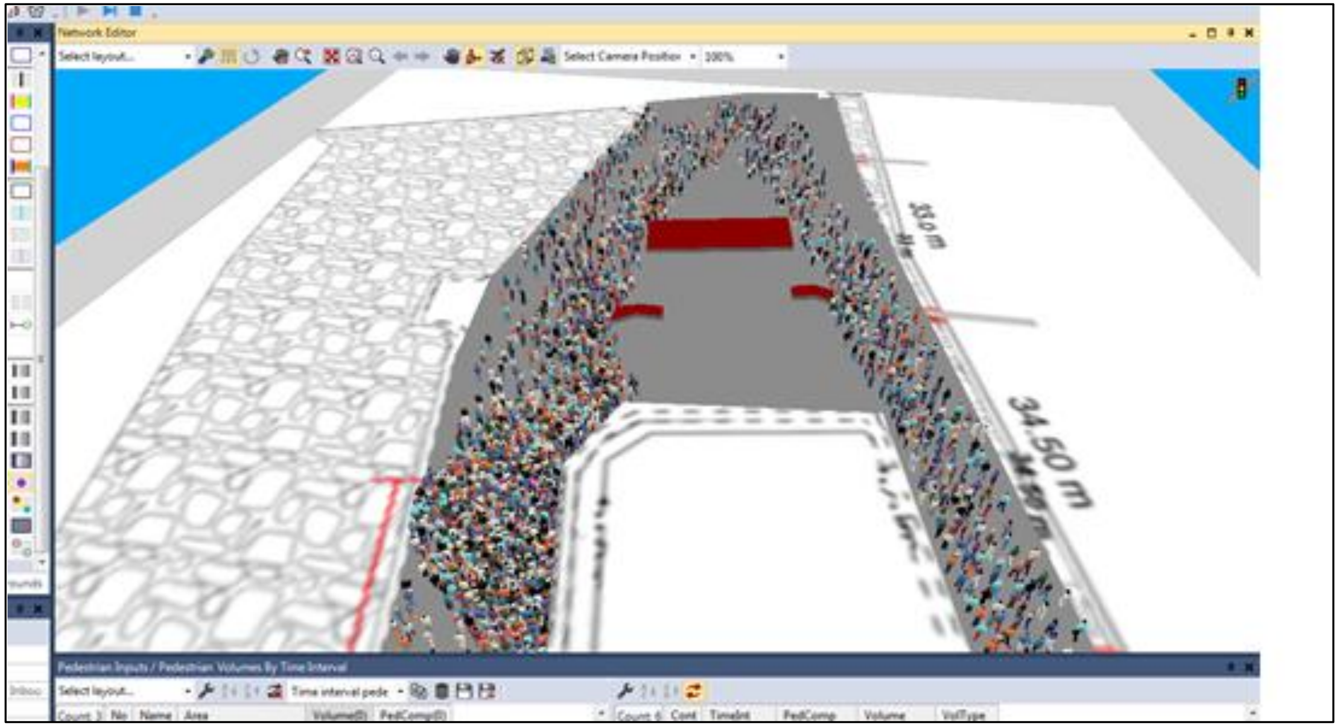

Figure 6-3 Pilgrim flow at Ajyad St. (current)

Simulated pilgrim speeds and densities were then recorded at the same two measurement locations as had been used for the video observations on Ajyad1 described in Chapter 5 and the two data sets (simulated and observed) plotted in Figure 6-4. The dotted line is line of best fit through the middle of the observed data; the solid line is the maximum speed model developed in chapter 5. It will be seen that the estimates for the intercepts and slopes of the simulated and observed data (when fitted with the Greenshield model from chapter 5) were consistent with each other as also confirmed in Table 6-1, albeit for relatively low densities.

Table 6-1 Validation of VISSIM Simulation Model- Speed vs. Density

Parameters	Observed[†††]	Maximum Speed Model	Simulated
Intercept (u_0)	1.407	1.64	1.5918
Slope	- 0.221	- 0.221	- 0.2772
k_m	6.34 (=1.407/0.221)	6.34	5.74 (= 1.5918/0.2772)

[†††] From Table 5-4

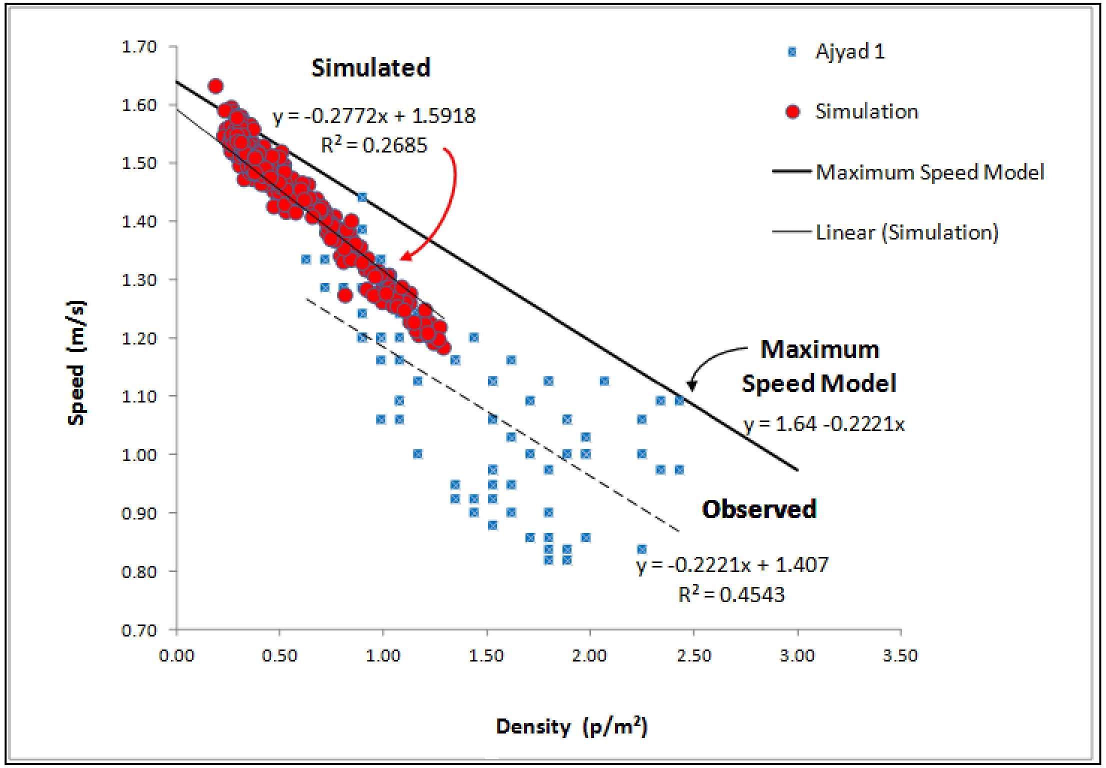

Figure 6-4 Observed and Simulated pilgrim speed-density

6.4 Experimental Scenarios and Results

With the model validated as described in section 6.3 and found to provide realistic results for the current situation as illustrated in Figure 6-2 eight future scenarios were investigated, all assuming an increase of 50% in traffic in both directions. The proposed changes and results are summarised in Table 6-2

6.4.1 Scenario 1

The results prove that with the existing layout, a 50% increase in traffic is likely to result in the inbound pedestrians getting stuck behind the control point and being unable to move, as shown in Table 6-2

6.4.2 Scenario 2

At present the geometry of the control point at the intersection of Ajyad1 and Ajyad2 is such as to disrupt the flow of Pilgrims. It was thought that a triangular footprint might ease this situation at relatively low cost. The simulation of which Figure 6-6 is a snapshot shows that there would indeed be an improvement. However this is only marginal and overcrowding results at the “neck” of Ajyad2.

6.4.3 Scenario 3

A more radical alternative would be therefore to widen both sides of Ajyad Street so that pilgrims can use a greatest width of road. This was found to result in a significant improvement in flow as shown in Figure 6-7 but overcrowding still arises behind the control point.

6.4.4 Scenarios 4, 5, and 6

It was then decided to investigate the likely benefit of a triangular control point together with a widening of Ajyad Street**; t**his is illustrated in Figure 6-8, which shows how the flow is slowed at the control point. Making Ajyad2 "one-way" (inbound only) as show**n** in Figure 6-9 alleviates the problem but only slightly. Reversing the flows (Ajyad1 inbound, Ajyad2 outbound) yields fairly free flow but still with some overcrowding at the control point (Figure 6-10).

6.4.5 Scenarios 7 and 8

Without the widening and directions of flow as at present (i.e. similar to scenario 3), the final pair of experiments involved investigating the effect of separating inbound pedestrians at the exit of the Plaza before entering Ajyad Street. With the original control point geometry Figure 6-11, no improvement was evident compared with scenario 3 but with the new geometry good flow was found throughout (Figure 6-12 and Figure 6-13)

Table 6-2 Experimental scenario results (all 50% increase in traffic)

Scenario	Control point Geometry	Widening of Ajyad	Ajyad1	Ajyad2	Separation of In/Out from Plaza	Results	Figure
1	▭	-	OUT	IN/OUT	-	Jamming of inbound pedestrians (Ajyad2) likely to start behind control point.	Figure 6-5
2	△	-	OUT	IN/OUT	-	Marginal improvement only; were overcrowding at neck of Ajyad2.	Figure 6-6
3	▭	2	OUT	IN/OUT	-	Significant improvement but overcrowding persists at control point.	Figure 6-7
4	△	1&2	OUT	IN/OUT	-	Flow slowed at control point.	Figure 6-8
5	△	2	OUT	IN	-	Slight improvement on scenario 4.	Figure 6-9
6	△	2	IN	OUT	-	Free flow except for some overcrowding at control point	Figure 6-10
7	▭	-	OUT	IN/OUT	✓	No improvement on scenario3.	Figure 6-11
8	△	1&2	IN	OUT	✓	Good flow throughout.	Figure 6-12 and Figure 6-13

Key: Control Point Footprint ▭ rectangular, △ triangular.

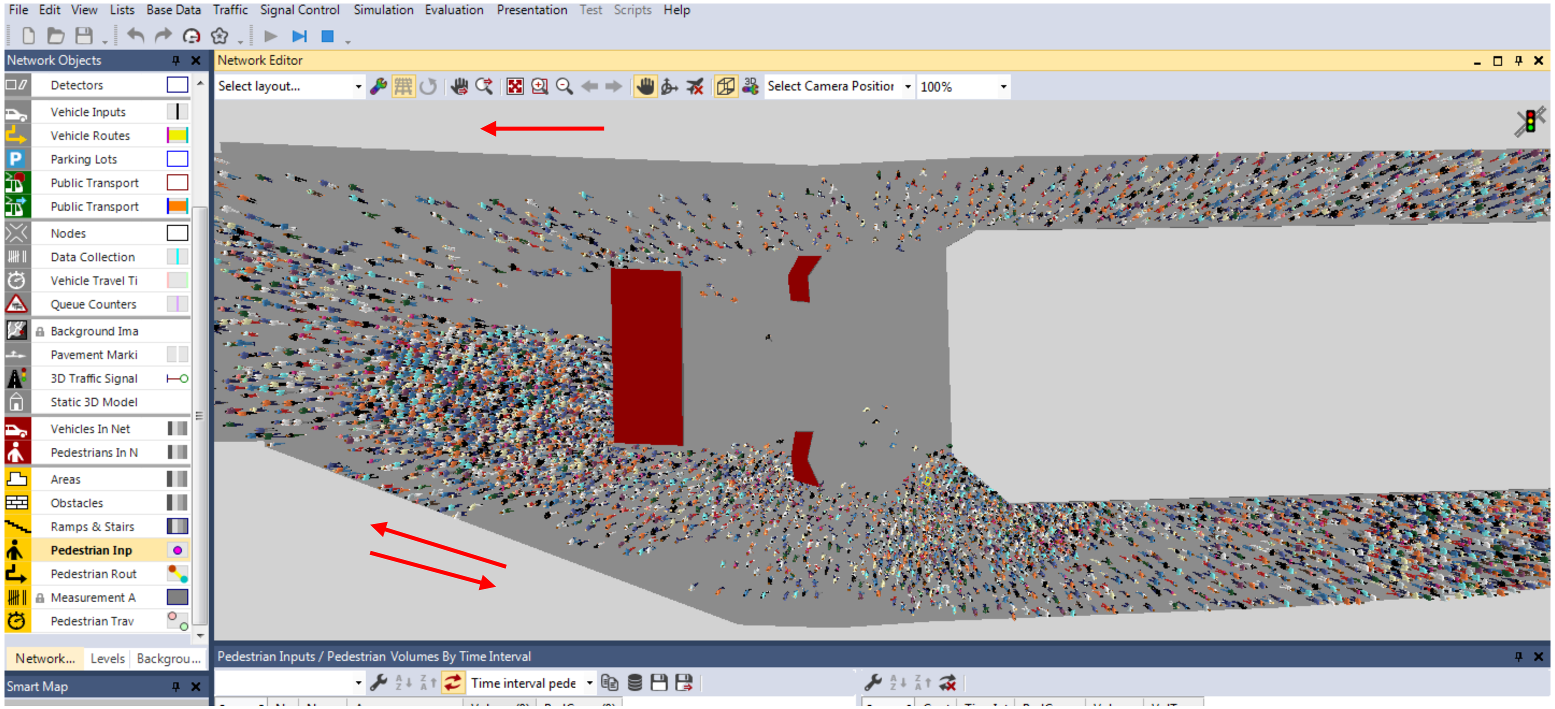

Figure 6-5 Pilgrim flow at Ajyad Street (Scenario1).

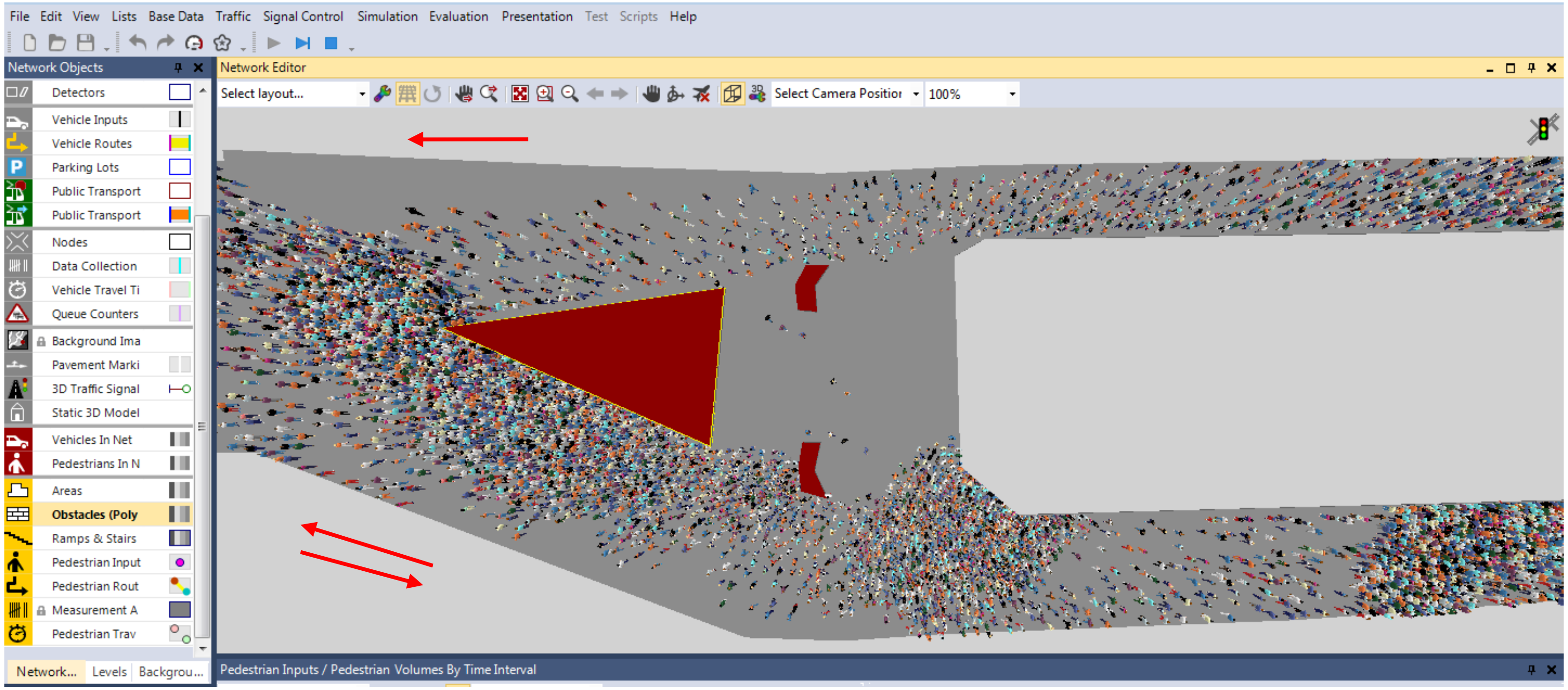

Figure 6-6 Control point Geometry (Scenario 2)

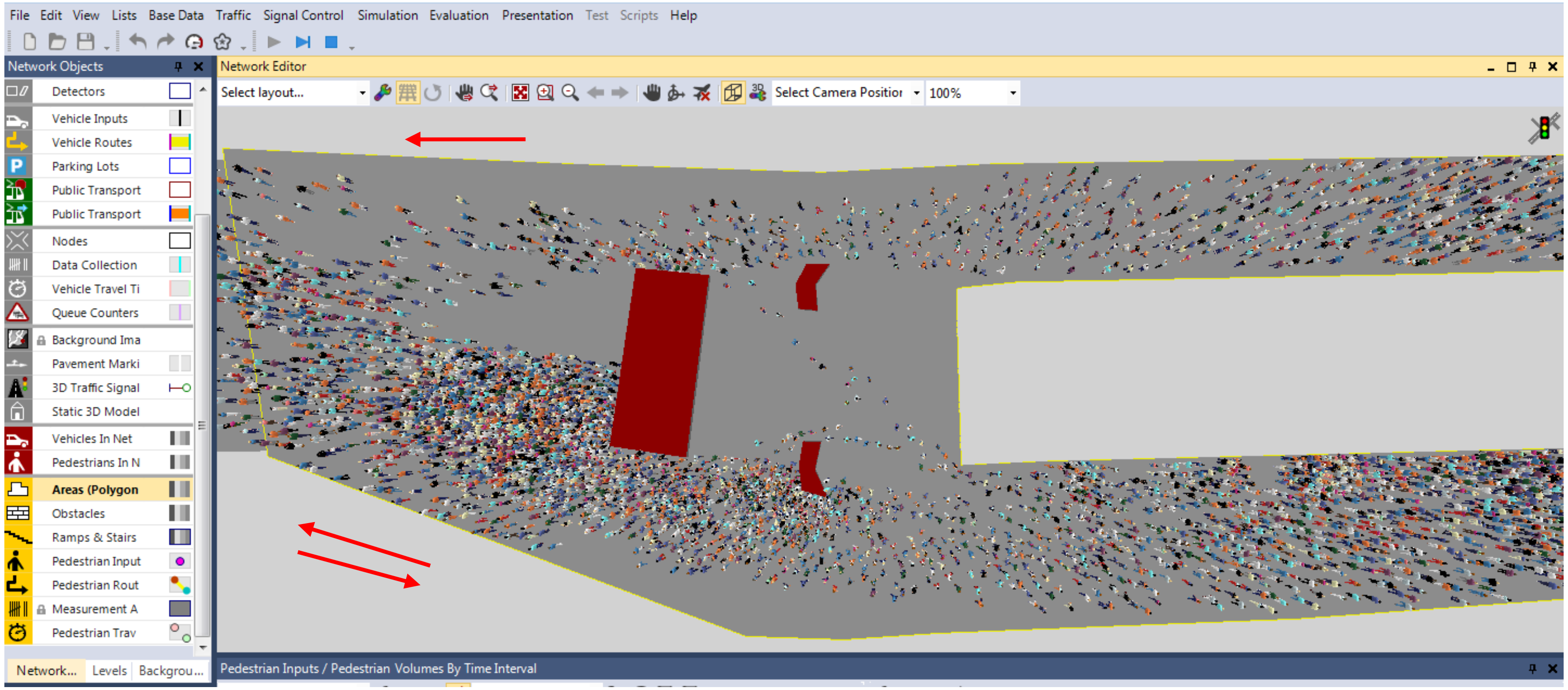

Figure 6-7 Widening of Ajyad2 (Scenario 3)

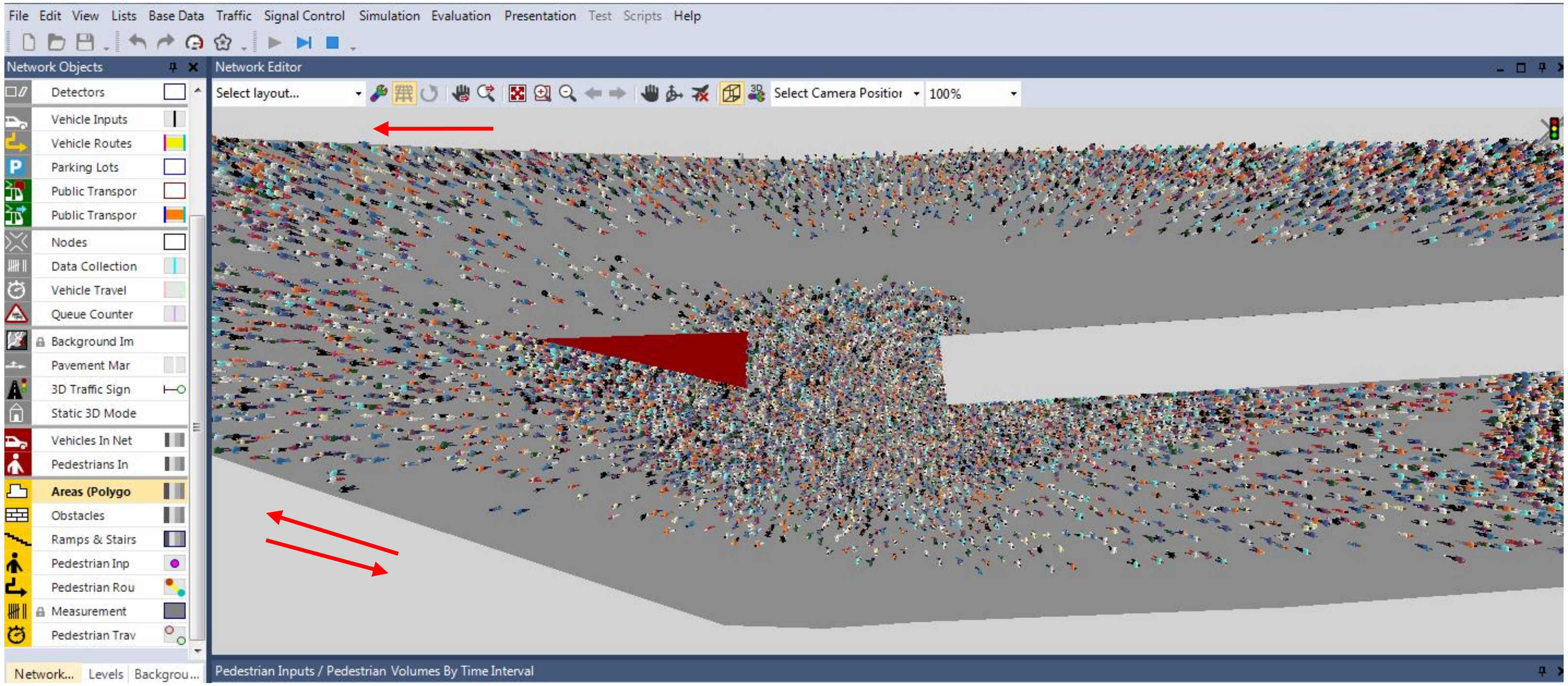

Figure 6-8 Triangular control point and widening of Ajyad 1& 2 (Scenario 4)

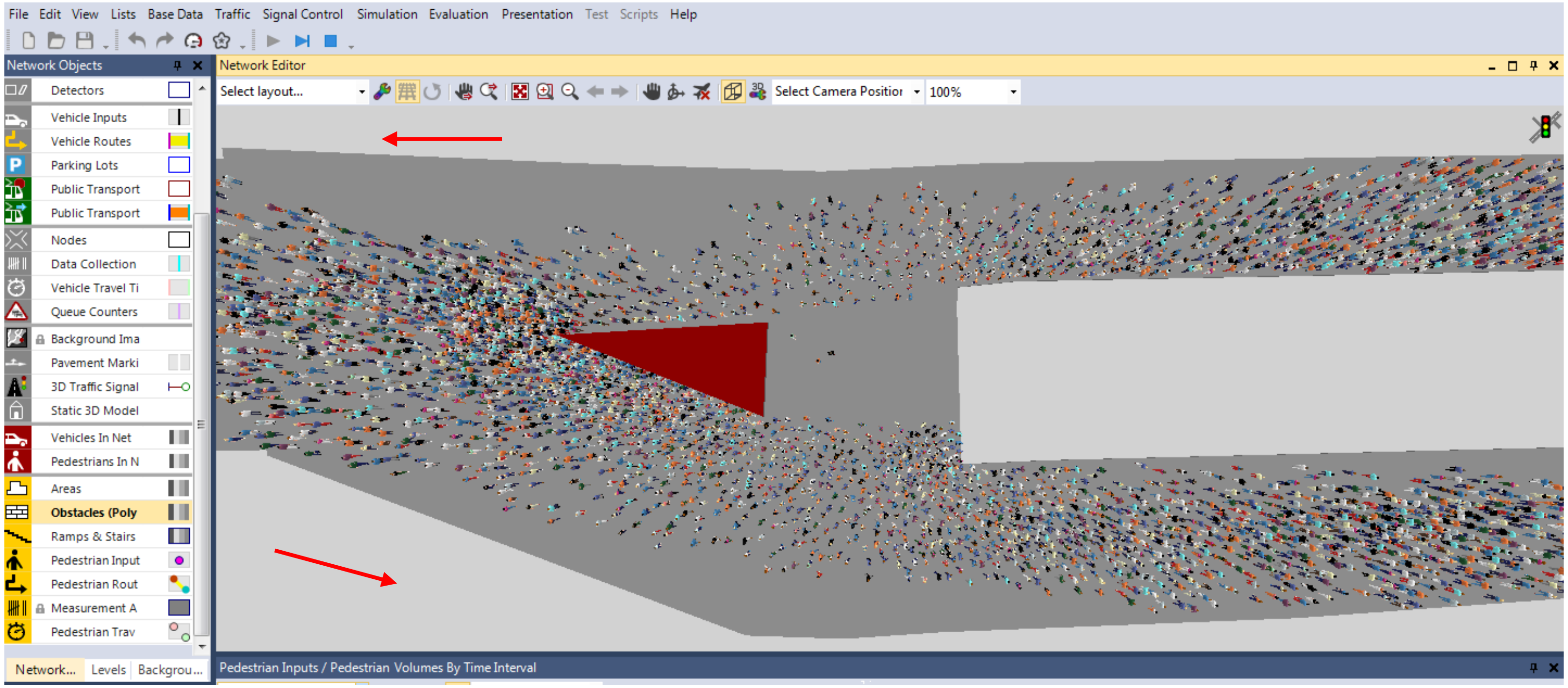

Figure 6-9 One way in Ajyad2, triangular control point and widening of Ajyad 2 (Scenario 5)

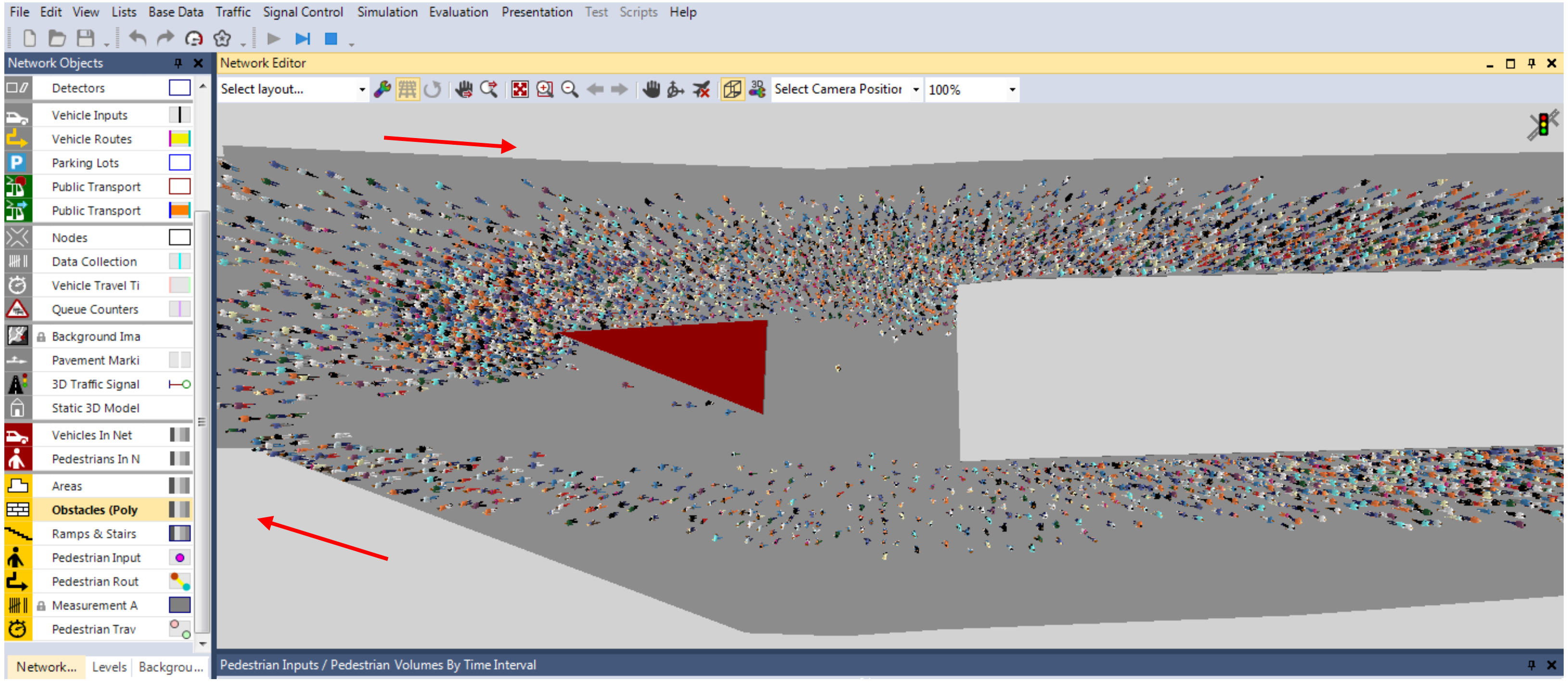

Figure 6-10 Ajyad1 inbound, Ajyad2 outbound with triangular control point and widening of Ajyad 2 (Scenario 6)

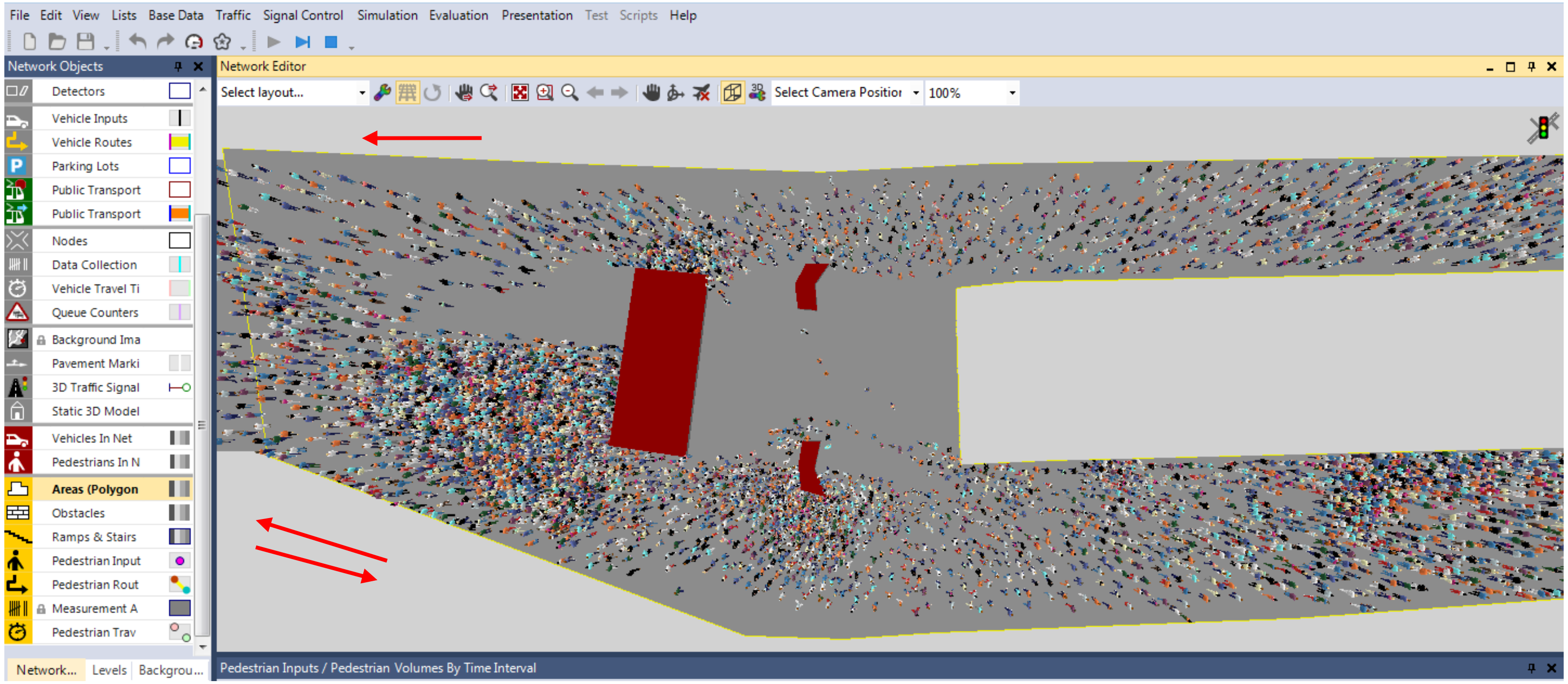

Figure 6-11 Separation of inbound from outbound in Plaza (Scenario 7)

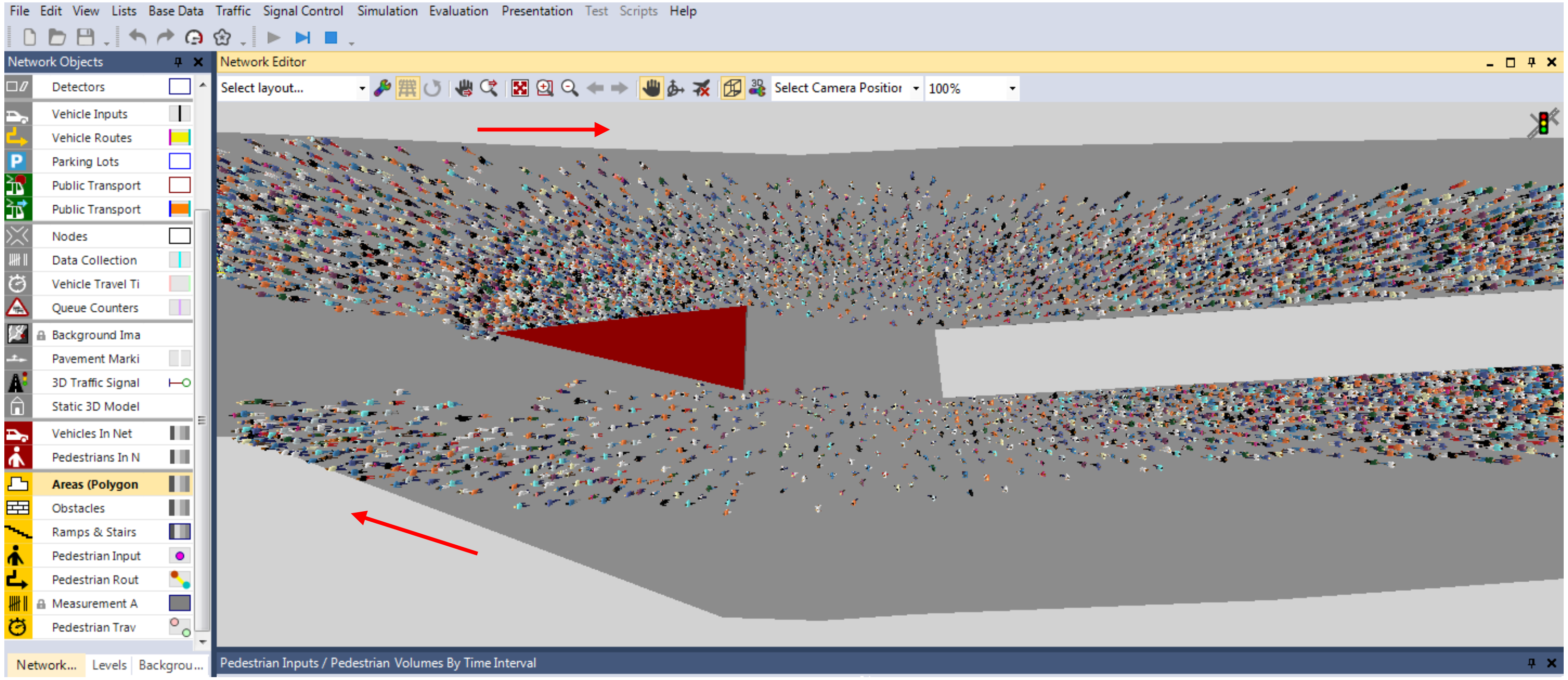

Figure 6-12 Separation in Plaza with triangular, one way inbound in Ajyad 1, one way outbound in Ajyad 2 and widening of both (Scenario 8)

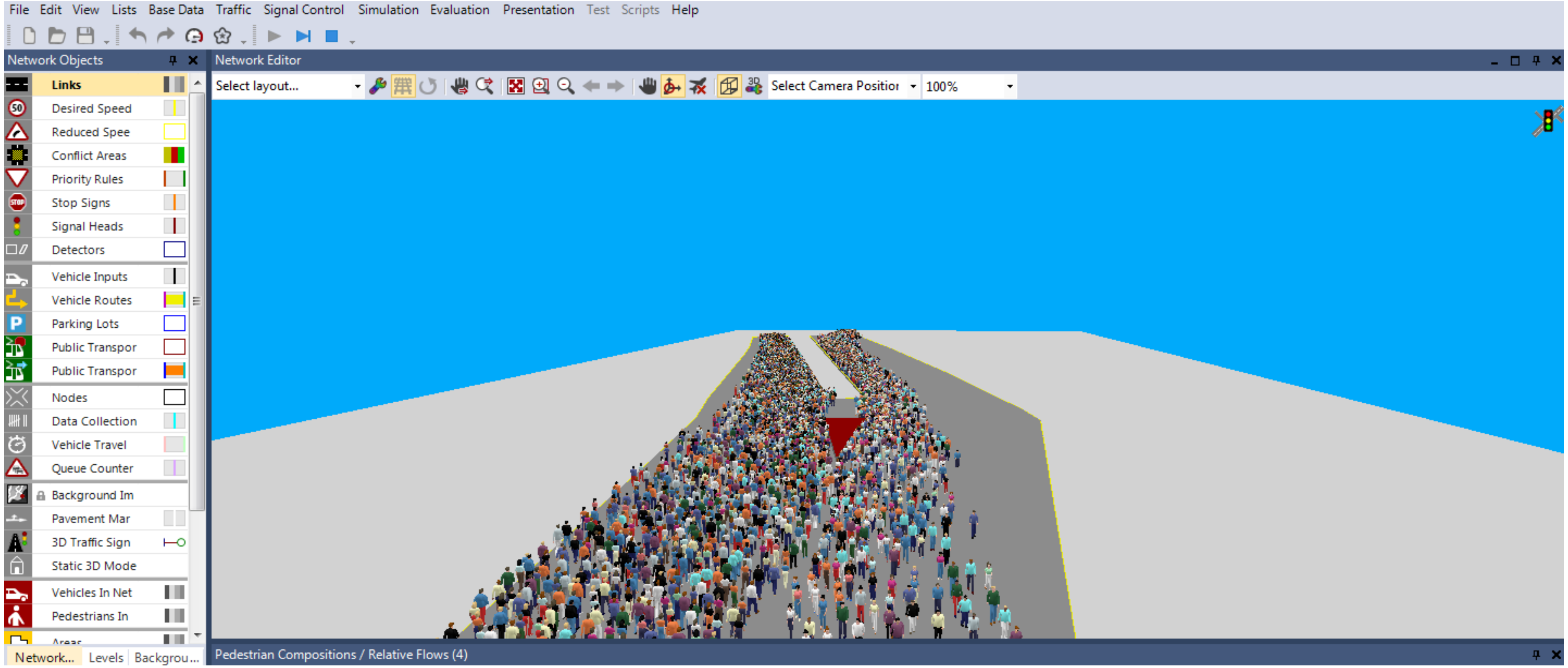

Figure 6-13 As Figure 6-12 but viewed from Plaza (Scenario 8).

Chapter 7

Conclusions and Future Work

7.1 Overview of Results

The intention of this study was to conduct a thorough investigation of the characteristics of pilgrim crowd dynamics during Hajj, and to determine the characteristics that cause overcrowding. The research design was carefully thought out to achieve the objectives listed in section 1.4.

The research design and methodology incorporated a systematic study of the literature, including a review and validation of the literature findings, which was followed by extensive data collection, analysis and interpretation. The findings of the secondary data, collected by video recording, are presented and analysed in chapter 5 of this study. These findings were then discussed, summarised and integrated. This concluding chapter summarises the study's contribution to both research and practice, and will provide suggestions for any further research directions that have emerged, considering that this is a relatively new area of study.

This study can be distinguished from others in that it considers the dynamic density of pilgrims during their journey towards the Holy Mosque although it should be possible to apply the findings to the mega-events worldwide this area of research has been neglected in the related literature and research. Secondly, the study was conducted on a typical mega-event, the Hajj, to meet the research objectives. This important international large-scale event has not been fully covered in the literature and research on crowd dynamics.

Because the Hajj involves a large number of pilgrims, and is of a short duration, a quantitative research approach was used to collect and analyse the research data. An exclusive tool (high-definition video cameras) was used to record the pilgrim movements in one of the main streets used by pilgrims to reach the Holy Mosque. This research tool was used to provide reliable and valid data which can be analysed to represent the pilgrim's dynamic characteristics.

The findings of the pilgrim dynamics data analysis in the current study compare with previous studies of pedestrian crowd dynamics in the literature. The pilgrim crowd dynamic in the context of the Hajj is unique in that approximately three million people move in the same direction simultaneously, towards one destination—the Holy Mosque—using a limited number of streets as conduits. Although we selected only one of these Ajyad Street is typical of the event as a whole, as described in Chapter 3 (the methodology).

Some pedestrian dynamics studies have been conducted on pilgrims performing Tawaf circumambulation inside the Holy Mosque, reviewed in detail in Chapter 2 (the literature review), but none of these studies were conducted on the pilgrims in the central area of Makkah during their journey towards the Holy Mosque.

In our study, a large amount of data was recorded, extracted and calculated for pilgrims traversing Ajyad Street on the main day of the Hajj event—the tenth day. These readings on pilgrim dynamics, taken throughout the day, were analysed and plotted, and the results summarised in figures and diagrams, providing clear relationships between several variables surrounding the pedestrians participating in the Hajj event. These were actual physical relationships between variables, such as speed, density, flow, capacity and time. Consequently, it was possible to determine mathematical relations representing the trend lines for each, which, in fact, did not provide the maximum and minimum readings, but represented the trend and tendency of every curve, and showed the maximum and minimum average readings.

7.2 Key Findings

1. The speed-density relationship most closely follows the (squared-Y reciprocal-X) form on the Ajyad1 walkway of unidirectional flow outbound, and the (reciprocal-Y squared-X) form on Ajyad2 (outbound and inbound) walkways, but none of these alternative correlations are particularly convincing overall.

2. The free speeds in Makkah at Ajyad Street were found to fluctuate more, and clearly varied at certain times. Moreover, this variation was due to certain religious and spiritual factors, and correlated with the prayer times (as detailed in Chapter 4).

3. The analysis of the video recordings showed that pilgrims tend to seek out the free space on Ajyad Street, resulting in relaxed walking. Even at a very high density, the pedestrians adjusted the space available without causing body-to-body contact, as indicated by the area module at capacity flow. This reflects that the study area in Ajyad Street is the first point from which pilgrims can see their destination (the Holy Mosque), which may conceivably have a positive psychological impact on pilgrims' ability to relax, and the way in which they walk and behave when arriving this point.

4. Furthermore the free speed at Ajyad 2 Street is not affected by the bidirectional flow, provided that the latter is at a low ebb. As the flow increases, the speed under the bidirectional flow is found to be higher than that under the unidirectional flow. The opposite behaviour is observed in congested conditions or at high-density values. The

pedestrians under the bidirectional flow show adjust their behaviour to accommodate fellow pedestrians within the space available, but without body-to-body contact.

5. One particularly interesting behavioural phenomenon was observed. i.e. psychological behaviour. According to the teachings of Islam during the pilgrimage, pilgrims do not deliberately crowd and harass others. Not one single instance of deliberate over-crowding or harassment was witnessed over the entire study period. Instead, they give them a wide berth and allow them space. In addition to psychological behaviour includes 'grouping' and 'avoidance of overcrowding' when on either side of Ajyad Street.

6. The various models listed in chapter 5 were of mixed quality, with correlation coefficients varying from over 98% to less than 5%. However there seems no reason for pilgrims to walk as fast as the crowd density will allow. Rather, some will hurry while others take their time. Fitting curves through the "middle" of the data thus makes no sense. A high degree of scatter can be expected so, instead, a far better approach is the "maximum possible speed" model proposed here, which limits the maximum speeds on the basis of density but acknowledges that in reality the maximum speeds may well be no more than zero. This maximum possible speed model is based upon the simplest of the recognized models i.e. that of Greenshield. There is neither any advantage nor any theoretical basis for using the more complicated Weidmann or Greenberg ones. Considering the observed data and those from the literature together suggests that this maximum speed model should be:

$$u \leq 1.75\,(1 - k/5.47) \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\; 7\text{-}1$$

7. Modelling the situation using VISSIM was found to give realistic results based on visual comparisons but the validation of such models is far from straightforward. Indeed this is an area that would merit further research.

8. The simulation scenarios demonstrate that isolated bitwise changes (to the geometry of the control point, the width of the road or the directions of flow) are insufficient to cater for an increase of 50% in traffic. However, implementing of several of them together (triangular control point, widened road, inbound on Ajyad1 and outbound on Ajyad 2 with prior separation of inbound pedestrian at the exit of the plaza) results in good flow throughout Ajyad Street. This improves the situation by displacing the problems away from Ajyad Street into the Plaza where considerably more space is available.

9. The findings suggest that different flow characteristics are adopted for pilgrim pedestrian facilities. The results of this study could be used as input for the development of dynamic continuum models which could help in understanding the pilgrims' movement and behaviour during the pilgrimage in the spatial-temporal domain.

7.3 Future Research Directions

As the number of pilgrims arriving in Saudi Arabia to perform their religious duties at the Hajj increases, further research is needed to expand the findings of this study, and to provide more conclusive answers. Despite its attempt to be exhaustive and to cover a broad area of research, there are many areas in which future research is needed on the following:

1) The limitations of the models in the literature.

2) Empirically testing and refining of the proposed Maximum Speed model particularly at high densities, and exploration of the relationships of the various variables that affect the pilgrim movement, through the collection of data from different areas and at varying times during the Hajj.

3) Accurately predicting the microscopic characteristics of the pilgrims' movements in the real world. Current pedestrian flow models are only capable of predicting pilgrims' flow characteristics based on the movements of normal pedestrians.

4) The effect of the weather on pilgrims, often leading to fatal incidents, with a better understanding of how these issues are involved in pilgrim crowd dynamics.

5) The perceived importance of the demographic variables on pilgrim crowd dynamics, and the associated direct and indirect impact on the management of pilgrim dynamics.

7.4 Towards Safer Crowd Control

This study has presented a holistic review of pilgrim crowd characteristics through comprehensive scrutiny of the relevant literature, and data analysis of numerous video recordings of pilgrim movements. It has also provided a detailed distribution of the flow of the pilgrims, and suggested estimation models for pilgrim flow relationships – the pedestrian fundamental diagram. It has presented a detailed discussion of dynamic pedestrian models as measurement tools with which to validate the relationships pertaining to the flow variables of pilgrims during the Hajj. These methodologies culminated in the model depicted in Figure 5-19.

The study suggests that the validated models are capable of yielding a wide range of benefits, of both a tangible and an intangible nature. In essence, applying these models would ensure that decision-makers would be able to derive maximum benefit in terms of planning and controlling pilgrim crowds during the Hajj.

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