MODELING PERCEPTION AND OVERTAKING BEHAVIOR FOR CROWD DYNAMICS USING MODIFIED SOCIAL FORCE MODEL

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by

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TABLE OF CONTENTS

APPENDICES

LIST OF PUBLICATIONS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

A	area
A_r	area of investigation
A^{att}	social attractive strength
A^{rep}	repulsion strength
$A_{i,density}$	perceived density area of pedestrian i
$A_{i,percep}$	perception area of pedestrian i
A_i^{rep}	repulsion strength of pedestrian i
B^{att}	range of attractive interaction
B^{rep}	range of repulsion interaction
c	curvature of repulsion strength towards other pedestrians
c_i	center of respect area of pedestrian i
c_j	center of respect area of pedestrian j
d_{iW}	distance between wall and pedestrian i
D_{ir}	radius of respect area of pedestrian i
$D_{i,percep}$	radius of perception area of pedestrian i
$D_{i,wall}$	distance between wall and pedestrian i in density area
d_{ij}	distance between pedestrian i and pedestrian j
$d_{x_{ij}}$	horizontal distance of pedestrian i and j
$d_{y_{ij}}$	vertical distance of pedestrian i and j

f	pedestrian flow rate
f_i	familiarity factor of pedestrian i
k	elasticity constant
L	length
LL	lower left
LR	lower right
M_i	memory parameter of pedestrian i
m_i	mass of pedestrian i
N	number of pedestrian
N_{A_r}	number of pedestrian in area of investigation
P_i	panic parameter
P_i	Pedestrian with high or lower velocity
$percep$	perception
r_f	respect factor of pedestrian i
r_i	radius of pedestrian i
r_j	radius of pedestrian j
r_k	radius of pedestrian k
r_l	radius of pedestrian l
r_f^D	dynamic respect factor of pedestrian i
r_{ij}	sum of radii of pedestrian i and pedestrian j
r_{ix}	radius of pedestrian i at x-axis

r_{iy}	radius of pedestrian *i* at y-axis
r_{jx}	radius of pedestrian *j* at x-axis
r_{jy}	radius of pedestrian *j* at y-axis
T	estimated time
t	current time
$thres$	threshold value for losing patience
UR	upper right
UL	upper left
$V_{relative}$	relative speed
$\mathrm{W}(\varphi_{ij})$	pedestrian perception function
y_i	y-position of pedestrian *i*
y_j	y-position of pedestrian *j*

Greek Letters

α	constant
δ	decision function
ε_i	individual fluctuations
$\eta(x)$	distance function
θ	visual angle
$\theta_{direction}$	angle between positive x-axis and desired direction
$\theta_{overtaking}$	angle of social repulsion force direction and vertical line

$\theta(x)$	horizontal dimension of Gaussian function
$\theta(y)$	vertical dimension of Gaussian function
κ	friction constant
λ_i	angular parameter of the pedestrian *i*
λ_i^D	dynamic angular parameter
μ_x	origin of pedestrian *i*
μ_y	origin of pedestrian *y*
ρ	density
ρ^{max}	maximum density of surrounding crowd
ρ_i	local density of pedestrian *i*
$\tilde{\rho}$	non dimensional product of the crowd density
σ_x	product of parameters and desired velocity of pedestrian *i*
σ_y	product of parameters and desired velocity of pedestrian *i*
τ_i	relaxation time
φ_{ij}	angle between desired direction of motion and opposite direction of normalized vector between pedestrian *i* and *j*
$\varphi_{ij(1,2,\ldots,N)}$	discretization of entire pedestrian *i*' visual angle

LIST OF ABBREVIATIONS

JuPedSim	Jülích Pedestrian Simulator
HMFV	Helbing, Molnar, Farkas and Vicsek
LKF	Lakoba, Kaup and Finkelstein
SFM	Social Force Model
RF	Respect Factor
DRF	Dynamic Respect Factor
MDRF	Modified Dynamic Respect Factor

LIST OF APPENDICES

PEMODELAN PERSEPSI DAN TINGKAH LAKU MEMOTONG UNTUK DINAMIK KERUMUNAN MENGGUNAKAN MODEL DAYA SOSIAL TERUBAH SUAI

ABSTRAK

Model Daya Sosial (SFM) merupakan salah satu model popular dalam pergerakan pejalan kaki kerana ia mampu mensimulasikan tingkah laku pejalan kaki menggunakan persamaan matematik yang mudah. Banyak pengubahsuaian telah dilakukan untuk memperbaiki model ini seperti mengabungkan mekanisme penghormatan dalam model faktor hormat dinamik (DRF). Walau bagaimanapun, simulasi model ini menghasilkan tingkah laku yang tidak realistik kerana tiada persepsi terhadap pejalan kaki lain. Dalam model pengubahsuai faktor hormat dinamik (MDRF), mekanisma penghormatan diubah suai dengan memberi persepsi ini kepada pejalan kaki yang disimulasi. Selain itu, sedikit ubah suai tingkah laku memotong dilakukan dalam model SFM I, dengan tingkah laku tolakan antara pejalan kaki dihapuskan dan model asas SFM diubah suai secara minimum. Walau bagaimanapun, tingkah laku memotong tidak sepenuhnya berjaya dalam model ini. Oleh itu, model SFM I ditambah baik (dinamakan model SFM II) dengan mengubah arah haluan perjalanan ke kawasan yang kurang interaksi antara pejalan kaki, dan kekuatan daya tolakan diubah suai dengan merujuk kepada ketumpatan setempat dan kelajuan relatif. Persekitaran fizikal simulasi–simulasi ini adalah pada laluan satu arah yang normal. Pergerakan pejalan kaki dibandingkan menggunakan gambar-gambar daripada simulasi video pada masa yang berbeza. Seterusnya, pergerakan pejalan kaki antara model DRF, model MDRF, model asal Helbing, model Persepsi Helbing, model sudut penglihatan Yuen dan model-model yang telah diubah suai iaitu SFM I dan SFM II dibandingkan. Perbandingan masa keluar di laluan pe-

jalan kaki antara model sudut penglihatan Yuen dan model SFM II turut dikaji, dan keputusan menunjukkan masa keluar model SFM II lebih cepat berbanding model sudut penglihatan Yuen. Juga, didapati model MDRF dan model SFM II menunjukkan tingkah laku pejalan kaki yang lebih realistik, dan pembentukan lorong dalam model SFM II berjaya dipamerkan.

MODELING PERCEPTION AND OVERTAKING BEHAVIOR FOR CROWD DYNAMICS USING MODIFIED SOCIAL FORCE MODEL

ABSTRACT

The Social Force Model (SFM) is one of the most popular models to describe the motion of pedestrians as it is able to simulate the behavior of pedestrians using simple mathematical equations. Many modifications have been done to improve the SFM such as the incorporation of the self-slowing mechanism in dynamic respect factor (DRF) model. However, the simulations of the pedestrians produce unrealistic behavior because of the lack of the pedestrian's perception. In modified dynamic respect factor (MDRF) model, the self-slowing mechanism is enhanced by granting this perception to the simulated pedestrian. Another modification is to incorporate the overtaking behavior in modified SFM I model, in which the pushing behavior is completely eliminated, and the overtaking behavior is modeled with minimal modifications to the basic SFM. However, the overtaking behavior is partially successful in this model. Therefore, we enhance the modified SFM I (named as modified SFM II) by modifying the desired direction towards an area with less interaction between pedestrians, and modeling the repulsion strength with respect to local density and relative speeds. The physical environment is in the normal unidirectional walkway. The pedestrians movement is compared using the snapshots of the video simulations at various times. Subsequently, comparisons of the pedestrian flow pattern between DRF model, MDRF model, original Helbing model, Helbing Perception model, Yuen Visual Angle model, and modified SFM I and II models are conducted. Subsequently, a comparison of pedestrians' leaving time in a unidirectional walkway between the Yuen Visual Angle model and modified SFM II model is performed, and the result shows that the leaving

time of modified SFM II model is faster than Yuen Visual Angle model. It is also found that MDRF model and modified SFM II model demonstrated more realistic pedestrian behavior, and the lane formation phenomenon is successfully exhibited in the modified SFM II.

CHAPTER 1

INTRODUCTION

1.1 General Background

Improperly designed walking facilities may lead to the possibility of crowd-related disasters. With the increase in the growth rate of the population, especially in urban cities and famous places, the pedestrian demand exceeds the walkway capacity, later causing the available space for pedestrians' movement becoming smaller. This demand is based on pedestrians' activities when there is a massive pedestrian flow in the facilities. As a consequence, it leads to congestion which resulted in injuries and loss of lives. Hajj is one of the largest mass gatherings in the world, and there is a possibility of crowd disasters in mass gatherings due to overcapacity. Figure 1.1 shows the world crowd disaster sites displaying the world crowd disasters. The blue colored circle over Mecca indicates the frequent occurrence of crowd disasters at that site. During hajj in September 2015, more than 2,000 pilgrims had died due to the overcrowding of enormous masses where they were crushed in the blocked road of Mina leading up to Jamarat (Salamati and Rahimi-Movaghar, 2016). Other examples of crowd disasters include a mass panic at the Love Parade German Music Festival in July 2010. 19 people were killed, and about 100 people were injured due to overcrowding inside the tunnel. With thousands of people inside, the tunnel abruptly became packed and hot causing panic to quickly spread among people inside the tunnel, whom tried to escape but failed (Helbing and Mukerji, 2012). In February 2013, during the Hindu festival Kumbh Mela, a stampede occurred at a railway station in Allahabad, northern India.

36 people had died because of too many people standing on the platform. The victims were among the 30 million Hindu pilgrims who had returned home after attending the gathering of Kumbh Mela (Greenough, 2013).

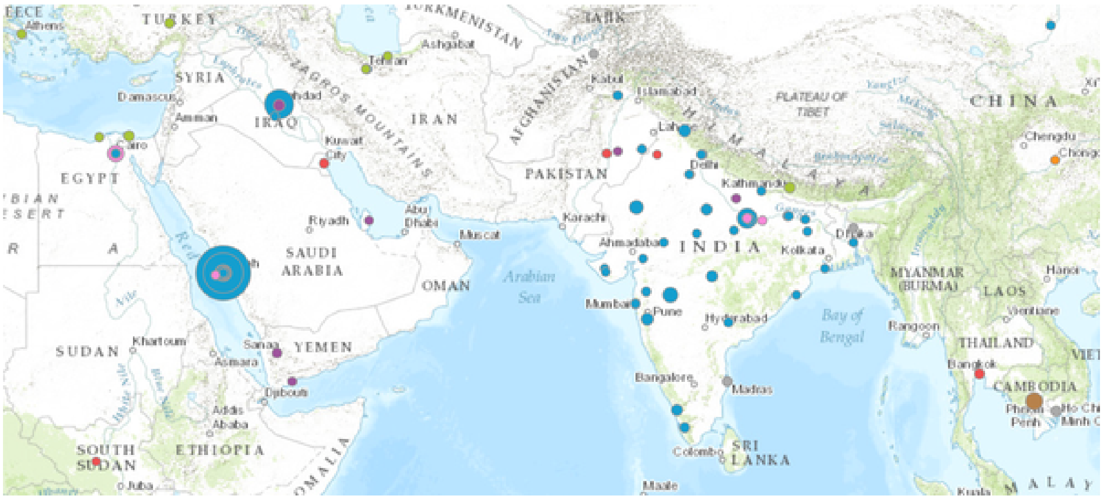

Figure 1.1: The world crowd disaster sites displaying the world crowd disasters. (Source picture: `https://www.gkstill.com/ExpertWitness/DisasterMap.html`).

One of the efforts to seek solutions to the consequences of crowd disasters is to improve crowd management by enhancing current or existing facilities and establishment of new facilities to meet this demand. In addition, understanding pedestrian dynamics is also essential for crowd management and to study pedestrian movement behavior because pedestrian movements are unpredictable (Helbing and Johansson, 2009). From the observations based on pedestrian walking behavior, Hoogendoorn et al. (2001) introduced the behavior of the pedestrian into three levels: 1) the strategic level (long term decisions); 2) the tactical level (short term decisions); and 3) the operational level (decisions for the immediate next moment). At the strategic level, a pedestrian makes a long term decision to plan his routes. He generates multiple ways to reach his destination. Next, at the tactical level, a pedestrian decides a path once he identifies the best path to reach his destination. Lastly, at the operational level, the pedestrian moves toward the destination based on the information he has gotten from the strategic level and tactical level. The pedestrian's moves include moving to a less dense crowd or overtaking a slower pedestrian. At this level, interactions with other pedestrians play an important role. By understanding the pedestrian's movement, the facilities can be designed effectively with a high level of safety. Therefore, the pedestrian crowd during normal and emergency situations can be predicted through mathematical modeling and simulation.

Therefore, to guarantee efficiency and providing safe pedestrian flows during normal situations and emergencies, the pedestrian crowd simulation is used. This simulation is a reliable tool to design and assess all kinds of facilities. Also, it is useful to study and to understand the pedestrian crowd behaviors in various situations. One of the open softwares to simulate and to analyze pedestrian dynamics is the Jülích Pedestrian Simulator (JuPedSim) (Chraibi and Zhang, 2016).

In this thesis, we further developed, modified and applied the simulation model which is based on "social forces" known as the Social Force Model (SFM). This model has been considered as the most realistic model that expresses the motivations of pedestrians to act as forces. In addition, this model has successfully shown the self-organization phenomena such as lane formation, oscillations at bottlenecks, crowd transition to in-coordination due to clogging, and 'faster-is-slower' due to impatience. Up to now, the model has gone through numerous modifications to make the model realistic and produce the self-organization phenomenon (Parisi et al., 2009; Yuen and Lee, 2012; Johansson et al., 2015; Zhang et al., 2018).

1.2 Research Problem

The SFM has been modified to produce a realistic model. However, several problems have not been analyzed by other researchers regarding the SFM which are as follows:

- The basic SFM has included pedestrian perception to simulate the model. The pedestrian perception is one of the most important parts to make a model more realistic. Up to now, there is very little attention being paid on the pedestrian perception. In the self-slowing mechanism, which is the constant and dynamic respect factor parameter, proposed by Parisi et al. (2009) and Zainuddin et al. (2010), respectively, the pedestrian perception in their model is granted with full perception, where this mechanism allows the pedestrians' movements to gradually stop as soon as they approach each other. However, when the pedestrian gradually stops, the pedestrian walkway becomes jammed because of pedestrians' lack of perception. This movement is unrealistic. Usually, when there is jamming occurring in front of the pedestrian, he will deviate his direction towards the less interaction or less density area. Therefore, in the self-slowing mechanism, the effect of pedestrian perception towards the density of his surrounding has not been studied.

- Previous studies have proposed overtaking behavior using artificial force (Yuen and Lee, 2012). The artificial force has a similar function with the pedestrian perception. Both terms are defined to model the overtaking. However, the artificial force is derived based on the social repulsion force in the SFM (Helbing et al., 2002), which implies that the equation of the pedestrian motion has two additional social repulsion forces. As a result, it gives the pedestrian a double social repulsion force towards other pedestrians around him. Therefore, a minimal modification of the SFM, which involves the social repulsion force, to model the overtaking behavior using the simplest equation has not been pursued yet.

1.3 Research Objectives

This research aims to obtain more realistic movements of the pedestrian which conforms to the real-life situations by incorporating several aspects, such as pedestrian's perception and overtaking behavior in SFM. The specific objectives of this study are:

- to incorporate the effect of perception, based on the density, into the modified dynamic respect factor in SFM,
- to incorporate the overtaking behavior into the SFM with minimal modifications to the original SFM, and
- to compare the pedestrians' leaving time in a unidirectional walkway between the Yuen Visual Angle Model and the modified model.

1.4 Importance and Significance of the Research

The major problem of crowd disasters is congestion. With the increase in the number of pedestrians, the need for proper and safe walking areas is essential to prevent injuries and loss of lives. The leading causes of this problem are the movement of pedestrians. By understanding the movement of pedestrians, it will help the researchers to incorporate realistic behaviors and also develop the simulators adequately. Thus, powerful simulators, based on mathematical models, need to perform large-scale pedestrian simulations with complex geometries. As a result, the simulation of the pedestrian movement is more realistic when compared with real-life situations. This research is useful mainly for event planners or architects to ensure the safety of the pedestrians and to test the reliability of architectural designs such as concert, shopping malls, public transport and religious ritual areas. This research focus is to mimic pedestrian behavior in real-life situations.

1.5 Research Scope

The primary goal of this study is to incorporate pedestrian behaviors such as the perception and overtaking behavior into the microscopic pedestrian dynamics model in a normal situation. The environment of this study is focused on the unidirectional walkway which is a representative environment in many areas. In addition, specific parameters will be modified in this study to produce realistic pedestrians' movements.

1.6 Research Methodology

The simulation of the microscopic pedestrian model is based on pedestrian movements. To develop a suitable simulator that conforms to real-life situations, understanding the specific aspects of pedestrians' behaviors is essential. In this research, the continuous microscopic pedestrian model, SFM, which has been proposed by Helbing and Molnár (1995) is used, where the focus is primarily on the tactical level of pedestrian behavior where the decision to choose a walking path is made. There are two main contributions of this research. Firstly, pedestrian perception is incorporated into the self-slowing mechanism, which is the dynamic respect factor. This modification is an extension to the contribution of Parisi et al. (2009), where the authors modified the self-stopping mechanism (Seyfried et al., 2005) into the self-slowing mechanism (constant respect factor) to make the pedestrians' behavior more realistic. Then, the density of the surrounding pedestrian, proposed by Shuaib (2014), is added into the pedestrian perception. The effect of the pedestrian perception, which is dependent on the density of the surrounding is examined in Chapter 3.

Secondly, the overtaking behavior is incorporated into the SFM in Chapter 4. There is an issue about the overtaking process in the aspect of the pedestrian perception and visual angle from previous studies. Therefore, the difference between pedestrian perception and visual angle is investigated in Chapter 4. Subsequently, a minimal modification of the SFM to model the overtaking behavior, which involves pedestrian perception is proposed and incorporated. These modifications are introduced in the social repulsion force to mimic pedestrians' behavior in real-life situations. These contributions are extensions to the original model, in the aspect of respect factor and overtaking. The pedestrians' behaviors are studied based on the video simulations, which help to confirm their behaviors in real-life situations. The effects of these contributions relevant to the self-organization phenomena are examined.

1.7 Organization of Thesis

This thesis consists of five chapters as shown in Figure 1.2. Chapter 1 presents the background of the study on crowd dynamics. Chapter 2 reviews the pedestrian studies in crowd dynamics. Chapter 3 discusses the self-slowing mechanism. The problem regarding this mechanism by using dynamic respect factor is explained, and the modified dynamics of the respect factor is introduced to the respect mechanism in the uni-directional walkway to produce realistic behavior. Chapter 4 introduces the overtaking behavior where the contributions are divided into two parts. The first part is about providing faster pedestrians with the ability to perform overtaking process. In the second part, the overtaking behavior is refined by considering the magnitude and direction of the overtaking process. Chapter 5 is the conclusions and recommendations of the research and summarizes requirements and ideas for further work.

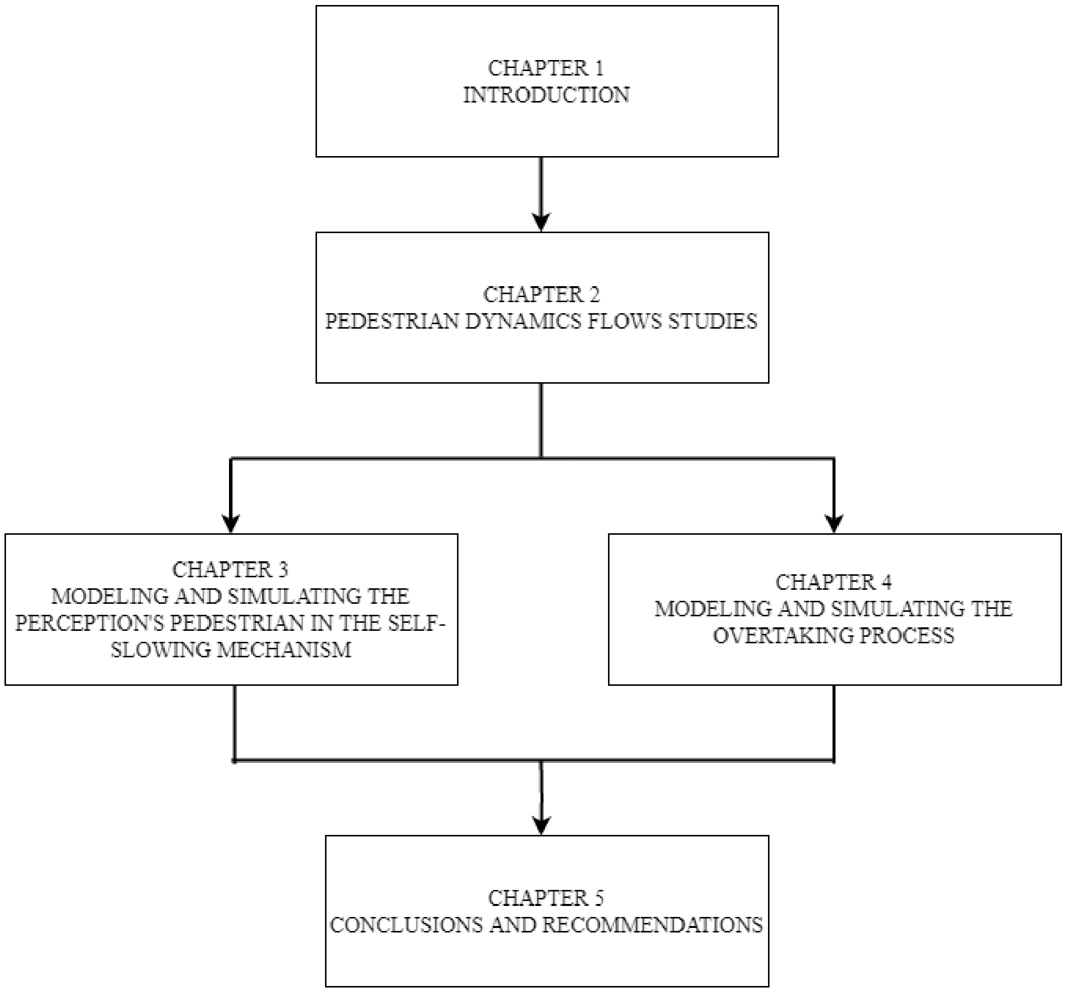

Figure 1.2: Overview of the thesis outline.

CHAPTER 2

PEDESTRIAN DYNAMICS FLOW STUDIES

2.1 Introduction

Understanding the fundamental mechanisms governing crowd movements is essential to minimize the risk of injuries or loss of lives in the large mass gatherings. Reliable analysis approaches such as qualitative and quantitative analysis are required to analyze pedestrian walking flow. These approaches are useful for the practical applications of pedestrian dynamics such as an optimization of pedestrian facilities and assessment of escape routes. In addition, these approaches are also useful to describe the collective behavior either individual or a group in the simulations such as overtaking, self-slowing mechanism and following leader. Therefore, it is possible to develop realistic crowd modeling models that can be validated and calibrated against the results of these approaches. In this chapter, an overview for the pedestrian dynamics flow is presented, where Section 2.2 presents crowd movements phenomena, Section 2.3 discusses about the empirical results for pedestrian flow, Section 2.4 reviews the pedestrians dynamic models, Section 2.5 described the details about SFM and it modifications in Section 2.6.

2.2 Crowd Movement Phenomena

A pedestrian model should be able to mimic the pedestrian movement as well as simulate the collective phenomena to produce a realistic behavior. A summary of the pedestrian movement and the self-organization phenomena are presented in the following section.

2.2.1 Motion Base Cases

The motion base cases can be observed in macroscopic and microscopic pedestrian level and also, it can be classified into crowd and individual movement base cases. For crowd movement base cases, Duives et al. (2013) has proposed eight types of crowd motion base cases (see Figure 2.1 A1-A8). Subsequently, individual movements proposed by other researchers such as avoiding, self-stopping, following and overtaking are added into the motion base cases. Figure 2.1 shows the crowd and individual motion base cases.

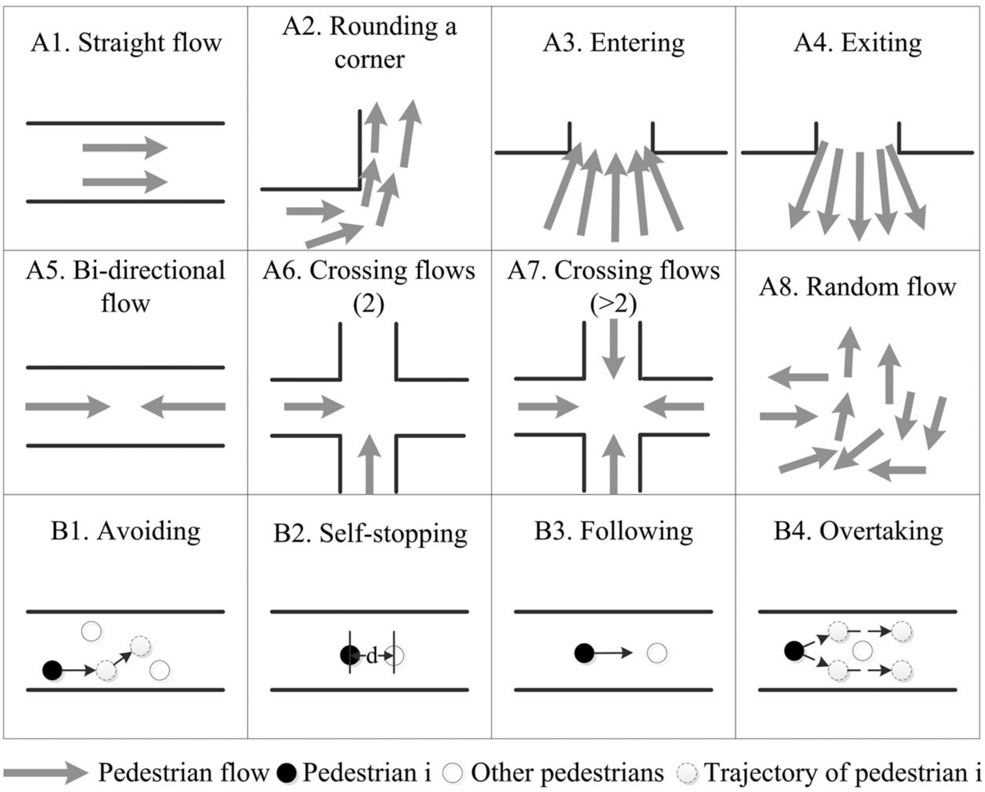

Figure 2.1: A visualization of the crowd (A1-A8) and individual (B1-B4) motion base cases (Chen et al., 2018).

Crowd motion can be classified into two types of a walkway, which are a uni-directional and a multi-directional walkway. The uni-directional walkway can be in straight flow (Figure 2.1 (A1)), flow rounding a corners (Figure 2.1 (A2)), flow entering a bottleneck (Figure 2.1 (A3)) and flow exiting a bottleneck (Figure 2.1 (A4)). In a uni-directional flow, pedestrians move with one direction and changing their direction when pedestrians are rounding a corner. The bottleneck flow can be either in two situations, which are pedestrian entering or exiting a bottleneck. When pedestrians are entering a bottleneck, pedestrians' available walking space become decrease, and the pedestrians' available walking space will be increase as soon as they are exiting a bottleneck. For multi-directional walkway, it can be classified into parallel flows or crossing flows. A parallel flow, which is bi-directional flow (Figure 2.1 (A5)), is described when two uni-directional pedestrian flows are moving in the opposite directions. For crossing flows, it occurs at the junction when the pedestrian flow is more than two (Figures 2.1 (A6 and A7)) or random flows (Figure 2.1 (A8)).

The analysis of individual behavior is particularly useful in observing the movement changes made by pedestrians in order to adapt to specific environmental changes, such as speeding up their speed to follow a group of pedestrians or shifting to prevent collisions with other pedestrians. Another collective pedestrian movement occurs, in reality, are overtaking and respect mechanism. Pedestrians with high velocities tend to overtake other pedestrians who have lower velocities to maintain their own desired walking velocity. The respect mechanism describes that the movement of the pedestrian will be slowly stops when he is facing a pedestrian who is in the opposite direction as him or approaching pedestrians who are in the same direction as him. These type of behavior usually found in a railway station during rush hour or pedestrian streets.

2.2.2 Self-organization Phenomena

Self-organization phenomena is defined as patterns produced by pedestrians which is not externally planned, prescribed or organized (Helbing et al., 2001). Many researchers are interested in investigating pedestrian dynamics because a variety of self-organization phenomena can be observed in pedestrian dynamics. These effects are caused by individual interaction or individual desire. Also, it gives essential information for crowd modeling approaches. The most common self-organization phenomena produced by pedestrians are lane formation, jamming and clogging.

2.2.2(a) Lane Formation

Lane formation is formed when two groups of pedestrians are moving in the opposite directions. By forming this phenomenon, it helps to reduce the interactions among pedestrians, allowing the pedestrians to move with comfort. Usually, this phenomenon occurs where the gap between pedestrians are not large. For example, in a bidirectional walkway, if a pedestrian happens to move in the opposite direction of other pedestrians, he makes a decision to avoid other pedestrians either by moving to the left or to the right side. The lane formation formed by this pedestrian is usually inconsistent and always varies in time, if there is a small change in density. Figure 2.2 shows the lane formation in opposite walking directions.

2.2.2(b) Jamming and Clogging

Jamming and clogging occur in high densities. Clogging happens when the pedestrians flow exceeds the capacity. Under high pressure, the jamming phenomenon is formed in front of the bottleneck at the exit, as shown in Figure 2.3. This type of jamming is necessary for practical applications, especially in evacuation simulation. Besides that, jamming also occurs if two groups of pedestrians mutually block each other under high densities; hence, they are unable to turn around and move back.

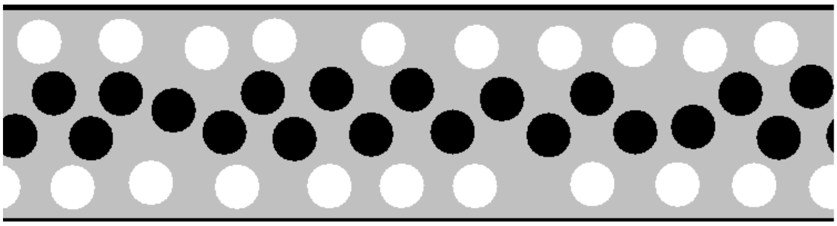

Figure 2.2: Lane formation formed in the opposite walking directions. White pedestrians are moving from left to right and black pedestrians are moving from right to left (Helbing et al., 2002).

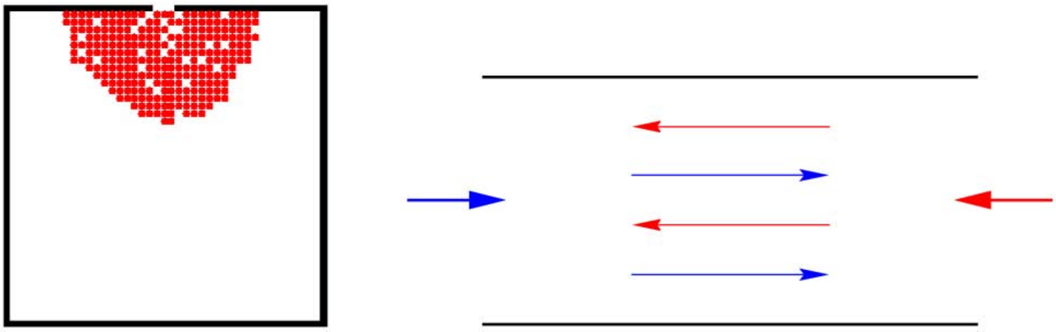

Figure 2.3: Schematic representation of collective phenomena observed in pedestrian dynamics. Left: Clogging at a bottleneck. Right: Lane formation in bidirectional walkway (Schadschneider et al., 2009).

2.3 Empirical results

Empirical results are essential for design, validation and calibration. These results are useful for the development of models and their applications such as safety studies and legal regulations. The approaches that are usually used to analyze the data in pedestrian studies are the trajectory, the pedestrian flow characteristics and the fundamental diagram.

2.3.1 Trajectory

The trajectory of a pedestrian is defined as his walking path over time, which is introduced graphically and provides complete information about the pedestrian motion such as the location and the movement in longitudinal and lateral directions. The data of the pedestrian trajectory is extracted from video recordings.

2.3.2 Pedestrian Flow Characteristics

Pedestrian flow characteristics such as density, mean speed and pedestrian flow rate can be observed at the microscopic and macroscopic pedestrian level.

2.3.2(a) Density

The density of a pedestrian flow is defined as the number of pedestrians N within a specific area A at a given moment t. It is calculated by

$$\rho = \frac{N}{A}. \tag{2.1}$$

The unit for density is represented by Pm^{-2}, where P denotes the number of pedestrians and m is denotes meter.

2.3.2(b) Mean Speed

The instantaneous mean speed $\bar{V}_{inst}$ is defined as the average value of the pedestrians' speed (the components of the velocities in the considered direction) that are presented in an area A at any given moment. It is expressed by

$$\bar{V}_{inst}(t) = \sum_{i=1}^{N} \left(\frac{\bar{v}_i(t).\bar{e}_i{}^o(t)}{N} \right), \tag{2.2}$$

where N is the number of pedestrians inside area A at time t; $\bar{v}_i(t)$ is the actual velocity of pedestrian i at time t; and $\bar{e}_i{}^o(t)$ is the desired direction of pedestrian i at time t.

2.3.2(c) Pedestrian Flow Rate

The flow rate is defined as the number of pedestrians passing a cross-section of an area during a specific period of time. It is defined as

$$f = \frac{N}{L/T}, \tag{2.3}$$

where N is the number of pedestrians passing the cross-section which has length L in meters; and T is the time period in seconds. Hence, pedestrian flow rate is expressed as number of pedestrians per meter per second (P/m/s).

2.3.3 Fundamental Diagrams

Pedestrian flow characteristics can be well explained in the form of fundamental diagrams, which show the relationship between two macroscopic variables such as speed-density, flow-density and flow-speed. Understanding these relations are essential in the planning, design, and implementation of pedestrian facilities (Vanumu et al., 2017). Many researchers have conducted simulations to fit the models with fundamental diagrams under normal situations (Daamen et al. (2005); Seyfried et al. (2005); Parisi et al. (2009)). However, due to the variations of pedestrian environments, the

Table 2.1: Examples of estimated speed-density and flow-density relations for uni-directional pedestrian traffic flow from Fruin, Sarkar and Janardhan, Weidmann and Older (Shuaib, 2011).

Reference	Speed-density and flow-density relation	Situation
Fruin (1971)	$v(\rho) = 1.43 - 0.35\rho$ $f(\rho) = 1.43\rho - 0.35\rho^2$	Peak-hour flows at large commuter bus terminal
Weidmann (stated in Lakoba et al., (2005))	$v(\rho) = 1.34\left[1 - \exp\left(-1.91\left(\frac{1}{\rho} - \frac{1}{\rho^{max}}\right)\right)\right]$ $f(\rho) = \rho * 1.34\left[1 - \exp\left(-1.91\left(\frac{1}{\rho} - \frac{1}{\rho^{max}}\right)\right)\right]$ $\rho^{max} = 5.4\ \mathrm{P/m^2}$	Pedestrian traffic
Sarkar and Janardhan (1997)	$v(\rho) = 1.46 - 0.35\rho$ $f(\rho) = 1.46\rho - 0.35\rho^2$	Metropolitan transfer area
Older (1968)	$v(\rho) = 1.31 - 0.34\rho$ $f(\rho) = 1.32\rho - 0.34\rho^2$	Shopping street

conditions which the researchers adopted in their studies also vary as shown in Table 2.1. Therefore, it leads to various fundamental diagrams as shown in Figures 2.4 and 2.5. Most researchers have conducted their studies to obtain fundamental diagrams for their own models, with common attainable conditions: homogeneous and stationary flow in unidirectional walkway and normal situation, with no repulsion or attractive sources.

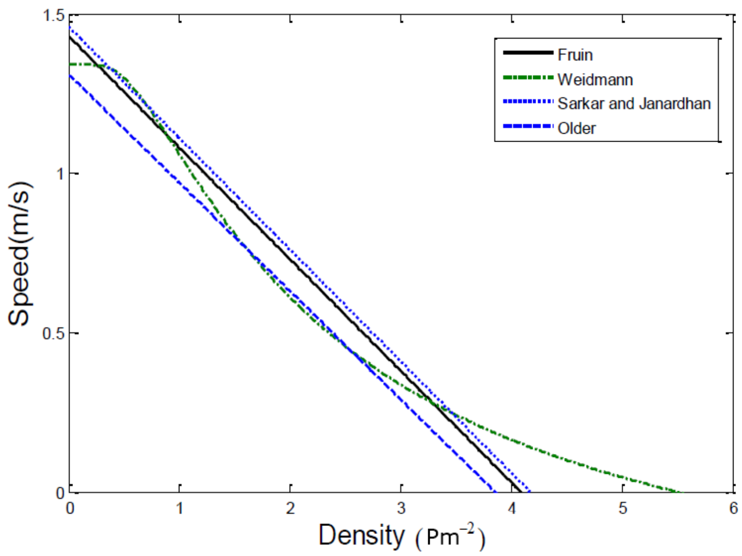

Figure 2.4: The estimated speed-density relations for unidirectional pedestrian traffic flow (Shuaib, 2011).

As can be seen in Figure 2.4, most of these models are based on linear speed-density relation except for Weidmann (1993), where he used a double S-bended curve. For flow-density relations, the diagrams are quadratic as shown in Table 2.1 and Figure 2.5.

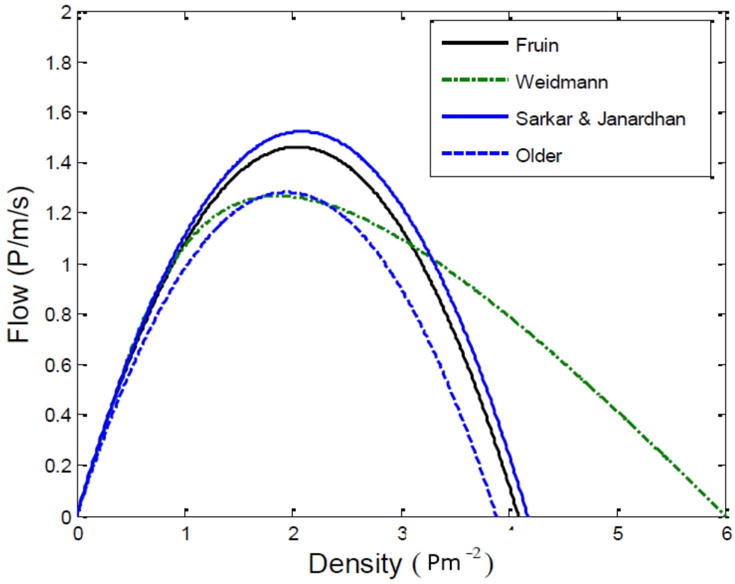

Figure 2.5: The estimated flow-density relations for unidirectional pedestrian traffic flow (Shuaib, 2011).

Weidmann fundamental diagram is a quantitative benchmark for models of pedestrian dynamics (Daamen, 1999; Kirchner & Schreckenberg, 2004; Seyfried et al., 2006; Parisi et al., 2009; Zainuddin et al., 2010; Shuaib, 2014). Here, we are focused on the fundamental diagrams proposed by Weidmann (1993), where it is used as a comparison by a proposed model in order to reproduce the fundamental diagram of the pedestrian flow. According to Weidmann (1993), the fundamental diagram of pedestrian flow on flat areas is plotted by collecting 25 data sets. The velocity versus density curve in Figure 2.6 is plotted using (Weidmann, 1993)

$$v(\rho) = v_i \left(1 - \exp\left[-1.91\left(\frac{1}{\rho} - \frac{1}{\rho^{max}}\right)\right]\right), \tag{2.4}$$

where v is the average speed of a pedestrian moving in a crowd in a sufficiently wide walkway; $v_i^o = 1.34$ m/s is the desired speed of pedestrian i; ρ_i is the density of the surrounding crowd; $\rho^{max} = 5.4$ P/m^2 is maximum density of the surrounding crowd. Figure 2.6 shows that as the density-domain increases, the velocity decreases. According to Weidmann (1993), ρ are divided into 4 domains and it is explained as below.

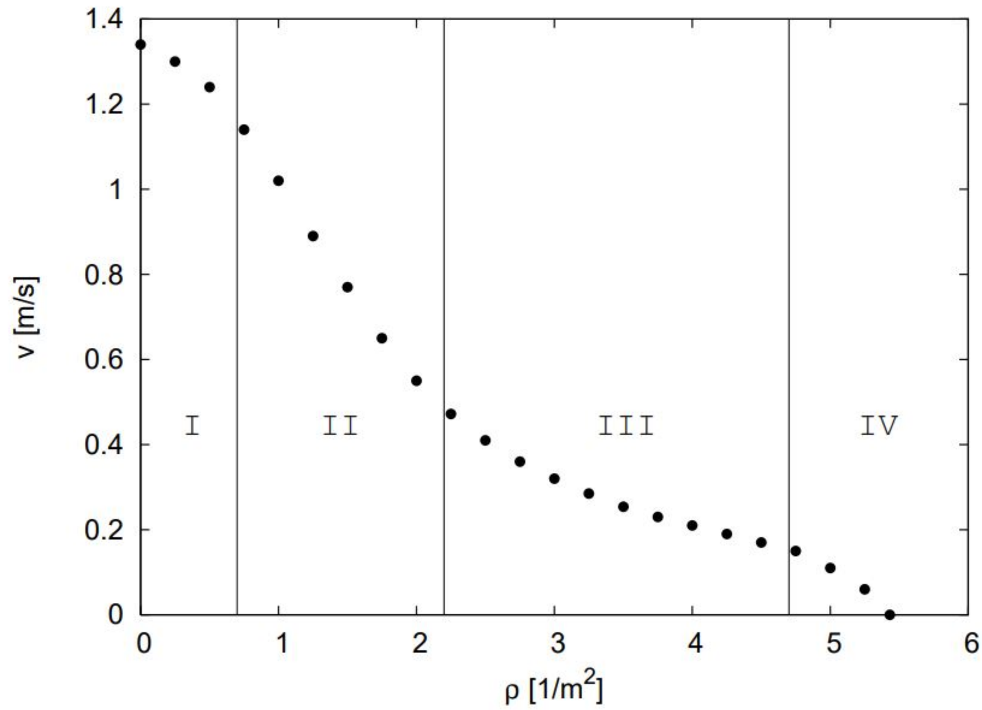

Figure 2.6: The empirical relation between density and velocity based on average speed by Weidmann (1993).

- **Domain I**: $0 \leq \rho < 0.7$

  In domain I, the velocity of the pedestrian decreases gradually. Pedestrians in the area of lower density moves at their own desired velocity. The decrease in the velocity is caused by the passing maneuvers.

- **Domain II**: $0.7 \leq \rho < 2.3$

  The velocity linearly decreases with increasing density. As the density increases, the pedestrian has a limited choice to choose his desired velocity due the reduction of space. However, the physical forces between pedestrians are less in this domain.

- **Domain III**: $2.3 \leq \rho < 4.7$

  The linear decrease in velocity ends in this domain, where the velocity of the pedestrians becomes nearly constant. The physical contact is unavoidable causing the physical forces to increase.

- **Domain IV**: $\rho \geq 4.7$

  The velocity of the pedestrian decreases drastically. Pedestrians in the area of higher density hardly move due to the restricted space. The physical forces determine the velocity of the pedestrians. Pedestrians are completely unable to move at their desired velocity.

2.4 Pedestrians Dynamic Models

The development of dynamic pedestrian models has become an important area in a variety of fields of study. Pedestrian models can be divided into two types, which are microscopic and macroscopic (May, 1990). Microscopic pedestrian models focus on pedestrian characteristics such as individual interactions, direction and speed. The behavior of pedestrians is influenced by the natural environment or the building structure. There are numerous simulation approaches, such as SFM (Helbing & Molnár, 1995; Helbing et al., 2000; Helbing et al., 2001; Helbing et al., 2002; Helbing et al., 2005), Optimal Velocity Model (Nakayama & Sugiyama, 2003; Nakayama & Sugiyama, 2005) and Cellular Automata (CA) Model (Ji et al., 2013; Ji et al., 2016; Fu et al., 2017).

Macroscopic pedestrian models are described by locally averaged quantities, specifically density, velocity and energy. This approach is applicable in large crowds, where it deals with group behavior and the crowd as a whole. Pedestrian interactions and relationships are ignored in this approach. The advantage of these models is that, they are less computationally intensive compared to the microscopic models, because they are more concerned with collective behavior of the crowd. These models can can be derived from conservation equations related to mass, linear momentum and energy. They are usually represented by partial differential equations, where the initial and/or boundary value has to be prescribed in order to obtain a solution. Examples of first order macroscopic models can be found in Helbing et al. (2006), Venuti et al. (2007), Coscia and Canavesio (2008) and Huang et al. (2009), and for second order macroscopic models, they can be found in Bellomo and Dogbe (2008), Jiang et al. (2010) and Jiang and Zhang (2012).

2.5 Social Force Model

The SFM is the most important model in pedestrian studies because it can reproduce the self-organized phenomena and simulate realistic pedestrian behavior. Many modifications have been done to improve the model. The development of the SFM was inspired by Lewin's model (Lewin, 1951), where the behavioral changes are guided by the social forces. Helbing and Molnár (1995) has developed the SFM based on this idea and expressed it into mathematical terms. Subsequently, this model was extended by including the physical forces into the model of Helbing et al. (2000). Therefore, the pedestrian motion of this model is described as a combination of social-psychological and physical forces based on Newtonian equation.

A pedestrian is defined as a particle with a centre, a radius r_i, a position $\bar{x}_i$ and velocity $\bar{v}_i$ at time t. According to Helbing and Molnár (1995) and Helbing et al. (2000), the pedestrian movement is driven by internal motivations and physical motions. Therefore, based on Newton second law of motion, the equation of the pedestrian movement can be expressed in the mathematical form using the following formulas (Wang, 2016):

$$\frac{d\bar{x}_i(t)}{dt} = \bar{v}_i(t), \tag{2.5}$$

$$\frac{d\bar{v}_i(t)}{dt} = \bar{a}_i(t), \tag{2.6}$$

$$m_i\bar{a}_i(t) = \bar{f}^{Total}(t), \tag{2.7}$$

$$m_i\bar{a}_i(t) = m_i\frac{d\bar{v}_i(t)}{dt} = \bar{f}^{Total}(t) + \varepsilon_i(t), \tag{2.8}$$

where $\frac{d\bar{x}_i}{dt}$ is the instantaneous change of pedestrian i's position; $\frac{d\bar{v}_i}{dt}$ is the rate of change of pedestrian i's velocity; m_i is a mass of pedestrian i; $\bar{a}_i$ is an acceleration of pedestrian i; $\bar{f}^{Total}$ is the sum of all forces acting on pedestrian i; ε_i are individual fluctuations when pedestrians suddenly change their minds and change their walking direction. Figure 2.7 shows the graphical representation of the forces acting on pedestrian i.

$\bar{f}^{Total}$ is defined as the summation of all forces acting on the pedestrian i, which consists of the preferred force $\bar{f}_i^{pref}$, the social interaction force between pedestrians $\bar{f}_{ij}$, and the social interaction force between pedestrian and wall $\bar{f}_{iW}$ (Helbing et al., 2000). It is defined as

$$\bar{f}^{Total}(t) = \bar{f}_i^{pref}(t) + \sum_{j \neq i} \bar{f}_{ij}(t) + \sum_{W} \bar{f}_{iW}(t). \tag{2.9}$$

$\bar{f}_{ij}$ is the summation of the interaction forces between pedestrians, which consists of the attraction force $f_{ij}^{\bar{att}}$, the social repulsion force $f_{ij}^{\bar{rep}}$ and the physical force $f_{ij}^{\bar{phy}}$ (Helbing et al., 2000). It is expressed as

$$\sum_{j \neq i} \bar{f}_{ij}(t) = f_{ij}^{\bar{att}}(t) + f_{ij}^{\bar{rep}}(t) + f_{ij}^{\bar{phy}}(t). \tag{2.10}$$

Analogously, $\bar{f}_{iW}$ is a summation of the interaction forces between pedestrian and wall, which consists of the attraction force $f_{iW}^{\bar{att}}$, the social repulsion force $f_{iW}^{\bar{rep}}$ and the physical force $f_{iW}^{\bar{phy}}$ (Helbing et al., 2000). These forces are defined as

$$\sum_{W} \bar{f}_{iW}(t) = f_{iW}^{\bar{att}}(t) + f_{iW}^{\bar{rep}}(t) + f_{iW}^{\bar{phy}}(t). \tag{2.11}$$

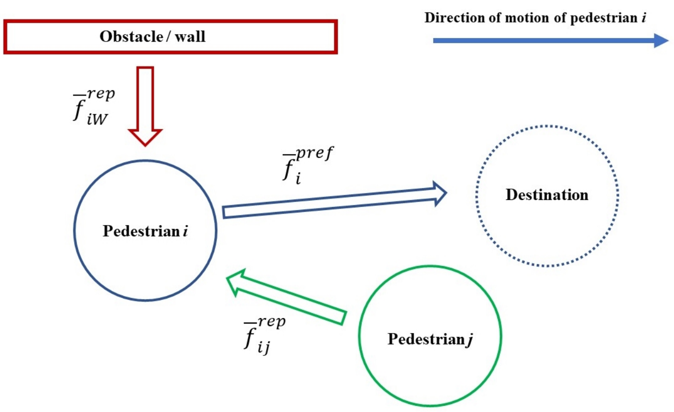

Figure 2.7: The graphical representation of the different forces acting on pedestrian i.

2.5.1 The Preferred Force

The preferred force is defined as a motivation of the pedestrian i who wants to reach his desired destination $\bar{x}_i^o$ as comfortable as possible and it is graphically presented in Figure 2.8. Therefore, he is looking for a uniform velocity, which represents his desired velocity $\bar{v}_i^o$ (Helbing and Molnár, 1995):

$$\bar{v}_i^o(t) = \frac{\bar{x}_i^o - \bar{x}_i(t)}{T - t} = \frac{s_i(t)}{T - t}\bar{e}_i^o, \tag{2.12}$$

$$\bar{e}_i^o(t) = \frac{\bar{x}_i^o - \bar{x}_i(t)}{\left\|\bar{x}_i^o - \bar{x}_i(t)\right\|}, \tag{2.13}$$

where s_i is the distance between the current location $\bar{x}_i$ of pedestrian i and his desired destination $\bar{x}_i^o$; T is estimated time to arrive his desired destination; t is current time at his current location; $\bar{e}_i^o$ is desired direction towards his desired destination. If a pedestrian's motion is not disturbed, he will adapt his actual velocity to his desired velocity within a relaxation time τ_i. The preferred force $\bar{f}_i^{pref}$ can be described by an acceleration term of the form (Helbing and Molnár, 1995)

$$\bar{f}_i^{pref}(t) = \frac{m_i}{\tau_i}(\bar{v}_i^o(t) - \bar{v}_i(t)), \tag{2.14}$$

where m_i is the mass of pedestrian i; τ_i is the relaxation time; $\bar{v}_i^o$ is the desired velocity and $\bar{v}_i$ is the actual velocity.

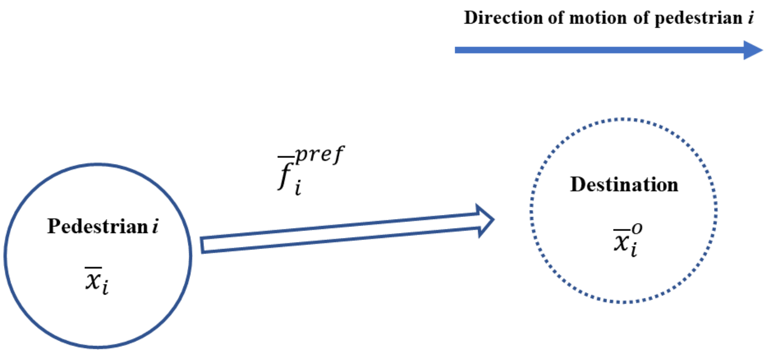

Figure 2.8: The graphical representation of the preferred force acting on pedestrian i.

2.5.2 The Repulsion and Attraction Forces

The motion of a pedestrian i is influenced by all the pedestrians surrounding him, as shown in Figure 2.9. He always keep a certain distance from other pedestrians. This distance forms the pedestrian area which is owned by the pedestrian, also known as the private sphere or the territorial effect area. The territorial effect area plays an essential role when the pedestrian i feels uncomfortable if pedestrian j is closer to him. As the distance between pedestrians increases, the social repulsion force between pedestrians becomes weaker. So, the social repulsion force $\bar{f}_{ij}^{rep}$ is formulated in exponential form by Helbing and Molnár (1995) and it is defined as

$$\bar{f}_{ij}^{rep}(t) = A^{rep}.\exp\left(\frac{r_{ij} - d_{ij}(t)}{B^{rep}}\right).\bar{n}_{ij}(t).W(\varphi_{ij}(t)), \tag{2.15}$$

where A^{rep} denotes the repulsion strength; B^{rep} is the range of the repulsion interactions, which is culture-dependent and individual parameters; $r_{ij} = r_i + r_j$ is the sum of radii r_i and r_j; $d_{ij} = \left\|\bar{x}_i - \bar{x}_j\right\|$ is the distance between the centers of pedestrian i