MICROSCOPIC MODELLING OF PEDESTRIAN DYNAMICS

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CERTIFICATE

This is to certify that the thesis entitled, **"*Microscopic Modelling of pedestrian Dynamics*"** submitted by **Tarapada Mandal** bearing roll no. **612CE3009** in partial fulfilment of the requirements for the award of **Master of Technology (Research)** degree in C**ivil Engineering** with specialization in **"Transportation Engineering"** during 2013-2015 session at the National Institute of Technology, Rourkela is an authentic work carried out by him under our supervision and guidance.

To the best of our knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

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ABSTRACT

Walking is the most primitive mode of transportation. In modern age this primary mode has not become obsolete as it furnishes access to those stretches of places which are not reachable by any vehicular mode of transport. Pedestrians are multiplying day by day in cities. Hence Pedestrian motion has immensely become a complex phenomenon. It is important to make out critical aspects of pedestrian motion to avoid collisions between pedestrians or any unexpected occurrence that has many precedents, like stampede. To understand this fuzzy motion, it is important to closely oversee this process of human movement and relate it to some mathematical form for easy understanding. In this study, a lot of data related to pedestrian motion are collected from various places in eastern India. The study has mainly observed and recorded speed, flow and density of individual pedestrians. Statistical analysis is done here for comparing different types of data sets. Behaviours of pedestrians on different facilities and how these behaviours affect the flow parameters are studied here. The study analyzes Level of service of different pedestrian facilities. Oscillation phenomena occurring at bottlenecks are illustrated taking reference from already conducted experiments by other researchers. In this study a model is developed to mimic the pedestrian flow while moving along a corridor or evacuating from a closed space. The model is a microscopic discrete model using cellular automata. The model imitates some simple rules practiced by the pedestrians for decision making while moving in a space. It can explain the lane changing phenomena in pedestrian streams. The model is very realistic in the direction choice approach of pedestrians. It is capable of modelling different crowd levels. The model is validated by the data collected from different facilities.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Background

The most primitive and elementary mode of transportation is walking. This mode helps people to reach different establishments which are inaccessible by other modes of transportation and this is found to be an integral part of any journey by any mode. Lots of efforts have been made in comprehending vehicular traffic flow in Indian context but not much work has been found in literature on pedestrian flows. It can be conjectured that less attention on pedestrian motion is furnished as pedestrian motion is not directly related to economy as compared to vehicular motion.

It is very important to understand pedestrian motion to design any facility for pedestrians. Understanding pedestrian movement also encourage calculating the level of service (LOS) of the facilities (i.e. safety, efficiency, comfort and evacuation time of numerous pedestrians). These help in better designing and forecasting usability of those facilities. It can’t be contradicted that understanding pedestrian motion is paramount crucial in a country like India where population is huge and growing consistently at a faster rate. Pedestrian motion is a very complex phenomenon to understand and to model. At larger densities, it becomes a matter of concern, if the pedestrians do not behave coherently and orderly. In very recent past due to chaotic behaviour of the panic stricken pedestrians disasters took place claiming several fresh lives. Stampede which occurred in Patna (October’2014), Mumbai (January’2014), Madhya Pradesh (October’2013) are still fresh in our memories. These tragic incidents were caused due to freakish (with full of various emotions like excitement, fear, anger, confusion etc.) behaviour of pedestrians, poor level of service of the facilities and poor crowd management that led to crowd crushing. Modelling crowd motion is a tough task as crowd movement is a very complex and fuzzy process and needs a lot of factors to be taken into consideration. This study focuses to understanding and modelling pedestrian motion in normal conditions.

Cellular Automata (CA) is a mathematical tool that has been used for years to describe complex systems. It can be viewed as a simple model of spatially prolonged decentralized system comprised of a number of cells (individual components). The dissemination between these cells is restricted to local interaction. The overall formation can be perceived as a parallel processing device. This simple structure of cellular automata is dynamically stable i.e. addition of some new features would not lead to instability of the form and when these simple conformations are iterated several times it produces complex patterns which are similar in nature to those made by pedestrians. Cellular automata modelling involves in very less computational cost. There are various cellular automata models available in literature (*references*).

Blue Alder model which is one of the simplest models to understand pedestrian motion in pedestrian circulation areas but it is not logical in terms of direction choice of pedestrians when some obstacles (slow moving pedestrians or other obstacles) are found near vicinity.

There is a need to understand the correlation between different sizes of the sidewalks, different densities and how the pedestrian motion depends on them. Fuzzy inference based modelling is a tool that can be to fill up the gaps which were not addressed earlier. Fuzzy logic can help describe the fuzzy relationship between different parameters.

1.2 Objectives and Scope

It is attempted to

(a) Observe pedestrian motion empirically (as there is no exact method till today) on long corridors (Foot over bridge, footpath, platform, stairwell etc.)

(b) To make a real life dataset of the basic flow parameters (speed, flow, density)

(c) Statistically analyse different datasets for different cases.

(d) LOS prediction on different types of facilities.

(e) Model pedestrian motion on those facilities.

Scope of this research work:

(a) Five pedestrian facilities (Foot over bridge in Kolkata, two sidewalks in Rourkela, two Railway platforms in Rourkela and Manoharpur) are chosen to observe pedestrian motion on them.

(b) Huge number of data on pedestrian speed, density, flow and evacuation time are collected.

(c) Several statistical tests are conducted to make analogies among different data sets.

(d) LOS is predicted on the basis of limited data collected on different facilities to get an idea about the serviceability of those facilities chosen in this study.

(e) Modelling pedestrian motion on only sidewalks are done. Two different models are formulated. CA based model provides important insight in the direction choice of pedestrians in a more logical way. However, the CA model considers only unidirectional movement. Another Fuzzy inference based model helps understanding the effects of sidewalk width and crowd density on pedestrian speed and evacuation time.

1.3 Organisation of the thesis

This thesis is organised in six chapters of which this is the first. Chapter two deals with literature review. Chapter three comprises of empirical studies. Chapter four describes the proposed model while chapter five manifests the validation of the model. Chapter six concludes the thesis by summarizing the works done here.

Chapter 2

Literature Review

In this chapter a review of past studies on pedestrian dynamics is presented. After that the motivation behind this thesis is proclaimed followed by a problem statement.

Literature review is necessary in two major fields to satisfy the objective and scope of the present study. One of the areas is empirical studies to understand from the literature how different pedestrian flow parameters are observed empirically in the earlier studies. The second phase of the literature review is required in the area of modelling pedestrian movement on different sidewalks.

This chapter is divided into four subsections; the first discusses those empirical studies done to understand pedestrian dynamics while the second one describes the models already developed for pedestrian motion by other researchers whereas, in the third and fourth subsections, motivation and problem statement are presented respectively.

2.1 Empirical studies on pedestrian flow

Empirical studies on pedestrian flow can be widely classified into:

i. Studies on speed, flow, density of pedestrians while they move along different spaces and their interconnection.
ii. Observing different phenomena that can be apparently noticed during pedestrian motion at different locations and recognition of some patterns of their movement.

Over the years (approximately five or six decades) different studies have been accomplished for understanding pedestrian fundamental diagram, i.e., relationship between flow-density or speed-flow (for example, Hankin and Wright (1958), Older (1968), Navin and Wheeler (1969), Fruin (1971), Mori and Tsukaguchi (1987), Seyfried *et al*. (2005), Helbing *et al*. (2007)).

Henderson and Lyons (1972) observed that male and female pedestrians in the same homogeneous mix follow different speed distributions.

A similar, but more restrictive, remark was also made by Polus *et al*. (1983), who observed that speed of male pedestrians is greater than female pedestrians.

Young (1993) has also done some speed studies on pedestrians in airport terminals.

Lam *et al*. (1995) observed speed of pedestrians from different geographical regions is different for same kind of facilities. Lam *et al*. (2003) proposed a generalized flow function (walking time function) with bi-directional flow ratio using land use as a variable for various flow conditions (free-flow and congested-flow condition). Lam *et al*. (2002) observed statistical relationship between mean speed and variation of speed at stairways (both unidirectional and bi-directional).

Schadschneider *et al.* (2009) showed empirical results on evacuation from flow spaces. Steffen *et al.* (2010) theorized some measurement methodologies for pedestrian density, speed, flow and direction with minimal scatter using video tracking technology.

Zhang *et al.* (2011) flaunted some fundamental diagrams of pedestrian motion through straight corridors and T-junctions.

Burghardt *et al.* (2013) analyzed performance of stairs and studied fundamental diagram and topographical measurements.

Several literatures are found on experiment based empirical analysis of pedestrian dynamics. An ample amount of experimental studies are done by Seyfried *et al.* (2005) which show the effects of density on speed. Others have studied the same without considering the corridor geometry as an influencing parameter.

Kretz *et al.* (2006) did experimental study to observe pedestrian counter flow in a corridor. Tian *et al.* (2012) conducted experimental studies and could establish considerable relations between flow, density and mean velocity and they also could graphically show relation between time-headway and lane formation.

Chattaraj *et al.* (2010), through experimental observations established impacts of corridor geometries on pedestrian motion. Morrall *et al.* (1991), Chattaraj *et al.* (2009) and Ma *et al.* (2010) experimentally showed the impacts of cultural differences on pedestrian fundamental diagram.

Zhang and Seyfried (2013) observed empirical characteristics of different pedestrian streams (both unidirectional and bi-directional) through a series of experimental studies. They used Voronoi method to resolve the fine structure of the velocity-density relations and spatial dependence of measurements.

Some interesting observations like lane formation (Hoogendoorn and Daamen, 2004 and Kretz *et al*., 2006), zipper effect (Hoogendoorn and Daamen, 2005), Oscillation (Helbing *et al.*, 2005), shock wave formation (Helbing *et al.*, 2007) and capacity drop (Cepolina and Tyler, 2005) at bottlenecks of bi-directional pedestrian flows are found to be in existence in literature. Isobe *et al*. (2004) have observed pattern formation and jamming transition (occurrence of jam when density exceeds certain threshold value) in pedestrian counter flow.

Some literatures related to LOS of pedestrian facilities are reported here. Hoogendroon and Daamen (2005) have studied the capacity of bottlenecks. Seyfried *et al*. (2009)'s study relates exit widths with immediate upstream capacity. Polus *et al*. (1983) have tried to determine the LOS (level of service) definitions in terms of nature of flow (free flow, unstable flow, dense flow, jammed flow). Petritsch (2006) made LOS models for pedestrians travelling along urban arterials with sidewalks. Sisiopiku *et al*. (2007) compared various sidewalk LOS ratings and found the assessments are coming out differently for different methodologies used. Kim and Yamashita (2006) used k-means clustering technique for analysing pedestrian crash pattern. Sahani and Bhuyan (2013) estimated six different types of pedestrian level of service using affinity propagation clustering based on parameters like average pedestrian space, flow rate, speed and volume to capacity ratio.

Ma *et al.* (2010) modelled pedestrian motion in a corridor using digital image processing technique.

These are interesting empirical observations found in literatures. Some of them discuss collection of pedestrian data from real life scenarios but they are only facility specific. Mostly they lack in less statistical analysis. Pedestrian behaviours are not much explained by these observations. Oscillation Phenomena is not at all measured or even addressed by these studies.

2.2 Pedestrian flow models

Pedestrian flow models can be categorised as macroscopic and microscopic models. Though mesoscopic models do exist with simplification of dynamics and less data demand. Macroscopic models can give fundamental flow parameters as outcomes and predict their interrelations whereas microscopic models are capable of imitating the decision making quality of pedestrians while moving inside a flow space. Microscopic models can distinguish individuals and their interactions. In this thesis a microscopic model of pedestrian decision making is developed. Thus, in this literature of pedestrian models, microscopic models are preferred to be cited although a brief overview of the existing macroscopic models are also given.

Macroscopic models are generally based on fluid dynamics, well-defined observations (hypothesis), flow-density diagrams, altered LWR (Lighthill, Whitham and Richards) traffic models. Helbing (1992) developed a fluid-dynamic model where analogy is made between pedestrian flow and fluid flow, based on Boltzmann-like gas-kinetic model. Henderson (1974) developed fluid-dynamic theory of pedestrian flow. Hughes (2003) hypothesized a flow model for human crowd. Daamen and Hoogendoorn (2012) developed a model for different pedestrian evacuating through emergency doors. Colombo and Rosini (2009) formulated a macroscopic model for pedestrians in panic conditions in which altered LWR model remained the cornerstone. Bruno *et al.* (2011) made a macroscopic model (non-local first order) that describes the diffusive effect of the pedestrian crowd. Qingyan *et al.* (2011) modelled and simulated pedestrian flow and human behavior reflection in terms of automatic drainage phenomenan appearance and arch formation at the exit of a rail transit station.

Microscopic models are basically of two types: (i) Force based and (ii) Decision based.

i. Force based models are generally formed on the assumption that pedestrians move in accordance with the interactions between different attractive (goals) and repulsive (obstacles and other pedestrians) forces. Some of these models are briefly reported in the following paragraphs.

Social force model describes the reciprocal actions between pedestrians, obstacles, goals (destination of pedestrians) etc. First developed by Helbing and Molnar (1995), this model evolved into different types of its kind (for example, Helbing (2000); Helbing *et al.* (2002)). Social force model can be used for both continuum and discrete space. Social forces in continuum models can be envisaged as Newtonian forces (Mehran *et al.* (2009)). Song *et al.* (2006) suggested another variant of social force model which is named as multi-grid model, works in finer discrete space.

Magnetic force model, first divulged by Okazaki and Matsushita (1993) is based on the assumption that pedestrians are positively charged particles those travel through a magnetic field to reach their goals which are negatively charged poles.

Centrifugal force model was proposed by Yu *et al.* (2005) with a similarity between pedestrian motion and the theory of centrifugal force in mechanics. It states that the repulsive force between pedestrians is inversely proportional to the separation between the pedestrians and directly proportional to the square of the distances in between them. Chraibi *et al.* (2010) introduced a spatially continuous generalised centrifugal force based model for pedestrian dynamics. This model includes elliptical volume exclusion of pedestrians and also discusses the oscillation and overlapping phenomena which occurs for certain choices of forces.

ii. Rule based models perceive both space and time as discrete quantity. This consideration helps in computation. These models use some rule sets which regulate the pedestrian flow. Some important rule based models are briefly described in the following paragraphs.

Lattice gas model was introduced by Rothman and Zaleski (1994, 1997). Usages of this model were limited to molecular motion only. Later it was utilised to model various types of pedestrian motion like uni-directional and bi-directional flow, cross-directional flow, flow through a T-junction and flow in suddenly narrowed corridor and many other situations (Marconi and Chopard, 2002; Muramatsu *et al.*, 1999; Muramatsu and Nagatani, 2000; Tajima and Nagatani, 2001; Tajima *et al.*, 2001; Tajima and Nagatani, 2002; Tajima *et al.*, 2002; Takimoto *et al.*, 2002; Itoh and Nagatani, 2002). Liang *et al.* (2013) presented a small grid lattice gas model for modelling pedestrian counter flow.

Mean field model was introduced by Nagatani (2001, 2002) and is similar to the lattice gas model. Guo and Huang (2008) developed a mobile lattice gas model for simulating pedestrian evacuation.

Benefit cost model introduced by Gipps and Marksjoe (1985). In this model pedestrians move to the next cell with maximum benefits that is calculated by some scoring techniques (cost score, for closeness to other pedestrians; gain score, for closeness to the destination).

Radial grid model was suggested by Antonini *et al.* (2006). It illustrates that the direction choice of pedestrians is determined by the goodness of that direction.

Cellular automata approach has been successfully implemented in modelling pedestrian dynamics for several years. In this model the simulation domain is divided into cells. These cells form a regular grid. There are different types of grid pattern, like, triangular, rectangular and hexagonal. Rectangular grids can represent straight walls and can be implemented easily. Pedestrians can move to chosen empty cells within the domain. The update of the state of each cell which controls the movement of the pedestrians is done after each discrete time-step and relies on the states of the neighbouring cells and on a set of rules from current time-step to the next time-step. Update rules are broadly classified as parallel and sequential update rules. Parallel update rule enables all pedestrians move simultaneously whereas sequential update rule considers pedestrian motion one by one. Parallel update rules are more realistic as they take into account the conflict that is created between pedestrians while moving along the flow space and they also represent classical cellular automata treating all cells equally.

Here in this thesis work a cellular automata model of rectangular grid pattern considering Moore's neighbourhood (as cells sharing at least one corner with the basic cell) is developed. Parallel update rule is administered.

In literature the proposition of cellular automata model for various types of pedestrian flow (uni- directional, bi-directional and cross-directional) is present in ample amount (Fukui and Ishibashi, 1999; Blue and Adler, 1998, 2000; Dijkstra *et al.*, 2000; Weifeng *et al*., 2003). Burstedde *et al.* (2001) proposed the concept of floor field on cellular framework. Qiu *et al.* (2009) modelled group structures in pedestrian crowd simulation. Inter group and intra group behaviours can be easily defined using this model. Bandini *et al.* (2011) suggested one cellular automaton based model for pedestrians and group dynamics. Fu *et al*. (2012) used an improved cellular automata model for pedestrian dynamics and simulated evacuation process in a large classroom. This model is capable of predicting route choice behaviour during evacuation.

Moussaïd *et al.* (2010) could model the walking behavior of pedestrian social groups and also indicated the impacts of this behavior to crowd dynamics.

Davidich *et al.* (2013) modelled waiting pedestrians at a major German railway station and found that during rush hours waiting pedestrians may prolong walking time by nearly upto 20%. They also demonstrated how the developed model can be used for the analysis of infrastructure and prediction of problematic areas in public spaces.

Here, it needs to be mentioned that, in this thesis work Blue Adler model is chosen for simplicity and that is modified with some changes in the algorithm making it more realistic and significant.

Pedestrian flow models discussed above do not focus on the simple rule based direction choice of pedestrians while moving on a sidewalk. No models could be found discussing the strong correlation among sidewalk width, crowd density of the corridor and pedestrian speed on sidewalks with simple mathematical logic.

2.3 Motivation

Kumbh mela and Madhya Pradesh crowd crush causing 36 and 115 death and recent occurrence of stampedes (Patna and Mumbai) claiming 18 and 32 lives demonstrate that it is very much complicated and difficult to manage and forecast the dynamics of a large number of pedestrians, especially if pedestrians are panic-stricken. Many accidents take place where planning mistakes are primary factors rather than panic. When escape is the main target of pedestrians those are driven by fear of something bad to happen in their mind, they behave in anomalous way. Routes of pedestrians clash with each other as one can't predict the route choice of others and they exert pressure on other. Due to planning problem or slow moving pedestrians some bottlenecks are created and these bottlenecks are dangerous as they interrupt the crowd motion and create huge pressure of those who try to pass through these bottlenecks from behind and accidents take place.

Various empirical studies have been carried out by various researchers to understand the pedestrian motion in different pedestrian circulation areas. During last ten years various evacuation studies through controlled experiments have been conducted to understand the pedestrian motion. These experiments cover evacuation from halls, stadiums, various types of buildings etc. Some experiments are also done creating artificial corridors with varying geometries to study the movement of pedestrians. Numerous pedestrian flow models are there to mimic the pedestrian flow. From different types of models cellular automata model is found to be effective of all.

It is found that level of service of the existing pedestrian facilities (especially stairwells of foot over bridges) are not defined in the Indian context as Indian pedestrians are different from American or European pedestrians and there is a need to understand the LOS criteria in Indian context. It is also found that though there are several models in existence, there is no such simple model to simply describe the route choice behaviour of pedestrians while they move through different facilities. It is also found that in almost all previous research works the models which are developed are validated by experimental outputs. There is a need to find real data from the field as that will be much accurate.

2.4 Problem Statement

The problem statement has been described as two different ways.

'Empirical studies on pedestrian motion to understand the flow of pedestrians' and then 'development of a reasonable model to emulate the pedestrian motion in different circulating areas'.

Structural data (Length, width, height, slope etc) and some traffic data of pedestrian movement (speed, flow, and density) are recorded from various pedestrian facilities. Level of service conditions of the existing facilities where the data are collected from, are calculated. Various statistical analyses are done to understand whether the movement of pedestrians differ from each other on different facilities. A simple cellular automata model that can efficiently and logically show the route choice behaviour of pedestrians is developed. Another fuzzy inference based model is also formulated to understand the correlation among sidewalk width, crowd density on the sidewalk and pedestrian speed on the sidewalks. It is aimed to validate the models with real data collected from field.

Chapter 3

Empirical studies

Pedestrian movement vary significantly on different pedestrian facilities. In this study empirically the difference of pedestrian motion on unalike pedestrian facilities is observed. This whole empirical study is carried out through real-life data collection of movements of pedestrians on multiple pedestrian spaces. In section 3.1 the data collection methodology is detailed while section 3.2 illustrates the statistical analysis of the data. T-test, analysis of variance test (ANOVA) is conducted to find out whether there is any significant difference in the sample means. In section 3.3 Oscillation Phenomena occurring in pedestrian streams is empirically illustrated.

3.1 Data collection

For this study, pedestrian motion is recorded using high quality video camera from various pedestrian facilities across the eastern part of India. Railway platforms, Railway foot over bridges are cherry-picked as pedestrian movement is found at a constant rate on those facilities. Rourkela (Odisha) and Manoharpur (Jharkhand) station are selected for this purpose. There is another reason why Railway foot over bridges and platforms are chosen so deliberately. It is the recent gloomy episode of crowd crush at a railway station. Video of pedestrian movement on platforms is recorded in different densities. Pedestrians are categorized as male and female pedestrians and their speeds on the platform and on staircases of the foot over bridges are calculated and compared. Pedestrian data is also collected from foot over bridges on roadways from two different places of Kolkata (West Bengal). Pedestrian movement is recorded at different walkways of Rourkela (Odisha). If one needs any convincing of how things quickly can change, of how rapidly order can turn into chaos, history offers us a number of painful reminders. Walkways or rather straight corridors are chosen after ruminating on the very recent events like Patna stampede. Stampede on 1st January 2015 at Shanghai brings melancholy as many people died and several injured. It was a straight corridor (shopping ally) where people gathered to revel. To get an idea of how bad things get and how quickly they escalate, one needs to study the behaviour of pedestrian's movement. In this study, in the following chapters an effort is made to understand and model the flow of people through corridors. However, extreme crowd events are not taken into consideration as such situations can't be created by experimental setup neither real data of speed flow can be collected for crowd on the spot. The camera set up and data collecting process is described using a typical sketch in figure 3.1 and figure 3.2. Camera used here is a high resolution video camera and positioned at a reasonable height for the convenience of accurate data collection.

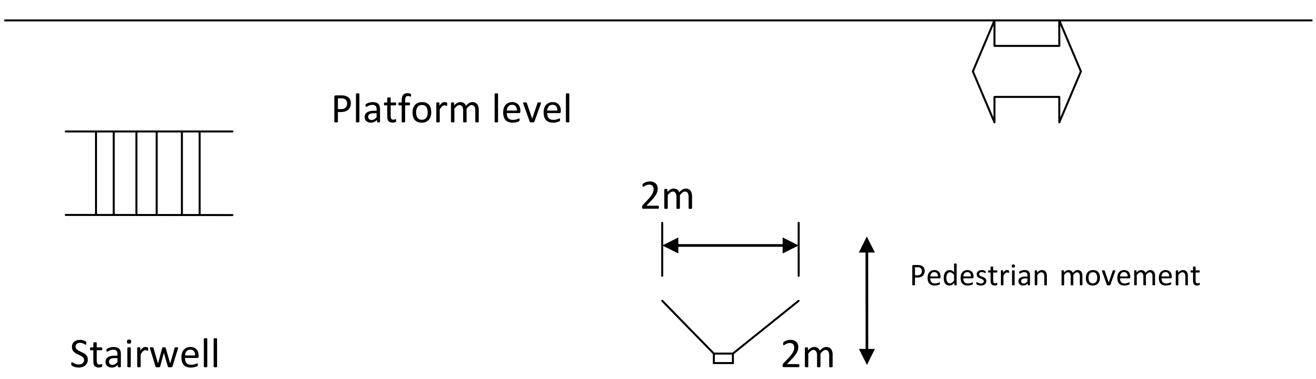

Figure 3.1: Typical sketch for data collection methodology on platform

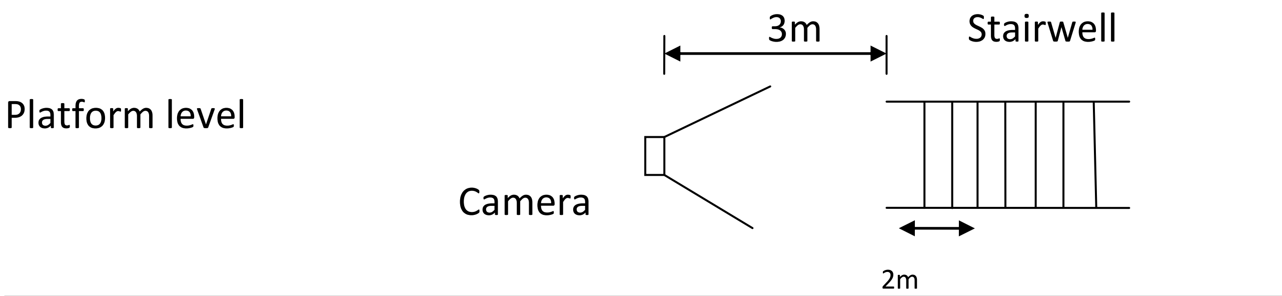

Figure 3.2: Typical sketch for data collection methodology on stairwell

Pedestrian field data is also collected in the same way from various walkways (footpath) in Rourkela and also from pedestrian foot over bridges on motorway in Kolkata city. Table 3.1 gives physical information on various pedestrian facilities (corridor type or non-staircase) on which field data is collected. Figure 3.3 presents a histogram of the data provided in table 3.1.

Table 3.1: Details of different types of pedestrian facilities

Type of facility	**Place**	**Width**	**Sectional length of data collection**	**Number of pedestrians**	**Average speed**	**Standard deviation**
Platform	Rourkela	4m	2m	2000	0.875(m/s)	0.2
Platform	Manoharpur	4m	2m	2000	0.88(m/s)	0.21
FOB	VIP Road, Kolkata	3m	2m	2000	1.11(m/s)	0.11
Sidewalk	IG park, Rourkela	5m	2m	2000	0.908(m/s)	0.23
Sidewalk	Daily market, Rourkela	3m	2m	2000	1.22(m/s)	0.12

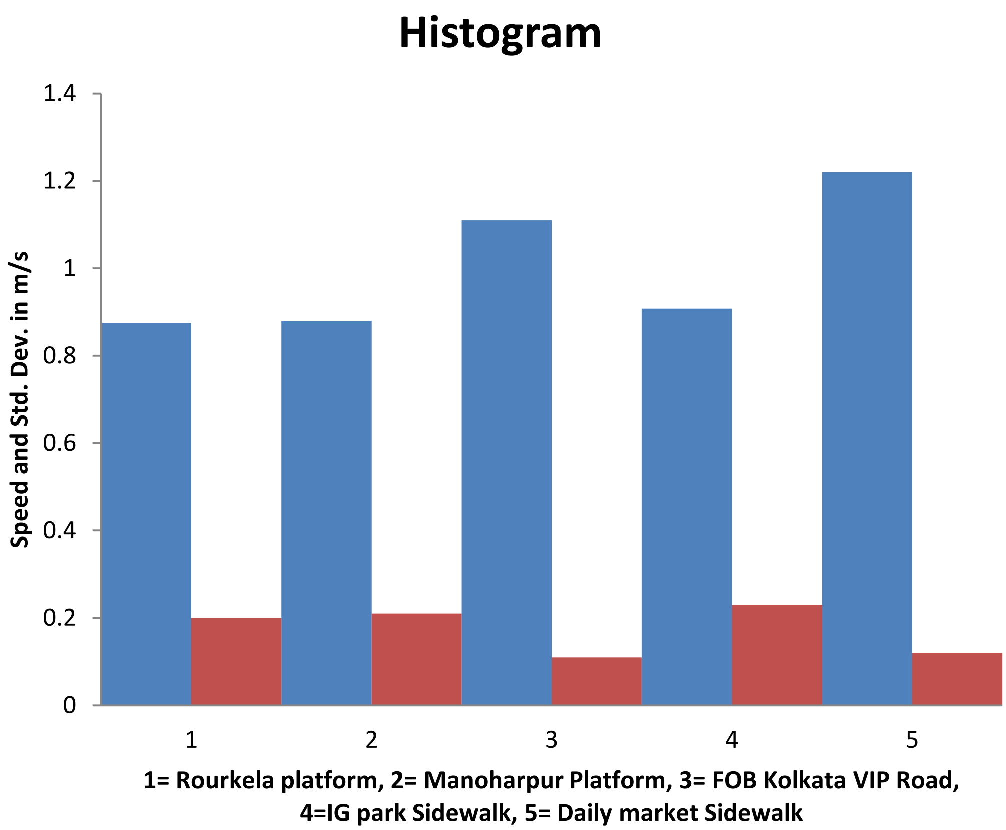

Figure 3.3: Histogram of the data presented in table 3.1

Stairwells are equally important as pedestrian facilities to study the pedestrian dynamics on those. The function of a stairwell for furnishing a connection from one platform to another platform (in case of Railway) and from one footpath to another (in case of motorway), is inevitable. Speeds of pedestrians vary significantly in different types of stairwells with different geometric features. It is a formidable undertaking to study the pedestrian dynamics on stairwells as movements on the stairs are distinctively toilsome compared to the motion on corridor type facilities (platform, sidewalks). Table 3.2 gives description of field data collected on stairwells of different geometric features.

Table 3.2: Details of stairwells and data collected at two different stations

Stairwell	**Rourkela Railway Station**	**Manoharpur Railway Station**
Stair width (m)	3	1.5
Stair riser (mm)	150	150
Stair trade (mm)	333	170
Sample size	2000	2000
Average speed (m/s)	0.50	0.37

3.2 Data analysis

Statistical analysis is done for different types of data sets collected at different pedestrian facilities. It is found that the mean speed of Men and Women are somewhat similar. It is also observed in this research that the mean speed of Men and Women on staircase is similar while mean speed of Men at ground (non-staircase) and stairwell is found to be somewhat different. But to study the reliability of the difference, inferential statistics is used; more precisely a T-TEST is conducted. Here *t*-test is conducted using SPSS software using the independent sample "T-test tab" and tabulated in table 3.3. Comparison is done for the following cases:

(i) Mean speed between Men and Women at platform

(ii) Mean speed between Men and Women at stairwell

(iii) Mean speed of Men at platform and stairwell.

(iv) Mean speed of pedestrians on stairwell at Rourkela and Manoharpur station.

Here null hypothesis is $H_0 : v_0^m - v_0^w = 0$ and alternate hypothesis is $H_A : v_0^m - v_0^w \neq 0$. Where, v_0^m and v_0^w : mean speeds of pedestrians (male and female OR male pedestrians on two different types of facilities OR two different places of same type facility).

If the value of the expression $t = \dfrac{v_0^m - v_0^w}{\sqrt{S_{v,m}^2 + S_{v,w}^2}}$ (3.1)

comes out to be greater than some critical value at a certain level of confidence the null hypothesis can be rejected by saying that there is difference between the means of the speed data compared. Here, $S_{v,m}$ and $S_{v,w}$ are the standard errors of different speed data. After the statistical analysis, some results were found and tabulated in table 3.3.

Table 3.3: Statistical comparison of datasets using independent sample *t*-test

Sl. No	**Mean speed comparison between**	**Mean speed (m/s)**	***t*-test result (significance level)**	**Conclusion**
1	Men & Women at platform	0.905 (m) and 0.887 (w)	0.172	Same
2	Men & Women at stairwell	0.502 (m) and 0.457 (w)	0.105	Same
3	Men’s speed at Platform and stairwell	0.887 (p) and 1.144 (fob)	0.004	Different
4	Men’s speed at Rourkela and Manoharpur Station FOB stairs	0.50 (R) and 0.37 (M)	0.004	Different

It becomes necessary to compare more than two sample means at the same time to understand the difference in pedestrian speed on different facilities while the density (number of pedestrian per square meter area) remains constant. A *t*-test does not provide the platform to compare more than two means while ANOVA (analysis of variance), another statistical test does. ANOVA (one way ANOVA) compares the means between groups, in which, one is interested in and decides whether any of those means are significantly different from each other. Particularly, it tests the null hypothesis $H_0 = \mu_1 = \mu_2 = \ldots = \mu_k$, where μ = the group mean and k = the number of groups. The null hypothesis is rejected if the one way ANOVA test returns a significant result and the alternate hypothesis is accepted. The alternate hypothesis is that there is significant difference between at least two group means.

One way ANOVA test is conducted in SPSS software to compare means of speed among three different facilities, viz. Sidewalk, Foot over Bridge and Railway platform under similar densities. The result of the test reveals that there exists a significant difference among the means of the three sample means of speed data. Using SPSS, 50 samples of speed data from each of the three facilities (facility 1= Sidewalk, facility 2= Foot over Bridge, facility 3 = Railway Platform) were tested for comparing their means. Table 3.4 is the output of the one way ANOVA test with a significance value of 0.00 (less than 0.05 significance) which means there is strong evidence of difference between the means of the speed values on different facilities and the difference is statistically very significant.

Table 3.4: ANOVA test for speed means of three types of facilities

ANOVA

Speed

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.736	2	.868	36.266	.000
Within Groups	2.919	122	.024		
Total	4.655	124			

From table 3.4 the seemingly difference between the three groups is established. ANOVA test can evidently show the existence of difference between groups of sample means but it cannot precisely point out which specific group differs. In this context, a post hoc test eases such constraints. A post hoc test controls the experiment wise error rate (usually alpha=0.05) in the same way the one way ANOVA does, instead of multiple *t*-tests. Post hoc tests are called posterior tests as these are conducted after a particular event (in Latin post hoc means “after this”). If the data meet the assumption of homogeneity of variances, Tukey’s honestly significance difference (HSD) test or Scheffe post hoc tests can be conducted. Generally a

Tukey's test is preferred for being less conservative and for giving better results. Here Tukey's test is conducted (in SPSS) as a post hoc test as the data matches the assumption of homogeneity of variations. Table 3.5 gives the corresponding results of the Tukey's test. It is clear from the test that significant difference is found for speed means between sidewalk and Foot over Bridge and between Foot over Bridge and Railway platform. Speed mean on Foot over Bridge comes out different and this difference is statistically very much significant. The mathematical form of the Tukey's HSD test is

$$HSD = q\sqrt{\frac{MSE}{n}} \tag{3.2}$$

Where, q = the relevant critical value of the range statistics,

MSE = mean squared error with groups and

n = number of scores used in calculating group means of interest.

Table 3.5: Tukey's test result

Multiple Comparisons

Dependent Variable: speed

Tukey HSD

(I) facility	(J) facility	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1	2	-.21500*	.03094	.000	-.2884	-.1416
	3	.06280	.03789	.226	-.0271	.1527
2	1	.21500*	.03094	.000	.1416	.2884
	3	.27780*	.03789	.000	.1879	.3677
3	1	-.06280	.03789	.226	-.1527	.0271
	2	-.27780*	.03789	.000	-.3677	-.1879

*. The mean difference is significant at the 0.05 level.

Similar result is found from a box plot type graph (non statistical study) using SPSS. Figure 3.4 gives the box plot for different facilities and corresponding speed of pedestrians on those facilities. It is clear that facility 2 (i.e. foot over bridge) helps pedestrians walk faster than other two facilities (Sidewalk and Platform). This study shows that human locomotion display distinct characteristics on different facilities. This may be possibly because of the different psychological earmarks of the pedestrians in locomotion on different facilities. It could likely be the sense of safety of the pedestrians when they move on the foot over bridges. On the other hand, pedestrians move slower on platforms and on sidewalks as their vision is not confined in these cases unlike the previous one and they are not attracted by certain things available on the platforms (food-stalls, other people on resting benches etc.) and sidewalks (food stalls, temporary and permanent shops etc.). These observations are irrespective of the purpose of the trip maker. There are distinct differences in speed in different sidewalks in Rourkela. The average value of speed of pedestrians near IG Park is found to be less compared to the average speed value of pedestrians on the sidewalks of Daily market. These may also due to different psychological attributes of the surroundings of the different walkways.

However, normality test is also conducted to understand the distribution of the speed data collected from different facilities. It is done using SPSS software. The skewness and kurtosis (Cramer, 1998; Cramer and Howitt, 2004) of z values are found to be within the defined range of -1.96 to +1.96 for all the facilities. So it is observed that the speed data is normally distributed (approximately) in terms of skewness and kurtosis. Again the Shapiro-Wilk (ρ>0.05) test (Shapiro and Wilk, 1965; Razali and Wah, 2011) also indicates that speed data on all the facilities are normally distributed. The normal *Q*-*Q* plots in SPSS also show that all data are normally distributed.

The normality is confirmed by the *Q*-*Q* plots of the normality test for different facilities. Figure 3.5 gives us the normality *Q*-*Q* plot for foot over bridge. Similar results are found for sidewalks and platforms using this test. These tests exhibit the distribution of the speed data to be normal.

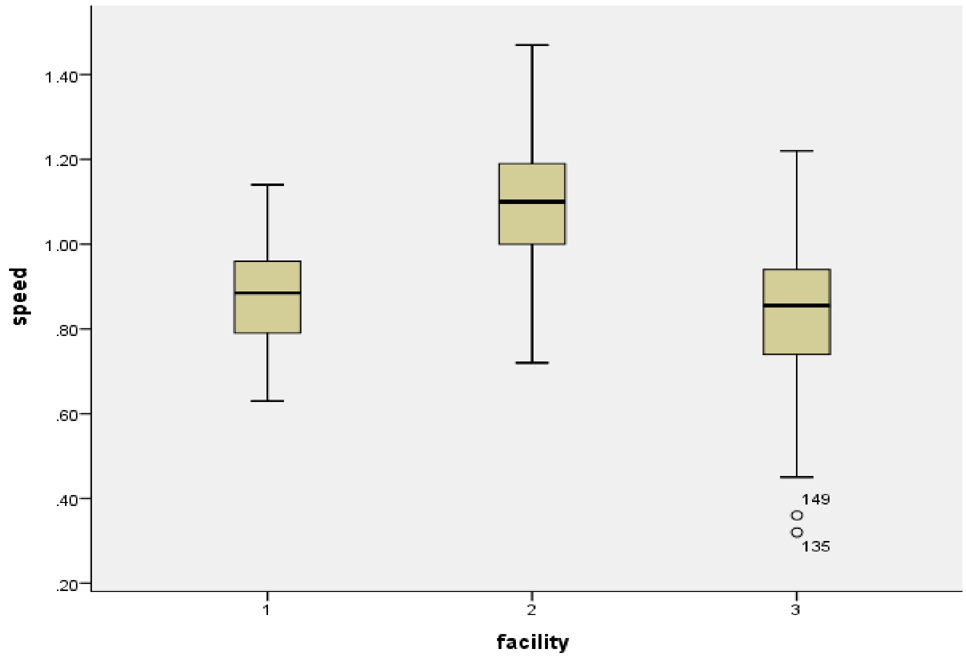

Figure 3.4: Boxplot for speed in different facilities (1= sidewalk, 2= foot over bridge, 3= railway platform)

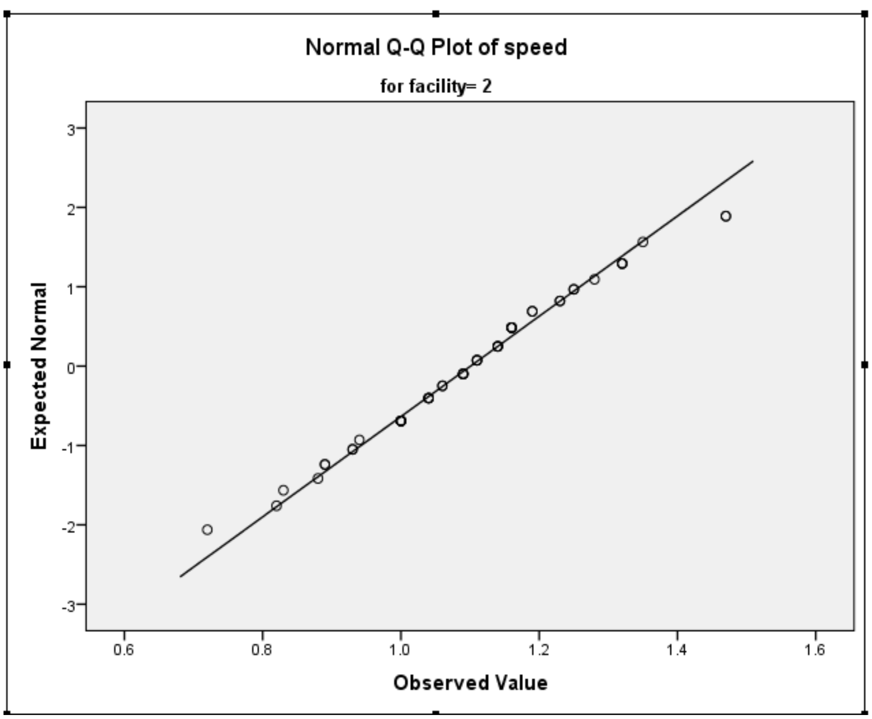

Figure 3.5: Normal *Q-Q* plot for foot over bridge.

A small study on Level of service attributes of different facilities where field data were recorded is also done. Apart from speed data, some other fundamental traffic parameters were also analyzed and recorded. Flow rate, density, average pedestrian space were observed and calculated. In this study Fruin's handbook and HCM 2010 are taken as reference to comment on the LOS conditions of the pedestrian facilities where all the relevant data were collected.

Flow rate is the number of pedestrians passing a cross-section of the walkway per minute. Density is calculated as the number of pedestrians per square meter of area at any instantaneous time. Average pedestrian space is the reciprocal of the density observed. Pedestrian space is calculated as the area (in m^2) per pedestrian in locomotion on different pedestrian installations.

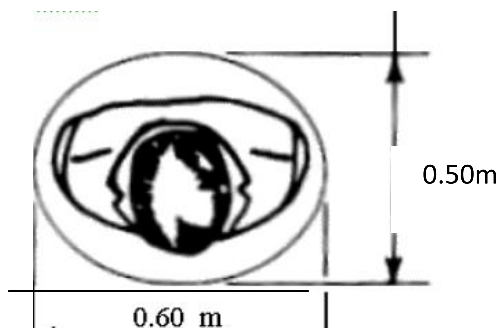

Figure 3.6: Body Eclipse of a pedestrian

Figure 3.6 gives the body eclipse of a normal person. The shoulder length is 0.60 m and the body depth is 0.50 m. It is observed by Fruin that for normal walking speed on walkways 0.65 m^2/pedestrian space is required. In his handbook it is also suggested that 25 pedestrians per minute per meter width should be the flow rate for smooth pedestrian motion on walkways. Level of service is categorised into different criteria. Both HCM and Fruin's handbook give six different levels of service criteria for walkways. Different LOS criteria are also given by Brilon (from Germany) for walkways and these values are tabulated in table 3.6.

Table 3.6: Different LOS criteria for walkways

LOS	**HCM**		**Fruin**		**Brilon**	
	Flow Rate (ped/min/m)	**Space (m^2/ped)**	**Flow Rate (ped/min/m)**	**Space (m^2/ped)**	**Space (m^2/ped)**	
A	6.6	12	23	3.2	-	10
B	6.6-23	3.7-12	23-33	2.3-3.2	-	3.3-10
C	23-33	2.2-3.7	33-49	1.4-2.3	-	2-3.3
D	33-49	1.4-2.2	49-66	0.9-1.4	-	1.4-2
E	49-82	0.6-1.4	66-82	0.5-0.9	-	0.6-1.4
F	>82	0.6	>82	0.5	-	0.6

There are different definitions of these six levels of service criteria. The definitions are tabulated in table 3.7. These definitions are found to be the same in different handbooks and guidelines. Understanding level of service helps one to understand the capacity and existing service conditions of the existing pedestrian facilities and also motivate to give some measures to change or modify them to attain favourable conditions for pedestrian usage. ‘A’ level of service is the most desirable one as it encourages smooth pedestrian motion without any curtailment of speed. It also provides sufficient pedestrian space for each pedestrian for unrestrained pedestrian motion. Antithetically, level of service ‘F’ impedes pedestrian motion providing very lesser space for each individual. ‘F’ level of service is the most unwelcome.

Table 3.7: LOS definitions for both walkways and stairwells

LOS	Definition
A	Ability to move in desired path, no need to change movements
B	Often there is a need to change direction
C	Speed is slowed down. Direction change necessary to avoid tripping
D	Speed is minimized. Overtaking slower pedestrian restricted
E	Speed restricted, no overtaking possible
F	Speed highly restricted, tripping occurs

There is provision of free or normal movement of pedestrians in Fruin's handbook. It recommends that 0.73 m/s is the necessary speed for motion without restriction and shuffling on walkways and for staircases the value is 0.48 m/s. HCM and Fruin's handbook have provisions for stairwell design. Both of them recommend stair tread width should be at least 300 m. They endorse the value of the riser to be not more than 177 mm. These values are in coherence with the provisions given in American Standards specifications for barrier free building design (A.117.1, 1961). Nosing is advised to be rounded nosing flush with the riser rather than the projected nosing in common use. Nosing provisions were found irrelevant with the given standards in both Rourkela and Manoharpur stairwell of the foot over bridges. Other details are provided already in table 3.2. For Rourkela stair angle was observed to be 35° whereas in Manoharpur it was almost 62° (recommended stair angle for preferable locomotion is within 30°-50°). Table 3.8 gives different LOS criteria for stairs given in HCM and in Fruin's handbook.

Table 3.8: Different LOS criteria for staircases

LOS	HCM		Fruin	
	Flow Rate (ped/min/m)	**Space (m^2/ped)**	**Flow Rate (ped/min/m)**	**Space (m^2/ped)**
A	16	1.9	5	1.8
B	16-20	1.6-1.9	5-7	1.4-1.8
C	20-26	1.1-1.6	7-10	0.93-1.4
D	26-36	0.7-1.1	10-13	0.65-0.93
E	36-49	0.5-0.7	13-17	0.37-0.65
F	>49	<0.5	>17	<0.37

After a huge number of data collection on different walkways and staircases some empirical observations are made. It is found in this study that a speed of 0.74 m/s is necessary for movement of pedestrians in moderate densities in the walkway; whereas, the value is 0.49 m/s for the staircases. From this empirical study some observations about LOS for different facilities can also be predicted. These are tabulated in table 3.9; whereas, table 3.10 gives the current LOS of the different facilities where these huge data collection took place. These are somewhat competent with Fruin's handbook.

It is found from the study that there is no accessible facility for physically challenged persons on staircases of both Rourkela and Manoharpur station. Universal design is not followed. Foot over bridges are designed for those who are physically strong and have no physical problem which is not humanitarian. Figure 3.7 to figure 3.10 gives some snapshots of the data collection of some facilities.

Table 3.9: Empirically obtained LOS criteria for different facilities

Facility	**Flow Rate (ped/min/m)**	**Space (m^2/ped)**
Rourkela Platform	32-40	1.4-2.3
Manoharpur Platform	32-40	1.4-2.3
FOB Kolkata & Salt lake	25	3.2
IG Park Sidewalk	25	3.2
Daily market Sidewalk	25-32	2.3-3.2
Rourkela Staircase	5	1.8
Manoharpur Staircase	>20	<0.36

Table 3.10: LOS obtained in different facilities studied

Facility	**LOS**
Rourkela Platform	C
Manoharpur Platform	C
FOB Kolkata	A
IG Park Sidewalk	A
Daily market Sidewalk	B
Rourkela Staircase	A
Manoharpur Staircase	F

Figure 3.7: Rourkela Platform

Figure 3.8: Rourkela Stairwell

Figure 3.9: FOB VIP Road, Kolkata

Figure: 3.10: Rourkela Sidewalk

3.3 Explanation of Oscillation Phenomena in Pedestrian Motion:

3.3.1 Definition of oscillation phenomena

Oscillation is one of the interesting self-organization phenomena observed in pedestrian dynamics. This can be observed at bottlenecks with a counter flow (flow in both directions through the bottleneck). This is nothing but the fluctuations in motion. When one pedestrian from one direction manages to pass the bottleneck, other pedestrians who are closely spaced with that pedestrian and following him or her also manage to pass the bottleneck and this continues until one pedestrian from the other direction can manage to pass the bottleneck leaving opportunity to his or her immediate followers to pass the bottleneck from the same direction. Oscillation has not been quantified in earlier studies. In this present study, oscillation is empirically quantified. Oscillation phenomena in pedestrian stream reflect one of the self organizing behaviour of pedestrians.

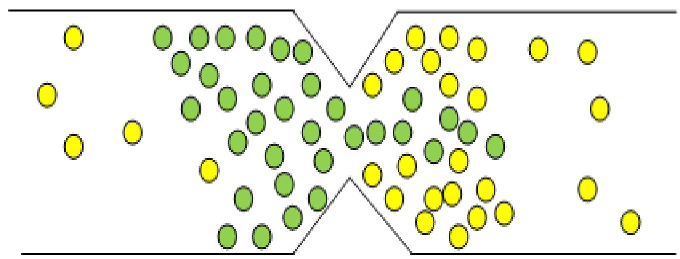

Figure 3.11: Sketch of Oscillation occurring at a bottleneck

Figure 3.11 is the typical sketch of Oscillation phenomena occurring at the constricted portion of a corridor. Green and yellow dots represent pedestrians from left and right side of the corridor. It can be noticed that after some pedestrians from the right side (yellow dots) pass through the constricted zone, those waiting impatient pedestrians from the left (green dots) dominate the movement and the flow switches from left to right for that sort of time until one pedestrian from the right side manage to pass through switching the flow from right to left.

This fluctuation in pedestrian motion is observed microscopically in this study. For this a large corridor with bottlenecks is chosen. Experiments on pedestrian motion are extensively studied by Chattaraj *et al.* (2010). So in this study one experiment conducted by Chattaraj *et al.* (2010) is referred.

3.3.2 Brief discussion of the experiment referred

This section illustrates the experiment conducted by Chattaraj *et al.* (2010) in a large corridor with artificially created constricted zones.

Some parameters to understand the density variations due to different geometries of the corridor have been introduced in Chattaraj *et al.* (2010). Those parameters are briefly discussed below.

Relative zonal directional lane density ($RZDLD_{l,z}$): This is defined as the ratio of number of people occupying lane l for a particular time to the total number of people present inside the whole corridor (total number of people inside the corridor is restricted to 50 throughout the total experiment) in a given zone.

Zonal directional lane density and relative zonal directional lane density is defined by:

$$ZDLD_{l,z(a\rightarrow b)} = \sum_{t=1}^{T} \sum_{j=J_{L,z}}^{J_{U,z}} O_{l,z(a\rightarrow b)}^{t} \tag{3.3}$$

Where, $O_{l,z(a\rightarrow b)}^{t}$ is valued as 1 if the cell (*i*, *j*) is occupied by pedestrians moving from *a* direction to *b* direction (left to right or right to left) and it is valued as 0 if it is empty (considering one cell can accommodate only one pedestrian) at a particular time *t*. Here $J_{L,z}$ and $J_{U,z}$ are the lower and upper limit of *j* for a given zone. Equation 3.3 are 3.4 are adopted from Chattaraj *et al.* (2010).

$$RZDLD_{(a\rightarrow b)} = \frac{ZDLD_{l,z(a\rightarrow b)}}{\sum_{l=1}^{L} ZDLD_{l,z(a\rightarrow b)}} \tag{3.4}$$

3.3.3 Explanation of Oscillation phenomena

Existence of Oscillation phenomena occurring at the constricted zones of the corridor has not been explained by Chattaraj *et al.* (2010). In this current study, oscillation phenomenon in pedestrian motion is found to be in existence at the constricted zones in the corridor when the corridor is symmetrically, asymmetrically constricted and partially bifurcated. This Oscillation phenomenon is explained using the parameters introduced by Chattaraj *et al.* (2010). The phenomena can be perceived by calculating the *RZDLD* (relative zonal directional lane density) for each of the five lanes for different times. It is noted that there is variations of *RZDLD* for L-R (left to right) & R-L (right to left) pedestrians. Lanes are numbered from the left side i.e. lane 1 is the left most lane for the L-R (left to right) pedestrians while it is the right most lane for the R-L (right to left) pedestrians. Oscillation is clearly visible in case of symmetrically narrowed corridor and partially bifurcated corridor. Figure 3.12 to figure 3.15 shows variations of *RDZLD* with respect to lanes in different times (1 to 4 minutes) for partially bifurcated corridor while figure 3.16 to 3.19 shows the same for symmetrically narrowed corridor.

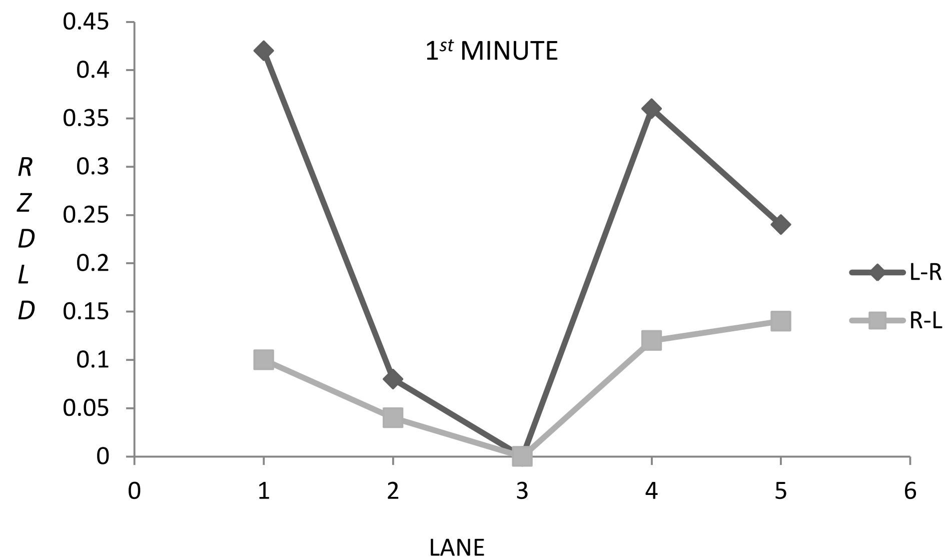

Figure 3.12: Variations of *RZDLD* in lanes in 1st minute in partially bifurcated corridor

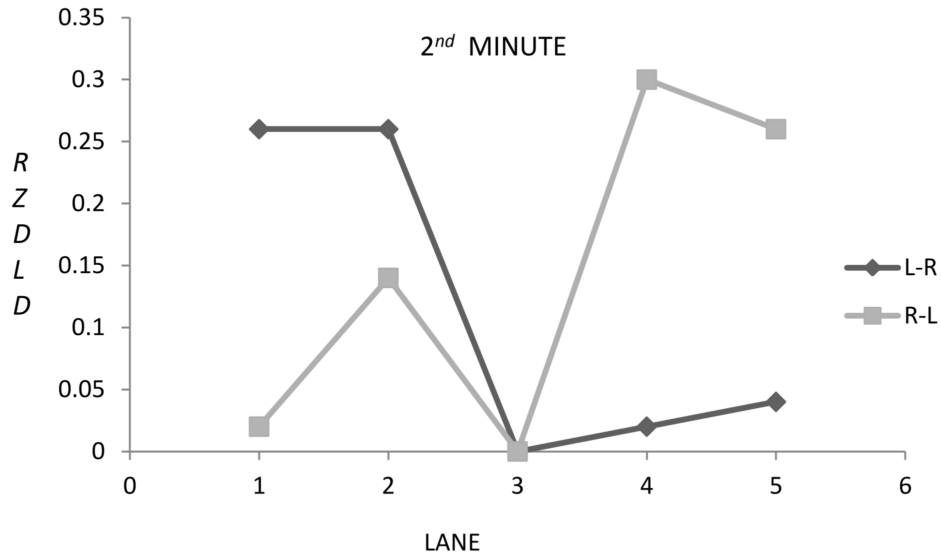

Figure 3.13: Variations of *RZDLD* in lanes in 2nd minute in partially bifurcated corridor

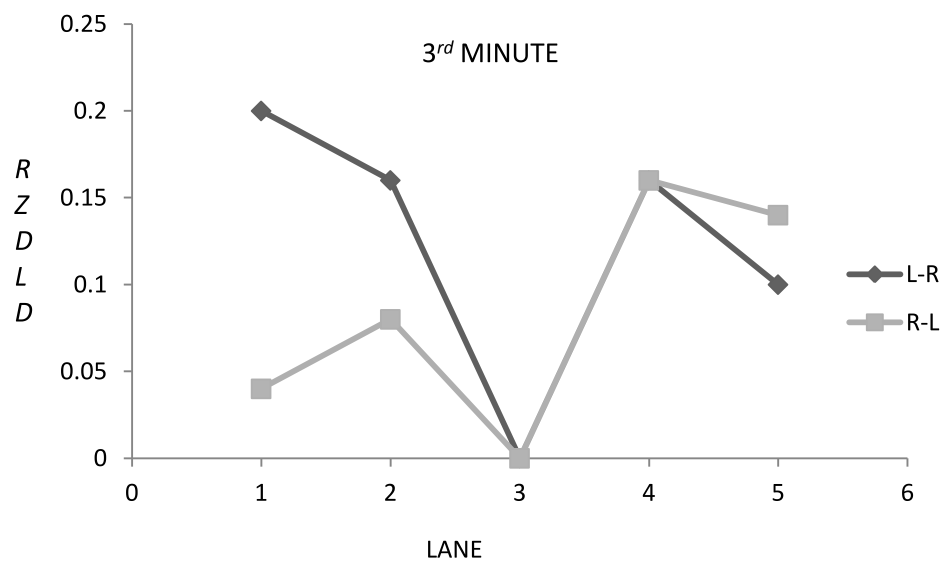

Figure 3.14: Variations of *RZDLD* in lanes in 3rd minute in partially bifurcated corridor

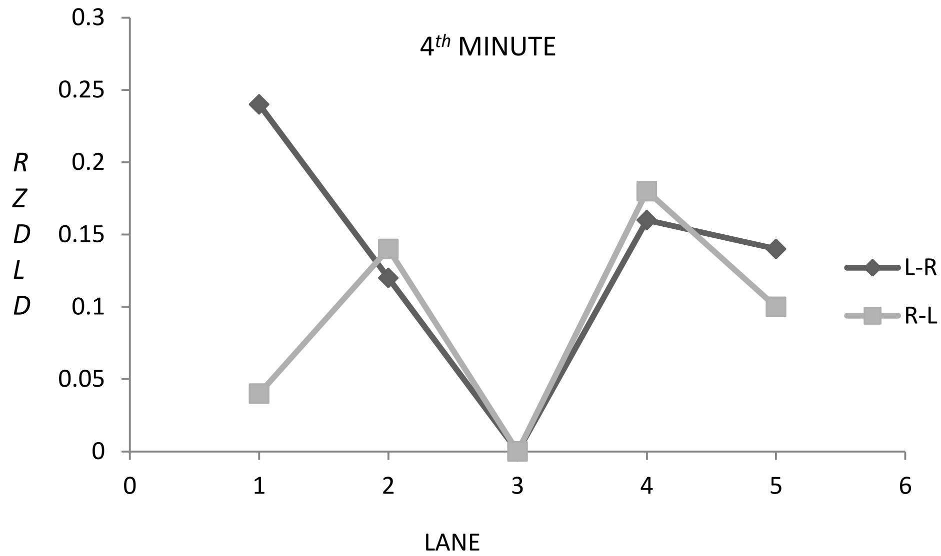

Figure 3.15: Variations of *RZDLD* in lanes in 4*th* minute in partially bifurcated corridor

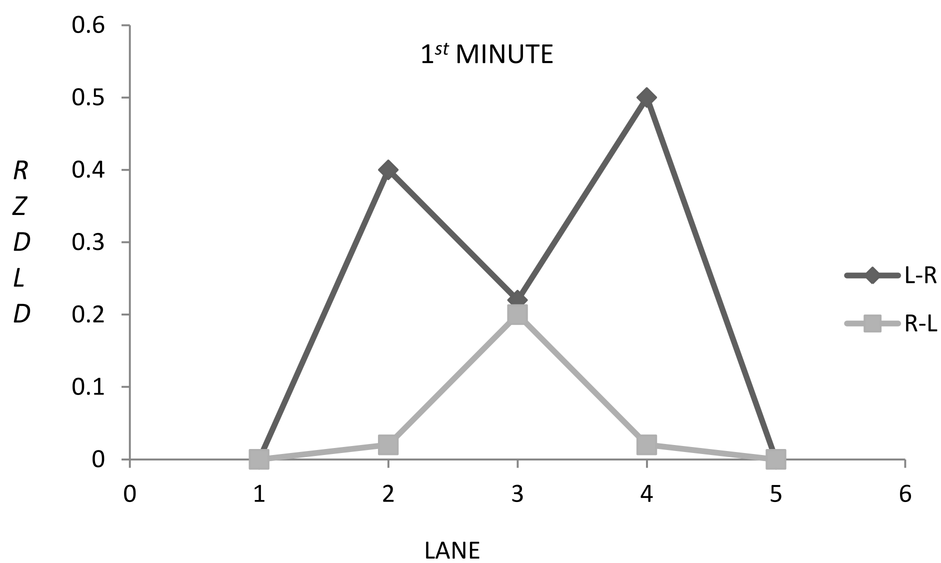

Figure 3.16: Variations of *RZDLD* in lanes in 1*st* minute in symmetrically narrowed corridor

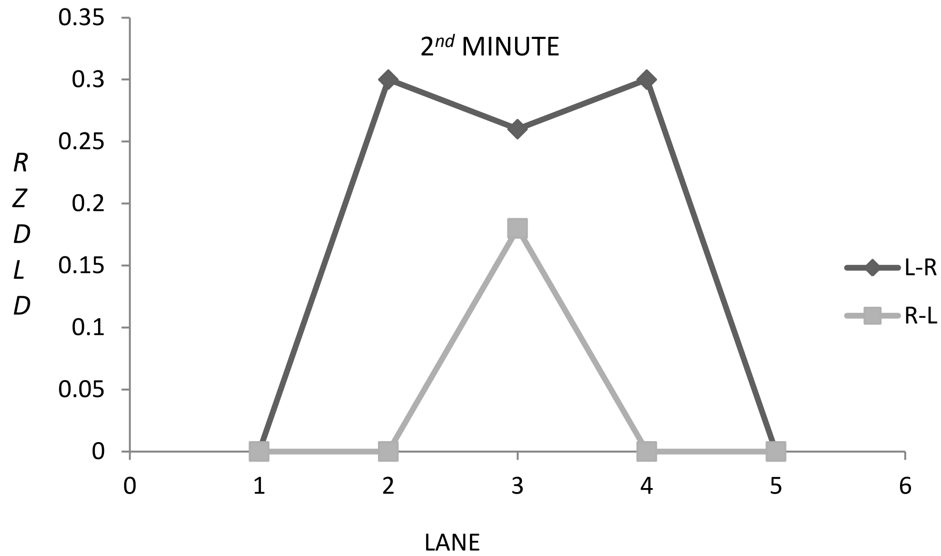

Figure 3.17: Variations of *RZDLD* in lanes in 2nd minute in symmetrically narrowed corridor

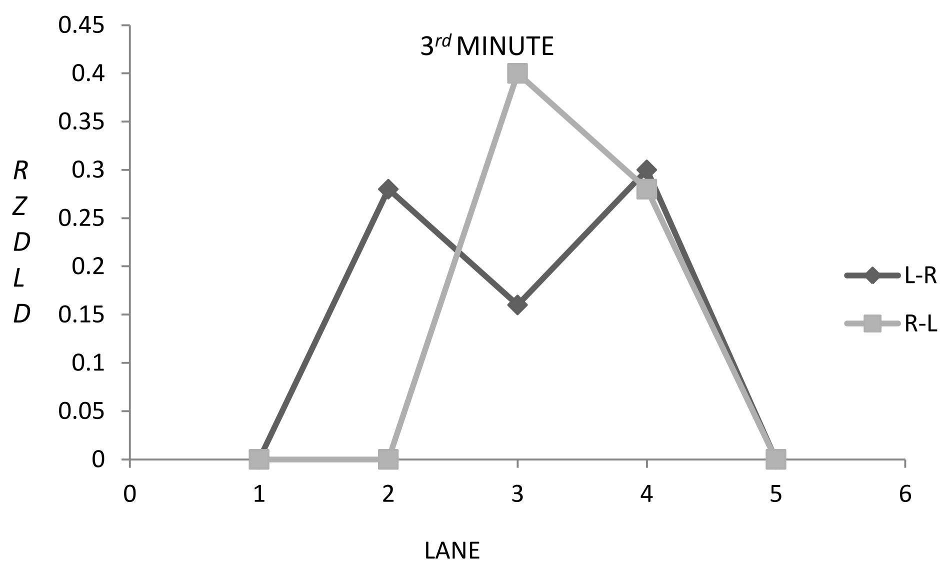

Figure 3.18: Variations of *RZDLD* in lanes in 3rd minute in symmetrically narrowed corridor

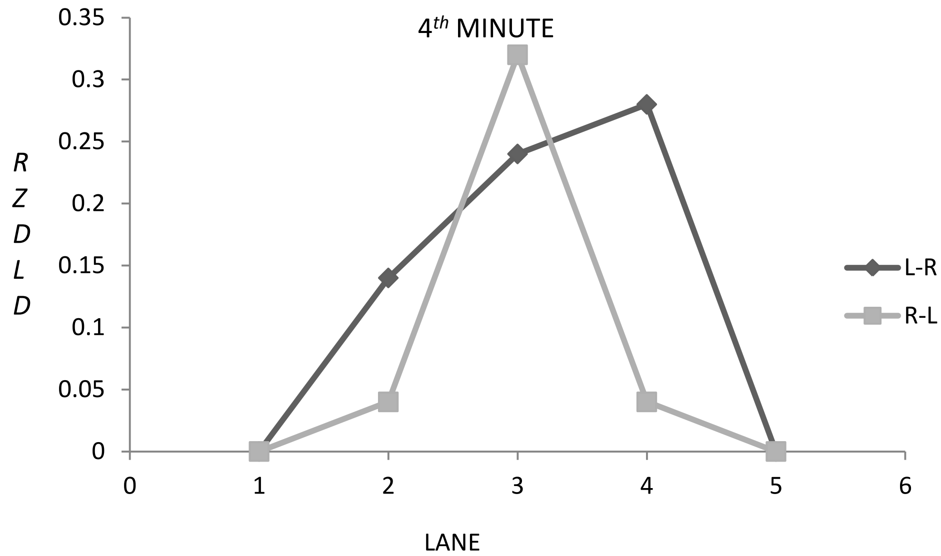

Figure 3.19: Variations of *RZDLD* in lanes in 4^{th} minute in symmetrically narrowed corridor

It is notable that, for partially bifurcated corridor, the 3^{rd} lane is completely blocked. Variations in 2^{nd} and in 4^{th} lane are clearly visible. From figure 3.12 to figure 3.15, it is observed that there is a change in *RZDLD* of L-R (left to right) and R-L (right to left) pedestrians in every minute. For instance, *RZDLD* in lane 2 is more for L-R (left to right) pedestrians for 1^{st} to 3^{rd} minute but suddenly in the 4^{th} minute R-L (right to left) pedestrians take control and *RZDLD* is found to be more for them in the 4^{th} minute. In the 4^{th} lane for the 1^{st} minute L-R (left to right) pedestrians are more in number and the next minute R-L (right to left) pedestrians take over and the number of R-L (right to left) pedestrians are more in the 2^{nd} minute.

From figure 3.16 to figure 3.19 variations of *RZDLD* can be found for bi-directional pedestrian movement in symmetrically narrowed corridor. In this case lane 1 and 5 are blocked and variations are mostly found in the 3^{rd} lane.

This observation can be extended for couple of minutes to find the variations and find a pattern.

Chapter 4

Proposed Model

The art of modelling is not to include everything that can be incorporated but rather to make the model as simple and tractable as possible to help answer the question that was posed. Consequently the judgement on the usefulness of a model is intricately linked to what problem it tries to address or the question for which it was devised to answer. In this study an attempt has been made to formulate a model which mimics the direction choice behaviour of pedestrians while they move along a long corridor. Here the proposed model is a very simple cellular automata model and only unidirectional motion is considered.

4.1 concept of the flow space

A flow space is the space where pedestrians move. The flow space in this cellular automata mathematical model is considered to have the following properties:

(i) it is considered as a dynamical system

(ii) it is discrete in time

(iii) it is discrete in space

(iv) only local interactions are possible

(v) Global phenomena may emerge out of local interactions.

(vi) Entire flow space is divided in regular grid (rectangular, triangular, hexagonal etc.) of lattice cells.

(vii) At each time step each cell is in one of the states (occupied or empty).

(viii) The state of each cell at time step t+1 is a function of some of its surrounding cells (the neighbours) at time step t.

4.1.1 Neighbourhood:

Here in this proposed model, rectangular grid is chosen over other grid patterns because it is perfectly suited for the corridors with straight walls. A straight corridor is considered in this model. There is no geometrical variation or no bottleneck. No stationary obstacles remain inside the corridor. Co-pedestrians moving at a relatively slower rate are considered as obstacles for those pedestrians who are moving at a moderately higher speed. For the change of the cell states in cellular automata only information from the neighbouring cells are considered. Mostly there are two types of neighbourhoods which are basically used in cellular automata. These are:

(i) Von Neumann: Neighbouring cells sharing only one side with the basic cell are considered.

(ii) Moore: All neighbouring cells sharing at least one corner with the basic cell are taken into account.

Here in this study, Moore neighbourhood is contemplated. Figure 4.1 shows different type of neighbourhood in cellular representation. While formulating and simulating the model, the forbidden moves of the Moore neighbourhood is kept in mind.

The Moore neighbourhood's forbidden moves should not be confused with the diagonal direction choice of pedestrians which is proposed in this study. A pedestrian can move diagonally when there is a vacant cell ahead of him/her or the pedestrian can change his direction of motion either diagonally right or diagonally left. This diagonal movement to the cell in the forward direction is made by the pedestrian if it is perceived by the pedestrian that there will be no conflict in stepping to that cell with other pedestrians who are moving forward and positioned parallel to him/her in side by lanes.

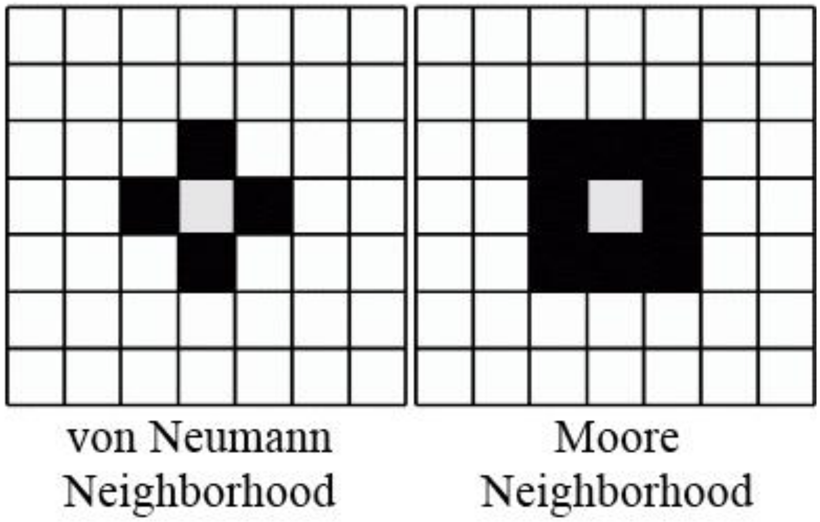

Figure 4.1: Neighbourhood in Cellular Automata

4.1.2 Complete coverage of path

In most of the cases, the general form of pedestrian facility is assumed as a rectangular flow space. In this proposed model, the flow space is considered to be made of rectangular grid of small cells. In this way the whole flow space provide complete coverage of the path unlike hexagonal cells which are unable to provide the whole space for pedestrian use.

4.1.3 Transition function

For each possible combination of states of the neighbourhood cells there is a target state that the centre cell develops into. Here in this model Moore Neighbourhood is having two possible states i.e. it can be vacant or occupied. The neighbourhood and the transition function define the local interactions. This proposed model enables a pedestrian having three desired transitions during his/her forward movement in the flow space. Figure 4.2 explains the possible transitions. A pedestrian moves into that cell which has the maximum desirability. A pedestrian is unable to estimate the exact desirability of moving into a particular cell. He/ She only guesstimate the desirability of the three cells and moves into any one of them. This movement is governed by the thought process of the pedestrians. These are explained as update rules in the section 4.2.

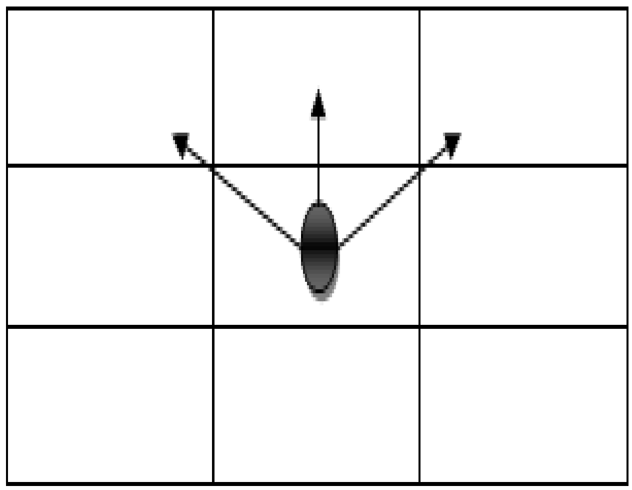

Figure 4.2: Possible transitions

4.1.4 Partial collision

Pedestrian motion is considered as two dimensional. The space of movement is divided into small cells of size 0.4×0.4 m. Pedestrians are allowed to move 0,1,2,3 or 4 cells at a time step. These equal to speeds of 0, 0.4, 0.8, 1.2 or 1.6 m/s. The speed range of 1.6 m/s is acceptable considering that the average speed of a pedestrian is about 1.3 m/s. This is done as the speed ranges of slow and fast moving pedestrians differ. A pedestrian has eight neighbouring cells. Pedestrians move forward understanding the movement possibilities which depend on the occupancy of the neighbouring cells. This rectangle is considered as the flow space of the pedestrian. The space is 1.44 m^2/pedestrians. This is in compliance with the value of flow space proposed for facilities with level of service 'C' where speed is average and direction change is necessary (table 3.9, chapter 3). A pedestrian at the centre of the rectangle and having eight neighbouring cells may share his/her flow space partially with another pedestrian in current or different time steps. Here co-pedestrians do not engage themselves bumping into or invading into each other's space fully but share only a partial amount of each other's space while moving along the corridor. The model is perfectly capable of simulating highly populated facilities where the level of service is poor and pedestrians yearning for free movement with higher speed and larger flow space need to change direction frequently. Figure 4.3 compares the model with rectangular cellular automata.

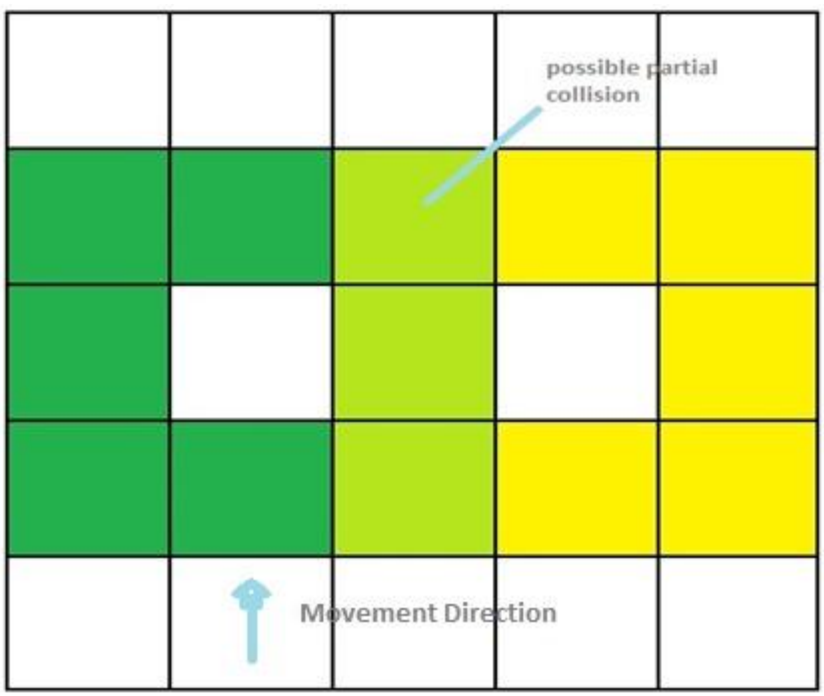

Figure 4.3: Partial overlap of flow space and possible collision

4.2 Update rules

The update rules establish a time development from time step *t* to *t*+1. Typically, there exist two types of update rules. They are as follows:

(i) Parallel Update rules

(ii) Sequential update rules

Parallel update rules enable all pedestrians inside the flow space to move simultaneously. There can be a tussle if two or more numbers of pedestrians want to move to the same target cell. Only the winner of the conflict moves to the target cell whereas the other competitors remain on the same position as they were in the previous time step.

Sequential update rules are contradictory propositions to parallel update rules. By following sequential update rules pedestrians can move one by one. So, there are no possible conflict and a higher flow (higher speed) may be achieved. This rules are obsolete and do not possess the standard of classical cellular automata where each cell is treated equally.

In this study, parallel update rules are used to simulate the model as conflicts are important elements in pedestrian dynamics. In this study the proposed model is the modification of some update rules in the existing Blue Adler model for unidirectional pedestrian motion along a corridor.

4.2.1 Update Rules for existing Blue Adler model

(i) An empty cell is available with 50/50 possibility between two pedestrians.

(ii) Gaps are identified and lanes are chosen considering the maximum gap among left, centre and right side.

(iii) Two way tie of movement to the target cell from two adjacent lanes is mitigated by random allocation.

(iv) Two way tie of movement between the current cell and the cell in the adjacent lane is dissolved by assigning the pedestrian the same lane where he/she is in the current time step.

(v) A three way tie among current and adjacent two lanes are resolved by same way as in step 4.

(vi) For forward movement, a pedestrian need to look ahead, if 8 cells are vacant ahead, the pedestrian can move with maximum speed. No cross directional movement is possible.

4.2.2 Update Rules for the proposed model

(i) Cross directional movements are possible if target cell is vacant without any conflict.

(ii) Pedestrian can move with average speed after looking ahead up to 2 vacant cells.

(iii) If pedestrian movement is blocked in current time step, he/she can move diagonally (left or right) if there is any possible transition or wait for the next time step.

(iv) If a pedestrian finds a possible transition diagonally to the third lane and so, he/she moves to that target cell in the current time step.

(v) A target cell is assigned randomly to any of the two pedestrians who desire to move into it at the same time step. This random assignment is sometimes based on the confidence level of the pedestrians. One of them wins the conflict.

This model can satisfactorily describe the lane changing phenomena occurring in crowded pedestrian streams in unidirectional motion along a corridor. Figure 4.4 shows the sketch of pedestrians changing lane while they move along a corridor. This proposed model can properly mimic pedestrian flow in crowded situations and in facilities where level of service is extremely poor. Figure 4.5 and 4.6 show the pedestrian motion in two consecutive time steps. To illustrate the modification made in this proposed model, lane changing behaviour of pedestrians in Blue Adler model and in this current model is represented in two different sketches. These sketches can elaborately establish the logical difference between the two models and can also justify the realistic approach of the proposed model. Figure 4.7 and figure 4.8 give an idea about the lane changing behaviour of pedestrians in Blue Adler model and the proposed model.

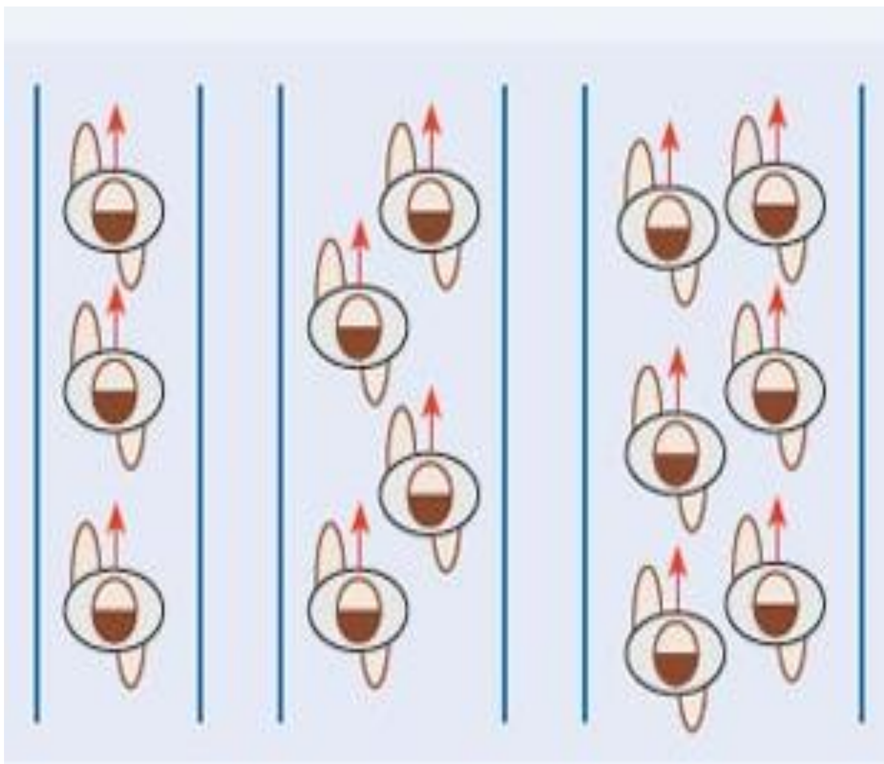

Figure 4.4: Lane changing of pedestrians

Figure 4.5: Pedestrian motion in time step *t*.

The green colour represents the pedestrian whose motion is considered while the yellow colour represents other pedestrians moving along a corridor which is divided into rectangular grids. The corridor is very crowded. So pedestrians are moving at the average speed of 2 cells per time step i.e. average speed is 0.80 m/s.

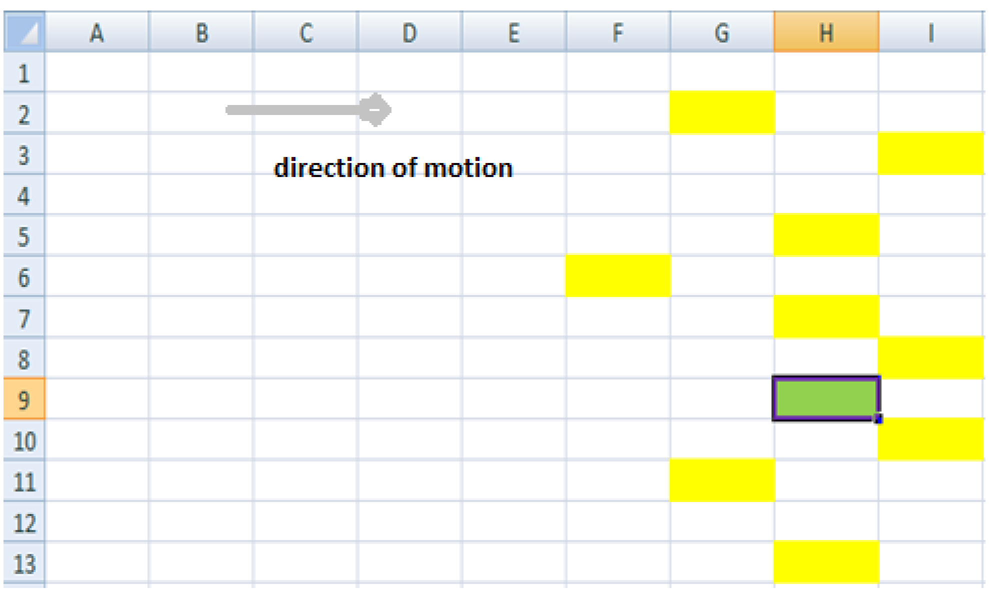

Figure 4.6: Pedestrian motion in time step *t*+1

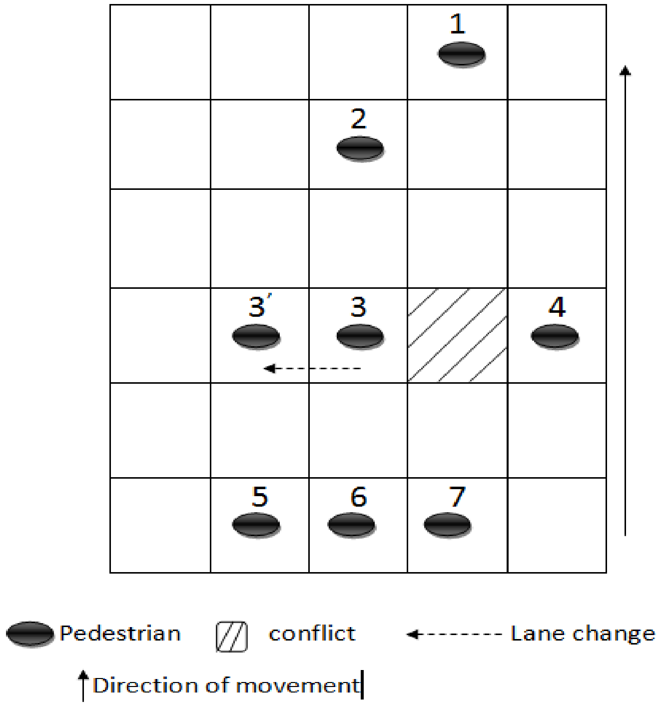

Figure 4.7: Lane changing behaviour of pedestrians in Blue Adler model

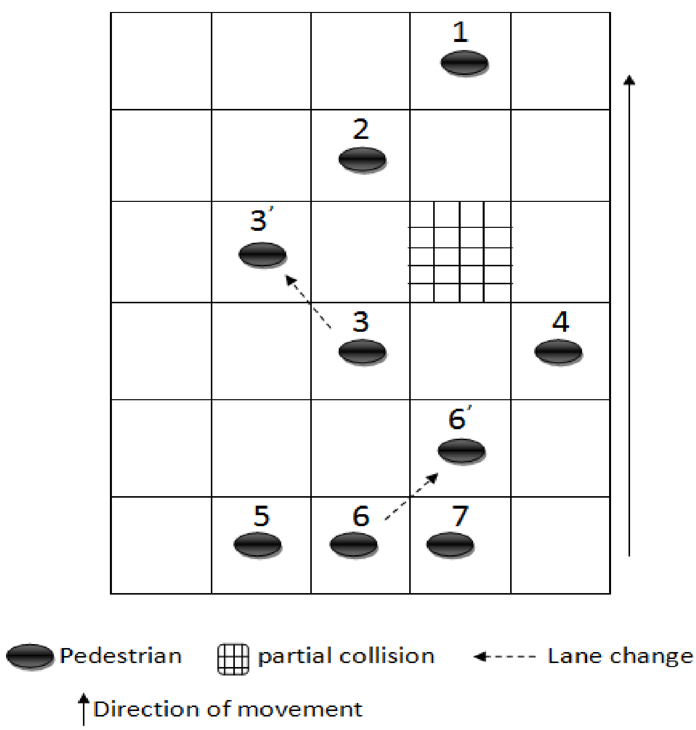

Figure 4.8: Lane changing behaviour in the proposed model

In figures 4.7 and 4.8 the relative positions of pedestrians moving along a corridor are shown. Their lane changing behaviour is demonstrated using simple sketches of the flow path. In figure 4.7 according to Blue Adler model pedestrian 3 cannot move diagonally in spite of having clear space along diagonal direction. But the same pedestrian in the proposed model can move diagonally to reach his/her destination. In figure 4.7 there is a conflict between pedestrian 3 and 4. Pedestrian 4 win it and pedestrian 3 changes lane. But in figure 4.8 an idea of partial collision is proposed i.e. pedestrian 3 and 4 can share that space reducing their speed and personal space or pedestrian 3 can change lane diagonally. Here pedestrian 3 changes lane in the diagonal direction. Pedestrian 4 may come to the cell where there could be a partial collision or may remain in his/her lane. In figure 4.7 pedestrian 6 is blocked but in figure 4.8 pedestrian 6 can change his/her lane in the diagonal direction and move towards the goal using the rule sets of the proposed model.

4.3 Basic Algorithm for the Model

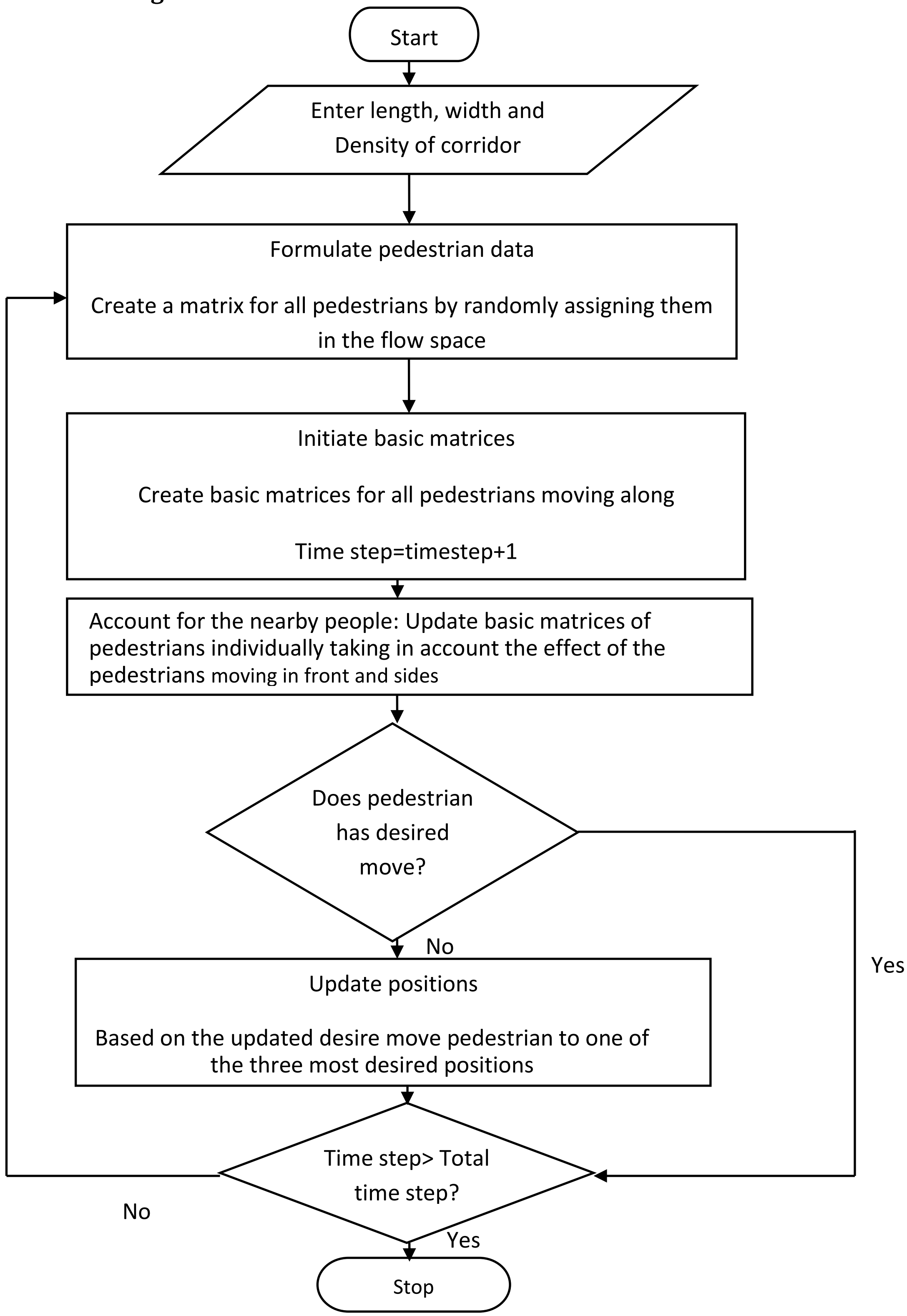

Figure 4.9: Flowchart explaining the computer implementation of the model

4.4 Description of the Algorithm

Figure 4.9 represents the algorithm in a flowchart. Based on this algorithm a coding is derived. In the first step the user need to define the corridor characteristics i.e. the length, width and the density (how much the corridor is populated) required to be defined. Corridor width is necessary to calculate the number of possible lanes inside the flow space. The program immediately distributes all the pedestrians randomly inside the corridor in various lanes and various positions. Then the program enables the pedestrians to move parallel using parallel update rules defined in the model. At each time steps a matrix is formulated showing the current positions of the pedestrians while they move along the flow space. In the next time step it is updated according to the rule sets.

At the end, the program gives an output in a separate window. This output contains every detail of each pedestrian. This output contains the positions of each pedestrian who moves inside the flow space in each and every time step. In this way the program describes the route which different pedestrians follow during his/her movement inside the flow space. The program also gives the individual speed of each pedestrian. Individual evacuation time of different pedestrians in different crowd (density level) can also be obtained using this program. When the corridor is very much crowded and a pedestrian cannot find a way to move, he/she waits for the next time step to get some vacant cells in his/her vicinity. This program is capable to simulate the model proposed in this study in a very realistic way. The model is able to mimic pedestrian behaviour in a wide range of varying densities and that is what makes the model realistic and reliable.

4.5 Modelling of Pedestrian Dynamics using Fuzzy Inference

Fuzzy logic is the way of getting the computers to make decisions more like humans. Fuzzy logic has mainly two primary components that help in modelling any non-linear system and make decisions. These are:

- Fuzzy Sets
- Fuzzy Rules

Fuzzy Sets: Fuzzy sets allow us to deal with a situation that is not precise. Real world decisions contain high level of uncertainly which needs to be taken into account.

A set is a collection of related items whereas a fuzzy set is collection of related items which belong to that set to different degrees. In fuzzy clustering, data elements can belong to more than one cluster, and associated with each element is a set of membership levels. These indicate the strength of the association between that data element and a particular cluster. Fuzzy clustering is a process of assigning these membership levels, and then using them to assign data elements to one or more clusters. Here we have used the C-means fuzzy clustering to obtain different clusters for different data sets (Inputs & Outputs).

Now, for our fuzzy model we have two input variables. These are:

- Corridor Width (CW)
- Density of the Corridor (Density)

Here output is the speed (Speed) of the pedestrians. These two inputs and the output are the fuzzy sets and they have corresponding fuzzy subsets.

Here the subsets for the fuzzy set corridor width are:

- Narrower
- Narrow
- Wide

Subsets of the fuzzy set density are:

- Low
- Medium
- High

Subsets for the fuzzy set speed are:

- Slow
- Moderate
- Fast

For all these fuzzy subsets triangular membership functions have been used as they were found to be more convenient and suitable for the datasets. Membership function of the subsets Narrower can be mathematically interpreted as below.

$$\boldsymbol{\mu}(\boldsymbol{Narrower}) = \begin{cases} \mathbf{0} & \boldsymbol{x} < 1 \\ \frac{\boldsymbol{x}-\mathbf{1}}{\mathbf{2}-\mathbf{1}}; \frac{\mathbf{3}-\boldsymbol{x}}{\mathbf{3}-\mathbf{2}} & \mathbf{1} < x < 2;\ \mathbf{2} < x < 3 \\ \mathbf{0} & \boldsymbol{x} > 3 \end{cases} \quad (4.1)$$

The equation 4.1 shows that the membership function $\mu(Narrower)$ takes input of the corridor of width 1 to 3 meters. Again, the subset Narrow can be mathematically expressed as in equation 4.2.

$$\boldsymbol{\mu}(\boldsymbol{Narrow}) = \begin{cases} \mathbf{0} & \boldsymbol{x} < \mathbf{2} \\ \frac{\boldsymbol{x}-\mathbf{2}}{\mathbf{3}-\mathbf{2}}; \frac{\mathbf{4}-\boldsymbol{x}}{\mathbf{4}-\mathbf{2}} & \mathbf{2} < x < 3; 3 < x < 4 \\ \mathbf{0} & \boldsymbol{x} > 4 \end{cases} \quad (4.2)$$

The above equation takes input of the corridor width between 2 to 4 meters. Similarly the membership function for the wide corridor can also be mathematically established.

Now, the equation 4.3 provides mathematical information about the fuzzy subset low of the set density. It takes input of the crowd density in between 0.20 to 0.30 pedestrians/m^2. Similarly other two subsets of the set crowd density can also be mathematically illustrated.

$$\boldsymbol{\mu}(\boldsymbol{Low}) = \begin{cases} \mathbf{0} & \boldsymbol{x} < 0.20 \\ \frac{\boldsymbol{x}-\mathbf{0.20}}{\mathbf{0.25}-\mathbf{0.20}}; \frac{\mathbf{0.30}-\boldsymbol{x}}{\mathbf{0.30}-\mathbf{0.20}} & \mathbf{0.20} < x < 0.25; 0.25 < x < 0.30 \\ \mathbf{0} & \boldsymbol{x} > 0.30 \end{cases} \quad (4.3)$$

Again, membership function high of the set speed can be mathematically described as in equation 4.4. It takes input of the speed between 1.2 m/s and 1.8 m/s.

$$\boldsymbol{\mu}(\boldsymbol{High}) = \begin{cases} \mathbf{0} & \boldsymbol{x} < 1.2 \\ \frac{\boldsymbol{x}-\mathbf{1.2}}{\mathbf{1.5}-\mathbf{1.2}}; \frac{\mathbf{1.8}-\boldsymbol{x}}{\mathbf{1.8}-\mathbf{1.2}} & \mathbf{1.2} < x < 1.5; 1.5 < x < 1.8 \\ \mathbf{0} & \boldsymbol{x} > 1.8 \end{cases} \quad (4.4)$$

Membership function moderate of the set speed is mathematically expressed in equation 4.5. This membership function takes input of the medium speed values of pedestrians. The range of the speed value for this linguistic variable is 0.7 m/s to 1.3 m/s.

$$\boldsymbol{\mu}(\boldsymbol{Moderate}) = \begin{cases} \mathbf{0} & \boldsymbol{x} < 0.70 \\ \frac{\boldsymbol{x}-\mathbf{0.70}}{\mathbf{1}-\mathbf{0.70}}; \frac{\mathbf{1.3}-\boldsymbol{x}}{\mathbf{1.3}-\mathbf{0.70}} & \mathbf{0.70} < x < 1; 1 < x < 1.3 \\ \mathbf{0} & \boldsymbol{x} > 1.3 \end{cases} \quad (4.5)$$

The membership function slow of the set speed (fuzzy output variable) is expressed in equation 4.6. This membership function takes input of speed between 0.30 m/s and 0.80 m/s.

$$\boldsymbol{\mu}(\boldsymbol{Slow}) = \begin{cases} \mathbf{0} & \boldsymbol{x} < 0.30 \\ \frac{\boldsymbol{x}-\mathbf{0.30}}{\mathbf{1}-\mathbf{0.30}}; \frac{\mathbf{0.80}-\boldsymbol{x}}{\mathbf{0.80}-\mathbf{0.30}} & \mathbf{0.30} < x < 0.55; 0.55 < x < 0.80 \\ \mathbf{0} & \boldsymbol{x} > 0.80 \end{cases} \quad (4.6)$$

Fuzzy Inference system:

Here the fuzzy inference system uses the input data and gives output. Mamdani type inference system is employed here using Matlab Software. Figure 4.10 shows the fuzzy inference system used here in this model.

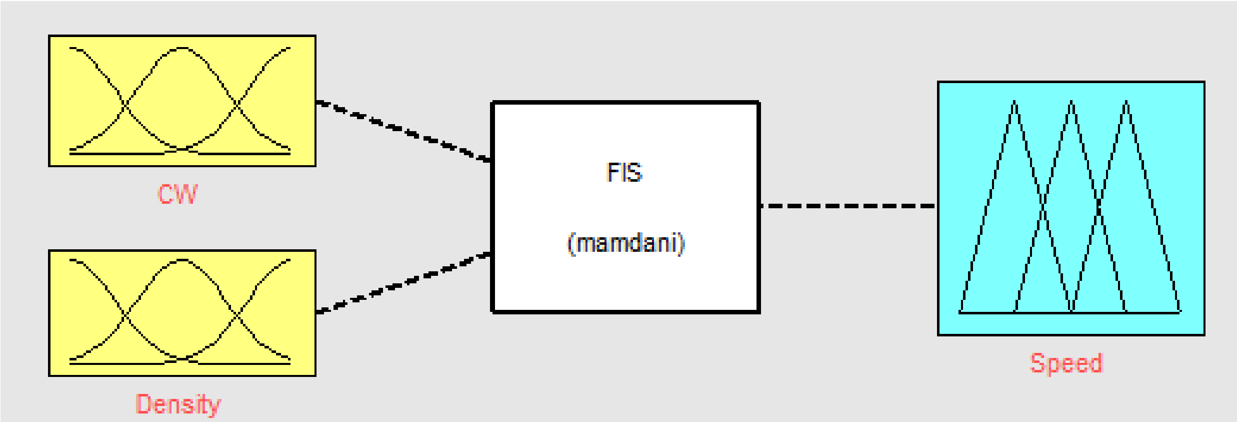

Figure 4.10: Fuzzy Inference System used in the model

Fuzzy Rules: Rules take partly true facts and finds out to what degree they are true. It then takes another fact making it true to that degree. A number of these rules can be combined and a final decision can be made. This whole process is called inference. This fuzzy inference system takes the input of the different corridor widths and Densities of the pedestrians inside the corridor and finds out the things we didn't know before; what will be speed of the pedestrians in the corridor. Rules here use human concepts, not strict measurements. In these rules words (in linguistic forms) are used not numbers. Here nine different rule sets are used. Based on the rules the model can give output data of speed provided any inputs of the two kinds already mentioned. Some of the output results are shown in the figures 4.11 to 4.13.

Multiple Regression Analysis: Multiple Regression Analysis has been performed to find the correlation between the dependent and the independent variables. It is found there is a good correlation between them. A model summery is given below.

Table: 4.1 Model summary of Multiple Regression Analysis in SPSS

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.923[a]	.852	.834	.119639

a. Predictors: (Constant), Density, CW

The regression Equation obtained can be interpreted as:

$$Speed=0.6998+0.1662*CW-0.6001*Density$$

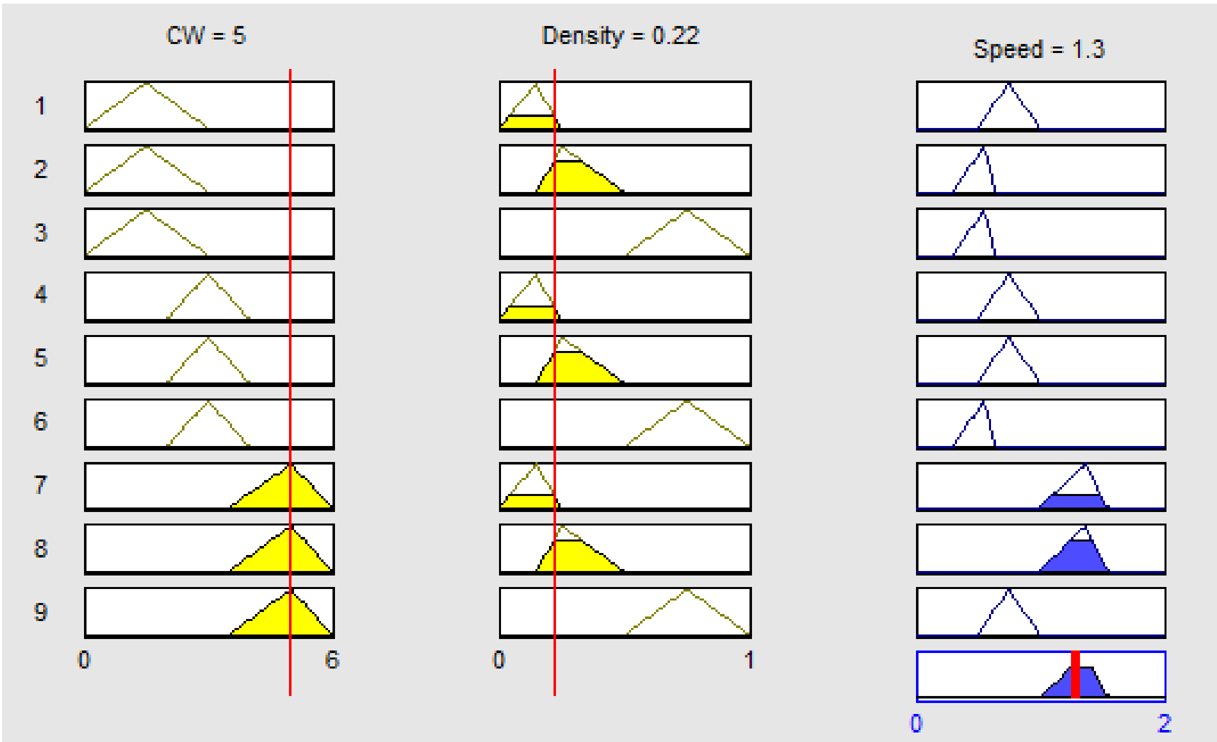

Figure 4.11: Inputs and output of the model

Figure 4.11 and 4.12 Show the Average speed of the pedestrians moving on the corridor for the different kinds of input sets of corridor widths and densities. For figure 4.11, corridor width is 5 meters and density of pedestrians is 0.22 pedestrians/m^2 and the speed obtained is 1.3 meters/ sec while in figure 4.12 inputs of corridor width as 2 meters and density as 0.90 pedestrians/m^2 gives speed value 0.489 meters/sec. It is perceived from the figures that the when the corridor is wide enough and the density is low, pedestrians move faster on the corridors. It is also perceived from the fuzzy model that when the corridor is narrow and density is higher, pedestrians move slowly. Figure 4.13 shows the surface view of the model for one set of inputs and output.

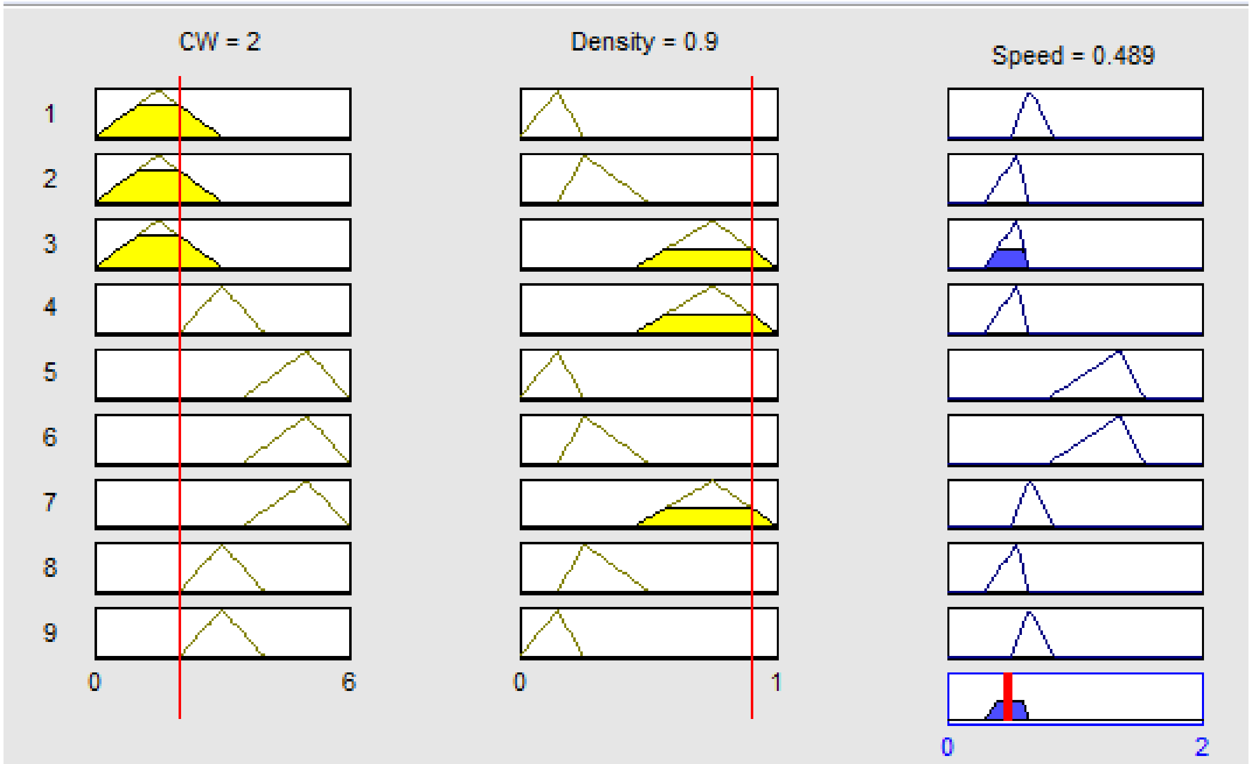

Figure 4.12: Inputs and output of the model

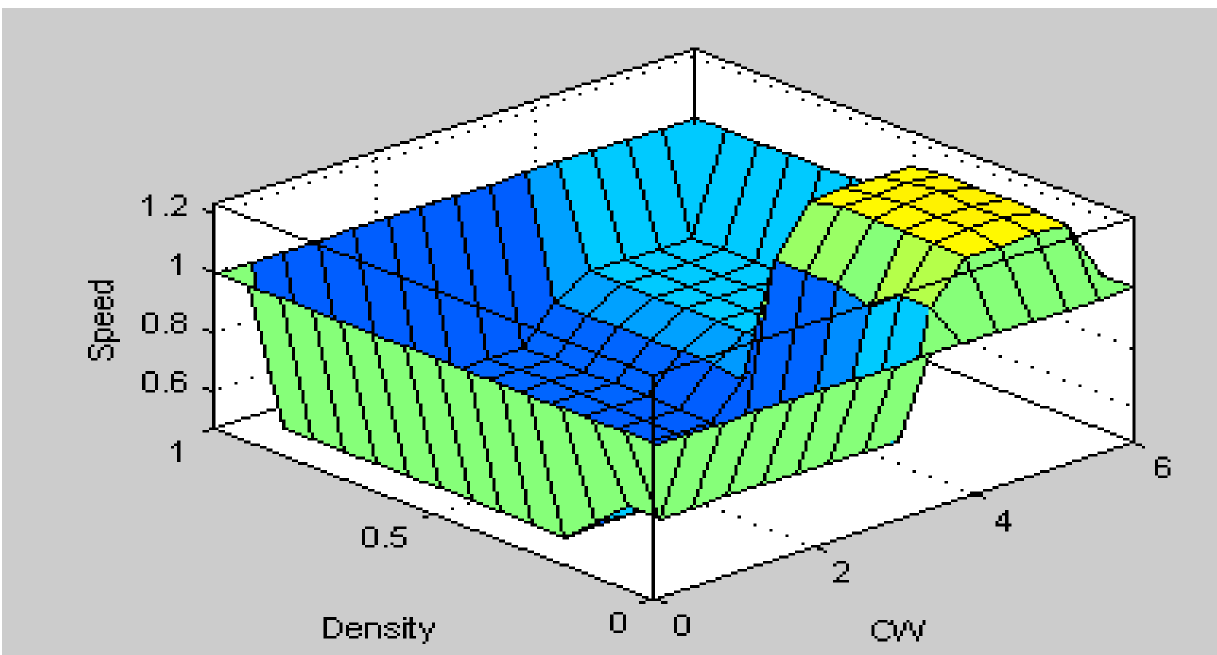

Figure 4.13: Surface view of the model

Chapter 5

Simulation results and comparison

In this chapter, simulated results are presented. Matlab 2009 software is used to simulate the model. Flow parameters (mainly speed) are compared in different facilities between the simulated results and results obtained from the empirical data collection (shown in chapter 3).

5.1 Model parameters

For simulating the model proposed in chapter 4, some parameters need to be chosen. This section describes those parameters used for simulating the model. Some user-defined space and time related parameters like cell size, time step, desired speed and distance of interactions are used for the simulation of the model. Cell size is adapted as 0.4×0.4m (average space occupied by a person). Each pedestrian moves two cells per time step while time step is taken as 1 sec. Speed is reduced by one cell per time step if a pedestrian finds other pedestrian near to his/her vicinity. Similarly, if the corridor is less crowded, a pedestrian may move into the cell which is vacant and is four steps ahead of him or her. In this way speed can be chosen by the pedestrians. Now, distance of interaction (DOI) is the parameter by which a pedestrian senses the gap between him/her and the pedestrian ahead of him/her. This *DOI* varies with the corridor density. If corridor density increases, *DOI* decreases and the pedestrian still manages to move along the corridor reducing his/her speed. Table 5.1 gives the different user defined *DOI* in different corridor densities.

Table 5.1: Values of *DOI* in different densities

Distance of interaction (number of cells)	Density of the corridor (pedestrian/m^2)
8	0.25
6	0.5
4	1.0

5.2 Validation of CA model: Comparison with Observation Results

Validation of the model is to demonstrate that the model is a rational and sensible representation of the actual system: that it regenerates system behaviour with enough fidelity to discharge analysis objective. Model verification is more general approach specific to model and system whereas model validation is related to the performance study of the system: serving a similar objective as model development. Model development is intended to solve a particular problem and portrays various parts of the system at different levels of generalization. Three separate aspects are considered for validating most of models. These are:

i. Assumptions
ii. Input parameter values and their dispensation
iii. Output values and inference.

Here in this validation of the developed model every aspect has been taken into consideration.

Broadly, there are three different approximations for the validation of a model. They can be applied independently or a combination of these can serve the purpose of validating different facets of the model formulated. These three approaches are as follows:

i. Expert intuition

ii. Real system measurements

iii. Theoretical analysis.

Here in this study, real system measurement which is most rational, reliable and preferred for validation of a model have been studied deliberately. Assumptions, input values, output values and system behaviour are tallied with those observed in real world.

Speed (average speed) variations at different densities are compared between simulated and real world results. Figure 5.1 gives the comparison.

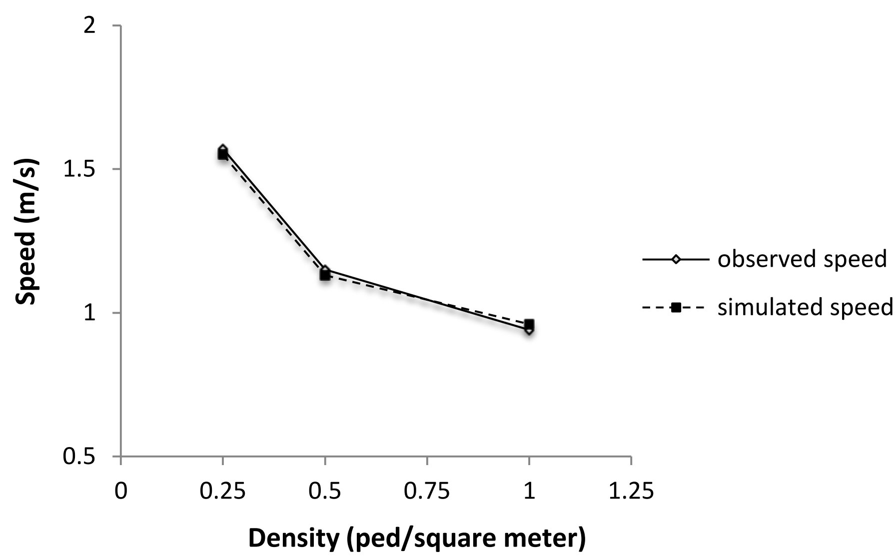

Figure 5.1: simulated and observed average speed at different densities

In this study the simulated and observed speed (from the field) is found to be similar. So the model is able to produce accurately similar results matching with the observed real life data.

It is notable that pedestrian densities above 1.0 pedestrians/m^2 is not considered for simulation as flow is heavily restricted above this densities both in simulation and in real life situations. It is learnt that pedestrian density of 0.25 per square meter is very much suitable for free flow conditions and no obstruction in flow has occurred both in model simulation and in real life conditions and the maximum speed is obtained in this density. A detailed study of evacuation time at different densities can give a clear idea about the corridor. Figure 5.2 shows comparison between simulated and real life evacuation time in a 5×10 m corridor (sidewalk).

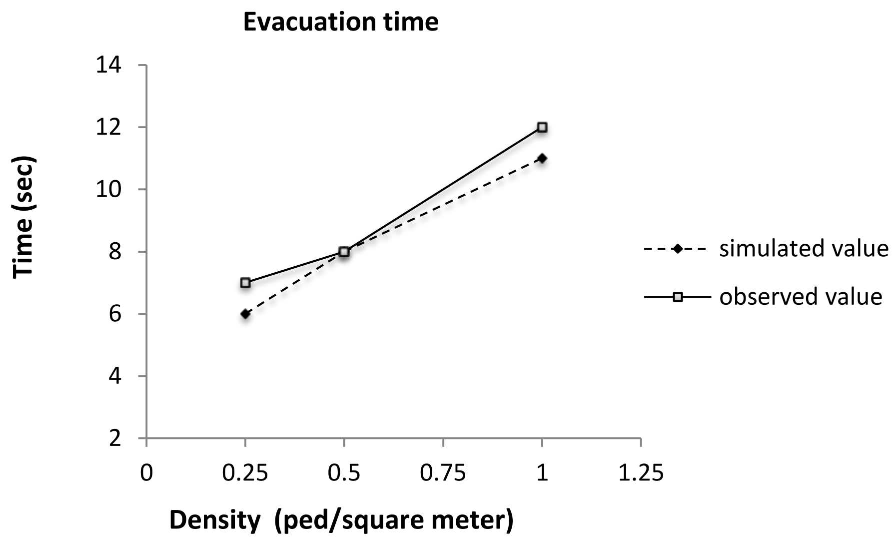

Figure 5.2: simulated and observed average evacuation time from a 5×10 m corridor

It is experienced from the simulation and real data observation that at higher densities flow is obstructed. A 1000 Matlab simulation of the model and a 1000 observed field data at different densities are collated and the number of times the flow is obstructed is recorded for both cases. This analogy is illustrated by figure 5.3 showing percentage of time the flow is obstructed in a corridor of 5×10 m. It is clear that the simulated results are analogous to the observed results and the validity of the model can be justified.

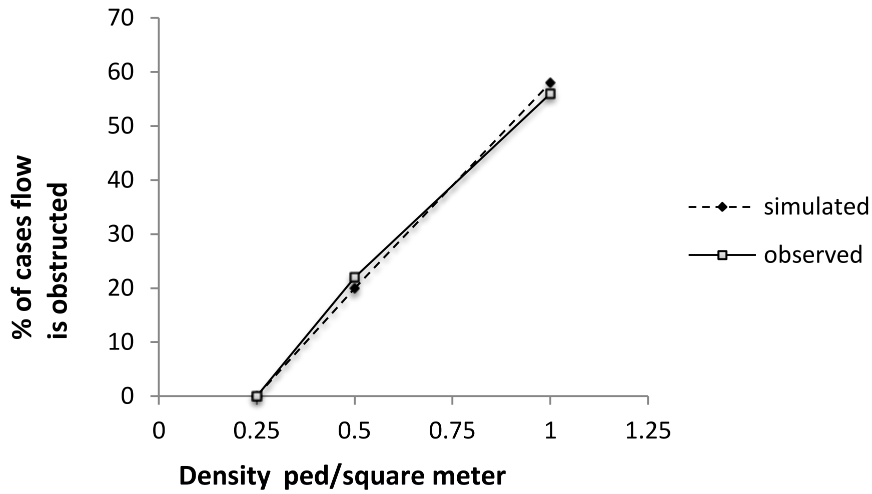

Figure 5.3: Flow obstruction at different densities in simulated and observed cases

It is fair to assume in most of the cases that models and systems will exhibit similar characteristics even if the workload varies. Here the speed of the pedestrians varies significantly at different densities for both simulation and real life cases. For a consistency check of the model, flow rate verses Speed is studied at 0.25, 0.5 and 1.0 pedestrian/m^2 densities for both the cases. Some results are illustrated in figure 5.4 and figure 5.5.

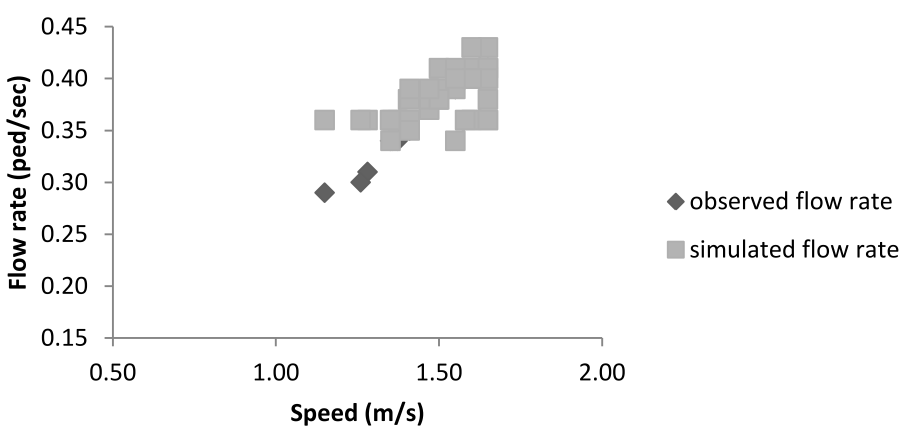

Figure 5.4: comparison of flow vs. speed scatter at 0.25 pedestrian/m^2 density

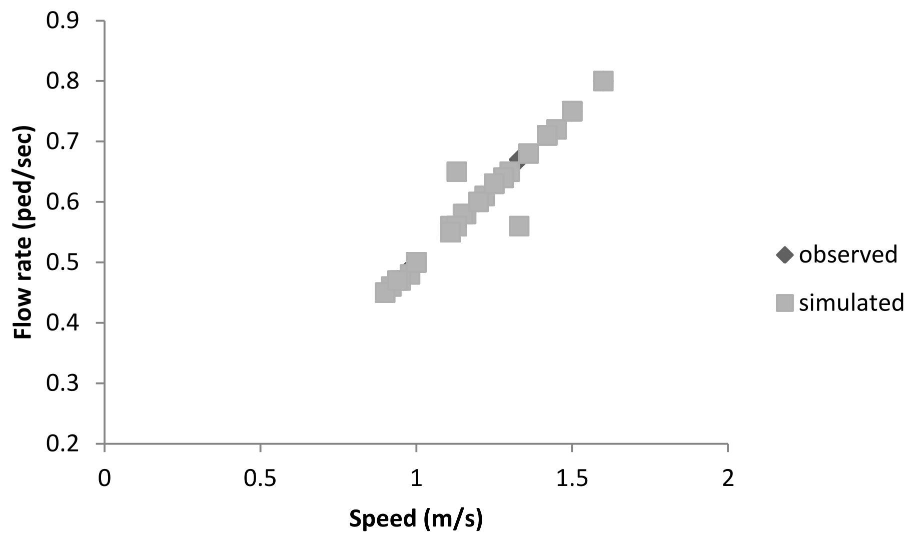

Figure 5.5: comparison of flow vs. speed scatter at 0.50 pedestrian/m^2 density

5.3 Validation of the model by statistical comparison

Apart from these comparison studies, some statistical comparison is also done. Independent sample *t*-test and *U*-test are performed. Comparison is done between simulated and observed speed values at 0.25, 0.5 and 1.0 pedestrian/m^2 densities. It is found that simulated and observed speeds are significantly similar in all these densities. Some results are tabulated (using SPSS results) in table 5.2 and 5.3.

Table 5.2: *U*-test comparison between simulated and observed speed at same density

Hypothesis Test Summary

	Null Hypothesis	***Test***	***Sig.***	***Decision***
1	*The distribution of speed is the same across categories of results.*	*Independent-Samples Mann-Whitney U Test*	*.677*	*Retain the null hypothesis.*

Asymptotic significances are displayed. The significance level is .05.

Table 5.3: *T*-test results at different densities.

Sl. No.	Simulated and observed speed data comparison at densities	Results
1	0.25 pedestrian/m^2	No significant difference
2	0.50 pedestrian/m^2	No significant difference
3	1.0 pedestrian/m^2	No significant difference

5.4 validation of the model in different corridor width

Corridor width plays a significant role in pedestrian crowd analysis. A corridor having larger corridor width can accommodate more pedestrians than those corridors having a smaller width. During simulation corridor width is taken into consideration. In the same manner corridor width is carefully measured during field data collection. If the corridor width is small, it can facilitate less number of pedestrians for a free motion. In such corridors pedestrians move in a comparatively slow speed when density is higher. Figure 5.6 and figure 5.7 show simulated verses observed speed (average) in corridors of different widths. Corridors of 3, 4 and 5meters are chosen for simulation and for validation of the results corridors of similar widths are used from the field data. These corridors include railway platform, foot over bridge and sidewalk (shown in chapter 3 table 3.1). In each case, 1000 simulations are done to obtain average speeds in different densities. It is found that the simulated and observed speed values are apparently similar in almost all cases. Thus the performance of the model is validated.

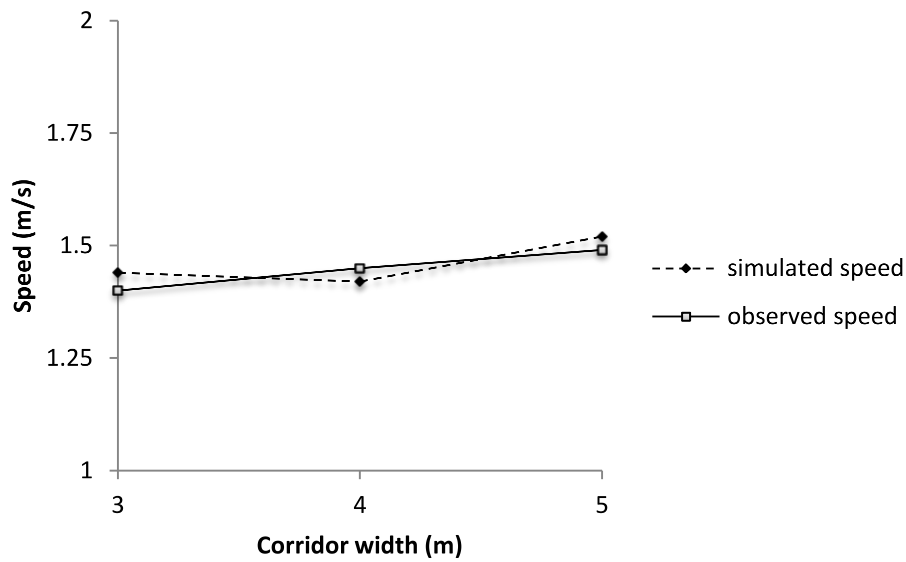

Figure 5.6: Simulated and observed speed variations in corridors of different widths when density is 0.25 pedestrians/m^2

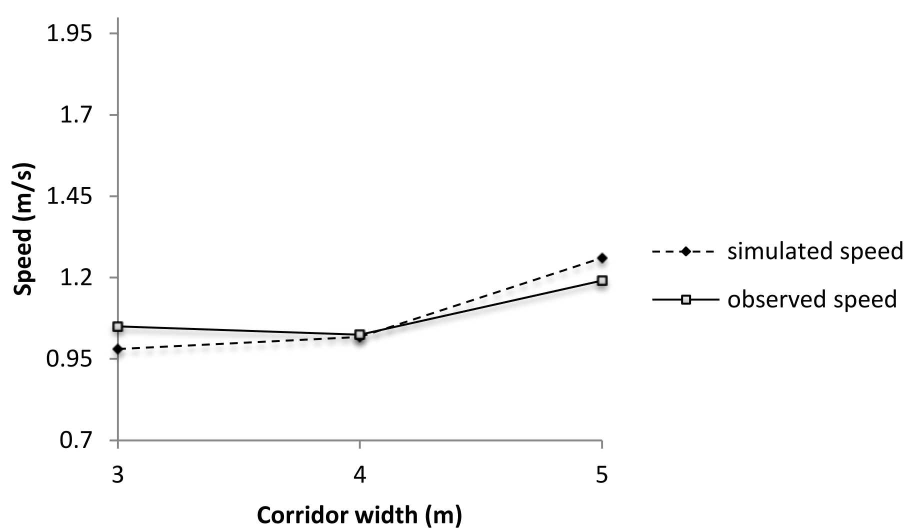

Figure 5.7: Simulated and observed speed variations in corridors of different widths when density is 0.50 pedestrians/m^2

Chapter 6

Summary and Conclusions and future scope of work

Summary: In this thesis, a huge amount of field data collection on pedestrian flow parameters is done. This video data collection is done for different pedestrian facilities. Some empirical studies are done using the collected field data. Some statistical tests are also conducted. Some existing phenomena in the pedestrian stream are explained. Some phenomena are explained through the microscopic model proposed here. Some are explained with some empirical parameters which are adapted from already conducted experiments (Chattaraj *et al.* 2010). Level of service is a measure of the existing condition and serviceability of a pedestrian facility. Level of service is evaluated for different pedestrian facilities in this current study. A microscopic model based on cellular automata is proposed for pedestrian dynamics. Another fuzzy inference based model which describes the correlation among sidewalk widths, sidewalk density and speed of the pedestrians has also been proposed. The models are validated with the real life collected data.

The main contributions of this thesis are:

i. Real life data collection of Indian pedestrians at different facilities
ii. Creation of a huge dataset of Indian pedestrians.
iii. Empirical observation of the flow parameters of pedestrian dynamics.
iv. Computation of level of service of different pedestrian facilities.
v. Development of microscopic models for pedestrian motion.

Major Conclusions: The major conclusions are as follows:

(a) Pedestrians move with different speeds on different facilities. This is one of the major behavioural findings in this thesis. This is established with the help of statistical tests. It is also found from the study that pedestrians walk with different psychology on different facilities.

(b) An oscillation phenomenon that occurs in bidirectional pedestrian movements in bottlenecks has been quantified with time series graphs.

(c) Pedestrians change their direction diagonally when they face some static or dynamic obstacles while moving along sidewalks. This direction choice behaviour is modelled proposing a cellular automata model.

(d) There is a strong relationship among sidewalk width, density of crowd on the sidewalk and the speed of the pedestrians moving along the sidewalk. This is modelled using fuzzy logic.

(e) Models can be validated with real-life data. In this study both the models are validated using real-life data collected on different pedestrian facilities.

Scope for future work:

(a) In this study the proposed cellular automata model considers unidirectional motion only. Future studies can be done to make one bidirectional motion

(b) Panic could not be included as a parameter while modelling pedestrian dynamics. Future work can be done to include panic in modelling.

(c) Only straight corridors are taken for modelling in present form. Future work can also be done to model pedestrian motion on facilities with complex geometry.

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