OPTIMIZATION BASED CONTROLLED EVACUATION USING PEDESTRIAN SPEED-DENSITY RELATIONSHIP: A CASE STUDY OF UNIVERSITI SAINS MALAYSIA

LUTHFUL ALAHI KAWSAR

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by

LUTHFUL ALAHI KAWSAR

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LIST OF SYMBOLS

A	Average walking speed of a lone occupant
Ar	Area
C	Walkway capacity
C_d	Decay rate of speed
dM	Change of storage mass in system
dt	An increment of time
E	Set of edges or walkways
E_i	Set of intermediate walkways
E_s	Set of source walkways
E_E	Set of walkways with empty adjacent sources
E_{Empty}	Set of empty walkways
E_{NE}	Set of walkways with nonempty adjacent sources
$E(N)$	Expected number of occupants in system
$E(S)$	Expected service time of a lone occupant
$E(T)$	Expected service time
$f(n)$	Service rate
G_k, G_N	Control gains
h	Infinitesimal interval
I_b	Set of in-nodes
k	Pedestrian density

k_j	Jam density
$\tilde{k}$	Standardized density that is Observed density/ Jam density
$k_{a,b}$	Average density of occupants in walkway (a,b)
$k_{a,b}^{Cr}$	Critical density in walkway (a,b)
$\dot{k}_{a,b}$	First order time derivative of average occupants density in walkway (a,b)
$\tilde{\dot{k}}_{a,b}$	Standardized value of first order time derivative of average occupants density in walkway (a,b)
l	Length of pedestrian trap
L	Length of walkway
L'	Weighted average of distance travelled for all arrivals
$L_{a,b}$	Length of walkway (a,b)
L_m	Maximum length of a walkway
n	Number occupants observed
N_b	Total number of occupants in node $b \in V_i$
$\dot{N}_b$	First order time derivative of total number of occupants in node $b \in V_i$
$\tilde{\dot{N}}_b$	Standardized value of first order time derivative of total number of occupants in node $b \in V_i$
N_m	Maximum number of occupants in a node
$\dot{N}_n$	First order time derivative of total number of occupants in exit node $n \in V_e$

$\dot{\tilde{N}}_n$	Standardized value of first order time derivative of total number of occupants in exit node $n \in V_e$
N_s	Total number of occupants in system
$N^r_{a,b}$	Number of occupants remaining in sources adjacent to walkway (a,b)
$\dot{N}^r_{a,b}$	First order time derivative of number of occupants remaining in sources adjacent to walkway (a,b)
$\dot{\tilde{N}}^r_{a,b}$	Standardized value of first order time derivative of number of occupants remaining in sources adjacent to walkway (a,b)
$N(t)$	Total number of events that occur by time t
$o(h)$	A quantity that becomes negligible when compared to h as $h \to 0$
O_b	Set of out-nodes
P_0	Probability of a walkway being empty
P_C	Probability of blocking
P_n	Probability of n occupants in a walkway
q	Flow
q_m	Maximum possible flow in walkway (a,b)
$\tilde{q}_m$	Standardized value of maximum flow
$q_{a,b}$	Flow into walkway (a,b) from node a
$\tilde{q}_{a,b}$	Standardized value of flow into walkway (a,b) from node a

$q_{a,b}^{out}$	Flow into node b from walkway (a,b)
$q_{a,b}^{r}$	Flow into walkway (a,b) from adjacent sources
$\tilde{q}_{a,b}^{r}$	Standardized value of flow into walkway (a,b) from adjacent sources
$(\tilde{q}_{a,b})_{Sl}$, $(\tilde{q}_{a,b}^{r})_{Sl}$, $(\tilde{v}_{a,b}^{f})_{Sl}$	Slack variables
$(\tilde{q}_{a,b})_{Su}$, $(\tilde{q}_{a,b}^{r})_{Su}$, $(\tilde{v}_{a,b}^{f})_{Su}$	Surplus variables
S	Speed
$\tilde{t}$	Average travel time
t_i^{in}	Time of i-th pedestrian to go in the pedestrian trap
t_i^{out}	Time of i-th pedestrian to go out from the pedestrian trap
T	Observation time
v	Space mean speed
v_a	Average walking speed of occupant when crowd density is 2 ped/m^2
v_b	Average walking speed of occupant when crowd density is 4 ped/m^2
v_i	Instantaneous speed of the i-th pedestrian
v_n	Average walking speed for n occupants in a walkway
v^f	Free flow walking speed
$v_{a,b}$	Walking speed of occupants in walkway (a,b)
$v_{a,b}^{exit}$	Exiting speed of occupants from walkway (a,b)

$\tilde{v}_{a,b}^{f}$	Standardized speed control variable
$\tilde{v}_{m}^{f}$	Standardized value of maximum free flow speed
$\hat{v}(t)$	Time mean speed
V	Set of nodes
V_e	Set of exit nodes
V_i	Set of intermediate nodes
V_s	Set of source nodes
w	Width of pedestrian trap
W	Width of walkway
$W_{a,b}$	Width of walkway (a,b)
W_m	Maximum width of a walkway
$\dot{x}$	First order time derivative of x

Greek Letters

β	Scale parameter
γ	Shape parameter
λ	Rate of Poisson process
θ	Steady state throughput through a walkway
ρ	Density

LIST OF PUBLICATIONS

Journal Papers

Kawsar, L. A., , Ghani, N. A., Kamil, A. A., & Mustafa, A. (2012). Restricted Pedestrian Flow Performance Measures during Egress from a Complex Facility. *World Academy of Science, Engineering and Technology*, 6(7), 323 - 328.

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Kawsar, L. A., Ghani, N. A., Kamil, A. A., & Mustafa, A. (2014). Empirical Relationships among Pedestrian Flow Characteristics in an Indoor Facility. *Research Journal of Applied Sciences, Engineering and Technology,* 8 (8), 952-963.

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Ghani, N. A., Khalid, R., Nawawi, M. K. M., Kawsar, L. A., Kamil, A. A., & Mustafa, A. (2013). *Comparison of Discrete Simulation Models' Results in Evaluating The Performances of M/G/C/C Networks*. Paper presented at International Science and Technology Conference, 25-27 June, 2013, Rome, Italy.

PENGOPTIMUMAN BERASASKAN PEMINDAHAN TERKAWAL DENGAN MENGGUNAKAN HUBUNGAN KELAJUAN-KETUMPATAN PEJALAN KAKI: SATU KAJIAN KES DI UNIVERSITI SAINS MALAYSIA

ABSTRAK

Hubungan kelajuan-ketumpatan merupakan satu kepentingan utama dalam kajian pemindahan kemudahan, kerana ia ada kaitan secara langsung dengan keupayaan laluan untuk mengikuti aliran pilihan pejalan kaki di sepanjang laluannya. Kajian ini bertujuan menentukan model hubungan kelajuan-ketumpatan yang lebih baik untuk aliran pejalan kaki yang mengambil kira kadar reputan kelajuan bagi peningkatan dalam kepadatan dan merumuskan satu metodologi kawalan yang efisien yang boleh membantu mengekalkan pemindahan yang lancar dan cepat semasa kecemasan. Bilik dewan Dewan Tuanku Syed Putra (DTSP) Universiti Sains Malaysia dianggap sebagai kajian kes. M/G/c/c model giliran bersandar keadaan digunakan untuk menilai ukuran prestasi rangkaian DTSP ini. Hasil kajian menunjukkan bahawa daya pemprosesan yang maksimum boleh diperolehi dengan meletakkan beberapa sekatan ke atas kadar ketibaan ke laluan sumber dan ke atas arahan perjalanan dari laluan sumber ke laluan keluar. Data daripada bilik dewan DTSP dikumpulkan pada setiap sesi semasa konvokesyen dari 21-25 September 2011 dengan menggunakan prosedur fotografi. Kesahihan model hubungan kelajuan-ketumpatan yang lebih baik telah disahkan oleh memasang kepada data utama dan lapan set data sekunder yang berbeza. Keputusan menunjukkan bahawa model tersebut menerangkan hubungan kelajuan-kepadatan dengan baik untuk semua dataset (semua $R^2 \geq 0.78$). Dengan menggunakan konsep keabadian jisim, satu metodologi aliran kawalan yang novel berdasarkan masalah pengaturcaraan linear dibangunkan untuk mengira kadar aliran yang optimum bagi rangkaian pemindahan

yang berbilang jalan keluar. Dalam keadaan kecemasan, reka bentuk aliran terkawal mampu mengesan nilai ketumpatan laluan, bilangan penghuni di nod dan dengan itu memastikan bahawa aliran dari sumber bersebelahan kepada laluan sumber berada pada tahap maksimum. Dengan menggunakan ruang dewan DTSP sebagai rangkaian berbilang jalan keluar, simulasi aliran menunjukkan bahawa laluan sumber disekat apabila terdapat aliran yang tidak terkawal. Oleh itu, tidak ramai penghuni boleh berjalan ke laluan pengantara dan pintu keluar. Untuk aliran terkawal, nilai ketumpatan penghuni dalam laluan sumber dan laluan pengantaraan beransur mendekati kepadatan kritikal, memastikan aliran yang maksimum. Satu kajian pengusikan bagi metodologi aliran terkawal untuk nilai kadar reputan kelajuan yang berbeza memberikan keputusan yang stabil dari segi pembolehubah keadaan dan kawalan. Metodologi yang dibangunkan berguna untuk arkitek dan pihak berkuasa pengurusan bencana yang terlibat dengan pemindahan kemudahan bangunan dan boleh digunakan sebagai paradigma untuk kajian masa depan.

OPTIMIZATION BASED CONTROLLED EVACUATION USING PEDESTRIAN SPEED-DENSITY RELATIONSHIP: A CASE STUDY OF UNIVERSITI SAINS MALAYSIA

ABSTRACT

The speed-density relationship is a major concern in the study of the evacuation of facilities, as it is linked directly with the capability of a walkway to keep up a preferred flow of pedestrians along its length. This research aims to determine an improved speed-density relationship model for pedestrian flow that takes into account the decay rate of speed for an increase in density and formulate an efficient control methodology which can help to maintain a smooth and quick evacuation during an emergency. The Dewan Tuanku Syed Putra (DTSP) hall room of Universiti Sains Malaysia is considered as a case study. The *M/G/c/c* state dependent queueing model is used to evaluate the performance measures of the DTSP network. The result shows that the maximum throughput can be obtained by putting some restrictions on the travelling direction from the source walkways to the exiting walkways. Data from the DTSP hall room was collected from each session during the convocation from 21st to 25th September 2011 using a photographic procedure. The validity of the improved speed-density relationship model has been verified by fitting it to the primary dataset and eight different secondary datasets. The results show that the model explains the speed-density relationship well for all the datasets (all $R^2 \geq 0.78$). Using the conservation of mass concept, a novel controlled flow methodology based on a linear programming problem is developed for computing the optimal flow rates for a multi-exit evacuation network. In an emergency situation, the controlled flow design is able to track the values of the walkway density, the number of occupants in nodes and thus assures that the flow

from adjacent sources to the source walkways is at their maximum level. Using the DTSP hall room as a multi-exit network, a simulation of the flow shows that the source walkways are blocked when there is an uncontrolled flow. Hence, very few occupants can make their way into the intermediate walkways and exits. For the controlled flow, the values of occupant density in the source and intermediate walkways gradually approach the critical density, ensuring a maximum flow. A perturbation study of the controlled flow methodology for the different values of the decay rate of speed gives stable results in terms of the state and control variables. The developed methodology is useful for the architects and disaster management authorities who are concerned with the evacuation of building facilities and can be used as a paradigm for future studies.

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter is an overview of the conducted research. This research firstly evaluates the different performance measures of an *M/G/c/c* state dependent queueing network. Then, it proposes an improved speed-density relationship model for pedestrian flow that is used in the formulation of a control flow methodology to maintain an efficient evacuation process. The Dewan Tuanku Syed Putra (DTSP) hall room of Universiti Sains Malaysia is considered for this case study. This chapter contains the sections as follows: Research Motivation in Section 1.2, Problem Statement in Section 1.3, Objective of Research in Section 1.4, Significance of Research in Section 1.5 and Scope of Research in Section 1.6. Finally, the structure of the thesis is presented in Section 1.7.

1.2 Research Motivation

A crowded building facility is vulnerable to various emergency situations that may lead to extensive and extreme destructions. Most of the emergency situations are of natural or man-made type such as technical failures and terrorist attacks. Quick and jam-free evacuation of the occupants in such situations is the most important issue. To deal with the evacuation situation, understanding of pedestrian traffic flow is necessary.

Pedestrian traffic flow studies can be divided into two categories: the microscopic approach and the macroscopic approach (May, 1990). Microscopic approach involves individual units with characteristics such as individual speed and individual interaction. The drawback to microscopic approach is that it involves complex, non-analytical mathematical models which require difficult and expensive simulation to solve.

Macroscopic models consider pedestrian behaviour in a continuum approach, where the movement of pedestrians exhibit many of the attributes of a fluid motion. As a result, pedestrian movements are treated as a fluid. The drawback of this modelling is the assumption that pedestrians behave similarly to fluids. Unlike fluids, pedestrians tend to interact among themselves and with obstacles in their model area, which is not captured by the macroscopic models (Kachroo, Al-Nasur, Wadoo, & Shende, 2008).

In normal conditions, pedestrians prefer to walk with an individual desired speed and keep a certain distance to other pedestrians and to borders (Conca & Vignolo, 2012). However, in emergency situations, Helbing, Farkas, Molnar, and Vicsek (2002) identified the following features of human crowd: people become nervous and they try to walk considerably faster than the normal situation; physical interactions among people occur and they start pushing one another; congestion arises near the exits; fallen or injured people are obstacles to other people in their escape, which slow down the evacuation process; people show herding behaviour, that is to do what other people do; and alternative exits are often overlooked, or not efficiently used.

Therefore, proper routing of pedestrian flow and timely regulation of flow control parameters are necessary in emergency situations. Routing of pedestrian flow means to direct pedestrians to the appropriate exits. Controlling the flow control parameters such as the pedestrian walking speed through the walkways, flow of occupants to the walkways from adjacent rooms and from rear end ensure that congestion levels in all the walkways are kept at an appropriate level. When the occupants are aware that their movements are being observed and they are getting the proper direction to get out of the facility, they will become less panicky. The proper routing of the occupants to the different exits will help to avoid the physical interactions among them by controlling the congestions.

Wigan (1993) stated that our knowledge of the flow of crowds is inadequate and behind that of other transportation modes. Studies conducted by Griffith (1982) and Southworth, Chin, and Cheng (1989), are concerned with evacuation strategies for regional areas like cities and states. They are important in the decision making of an emergency evacuation such as in the case of a natural disaster. In smaller areas like airports, stadiums, theatres, buildings, and ships, an evacuation system is an important element in design safety (Løvås, 1995). A good evacuation system in the case of an emergency can avoid a tragic outcome (Helbing, et al., 2002). Hence, this research is concerned with formulating a linear programming based controlled flow methodology to maintain a smooth evacuation process using an improved speed-density relationship model.

1.3 Problem Statement

There are several deterministic speed-density models for vehicular flow which are often used for studying pedestrian flow (Lam, Morrall, & Ho, 1995; Shende, Kachroo, Konda Reddy, & Singh, 2007). However, pedestrian flow is different from vehicular flow. Further, the studies on pedestrian flow show that the relationship equations are location-specific such as in outdoor walkways and indoor walkways. The use of linear speed-density relationship model is not appropriate for pedestrian flow (Pushkarev & Zupan, 1975) which leads to the use of the non-linear models. The most widely used non-linear models are the exponential models such as Underwood model (Underwood, 1960), Drake model (Drake, Schofer, & May, 1967) and the model developed by Yuhaski and Smith (1989).

The main drawback of the Underwood model is that it cannot properly describe the congested densities while the Drake model cannot properly predict speed for a free-flow and a congested region (Wang, 2010). Moreover, both of these models are unable to find the critical density which can ensure the maximum flow. For the exponential walking speed model developed by Yuhaski and Smith (1989), the shape and scale parameters are calculated by approximating three representative points from the six curves presented by Tregenza (1976). The assumption of the values of the parameters of the model restricts its use in the general cases as the model can only describe the speed-density relationship for specific datasets.

The methodologies presented on previous evacuation studies are mostly of a static nature and the variation of congestion with respect to time is ignored. Shende, Singh, and Kachroo (2013) have presented a single exit dynamic pedestrian flow model for pedestrian evacuation from a network of walkways based on a linear programming problem. The Greenshields Model (Greenshields, Bibbins, Channing, & Miller, 1935), which was primarily developed for vehicular flow, has been used in the dynamic model to account for the speed-density relationship of pedestrian. Moreover, in the control design of Shende et al. (2013), the walkways are considered of equal widths.

In order to design an effective evacuation system for a network of walkways, the capacities of the walkways which depend on their widths and lengths, should be taken into account (Yuhaski & Smith, 1989). Thus, a controlled evacuation methodology that incorporates the different widths and lengths of the walkways is needed to formulate to overcome the limitations of the previous one. Also, an improved speed-density relationship model for pedestrian flow is required.

1.4 Objective of Research

The main objective of the research is to formulate an efficient controlled flow methodology which can help to maintain a smooth and quick evacuation process during an emergency. To meet this main goal the following three objectives are considered:

i) To evaluate the performance measures of a building facility for the uncontrolled and controlled flows.

ii) To determine an improved speed-density relationship for pedestrian flow that takes into account the decay rate of speed for an increase in density.

iii) To optimize the evacuation process by controlling the speed and flow of occupants into the walkways inside a building facility.

1.5 Significance of Research

Evacuation from a disaster hit area is a very important problem in the present day situation given the heightened danger of a terrorist attack or a natural and equally hazardous situation like a fire, an earthquake, a hurricane etc. During an intentional or unintentional industrial disaster such as the release of harmful chemicals from a chemical plant or a radiation release from a nuclear power plant, or a natural disaster such as a wide spread flooding due to hurricanes or heavy rains, the affected area could be very large. The main focus of the evacuation in such cases is the efficient management of traffic out of such areas using the road network.

An equivalent pedestrian evacuation problem also arises when there is an intentional or unintentional fire or the release of toxins inside a large building with several occupants. The main focus of this research is on the active management of pedestrian traffic to evacuate pedestrians safely out of entrapped facilities as fast as possible. This study is concerned with the control of pedestrian evacuation flow in a network of walkways.

In developing a safe evacuation system for building facilities, pedestrian characteristics on such facilities should be well understood. The state dependent *M/G/c/c* queuing model is used to capture the bottleneck effects of pedestrian flow within the walkways of a facility involving combinations of merges and splits. The different performance measures of all the walkways of this facility during egress are computed. These measures are necessary to approximate the evacuation time of a facility in the case of an emergency and can be used to evaluate the optimal internal set up for which the maximum throughput can be obtained.

The pedestrians' walking speed is also a major concern in the study of the evacuation of facilities. Walking speed is mostly affected by the density. In this study, an improved speed-density relationship model is proposed for pedestrian flow. Using this improved speed-density model, a controlled flow methodology based on a linear programming problem is formulated to compute the optimal flow rates for a multi-exit evacuation network which also incorporates the different widths and lengths of the walkways. The methodology shows the required control on speed and input flows of occupants into the walkways inside a facility at each time instant to maintain a smooth evacuation process. Controlling of these parameters ensure that congestion levels in all the walkways are kept at an appropriate level, which can help to avoid congestion. The findings of this research can help the architects and disaster management authority to design an evacuation plan for building facilities.

1.6 Scope of Research

This study focuses on the formulation of a linear programming based controlled flow methodology to maintain an effective evacuation from a building facility. The macroscopic modeling approach is well suited for understanding the rules governing the overall behavior of pedestrian flow for which individual differences are not that important and therefore, the macroscopic level of pedestrian flow is adopted in this study. DTSP hall room of University Sains Malaysia is considered as a case study. The primary data has been collected from the DTSP hall room during the convocation from 21^{st} to 25^{th} September 2011 using a photographic procedure. A perturbation study of the controlled flow methodology for the different values of the decay rate of speed is done to check the stability of the state and control variables.

1.7 Structure of Thesis

The thesis is organized as follows:

Chapter 1 provides an overview of the research. It has research motivation, problem statement, objectives, significance, and scope of the research. Apart from this introductory chapter, there are seven other chapters in this thesis.

Chapter 2 reviews previous studies related to pedestrian flow characteristics and pedestrian evacuation problem.

Chapter 3 presents a discussion on the different methodologies that are used to conduct this research.

Chapter 4 evaluates the different performance measures for the uncontrolled and controlled flows during egress from the DTSP hall room of Universiti Sains Malaysia.

Chapter 5 proposes an improved speed-density relationship model for pedestrian flows.

Chapter 6 presents a linear programming based controlled flow methodology for an evacuation problem to compute the optimal flow rate so that a smooth flow of occupants can be maintained throughout the evacuation process.

Chapter 7 presents a comparison of the numerical results of the linear programming problem formulated in Chapter 6 for the uncontrolled flow and controlled flow scenarios. The DTSP hall room of Universiti Sains Malaysia is considered as a case study.

Finally, Chapter 8 concludes the research, reviewing the objectives and the findings of the study in brief and provides suggestions for possible future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter gives a review of earlier studies that are related to the research. This includes studies on pedestrian traffic flow in Section 2.2 along with its characteristics in Subsection 2.2.1 and pedestrian evacuation in Section 2.3. A summary of the chapter is given in Section 2.4.

2.2 Pedestrian Traffic Flow

Pedestrian flow modelling has become an active research area in the last decades. As the world population and urbanization are growing fast, the importance of understanding the crowd movement cannot be underestimated (Lachapelle & Wolfram, 2011).

May (1990) suggested that pedestrian traffic flow can be viewed as a vehicle traffic flow and can be categorized into the microscopic level or the macroscopic level. Henderson (1974) has introduced the microscopic pedestrian analysis studies. In microscopic pedestrian studies, each pedestrian in a crowd is considered as an individual agent and the behaviour of pedestrian interaction is assessed. It presents a detailed picture of space, individual pedestrian and considers personal abilities and characteristics (Kluepfel, 2003). Helbing and Molnar (1998) have showed the importance of a detailed design and pedestrian interactions through several case studies. However, microscopic study involves complex, non-analytical mathematical models which require difficult and expensive simulation to solve (Shiwakoti & Nakatsuji, 2005). Various researchers such as Okazaki (1979), Gipps and Marksjö

(1985), Watts (1987), Helbing (1991), Okazaki and Matsushita (1993), Løvås (1994), Helbing and Molnar (1995), Thompson and Marchant (1995a, 1995b), Blue and Adler (1998), Helbing and Vicsek (1999), Teknomo (2002), Steffen and Seyfried (2010), Guo and Tang (2012) and Zhang and Seyfried (2014) address the different aspects of microscopic pedestrian flow.

Macroscopic level of pedestrian studies presents the collective portrayal of pedestrian movements in a crowd through flow, density and speed relationships. Fruin (1971a) has proposed the macroscopic approach of pedestrian studies. In macroscopic approach, pedestrian movements are treated as a continuous fluid and rely on the behaviour of the fluid as a large scale interactive system. Therefore, macroscopic pedestrian models are easy to apply. They are more appropriate for the control designs since they describe the pedestrian flow process analytically and require less computational time (May, 1990). More details on macroscopic pedestrian flow can be found in Fruin (1971a, 1971b), *Highway Capacity Manual* (1985), Huges (2002, 2003), Seyfried et al. (2009), Cepolina (2009) and Tao, Peng, Wong, Chi-Wang and Meng-Ping (2011).

2.2.1 Pedestrian Traffic Flow Characteristics

Pedestrian traffic flow characteristics studies mainly focused on deriving model equations for relationships between speed, flow and density. Pedestrian traffic flow has first been studied by the Institute of Architecture of the Russian Academy of Arts (VAKH) in 1937 (Predtechenskii & Milinskii, 1978). The study has established the inverse relationship between the speed of pedestrian flow and density. However, the specific quantitative results obtained are unreliable because of the relatively small number of actual observations and other inadequacies. The well-known relation in traffic flow theory,

$$q = v * k \tag{2.1}$$

where, q= flow,

v= speed, and

k= density,

has been observationally verified by a study conducted between 1946 and 1948 by the Central Scientific Research Institute of the Russian Fire Protection Service (VNIPO) (Predtechenskii & Milinskii, 1978). They have also introduced the graphical approach of studying pedestrian traffic flow, in terms of time-space diagrams.

The relationships among flow, speed and density have also been studied by a number of other researchers, namely, Hankin and Wright (1958) on the passengers in London subways and on British school boys, Oeding (1963) on mixed traffic (e.g. shoppers, commuters, sports spectators), Predtechenskii (1966) on mixed mass within a relatively limited area, Older (1968) on shoppers, Navin and Wheeler (1969) on students and Fruin (1971a) on commuters. These studies mainly focused on the pedestrian flow on selected facilities which depend upon the socioeconomic situations of the country being studied. Some of these studies have considered unidirectional and some have considered bidirectional or mixed pedestrian flows. In all these studies, except those by Hankin and Wright (1958) and Predtechenskii (1966), the relationship between speed and density is specified as linear. However, linear speed-density relationship is not appropriate for both vehicular (*Highway Capacity Manual*, 1965) and pedestrian flows (Pushkarev & Zupan, 1975). On the basis of a study conducted in 1966, Russian Engineering construction Institute

(MISI) specified a polynomial relationship between pedestrian speed and density for horizontal movement under normal condition (Predtechenskii & Milinskii, 1978).

A detailed statistical study of different hypotheses regarding the pattern of the speed-density relationship for vehicular flow has been conducted by Drake et al. (1967). The results indicate that there are very little differences among these relationship patterns. Unfortunately, no such detailed investigation has been performed for pedestrian flows.

On the basis of the level of density, Henderson (1971, 1974), Henderson and Lyons (1972) and Henderson and Jenkins (1974) have divided pedestrian flow into loosely packed phase and densely packed phase and modelled it using the kinetic theory of gases. They measured the speeds of school children, university students and sidewalk pedestrians, for three different modes such as standing still, walking and running. It shows that the statistical distribution of speed approximately follow Maxwell-Boltzmann statistics in two dimensions. Burns and Lykoudis (1973) also have conducted a similar study of speed measurements of pedestrians walking alone, in pairs and in groups of three, and suggested that pedestrian speed at low densities follow Maxwell-Boltzmann statistics in two dimensions.

Based on some empirical studies, Tregenza (1976) presents a number of relationships between the walking speed of a pedestrian and the crowd density which is re-created in Figure 2.1. Among these relationships that capture the linear and non-linear effect of pedestrian density, the use of linear and exponential models has been showed to be very effective (Yuhaski & Smith, 1989).

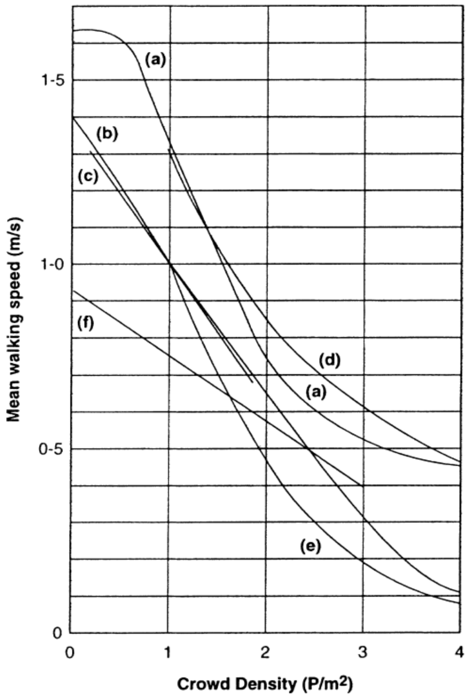

Figure 2.1. Variation of mean walking speed with crowd density (a) (Hankin & Wright, 1958), (b) (O'Flaherty & Parkinson, 1972), (c) (Older, 1968), (d) (Togawa, 1955), (e) (Togawa, 1955), (f) (Foot, 1973)

Fruin (1971a) has showed that the relationship between uni-directional, bi-directional and multi-directional flows have similar pattern as a function of pedestrian density. As such, uni- directional flow models can be used to capture the bi-directional and multi-directional flows of occupants during an evacuation. Fruin (1971a) also has showed that the flow relationships for stairwells are similar to the horizontal movements.

According to Tregenza (1976), at a mean density of five occupants per square meter (5 ped/m^2), walking speed comes to a halt. Walkway capacity is thus equal to the highest integer that is less than five times the area of the walkway in square meters. Thus the walkway capacity, C, is:

$$C = 5LW$$

where L and W are the length and width of the walkway in meters.

Linear and exponential models for uni-directional walking speed has been developed by Yuhaski and Smith (1989). The linear and exponential model for pedestrian speed can be given as follows:

$$v_n = \frac{A}{C}(C + 1 - n) \tag{2.2}$$

$$v_n = A\exp\left[-\left(\frac{n-1}{\beta}\right)^{\gamma}\right] \tag{2.3}$$

where,

$$\gamma = \ln\left[\frac{\ln(v_a/A)}{\ln(v_b/A)}\right] \Big/ \ln\left(\frac{a-1}{b-1}\right),\ \beta = \frac{a-1}{\left[\ln(A/v_a)\right]^{1/\gamma}} = \frac{b-1}{\left[\ln(A/v_b)\right]^{1/\gamma}}\ ,$$

γ, β = shape and scale parameters for the exponential model,

v_n = average walking speed for *n* occupants in a walkway,

v_a = average walking speed when crowd density is 2 ped/m^2,

v_b = average walking speed when crowd density is 4 ped/m^2,

A = v_1 = average walking speed of a lone occupant,

n = number of occupants in a walkway,

$a = 2LW$ and $b = 4LW$.

In this study, v_a, v_b and A are assumed to have values of 0.64 m/s, 0.25 m/s and 1.5 m/s, respectively.

Cheah (1990) has provided exponential walking speed models for bi- and multi-directional walkway, which are similar in the form to the uni-directional model, except that the values for two parameters are slightly changed. For bi-directional flows, v_a = 0.60 and v_b = 0.21, and for multi-directional flows, v_a = 0.56 and v_b = 0.17.

The linear model allows for pedestrian speed to be zero. However, pedestrian speed cannot be zero since they are able to manage a forward movement at high densities (Castle, 2007). The linear relationship for pedestrian flow is also opposed by Pushkarev and Zupan (1975). The exponential walking speed model represents the pedestrian speed-density relationship for walkways of an indoor facility. The shape and scale parameters are calculated by approximating three representative points from the six curves presented by Tregenza (1976). The assumptions of the values of v_a, v_b and A force the estimated curve to go through these points. Therefore, this model can describe the speed-density relationship only for some specific datasets.

Tanaboriboon, Hwa, and Chor (1986) have studied the walking characteristics of pedestrians in different sidewalks of Singapore and found a slower walking speed compared to Western countries. Tanaboriboon and Guyano (1991) also have pointed out that walking speeds are different for pedestrians of Asian and Western countries. Morall, Ratnayake, and Seneviratne (1991) have presented an extensive review of Asian pedestrian characteristics and compared the results with that of Canadian cities.

Based on a study on a particular site, Virkler and Elayadath (1994) have recommended that a multi-regime (probably 2-regime) model is a better portrayal of a pedestrian flow than the linear model. Lam and Cheung (2000) have found a higher free-flow and mean walking speed for outdoor walkways compared to indoor walkways.

Sarkar and Janardan (2001) have studied the pedestrian speed density relationships for an inter-modal transfer terminal in India and the rate of decrease of speed with density is found to be similar to the studies conducted by Older (1968) and Fruin (1971b). Considering the logarithmic relationships among pedestrian density, speed and flow, Fang, Lo, and Lu (2003) have presented a microscopic speed-density function for normal crowd flow. However, the function is unable to describe the relationship for a free flow or a high congested situation.

Lee (2005) has studied pedestrian flow on stairways and escalators in public transport facilities. He has formulated separate two-regime models for up and down directions on stairways and escalators. For both the cases, the speed-density relationships are linear, and flow-speed and flow-density relationships are quadratic.

Al-Azzawi and Raeside (2007) have collected video data on pedestrian flows and speeds and a variety of other variable from the sidewalks, which are representative of the different levels of service. They have derived a logarithmic equation for speed, flow and density relationships. However, the model is not appropriate because based on the physical relation $q=v*k$, speed is proportional to a positive power of density rather than being a decreasing function of density.

Jia, Yang, and Tang (2009) have conducted a data collection survey of pedestrian flow in the passenger transport terminal in Xizhimen underground station in China. They have derived a quadratic equation for pedestrian flow-density relationship; a multi-regime model for the flow-space relationship; and a single linear equation for speed-density relationship.

Chattaraj, Seyfried, and Chakroborty (2009) studied cultural differences in speed–density relationships of Indian and German pedestrians. The authors set up an experiment for Indian conditions same as the experiment set up for German pedestrians by Seyfried et al. (2009). They have compared the pedestrian characteristics on walkways of different lengths and found significant differences between the two pedestrian groups. It is suggested that the reason behind such differences could be the cultural differences of the two countries. The speed-density relationship is found to be nonlinear.

Alhajyaseen and Nakamura (2010) have generated the fundamental diagrams of pedestrian flow at signalized crosswalks. They have proposed the required crosswalk widths for various pedestrian demand combinations by utilizing the existing Level of Service (LOS) thresholds for pedestrian flow at signalized crosswalks.

Laxman, Rastogi, and Chandra (2010) have studied pedestrian characteristics at four crowded locations in north India in mixed traffic condition. They have showed that the characteristics of the location and pedestrian themselves have their effect on the pedestrian flow characteristics. At all four locations the speed-density relationship is linear. The flow-density and flow-speed relationships are quadratic. A polynomial relationship is found between pedestrian flow and area module.

Alhajyaseen, Nakamura, and Asano (2011) have studied the effects of bidirectional flow and various pedestrian age groups (middle-age, elderly and pupils) on the characteristics of pedestrian flow and the capacity of signalized crosswalks. They have concluded that elderly pedestrians might cause a significant reduction in capacity up to 30%.

Rahman, Ghani, Kamil, and Mustafa, (2012) studied the effect of different factors and their interactions on free flow walking speed in Bangladesh using mixed factorial design and found a significant effect of personal and locational factors on pedestrian walking speed.

Yao, Sun, Zhang, Wang, and Rong (2012) have studied and analyzed the behavioural characteristics of pedestrian crowd for weaving and without weaving flow in a transport terminal in Beijing, China. They have showed linear speed-density graphs and quadratic flow-density and flow-speed graphs; however, no model is derived from the obtained graphs.

Rastogi, Ilango, and Chandra (2013) have studied pedestrian flow characteristics for 19 locations in five cities of India. They have showed that speed-density, flow-density and flow-area module follow exponential relationship, while the flow-speed equation follows a logarithmic relationship. At very low density, the behaviour of pedestrians are similar irrespective of the type of facility, however, behaviour is different at higher densities. They have observed a different flow characteristics compared to those observed in the USA, UK, China and Southeast Asia, indicating a cultural effect. It is indicated that due to heavy pedestrian flows and limitation imposed by the width of the facility, pedestrians in India walk slower, but given an ideal condition, they may walk faster than their counterparts in other countries.

Gupta and Pundir (2015) have extensively reviewed the literatures for various existing studies on pedestrian flow characteristics under different traffic situations. These studies focus on the important fundamental parameters of pedestrian flow. These parameters are pedestrian speed, density and flow.

Numerous researchers have conducted their researches on the pedestrian characteristics for sidewalks, stairways and crosswalks of different countries such as Hankin and Wright (1958), Navin and Wheeler (1969), Fruin (1971a, 1971b), Tregenza (1976), Predtechenskii and Milinskii (1978), Weidmann (1993), Lam and Cheung (2000), Sarkar and Janardhan (2001), Seyfried, Steffen, Klingsch, and Boltes (2005), Helbing, Johansson, and Al-Abideen (2007), Liu, Zhou, and He (2008), Seyfried et al. (2009), Laxman et al. (2010), Rahman et al. (2012) and so on. These studies show that pedestrian characteristics vary due to age, gender and locations.

2.3 Pedestrian Evacuation Studies

Recently pedestrian evacuation problem has become one of the promising research topics (Shende, 2008). The study on evacuation of a building facility may consider either microscopic or macroscopic pedestrian flow. It is a multi disciplinary problem which includes the design of infrastructure, pedestrian behaviour, strategy etc. Therefore, the approaches to model such problems come from different fields.

Togawa (1955) and Melinek and Booth (1975) have tried to estimate the building evacuation time through mathematical models. Francis (1979, 1981) has been the first to formulate the building evacuation problem using Brown (1979) algorithm.

Some researchers such as Chalmet, Francis, and Saunders (1982), Choi, Francis, Hamacher, and Tufekci (1984), Kisko and Francis (1985), Choi, Hamacher, and Tufekci (1988), Fahy (1991), Kostreva and Wiecek (1993), Burkard, Dlaska, and Klinz (1993) and Montes (1994) have used dynamic network flows to model evacuation problems. Gupta and Yadav (2004) have presented an algorithm based on the network optimization theory and used graph theoretical approach to identify the available paths for pedestrian movement.

During evacuation process, the walking speed of occupants decreases because of the congestion created by the increased number of occupants in the circulation system such as walkways and stairwells. State dependent queueing network is an appropriate tool to model such a situation. In this type of formulation, the circulation systems are considered as servers to the occupants. Smith and Towsley (1981) have introduced the queueing theory to model the evacuation issues. Later, a number of researches have been done on this topic to design network links of proper dimensions to manage quick evacuation (Bakuli & Smith, 1996; Cruz & Smith, 2007; Cruz, Smith, & Medeiros, 2005; Mitchell & Smith, 2001; Smith, 1991).

Løvås (1995) has studied different performance measures for the evacuation system of a Norwegian offshore oil production platform and analyzed the effectiveness of two different evacuation strategies. He also has showed that queuing network theory and simulation methods can be used to evaluate the performance measures.

Lo and Fang (2000) have proposed a microscopic evacuation model which corresponds to a fine network approach that can efficiently portray the movement pattern of each occupant in a facility. To test the model a controlled evacuation is carried out at a lecture theatre in City University of Hong Kong and it is observed that the proposed model effectively describe the situation.

Xiang (2007) has formulated an equation to predict the evacuation time for young adults with a range of occupying density 0.24 ped/m^2 to 1.05 ped/m^2 in theatre-type rooms of size larger than 100 m^2. Chen and Miller-Hooks (2008) have formulated the Building Evacuation Problem with Shared Information (BEPSI) as a mixed integer linear program. The objective of the problem is to route the evacuees from multiple locations throughout the building to the building exits in minimum time.

They have performed the experiment on a network representation of an actual four-story building.

Liu, Yang, Fang, and Li (2009) have modified cellular automata (CA) evacuation model by considering the effect of occupant density around exits on human behavior in an evacuation. Comparison of the simulation and experimental results shows the usefulness of the improvement of the existing model. Lim (2011) has proposed another modification of CA model by using neural network. He also has found that density around exits played an important role on exit selection behavior of the occupants. Both Liu et al. (2009) and Lim (2011) have emphasized on the guidance and organization during emergency to help the occupants in selection of low dense exits and speed up the evacuation process.

Wadoo and Kachroo (2006a, 2006b) have developed feedback controls for an evacuation based on macroscopic models for one dimensional and two dimensional cases. Shende et al. (2007) have used optimal control strategy and obtained a smooth control profile as well as a smooth free flow velocity profile by using the method of steepest descent.

Shende et al. (2013) have presented a pedestrian flow model on a directed network of walkways with a single exit in which there are rooms of finite capacity adjacent to the walkways. They have proposed an optimal feedback control methodology for pedestrian evacuation from a network of walkways. The problem is formulated as a linear programming problem to make it appropriate for real-time execution. However, they have used Greenshields Model (Greenshields, et al., 1935) to account for the speed-density relationship which is linear and primarily has been developed for vehicular flow. Also, in the control design they have considered that all the walkways are of equal width. However, to design an effective evacuation system for a network of walkways, the capacities of the walkways are important. The capacity of a walkway depends on its width and length.

2.4 Summary

This chapter reviews existing literatures concerning pedestrian flow characteristics and pedestrian evacuation problem. A summary of the literatures reviewed in this chapter is presented in a tabular form in Appendix A. Through the literature review given in this chapter, it is identified that there is a need for an improved speed-density relationship model for pedestrian flow which can describe pedestrian speed more appropriately both in high dense and low dense condition. Also, a controlled evacuation methodology is required to compute the optimal flow rates for a multi-exit evacuation network to overcome the limitations of the research described by Shende et al. (2013).

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter describes the methodology used in this research. Section 3.2 gives several basic concepts related to pedestrian characteristics. Queueing theory along with the *M/G/c/c* queueing model and state dependent queueing model are described in Section 3.3. The performance measures of the *M/G/c/c* state dependent queueing system for pedestrian flow are presented in Section 3.4. Modelling of walkway with multiple arrival sources and topology with multiple walkways are given in Section 3.5 and Section 3.6, respectively. A brief description on optimization is given in Section 3.7 followed by a discussion on the conservation of mass in Section 3.8 and feedback linearization in Section 3.9. The facility under study is described in Section 3.10. The data collection procedure together with a complete description of the secondary datasets that are used in this research are presented in Section 3.11. A summary of the chapter is given in Section 3.12.

3.2 Definitions of Basic Concepts

This section gives a brief description of the pedestrian flow characteristics used in this thesis. These include pedestrian flow, speed and density.

3.2.1 Pedestrian Flow

The pedestrian flow refers to the number of pedestrians passing a cross-section of a pedestrian facility in a unit of time (Lee, 2005). The usual unit for flow is ped/m/sec (pedestrian per metre width per second). For example, let the width and length of a pedestrian trap be *w* and *l* respectively and *n* be the number of pedestrians observed during the observation time *T*. The pedestrian flow, denoted as q, can be calculated as

$$q = \frac{n}{T \cdot w} \tag{3.1}$$

3.2.2 Pedestrian Speed

The mean speed of pedestrian can be computed in two common ways. These are time mean speed and space mean speed. According to Teknomo (2002), the time mean speed is the average speed of all pedestrian passing a line on the pedestrian trap over a specified period of time. Let n and v_i be the number of observed pedestrians and the instantaneous speed of the *i*-th pedestrian, respectively. The time mean speed can be calculated as

$$\hat{v}(t) = \frac{\sum_{i=1}^{n} v_i(t)}{n} \tag{3.2}$$

The space mean speed is the average speed of pedestrians present on an area at a given moment (Lee, 2005). It is calculated on the basis of average travel time for the pedestrians to travel a fixed length of a pedestrian trap. If l is the length of a pedestrian trap and $\tilde{t}$ is the average travel time, then the space mean speed, *v* can be calculated as

$$v = \frac{l}{\tilde{t}} \tag{3.3}$$

If t_i^{out} and t_i^{in} are the time of *i*-th pedestrian to go out and go in the pedestrian trap respectively, then average travel time is given by