Modelling of Pedestrian Walking Behaviour over Elevated Walkways

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by

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Certificate

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Abstract

In a developing nation like India, where majority of the people walk approximately 1-2km per day, it is essential to construct well connected pedestrian facilities. However, pedestrian facilities, especially elevated walkways are neglected and poorly maintained. This discourages the pedestrians from using the elevated facilities and thus come in direct contact with vehicular traffic. Providing a safe, secure and comfortable walking experience over elevated walkways, could encourage pedestrians to avoid risky at-grade facilities and shift to a safer pedestrian elevated facilities. In the current study an attempt was made to understand the pedestrian movement behaviour characteristics over mid-block and vertical connectivity (stairway) sections of elevated walkways (FOBs: foot over bridges and skywalks).

To conduct the study, both videographic and questionnaire data were collected over seventeen FOB and seven skywalk locations across six different Indian cities. The extracted data was used for preliminary analysis related to demographic characteristics of pedestrians over mid-block and stairway sections of FOBs and skywalks. The young adult (21-40 years) male pedestrians were found to be the dominant users' across all locations. The percentage of mobile users varied between 8-15% (over mid-block sections) and 7-9% (over stairways sections). The pedestrians walking in groups of 3 or more pedestrians was observed to be more frequent across mid-block sections under moderate to heavy flow conditions.

For an overall estimate of the pedestrian flow characteristics (free flow speed, jam density, maximum flow rate, and flow rate) the fundamental diagrams were developed for both the mid-block and stairway sections of both the facilities. In case of both mid-block sections and stairway sections, a higher maximum flow rate was observed in case of skywalk facilities.

Subsequently, different walking behaviour models were developed using linear regression model based on individual (age, gender, luggage carrying conditions, mobile use and disability) and group (group size, lane formation, leader-follower relationship, lane shifting, overtaking, squeezing effect and faster-is-slower effect) behavioural characteristics to study the impact of these factors on the walking speed over mid-block and stairways sections. The mean absolute percentage error (MAPE) and root mean square error (RMSE) evaluation metrics showed that all the developed models performed well.

Further, walking speed prediction models of pedestrians over elevated walkways were developed using different tree-based machine learning algorithms (Gradient Boosting Regressor, Light GBM Regressor, XGBoost, Adaboost, Random Forest, Extra Tree Regressor and Decision Tree) based on different pedestrian flow characteristics (individual and group) along with geometric parameters. The mean absolute error (MAE) was found to be less than 10% in case of both FOB and skywalk walking behaviour predictions.

To identify the most significant parameters affecting the preference of pedestrians towards using elevated walkways under the current existing conditions, stepwise binary logistic regression modelling approach and machine learning tools (GLM: Generalized Linear Model, RF: Random Forest and GBM: Gradient Boosting Machines) were used on the perception data.

Recently developed Indo-HCM (2018) provides guidelines for quantitative LOS across different FOB facilities. However, for skywalk facilities no such LOS standards are available. Using the quantitative and qualitative data, level of service (LOS) standards were developed in this study for skywalk and FOB locations across different cities.

This study also attempted to develop a global simulation model which can replicate walking behaviour over elevated walkways using commercially available software (PTV Viswalk). Sensitivity analysis was carried out to identify the most significant parameters which affect the walking behaviour and thereby calibration using genetic algorithm was carried out through COM interface in MATLAB. The model was validated using remaining 20% data set. The MAPE was found to be less than 20% across different locations.

A semi-manual technique for data extraction was also developed for extracting pedestrian position (subsequently speed and trajectory) data using front inclined camera angle as many times top-down angle is unavailable due to height restrictions (especially over elevated walkways). Vanishing point method was used to extract data for pedestrian body dimensions across vertical and pedestrian-specific trajectory planes. Using the trajectory and body dimension information, the spacing maintained between pedestrians were estimated. Subsequently, JUPedSim software was used for extracting the fundamental macroscopic properties (speed, flow and density) from the pedestrian position data, and the results were compared using classical and voronoi approaches.

The major outcomes of the study can be beneficial in different ways:

i. The capacity of elevated walkways (both for mid-block sections as well as stairway sections) can be estimated using the developed fundamental diagrams.
ii. In order to understand the walking behaviour of pedestrians over elevated walkways, the identification of individual and group behaviour characteristics would be extremely beneficial. Moreover, such behaviour can be incorporated into microscopic simulation models.
iii. The prediction of walking speeds would be beneficial to designers and planners in understanding the significant variables affecting the walking speed and thus constructing better elevated walkways.
iv. The perception usability models would be extremely helpful to understand the qualitative factors impacting the pedestrians' preference towards using the elevated walkways.
v. To estimate and understand the existing Level of Service (LOS) over elevated walkways, the developed LOS standards would be quite beneficial.
vi. Researchers who plan to study microscopic behaviour over elevated walkways using Viswalk software, can utilize the global simulated model and the estimated calibrated parameters for studying the microscopic behaviour of pedestrians.
vii. The developed semi-manual technique can be helpful in studying pedestrian gap maintaining behaviour and also establishment of different threshold levels for the crowd management where data collection using top down video is not possible and only frontal camera angle view is available. Such approach can be directly applied to CCTV footage (which mostly gives front inclined views of camera) to ensure the physical distancing in the current ongoing pandemic (COVID-19).

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List of Abbreviations

Acronyms	**Full form**
	General terms
CCTV	Closed Circuit Television
CBD	Central Business District
FD	Fundamental Diagram
FFS	Free Flow Speed
FOB	Foot Over Bridge
FP	Following Pedestrian
FSE	Faster-is-Slower Effect
GPS	Global Positioning System
GS	Group Size
GSPS	Grade Separated Pedestrian System
GUI	Graphical User Interface
IBM	International Business Machines Corporation
Indo-HCM	Indian Highway Capacity Manual
IRC	Indian Roads Congress
JUPedSim	Jülich Pedestrian Simulator
LFR	Leader-Follower Relationship
LF	Lane Formation
LP	Leading Pedestrian
LS	Lane Shifting
MMRDA	Mumbai Metropolitan Region Development Authority
NCHRP	The National Cooperative Highway Research Program
NCR	National Capital Region
NCRB	National Crime Records Bureau
NH	National Highway
PLOS	Pedestrian Level of Service

PTT	Public Transport Terminal Location
SATIS	Station Area Traffic Improvement Scheme
SE	Squeezing Effect
SPSS	Statistical Package for the Social Sciences
QN-PLOS	Quantitative Pedestrian Level of Service
QL-LOS	Qualitative Pedestrian Level of Service
Q_{max}	Maximum Flow Rate
US-HCM	United States Highway Capacity Manual
WHO	World Health Organization

Evaluation metrics

ANOVA	Analysis of Variance
AUC	Area Under Curve
AUPR	Area Under Precision Recall Curve
AUROC	Area under Receiver Operating Characteristics Curve
B	Estimated Coefficient
CI	Confidence Interval
Exp B	Odds Ratio
HL	Hosmer and Lemenshow Test
K-S	Kolmogorov–Smirnov Test
-2LL	Log-Likelihoods
MAD	Mean Absolute Deviation
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
Max_depth	Maximum Depth
Min_split_gain	Minimum Split Gain
MOE	Measures of Effectiveness
MSE	Mean Squared Error
N_estimators	Number of Estimators
Num_leaves	Number of Leaves
NRMSE	Normalized Root Mean Squared Error

PAC	Percentage Accuracy in Classification
Q-Q	Quantile-Quantile
R^2	Coefficient of Determination
RMSE	Root Mean Square Error
RMSLE	Root Mean Squared Log Error
ROC	Receiver Operating Characteristic Curve
SE	Standard Error
SMAPE	Symmetric Mean Absolute Percentage Error
TT	Training Time

Modelling approaches

Ada Boost	Adapting Boosting Regressor
BPNN	Back Propagation Neural Network
BTCR	Boosted Tree Classifiers and Regression
CA	Cellular Automata
CART	Classification And Regression Trees
DCapsNet	Develop Capsule Network Model
DNN	Deep Neural Network
DNS-PS	Determined Structure Network-Particle Swarm
DT	Decision Tree
E-CHAID	Chi-squared Automatic Interaction Detector
ETR	Extra Tree Regressor
GA	Genetic Algorithm
GBDT	Gradient Boosting Decision Tree
GBRT	Gradient Boosted Regression Tree
GBM	Gradient Boosting Machine
GBR	Gradient Boosting Regressor
GLM	Generalized Linear Model
LGBM	Light Gradient Boosting Machine
LRM	Linear Regression Model
MARS	Multivariate Adaptive Regression Splines

ML	Machine Learning
MNL	Multi-Nominal Logit Model
NGSIM	Next Generation Simulation
RF	Random Forest
RFRC	Random Forest Regression and Classification
RT	Regression Tree
SAQPM	Smart Air Quality Prediction Model
SFM	Social Force Model
SVM	Support Vector Machine
XGBoost	eXtreme Gradient Boosting

Glossary of Terms

Terms	Description
Lane formation	Formation of lanes or line of pedestrians is a very common self-organization phenomenon observed when there is moderate to high flow of pedestrians.
Leader-follower relationship	It is a self-organizing phenomenon observed when two pedestrians are in lane formation and the time headway between them is ≤2 sec.
Lane shifting	It is a common phenomenon that occurs when a subject pedestrian shifts from the current lane to either overtake slower pedestrians or to avoid collision with the pedestrians coming from the opposite direction.
Overtaking/ Surpassing	Overtaking or surpassing is a common phenomenon in reality where pedestrians either shift their lane to overtake slower pedestrians in the front or walk on the same lane to bypass the slower pedestrians.
Faster-is-slower effect	It is a rare phenomenon which is generally observed when the subject pedestrian attempts to change lane and overtake the slower moving pedestrians in the front, but is forced to shift back to original lane due to heavy oncoming flow from opposite direction or lack space.
Squeezing effect	It is a self-organization phenomenon that occurs when pedestrians in the minor flow direction are forced to shift to one side of the walkway due to the major flow in the opposing direction.
Tau	It refers to relaxation time in seconds.
Lambda_mean (λ_m)	It is used to adjust the weight that defines how the force from other persons and objects would affect the pedestrian.
A_soc_isotropic (A_i), *B_soc_isotropic* (B_i)	A_i and B_i along with λ_m form the repulsive force between the pedestrians.
A_soc_mean (A_m), *B_soc_mean* (B_m) *and VD*	A_m decides the strength of the force in metres per square second, while B_m determines the ranges of force in metres. A_m and B_m along with VD (in seconds) forms the other one of the two repulsive forces.
Noise	It relates to the random force which adds to calculated social force if the actual walking speed of a pedestrian is below desired speed.

CHAPTER 1

INTRODUCTION

1.1. General

Walking is the most effective and efficient mode of transportation for short trips. Approximately 1-2 km length of urban trips are performed on foot daily (IRC: 103, 2012). At times, walking in itself comprises a complete mode or acts as a feeder/ connector to other mechanized travel modes. Arasan (1994) estimated that walking covered majority of work (52.5%), school (80.9%) and other (64.7%) trips among all other modes of transportation in a key city in India. Apart from improving urban life quality and decreasing air pollution, one major benefit of walking is health improvement (Hanson, 2015, Blaga, 2013, Frank, 2007; Lotfi, 2011; Southworth, 2005). As per Woldeamanuel (2016) "walking as the major transit access mode confers health benefits to the public while presenting planners with the challenge of overcoming walk-accessibility costs which deter mass-transit use". Thus in order to shift to a more sustainable society, it is extremely important to promote walking (Cotter, 1999). As per NCHRP Report 770 (2014) walking is highly influenced by:

- Type and connectivity of the facility.
- Natural environment (climate and topography).
- Socio-demographic characteristics (age, gender, presence or absence of luggage, trip purpose, occupation, group size, use of mobile phones, etc.).
- The perception and attitude of the pedestrians.
- The type of land use and built environment.

A person who walks and travels on foot is termed as a 'Pedestrian'. As per Morris (1962), the movement of pedestrians are fluid, flexible and far more adaptable to the existing pedestrian flow in comparison to the vehicular flow. The different abilities of the pedestrians which make them far more complex and significantly different from the vehicular traffic are: the ability to cross another stream of pedestrians, walk in the opposing direction of a major flow, maneuver easily without major conflicts as well as move in uni-, bi- and multi-directions. The flow of pedestrians, similar to vehicular traffic does not follow proper lane discipline under low flow condition. Also under moderate to high flow levels, the self-organization or group phenomenon such as lane formation, lane squeezing, lane shifting and leader-follower relationships are frequently observed.

As per US-HCM (2010) and Indo-HCM (2018), there are mainly nine different types of pedestrian facilities, namely:

- **Sidewalks:** These are located parallel and in proximity to roadways.
- **Walkways:** These are used to connect sidewalks and are located far away from the influence of the motorized traffic.
- **Pedestrian zones:** These are streets that are purely dedicated to pedestrians for full time or part time activity.
- **Queuing areas:** These are the locations for pedestrians to stand temporarily while waiting to be served (e.g.: corner of signalized intersections).
- **Crosswalks (marked and unmarked):** They provide at-grade connections between different pedestrian facilities across various sections of roadways used by the other modes of motorized and non-motorized transportation. Factors such as delay, safety and comfort influence the level of service of such a facility.
- **Underpasses (subway):** They are underground pedestrian facilities, which allow pedestrians to reach to the other side of the road safely.
- **Overpasses (FOB: foot over bridge and skywalk):** These are the overhead facilities which allow easy crossing of busy streets from one side of the road to the other (as in case of FOBs), and also enable lateral and longitudinal movement and can be the best substitute to the sidewalks and crosswalks (as in the case of skywalks).
- **Stairways:** They represent the vertical connectivity which provides shorter access to overpasses, underpasses or walkways located at different elevations. In general, the stairways should be provided in combination with a ramp, elevator or escalator.
- **Shared pedestrian-bicycle paths:** These are paths typically open to non-motorized traffic and are often constructed to serve areas without busy streets.

Figure 1.1 shows the different pedestrian facilities as per US-HCM (2010).

(a) Sidewalk (b) Walkway (c) Pedestrian Zone

(d) Queuing Area (e) Crosswalk (f) Underpass

(g) Overpass (h) Stairway (i) Shared Pedestrian–Bicycle Path

Figure 1.1. Pedestrian facility types *(Source: Exhibit 3.14, HCM 2010)*

However, the rapid urbanization in a developing nation like India (post the new millennium), led to exponential growth of vehicular traffic in India. To accommodate this sudden rise in motorized vehicular traffic, the pedestrian facilities began to be curbed. Also, the existing illegal vendor on the pedestrian facilities furthermore prevented pedestrians from using the facilities. As a result, pedestrians were forced to use the carriageway and come in direct contact with the vehicular traffic. As per the World Health Organization (2018) report, the pedestrians constituted 23% out of 43% vulnerable road users. Also, as per the WHO 2018 report, in the low and middle income countries, the road traffic injuries were found to be a major cause of death amongst children and adults (between the age of 5-29 years). The India Status Report (Mohan, 2016) reported that the pedestrian fatality rate in India was nearly 35-40% of the total fatalities, and metropolitan cities had the maximum fatality share (Mohan, 2009). Apart from the sidewalks, reports suggested that 22,375 out of 2,09,796 (i.e. nearly 10.7%) of the road accidents took place at urban road crossings (N.C.R.B. Report, 2015). Previous studies also indicated that drivers do have a propensity to break traffic rules and even tend to drive during the red signal phase, which could eventually lead to pedestrian-vehicular conflicts (Herms, 1972; Koepsell, 2002). Also, a study by Golakiya (2019) showed that the pedestrians had a general tendency to avoid properly designated crosswalks and cross the roads through illegal median openings to save time. Moreover, Leather (2011), presented that the median walkability rating for thirteen Asian cities was 58.43 (out of 100), with the lowest being Public Transport Terminals (PTTs). Also, the preference interview conducted by Leather (2011), revealed that 67% of the pedestrians would shift their mode to cars (29%) and two-wheelers (10%), if the walking conditions did not improve.

Providing a safe, secure and comfortable walking environment is key to protecting the pedestrians and promoting physical activity (Quistberg, 2017). Grade separated pedestrian systems (GSPS) thus seem to be the most feasible solution which completely segregates pedestrians and vehicular traffic, and prevents unforeseen accidents. Such pedestrian infrastructures not only enhance walkability but also reduce traffic interruptions (Oswald, 2016). GSPS can be mainly of two types, i.e., overpasses and underpasses. While both the facilities allow complete segregation, yet pedestrians feel more unsafe while using underpasses due to improper lighting, low-security measures, anti-social activities and water logging during monsoons (Anciaes, 2018). On the other hand, adequately maintained elevated walkways (FOBs and skywalks) could be the best solution to isolate pedestrians from the vehicular traffic, as well as fulfil the basic requirements of the pedestrians to feel safe and secured.

1.2. Foot Over Bridges (FOBs) and Skywalks

The elevated walkways or overpasses as discussed above are mainly of two types, namely, foot over bridges (which allow easy crossing from one side of the road to the other) and skywalks (which enable lateral and longitudinal movement and can be the best substitute to the sidewalks and crosswalks for travelling longer distances comfortably). Some of the major advantages of providing elevated walkways are:

- Provide complete segregation between pedestrians and vehicular traffic, and thus enhance the safety-security concerns as well as allow smooth traffic movement without congestions.
- They ensure efficient dispersal of pedestrians over shorter as well as longer distances.
- The complete segregation helps in reduction of consumption of air and noise pollutions from vehicular traffic.
- The all-weather shade helps to protect pedestrians from harsh weather while travelling.

As per Indo-HCM (2018), a foot over bridge is "a type of grade separate pedestrian facility consisting of an enclosed or covered bridge connecting two footpaths, and eliminates all potential vehicle conflicts faced by pedestrians while crossing a road". On the other hand, as per Robertson (1993), "A skywalk system is a network of elevated interconnecting pedestrian walkways. The network consists of bridges over the streets, second-story corridors usually shops and service within the buildings, and various activity hubs". In Canada, skywalks were initially developed to protect the people from the extreme cold and frigid weather (Morrall, 1991). In a study in the USA it was reported that 71.5% of the downtown pedestrians preferred to use skywalks rather than the street-level sidewalks (Robertson, 1987). The benefits gained from these elevated facilities eventually encouraged other western countries in adapting and expanding the elevated walkway systems to ensure better and easier pedestrian movement.

In India, such skywalk systems were first developed in 2007 in Mumbai city by the Mumbai Metropolitan Region Development Authority (MMRDA) under the Station Area Traffic Improvement Scheme (SATIS). This was done as nearly 52% of road trips in Mumbai were made on foot (MMRDA, 2008). Initially 50 skywalks were proposed for construction, but later on, 36 were constructed (ranging from 149m to 1780m in length). These skywalks connected Mumbai suburban railway stations or high concentration commercial areas with the heavily targeted destinations. The main aim of construction of such a skywalk system was to disperse pedestrians efficiently from congested areas to the strategic locations (such as shopping areas and public transport terminals), and vice versa.

Past researchers studied elevated pedestrian facilities (foot over bridges) and found that demographic factors such as age (Mutto, 2002; Abojaradeh, 2013; Rankavat, 2016; Wu, 2014), gender (Sinclair, 2016; Saha, 2013; Mutto, 2002; Rankavat, 2016), profession and purpose of trip (Saha, 2013 and Wu, 2014) affected the usability of such facilities. Similarly, other user factors such as absence of escalators or elevators (Rasanen, 2007; Sabet, 2013, Demiroz, 2015; and Hasan, 2018), the presence of obstructions in the form of vendors/ beggars/ standing pedestrians (Saha, 2013, Pasha, 2015 and Malik, 2017), lack of security (Mutto, 2002; Gallegos, 2012; Saha, 2013; Pasha, 2015; Sinclair, 2016; Malik, 2017 and Oviedo-Trespalacios, 2017), lack of proper horizontal connectivity due to improper location of the facilities (Rasanen, 2007; Sangphong, 2014; Das, 2015; Demiroz, 2015 and Hasan, 2018), discomfort (Pasha, 2015; Saha, 2013; Hasan 2014), and absence of proper law enforcement (Hasan, 2018 and Sabet, 2013) significantly affected the choice of pedestrians using such facilities. Properly designed elevated systems (with ensured safety and security) would not only encourage pedestrians to use the facilities but also allow smooth vehicular traffic movement as well, without any interaction between pedestrians and motorized traffic.

1.3. Motivation of the study

Elevated facilities (like foot-over bridges and skywalks) are important constituents of our transportation infrastructure since they provide vertical separation between non-motorized (i.e., pedestrians) and motorized (i.e., vehicular) traffic. The elevated facilities amplify the three pillars of the sustainable development (i.e., environment, social and economic), encourage walking and decrease the pollution load on the environment.

However, in India such elevated facilities are provided on an ad-hoc basis without much due consideration. So, pedestrians are reluctant to use such facilities due to the presence of stairways instead of escalators or elevators, longer travel distances, improper lighting, invasion by hawkers/ standing pedestrians, and absence of proper security measures. The proper designing (or redesigning) and maintenance of such elevated facilities are rarely done, and this leads to pedestrians being hesitant to use such facilities which ultimately result in pedestrians crossing illegally at-grade and thus interacting with the vehicular traffic.

Moreover, study on pedestrian flow behaviour over elevated facilities (based on different geographical locations and various cultural differences) have been less explored and in general level of service (LOS) for such facilities according to field conditions are less validated. Based on the identified needs, it is, therefore, necessary to carry out a thorough study on elevated facilities to examine the factors influencing pedestrians' traffic flow characteristics under different conditions. To develop pedestrian-friendly infrastructures, it is important to consider human perception along with engineering considerations. The outcome of this study would help the designers, engineers and transportation planners to evaluate the current status of the elevated walkways systems and provide indicatives towards its coherent solutions to encourage pedestrians to use the facilities.

1.4. Objectives of the study

The main goal of this work was to study the pedestrian movement behaviour over elevated pedestrian facilities. Two types of elevated facilities were considered – (i) Foot-over bridges (FOBs) and (ii) Skywalks. The above stated goal could be achieved through the following objectives:

i. Behavioural study of pedestrian movement over mid-block sections of FOBs and skywalks through perception survey, empirical data analysis and modelling.
ii. Behavioural study of pedestrian movement on vertical connectivity (stairways) of FOBs and skywalks through empirical data analysis and modelling.
iii. Study of pedestrians' perception survey towards the usability of FOBs and skywalks.
iv. Development of level of service (LOS) standards for FOBs and skywalks.

The various steps and processes involved in achieving the above objectives are listed below:

i. *Identification of sites:* To identify the cities and the respective sections where elevated facilities (non-mechanized foot over bridges, mechanized foot over bridges and skywalks) were present and in regular use.
ii. *Field data collection:* To collect quantitative (i.e., videographic) and qualitative (i.e., questionnaire) data from different types of identified elevated walkways located across various cities and regions of India.
iii. *Data extraction:* To extract different pedestrian flow parameters (flow, speed, density and area module/space), behavioural parameters (age, gender, luggage, mobile use, group size, disability impact, lane formation, leader-follower relationship, lane shifting, overtaking, squeezing effect and faster-slower effect) and perception parameters (demographic characteristics, existing satisfaction score and future usability dependents) from the collected field data.
iv. *Data analysis:* To study individual and group pedestrian characteristics (gender, age, luggage condition, group effect, mobile phone use, impact of disability, lane formation, leader-follower relationship, lane shifting, overtaking, squeezing effect and faster-slower effect) from collected video data and observe their effects on the overall pedestrian movement.
v. *Macroscopic modelling:* To develop fundamental diagrams between macroscopic pedestrian flow parameters for elevated walkways (considering mid-block and vertical connectivity/ stairway sections).
vi. *Microscopic modelling:* To develop a global microscopic model for representing elevated walkways using VISWALK software for its suitability to simulate the pedestrian flow characteristics.
vii. *Speed prediction modelling:* To model the influence of different microscopic, macroscopic and geometric parameters on the walking speed of pedestrians.

viii. *Perception modelling:* To model the perception of pedestrians towards using elevated pedestrian facilities.

ix. *Development of level of service (LOS):* To set the norms of the level of service standards for both types of elevated facilities (FOBs and skywalks) based on the quantitative as well as qualitative approaches.

1.5. Scope of the study

The proposed research work aimed to investigate the pedestrian behaviour over elevated walkways (FOBs and skywalks). The scope of the work was limited to elevated walkways (FOBs and skywalks) from six different cities of India (Gangtok, Mumbai, Kolkata, Bengaluru, Guwahati and National Capital Region) with reasonable flow of pedestrians. In case of FOBs, the selected locations had no at-grade facilities available within 50m stretch of the facility and were connecting from one side of the road to the other through a single entry-exit. In case of skywalks, the seven selected locations had five to eight entry-exit points and only the major vertical connectivity (stairway) was considered while data collection. In case of perception survey, the opinion of only the pedestrians in the neighbourhood of the facility was conducted at each survey location for weekdays either in morning (7.30-10.30am) or evening (4.30-7.30pm) peak hours depending on the videographic data collection.

1.6. Thesis organization

The Thesis was organized into eight chapters. The first chapter is the introduction chapter which introduces the concept about the current scenario related to pedestrian elevated walkways, along with the motivation, objectives and scope of the study. The second chapter discusses about the detailed literature review of various studies related to understanding of the fundamental characteristics, review of data collection techniques, study of flow characteristics over different pedestrian facilities, studies related to pedestrian level of service, effect of different pedestrian behavioural characteristics on speed of pedestrians, and microscopic study of pedestrian behaviour over different facilities. The gaps identified from reviewed literature are also discussed. Chapter 3 introduces the methodology of data collection and extraction. In chapter four detailed analysis is carried out to understand the pedestrian behaviour on mid-block sections of elevated walkways. The chapter discusses about the development of fundamental diagrams, development of simulation model, and development of different speed prediction models based on various macro, micro and geometric parameters. Chapter 5 discusses about pedestrian walking behaviour over vertical connectivity (stairway) sections of elevated walkways. The perception of pedestrians' choice towards usability of elevated walkways is discussed in chapter 6. The next chapter explains the development of level of service criteria for elevated walkways based on quantitative and qualitative data. Chapter 8 highlights the major research findings and conclusions of the present study. The research contributions, applications, recommendations, limitations and scope for further research work are also discussed in the final chapter.

CHAPTER 2

REVIEW OF LITERATURE

2.1. General

Pedestrians are an integral and pervasive part of the multimodal transportation system. Their walking process depends on the sequence of decisions as to where to put the next step (Antonini, 2007). The pedestrian study involves identifying the pedestrian facilities to be studied, collecting the field data, understanding the fundamental flow characteristics, studying the impact of different individual/ group characteristics on the walking speed of pedestrians, developing simulation models and level of service standards for different facilities.

In the appended sections and subsections, an attempt is made to understand the following:

i. Types of pedestrian facilities:
    - At-grade facilities (sidewalk, walkway, and crosswalk).
    - Grade separated facilities (overpass: skywalk and FOB, underpass, and stairway).

ii. Fundamentals characteristics of pedestrians:
    - Macroscopic pedestrian flow characteristics:
        - Pedestrian flow.
        - Pedestrian speed.
        - Pedestrian density.
        - Pedestrian area module.
        - Fundamental relationships between macroscopic flow characteristics.
    - Microscopic pedestrian flow characteristics:
        - Individual pedestrian characteristics (gender, age, luggage condition, differently abled, mobile use, and direction of movement).
        - Group pedestrian characteristics (group size, lane formation, leader-follower relationship, lane shifting, overtaking, faster-is-slower effect, and squeezing effect).

iii. Types of data collection techniques (videographic, questionnaire, controlled experiment and others).

iv. Study of pedestrian flow characteristics over different facilities (grade separated and at-grade facilities).
v. Study of pedestrian level of service (using quantitative and qualitative methods).
vi. Modelling approaches of pedestrian behaviour over different facilities:
    - Dynamic modelling approach.
    - Discrete modelling approach (Cellular automata model).
    - Continuous modelling approach (Social force model).
vii. Viswalk simulation using social force model.
viii. Application of advanced soft computing techniques in transportation sector.
ix. Shortcomings in the existing literature.

2.2. Pedestrian facilities

The different facilities can be categorized into at-grade (sidewalk, walkway, and crosswalk) and grade-separated (underpass, overpass, stairway and escalator) pedestrian facilities.

2.2.1. At-grade pedestrian facilities

A ***sidewalk or footpath*** is a raised path along the roadside that is separated from vehicular traffic by a kerb, do not allow bicycles or other users, accommodate the highest volume of pedestrians, have a width between 1.5 to 5m and may have slight changes in grade.

A ***walkway*** is a pedestrian facility that is located far away from the vicinity of motorized traffic at recreational or shopping areas where pedestrians can move around freely, without the intrusion of motorized vehicles. The walkway is different from the sidewalk as it is unraised and wider than sidewalks, with complete segregation from motorized traffic.

Crosswalks are the at-grade facilities that are provided for easy and safe dispersal of pedestrians from one side of the road to the other. These crosswalks/ crossings can be located either at intersections or at midblock sections with either presence of signals or can be unsignalized with/ without zebra crossings. Crosswalks are more critical than sidewalks due to higher pedestrian-vehicular interactions. At signalized intersections, pedestrians have a pedestrian green signal time during which they have to cross, while the pedestrians have to wait during the pedestrian red time. At uncontrolled/ unsignalized intersections or midblock crossings, generally no pedestrian signals are provided and pedestrians might have to wait for a longer time to cross depending on the pedestrian gap acceptance behaviour. If the waiting time increases beyond a certain threshold, then the tendency of taking risk while crossing illegally increases significantly.

2.2.2. Grade separated facilities

Pedestrian overpasses consist of two different types of pedestrian facilities: Skywalks and Foot Over Bridges (FOBs). In India, ***skywalks*** are elevated pedestrian facilities that connect major heavy-concentration commercial areas with targeted destinations and range from a few hundred meters to few kilometers. These skywalks ensure safe and efficient dispersal of pedestrians from highly congested areas to strategic locations and allow pedestrians to travel longer distances without any interaction with vehicular traffic and vendors (who occupy the sidewalks), along with reduced consumption of intoxicated and polluted air. Similarly, a ***foot over bridge (FOB)*** is an elevated pedestrian facility that allows easy and continuous access of crossing from one side of the road to the other without any interaction with vehicular traffic. These FOBs should have stairs on both sides of the road along with ramps, escalators or elevators on one or both sides to improve the usability (as per IRC: 103-2012). Moreover, high flow of vehicles, the presence of child while crossing at-grade, safety and connectivity are some of the major issues that encourage pedestrians to use the elevated pedestrian facilities.

Subways or underpasses are underground pedestrian facilities, which allow both pedestrians and cyclists to reach to the other side of the road safely. The main benefit of providing a subway is that pedestrians could prefer to use it more than an elevated facility, as in a subway the pedestrians need to go down first and then climb up. This psychological tendency to avoid stairways arrives when a pedestrian has to use an elevated facility. However, pedestrians feel more unsafe while using underpasses due to improper lighting, low-security measure, anti-social activities and water logging during monsoon season (Anciaes, 2018).

Stairways, escalators and elevators are the facilities that allow easy vertical connectivity access to and from grade-separated facilities (i.e., overpasses and underpasses). As per Fruin (1971), “locomotion on stairways is restricted because of the need to overcome gravity in ascent and to safely control it in descent”. However, stairways allow easy access only for a particular dedicated group of pedestrians (e.g. young and adult male/ female) for whom ascending or descending stairs is relatively easy. On the other hand, escalators or elevators, provide an easier accessibility and comfort to a wider range of pedestrians (e.g. disabled, elderly, children and female). Only properly designed stairways (ramp like with low riser height and low gradient) allow easy access for all groups of pedestrians.

Apart from the at-grade and grade-separated facilities, some other controlled pedestrian setups are exclusively used for experimental studies such as bottlenecks, queuing areas and angled corridors.

2.3. Fundamental characteristics of pedestrians

The fundamental pedestrian characteristics are a combination of macroscopic and microscopic characteristics that represent an aggregated and individual pedestrian behaviour over different pedestrian facilities. Factors such as pedestrian speed, flow, density, area module (space), free flow speed and jam density are location-based phenomenon and represent the fundamental pedestrian flow characteristics. In general, the behaviour of pedestrians over an area under variable condition is represented by flow characteristics. In order to allow planners, engineers and designers to construct and maintain proper pedestrian facilities, in-depth studies of the pedestrian flow characteristics along with fundamental relationships are extremely important. The fundamental diagrams (i.e. the representation of relationships between speed-flow-density-space) elaborately represent the pedestrian flow characteristics for under- and over-congested conditions. These diagrams exemplify the impact of change in one parameter on another and the variation of relationship between parameters over time and space. In order to predict the level of service and define the capacity of the pedestrian facilities, development of fundamental diagrams are extremely important. Apart from above mentioned macroscopic parameters, different microscopic factors such as age, gender, luggage condition, mobile use, disability, group size, lane formation, leader-follower relationship, squeezing effect, faster-is-slower effect, overtaking and lane shifting significantly impact the pedestrian walking behaviour over different facilities.

2.3.1. Macroscopic flow characteristics of pedestrians

2.3.1.1. Pedestrian flow

In general, pedestrian flow relates to the number of pedestrians crossing a section of a facility over some specified time. Generally, it is represented as ‘q’ and defined in terms of pedestrian per minute (ped/min). As per Highway Capacity Manual (US-HCM 2010), the pedestrian flow is similar to the vehicular flow such as the freedom to choose the individual speed and bypass others. But certain factors such as ability to cross a pedestrian stream, walk in opposing direction to the major pedestrian flow, maneuver without conflicts and delay experienced (at intersections) are related specifically to the pedestrians.

Similarly, pedestrian flow rate is used in defining the average flow of pedestrians per unit of effective walkway width, expressed in pedestrian per minute per meter (ped/min/m). In general, flow, speed and density are closely related to each other; such that when the pedestrian flow and density keeps on increasing, the speed is expected to decline proportionally.

2.3.1.2. Pedestrian speed

The pedestrian speed is defined in terms of time taken by a subject pedestrian to cross a stretch of a walkway over a time period. It is generally calculated in terms of meter per seconds but is converted to meter per minute for simplicity. Generally, it is observed that depending on the proportion of age (elderly and child pedestrians), gender (female pedestrians), trip purpose and presence of grade the average speed keeps on varying. In general, on walkways if the percentage of elderly pedestrians lies between 0-20 percent, then the average walking speed is approximately 72m/min (US-HCM 2010). Moreover, if the percentage of elderly increases above 20 percent, then the average speed drops below 60m/min (US-HCM 2010). The free flow speed is generally found to vary around 1.5 m/sec (90m/min) for sidewalk facilities.

2.3.1.3. Pedestrian density

As per US-HCM 2010, the pedestrian density is the average number of pedestrians within unit area of a walkway or queuing area, and generally expressed as pedestrians per square meter (ped/m^2). At free flow speed condition, the density is minimum as pedestrians have the freedom to choose their walking speeds; while at congested or jam density condition the pedestrians are forced to move with the crowd or their movement are completely stopped. In general, as the density keeps on increasing, the space available to each pedestrian keeps on decreasing and the mobility with which a pedestrian can move is highly restricted.

2.3.1.4. Pedestrian area module or space

The term ‘space’ refers to the average area a pedestrian requires to pass through a pedestrian facility and is expressed in terms of square meters per pedestrian (m^2/ped). The space available to a pedestrian is generally the inverse of density and is most practically used for designing pedestrian facilities. As per Indo-HCM 2018, it is observed that a human body is represented by an ellipse of 0.35m by 0.51m (~area of 0.18 m^2), which is assumed to be the practical minimum space for a standing pedestrian without baggage. Similarly, as for a pedestrian with luggage, an area of 0.52m*0.51m (i.e., 0.26m^2) is recommended (as per Indo-HCM 2018). The

Level of Service (LOS) or comfort level is also estimated with respect to the space available to each pedestrian.

2.3.1.5. Fundamental relationships

The relationships developed between the various pedestrian flow characteristics are represented through fundamental diagrams (FDs) or relationships. The FDs are useful in estimating the capacity and level of service of the facilities. The diagrams represent the relationships between speed-flow-density-space parameters that characterize the movement of pedestrian over different facilities.

Greenshields (1935) developed a linear speed-density relationship for vehicular traffic (as shown in Figure 2.1), which was later used for developing pedestrian flow models. The model representation is shown in Equation 2.1.

$$u = u_f - \left[\frac{k}{k_j}\right] \qquad \text{.............. Eq. 2.1}$$

where, u_f and k_j represents the free flow speed and the jam density conditions.

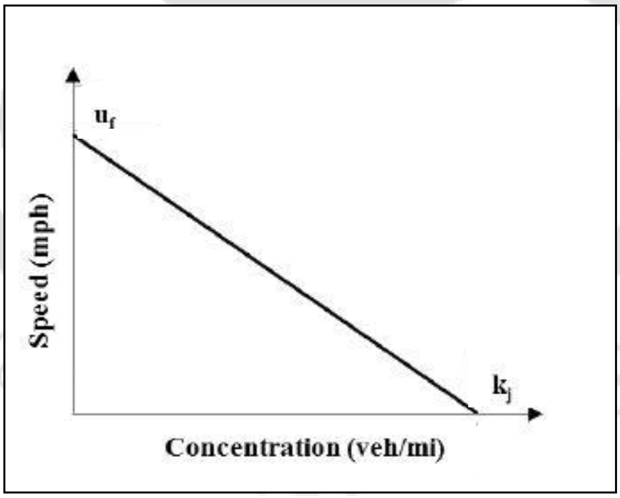


Figure 2.1. Greenshields' model for vehicular traffic (*Source: Greenshields', 1935*)

The fundamental diagrams (i.e. the relationships between speed-flow-density-space) elaborately explain the pedestrian flow characteristics under different congestion levels. Some of the benefits of establishing proper fundamental diagrams are estimating the capacity and level of service values, evaluating the pedestrian flow models (microscopic and macroscopic) and developing dynamic simulation models. The vast variations observed in fundamental diagrams based on similar pedestrian flow characteristics, encourages the researchers to study them with even more closer precision.

Daamen (2005), referred to empirical findings of other researchers, where fundamental diagrams of pedestrian flow characteristics were plotted for different types of infrastructures and under different flow compositions, (refer Figure 2.2) and which exhibited significant variations in jam density and capacity.

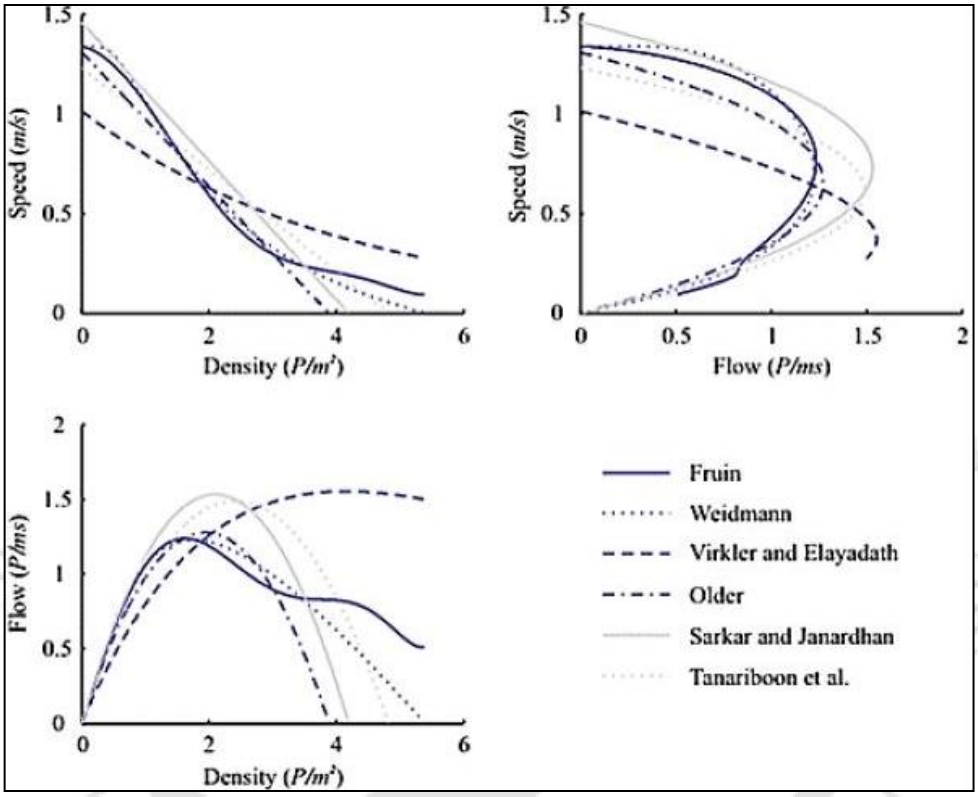


Figure 2.2. Fundamental diagrams of pedestrian flow characteristics (*Source: Daamen, 2005*)

Similarly, Zhang and Seyfried (2013) showed the variation of pedestrian flow characteristics for uni- or bi-directional flow movements (refer Figure 2.3). It could be observed from Figure 2.3 that for density (ρ) > 1.0ped/m^2, the fundamental diagram of unidirectional flow was above those of bi-directional flow. Moreover, the fundamental diagrams also showed clear differences in maximum flow values of 2ped/s/m and 1.5ped/s/m for uni- and bi-directional movements respectively.

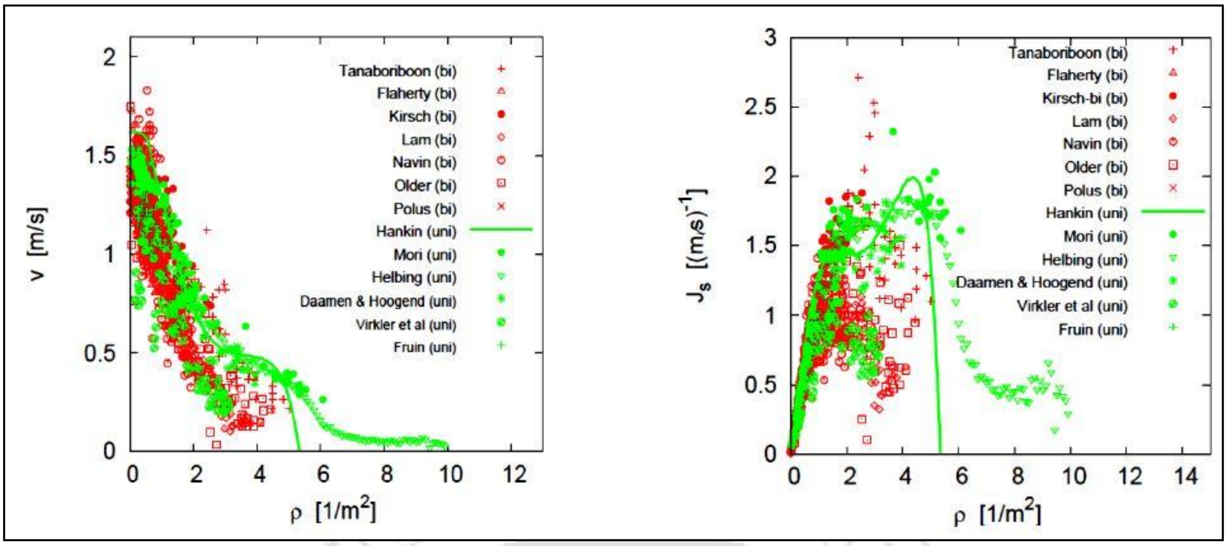


Fig. (a). Density-velocity **Fig. (b). Density-specific flow**

Figure 2.3. Fundamental diagrams for uni- and bi-directional movement from different studies (*Source: Zhang, 2013*)

Table 2.1 discusses about the existing literature related to pedestrian fundamental diagrams based on the type of facility and speed-density relationships.

Table 2.1. Facility wise speed-density relationship

Author	Facility	Speed-Density relationship
Oeding (1963), Older (1968), Navin (1969), Koushki (1993), Gerilla (1995), Nazir (2012), Rahman (2012), Das (2015)	Sidewalk	Linear
Christopoulou (2012), Shafabaksh (2013), Bargegol (2015), Rungta (2016)	Sidewalk	Linear, Exponential
Tanaboriboon (1986), Virkler (1994), Nazir (2014), Corbetta (2016)	Walkway	Linear, Exponential
Fruin (1971), Daly (1991), Weidmann (1993), Chen (2010), Shah (2015, 2017)	Stairways	Linear
Indo-HCM (2018)	FOB	Linear

It could be observed from Table 2.1 that majority of the studies conducted over different facilities used linear or exponential relationship to define the speed-density relationship. Figure 2.4(a-c) shows the different speed-density relationships for sidewalk, walkway and stairway facilities.

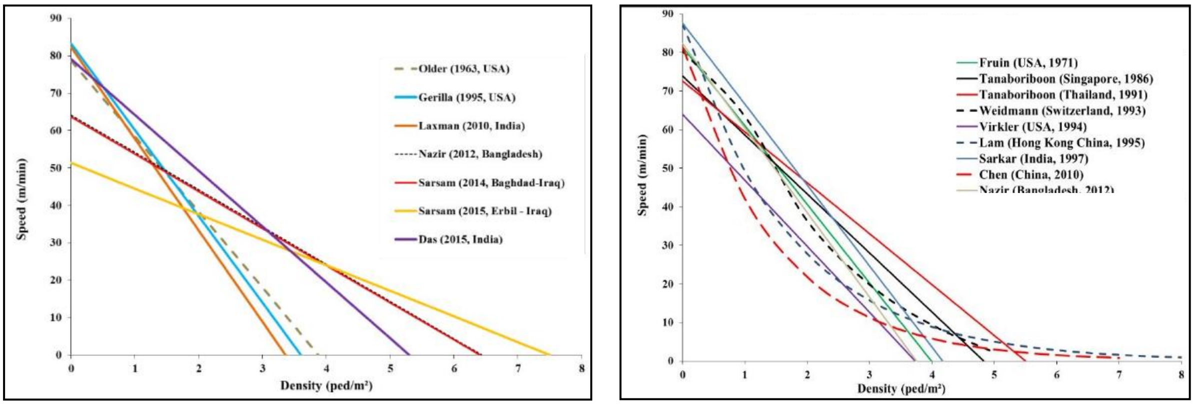


Fig. (a). Sidewalk facility **Fig. (b).** Walkway facility

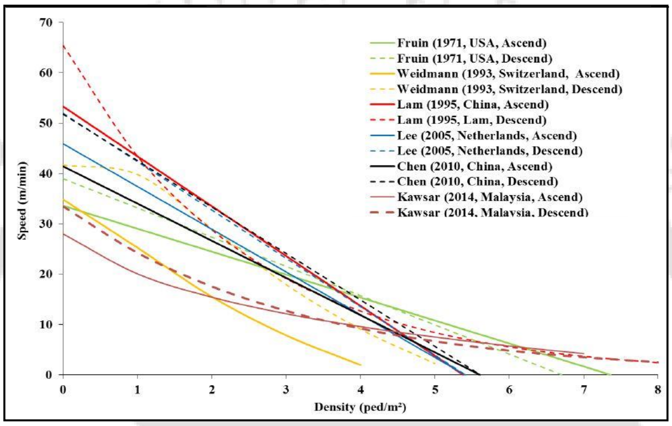


Fig. (c). Stairway facility

Figure 2.4. Speed-density relationships for different pedestrian facilities *(Source: Banerjee et al., 2018)*

Figure 2.4(a) shows the fundamental speed-density relationship for different sidewalk facilities reported by various researchers. It could be observed from Figure 2.4(a) that free flow speed (FFS) ranged between 65-85 m/min in most of the cases. The study by Sarsam (2015) showed that the FFS was reasonably low (52 m/min) at Erbil (Iraq) which was due to the attire worn by the pedestrians in Iraq. Further, in the studies by Nazir (2014) at Bangladesh and Sarsam (2014) at Baghdad (Iraq), lower pedestrian speeds were observed, and identical trends of speed-density relationships were also observed at both places. In Baghdad, the higher FFS in comparison to Erbil was mainly due to the western clothing worn by the pedestrians in Baghdad in comparison to the traditional attire worn in Erbil. Moreover, the jam density in the different studies ranged between 3.5-5.3 ped/m^2. The higher predicted jam density was observed in studies conducted at Bangladesh and Iraq due to limited field data points, which were mostly in low density range.

From Figure 2.4(b) it was observed that FFS ranged between 73-87m/min over walkway sections. Studies by Tanaboriboon (1986), Himann (1988), and Lam (1995) showed that factors such as age, gender and physique played a significant role on walking speed, while studies by Nazir (2014), and Corbetta (2016) showed that attire and group walking patterns significantly affected the pedestrian movement over walkways.

From Figure 2.4(c), the observed difference in speed between ascending and descending stairways varied between 4-12 m/min. It could also be observed that the reported pedestrians FFS varied widely for ascending (27-54 m/min) as well as descending (34-65 m/min) cases in different studies. As the speed over stairways greatly depend on various parameters (like riser and tread dimensions, width and direction of flow), which varies significantly from one study location to other; this could be the major contributor behind the wide spread of FFS over stairways. In China, Lam (2000) observed higher walking speed due to physical property of the stairways as the selected stairways had lower step-rise height and easier maneuverability. Similarly, in Malaysia, Kawsar (2014) observed the lower speed due to the higher density and unavailability of space to overtake the pedestrians in front. Moreover, in majority of the cases, it was observed that the ascending and descending speed curves intersected each other, and the jam density of descending maneuver was lower than the ascending maneuver. Such possibilities could arise while ascending as pedestrians maintain lesser gaps in between which lead to higher jam densities. In the descending maneuver, the pedestrians maintain higher gaps (i.e. lower jam density) to avoid pushing the pedestrians in front and reduce the probability of falling down. Further, the descending maneuver requires less effort than the ascending one, which results in higher walking speed than in ascending cases.

Some important observations related to macroscopic flow characteristics of pedestrians are:

- The fundamental diagrams were mostly developed for sidewalk, walkway and stairway facilities using linear or exponential speed-density relationships.
- Indo-HCM (2018) developed fundamental relationships for FOBs based on linear speed-density relationship.
- The FFS ranged between 65-85m/min (for sidewalks) and 73-87m/min (for walkways) depending on the attire worn, and group walking patterns. The jam density over sidewalk facilities varied between 3.5-5.3ped/m^2.
- The difference in speed between ascending and descending stairways ranged between 4-12m/min across different studies. The FFS for ascending and descending directions varied between 27-54m/min and 34-65m/min respectively. The differences were

majorly due to the stairway dimension (riser, tread and width), bi-directional split and demography.

2.3.2. Microscopic flow characteristics of pedestrians

Pedestrians are the most unpredictable road users and their walking behaviour changes randomly depending on whether a pedestrian is walking alone or in a group. An individual pedestrian’s walking behaviour is greatly impacted by his/ her age, gender, luggage condition, use of hand held devices (mobiles), direction of movement, and whether the pedestrian is differently abled or not. Similarly, when a group of pedestrians are walking together then different group characteristics such as the group size, lane formation, leader-follower relationship, squeezing effect, faster-is-slower effect, overtaking and lane shifting influence the walking behaviour.

2.3.2.1. Individual pedestrian characteristics

The individual pedestrian characteristics play vital role in analyzing walking speed behaviour over both grade separated as well as at-grade pedestrian facilities. Majority of the behaviour related studies tried to emphasize and collect data on the three basic individual characteristics, i.e., gender, age and luggage conditions.

Gender

Gender plays a significant part in walking speed analysis. Table 2.2 summarizes the studies carried out by various researchers across the globe to analyze the fundamental walking speed differences between male and female pedestrians for different facilities.

Table 2.2. Impact of gender on pedestrian speed related studies over different facilities

Facility	Author	City/ Country	Speed (m/min)		
			Male	**Female**	**Difference**
Sidewalk	Polus (1983)	Haifa (Israel)	73.0	66.0	7
	Tanaboriboon (1986)	Singapore	79.0	69.0	10
	Koushki (1988)	Riyadh	70.0	53.0	17
	Morrall (1991)	Colombo (Sri Lanka)	81.0	78.0	3
		Calgary (Canada)	86.0	81.0	5
		Singapore	79.0	69.0	10
		Bangkok	76.0	70.0	6
	Finnis (2008)	New Zealand	90.0	86.0	4
	Kotkar (2010)	India	78.0	70.0	8
	Rastogi (2011)	India	77.0	69.0	8

	Chandra (2013)	India	76.2	71.4	4.8
	Sarsam (2014)	Iraq	33.0	32.0	1
	Sukhadia (2014)	India	67.0	60.0	7
	Chandra (2014)	India	76.0	67.0	9
	Silva (2014)	Portugal	78.6	72.0	6.6
	Abdulameer (2014)	Iraq	35.7	33.7	2
	Siddharth (2018)	India	74.0	64.0	10
	Gore (2020)	India	73.6	59.7	13.9
Walkway	Nazir (2012)	Bangladesh	53.0	49.0	4
	Rahman (2012)	Bangladesh	74.0	64.0	10
Crosswalk	DiPietro (1970)	USA	40.2	34.8	5.4
	Wilson (1980)	USA	79.2	76.2	3
	Tanaboriboon (1991)	Thailand	68.0	65.0	3
	Tarawneh (2001)	Jordan	81.0	79.8	1.2
	Sarsam (2013)	Iraq	97.8	77.4	20.4
Stairway (ascend)	Fruin (1987)	USA	33.6	27.0	6.6
Stairway (descend)			37.8	29.4	8.4
Stairway (ascend)	Fujiyama (2004)	Japan	36.6	34.8	1.8
Stairway (descend)			40.8	40.8	0
Stairway (ascend)	Zhang (2009)	China	45.0	39.6	5.4
Stairway (descend)			55.8	40.2	15.6
Stairway (ascend)	Patra (2017)	India	42.0	31.8	10.2
Stairway (descend)			45.0	34.2	10.8
Stairway (ascend)	Shah (2017)	India	35.4	31.2	4.2
Stairway (descend)			38.4	34.8	3.6

From Table 2.2 it was observed that across different pedestrian facilities the male pedestrians tend to adopt higher walking speeds than their female counter parts. The difference between male and female pedestrian speeds on sidewalks, walkways, crosswalk, stairways (ascending) and stairways (descending) were 7.7m/min, 7m/min, 6.6m/min, 5.6m/min and 7.6m/min respectively. Apart from the above-mentioned studies, other studies by Al-Azzawi (2007), Ishaque (2008), Montufar (2007), Rastogi (2011) Ferenchak (2016) and Subaih (2020) also confirmed that gender played a significant role in the walking speed estimation.

Age

The face of a person holds many cues and thus emotion, gender and ethnicity of a person can be estimated through the face (George, 2000). Figure 2.5 shows the variation of speed with respect to age. Weidmann (1993) proved than with the increase in age from 0-20 years, the walking speed kept on increasing, and thereafter it drastically decreased.

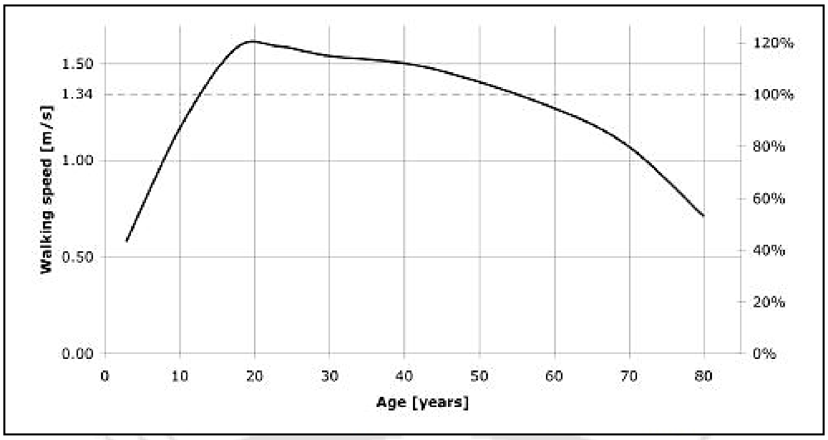


Figure 2.5. Correlation between walking speed and age (*Source: Weidmann, 1993*)

In Table 2.3 previous researchers also tried to divide the age into different categories based on the above mentioned feature. The age binning ranged between three to five categories. In Table 2.3 the age categories shows approximations of three main age categories (young: <18, middle-aged: 18-55, old: >55). However, for better estimation and detailed microscopic analysis, age needs to be categorized into four or five categories.

Table 2.3. Impact of age on pedestrian speed related studies over different facilities

Author	Facility	Country	Speed (m/min)		
			Young	Middle aged	Older
Sjostedt (1967)	*Crosswalk*	UK		86.4	68.4
Cresswell (1978)		UK		94.2	66.6
Wilson (1980)		UK		79.2	67.8
Griffiths (1984)		UK	103.2	88.2	69.6
Bowman (1994)		Sweden		87.0	61.8
Knoblauch (1996)		USA	90.6		75
Guerrier (1998)		USA		81.0	58.2
Tarawneh (2001)		Jordan		88.2	70.2
Fitzpatrick (2006)		USA	69.8		55.2
Gates (2006)		USA	93.0	87.0	75.6
Montufar (2007)		Canada	96.6		81.6
Fruin (1987)	***Stairway (ascend)***	USA	36.0		24.6
	Stairway (descend)		36.0		31.8
Fujiyama (2004)	***Stairway (ascend)***	Japan	38.4		34.8

	Stairway (descend)		44.4		38.4
Patra (2017)	***Stairway (ascend)***	India	44.4		29.4
	Stairway (descend)		47.4		34.8
Shah (2017)	***Stairway (ascend)***	India	33.0	32.4	31.2
	Stairway (descend)			39.0	
Al-Masaeid (1993)	***Sidewalk***	Jordan	86.4		73.2
Nazir (2012)		Bangladesh	51.1	52.8	47.6
Silva (2014)		Portugal	72.0	73.2	57.0
Abdulameer (2014)		Iraq	35.1	37.2	20.1
Pinna (2018)		Italy	61.2	59.4	50.4

Table 2.3 showed that across different facilities the walking speed reduced with the age of the pedestrians. In addition, majority of the speed related studies based on age were conducted over sidewalk, crosswalk and stairway facilities. Other studies by Polus (1983), Willis (2004), Finnis (2008), Arango (2008) and Subaih (2020) also stated that age played a significant role in the reduction of walking speed.

Luggage condition

Depending on whether a pedestrian is carrying luggage or not, the walking speed is expected to change. As per Shi (2020), in order to improve the safety level during emergencies, the knowledge about movement of pedestrian laden with luggage is essential. Young (1999) reported that luggage reduced the walking speed of pedestrians. Finnis (2008) observed that pedestrians tend to increase their speed while carrying something (86m/min to 91m/min) when no gradients were available. Laxman (2010) reported that presence of luggage reduced walking speed by 15%. In a study in China, Ye (2012) affirmed decline by 3-8% when pedestrians were carrying trolley cases. In studies by Schultz (2010) and Huang (2019), the difference in pedestrians with and without luggage was nominal while walking on level surface. Gao (2019) observed that pedestrians with similar luggage size and dimension tend to follow each other. Shah (2013, 2019) observed that while walking on stairways, the presence of luggage reduced the walking speed by 6m/min while both ascending and descending. On level surface in Portugal, Silva (2014) observed minor difference (of 1m/min) in walking speed between pedestrians with and without luggage. Morrall (1991) tried to analyze the impact of the presence of luggage on the walking speed of the pedestrians and reported that luggage does impact the walking speed of the pedestrians.

Differently abled

Across the globe, the pedestrians with disability represent a significant portion of the total population. However, the pedestrian facilities are not at all friendly to the specially-abled pedestrians. Few studies conducted showed the relevance of the walking speed involving pedestrians with disabilities. As discussed above, the different studies overlooked the heterogeneity of the pedestrians with special-ability in the total composition. Boyce (1999a) conducted a study on the movement capabilities of the individuals over different facilities under emergency conditions. Clark-Carter (1986) and Passini (1998) tried to measure the walking speed of people with visual impairment and found that under complex environments, the walking ability of the pedestrians decreased. In a study conducted by Miyazaki (2004), an experimental setup was developed to understand the impact of pedestrian behaviour on the presence of wheel chair users. Wrigbt (1999) found that visually impaired pedestrians walked at 43-69% of the typical speed on level routes and 70-80% on stairs. Arango (2008) studied the crossing speed of pedestrians with walkers or canes. In 2013, Kuligowski studied the stair evacuation of 45 residents with different mobility impairments. Sharifi (2016) tried to analyze the walking speeds of individuals with disabilities under different indoor walking environments and observed that pedestrians with disabilities reduced the overall walking speed of the crowd.

Mobile use

Mobile phone is a major source of distraction that not only influences the pedestrian walking behaviour but also causes severe injuries if pedestrians are unaware about their surroundings. Different modes of distractions while using the mobile phones are talking over the phone, texting, browsing and listening to music. Recent studies showed the change in walking behaviour pattern and interaction with environment while using mobile phones (Al-Yahya, 2011; Crowley 2016; Krasovsky, 2017). Majority of the previous studies tried to understand the effect of mobile phone use while crossing (New York Pedestrian Study, 2006; Loeb, 2009; Mwakalonge, 2015; Yoshiki, 2017; Lee, 2020). Timmis (2016) conducted a study of impact of mobile phone use while walking through obstacles. Barkley (2016) conducted a controlled experimental study and found that the walking speed decreased when a pedestrian used mobile phones while walking. A recent study by Reynold-Walsh (2019) observed the impact of mobile phone use, and found reduction in walking speed of pedestrians by 3m/min, 1.2m/min and 15.6m/min respectively while using phone, texting and calling. An experimental study by

Crowley (2019) studied the impact of mobile phone use on walking, and found that there was decrease in the walking speed and stride length while pedestrians were using mobile phones.

Direction of movement

The pedestrian walking direction significantly affects the walking behaviour depending on whether the pedestrian walks with the major/ minor flow or ascends/ descends the facilities. In order to capture realistic situations, Hughes (2002) pointed out the importance of capturing bi-directional movement. Similarly, a pedestrian who is ascending stairways is highly impacted in comparison to those who are descending (Lam 1995). The variation of walking speed and travel time is dependent on whether there is uni, bi or multi-directional flow. Studies by Daly (1991) and Cheung (1997) studied the impact of uni and bi-directional movements on the reduction of capacity of confined facilities (passageways and stairways). Lam (2002) carried out a bi-directional movement study at a signalized crosswalk in Hong Kong and found reduction in walking speed in minor flow direction. A study by Lee (2006) for stairways observed that under uncongested condition, when the mean speed decreased, the walking speed variation increased for both directional movements. Alhajyaseen (2011) studied the effect of bi-directional movement on the capacity of signalized crosswalk and observed equal pedestrian flow levels from both sides had maximum impact on reduction of capacity. Experimental and simulation studies conducted by Isobe (2004), Jian (2005), and Zhang (2014) also observed that the movement direction significantly influenced the walking behaviour of the pedestrians.

2.3.2.2. Group pedestrian characteristics

The formation of groups under moderate or high flow condition is a very common phenomenon. Previous researches showed that majority of the studies focused on the individual pedestrian walking speeds to estimate the capacity of the facilities. However, under different non-linear interaction of pedestrians, various types of spatio-temporal patterns arise, which are similar to bird swarms (Reynolds, 1987; Vicsek, 1995). These patterns are not externally planned, prescribed or organized and are commonly known as ‘self-organization’ phenomenon (Helbing, 2001). Previous studies showed that the size of a group, lane formation, leader-follower relationship, lane shifting, overtaking, faster-is-slower effect and squeezing effect were common interaction phenomenon that affected the walking behaviour of the pedestrians while moving in groups. Modelling such group factors together is an intimidating task and thus not many studies have tried to incorporate them together.

Group formation

Early studies by James (1953) and Coleman (1961) tried to analyze the distribution of the free-forming small group sizes and observed that group size formations followed Poisson distribution. In 1993, Al-Masaeid observed that group size affected the walking speed in Jordan. Tarawneh (2001) also found that pedestrians walking in a group had lower speeds than the ones walking as individuals. New York Pedestrian Study (2006) also observed that female pedestrians had a greater tendency to walk in groups. Pedestrians walking in groups walked slower as they tend to observe the surrounding more and engaged in talking to each other (Finnis, 2008). With the increase in the group size, the pedestrian walking speed linearly decreased (Moussaid, 2010). The study also showed that the group pattern changed from linear-shape to V-shape depending on the density level. A study by Laxman (2010) showed that with the formation of groups, the percentage reduction in mean speed was 12-16%. In a study by Costa (2010) it was observed that depending on the composition of the group and the spatial arrangement, the walking speed changed. Rastogi (2011) found that the pedestrian speeds reduced by 15-20% when pedestrians were crossing in a group. A study by Silva (2014) observed that the walking speed when a pedestrian was walking alone and in a group were 78m/min and 71m/min respectively. Duives (2014) tried to analyze the influence of group size on the distance headway, and found that factors such as age, gender, group size and composition influenced the walking behaviour. A recent study by Vanumu (2017) showed that the pedestrian group behaviour followed logarithmic distribution and the behaviour of pedestrians while walking in a group were significantly different from the pedestrians walking alone. Other studies by Tarawneh (2001), Carey (2005), Gates (2006) and Schultz (2010) also observed that the group formation significantly reduced the walking speed of pedestrians and impacted the walking behaviour over different facilities.

Lane formation

Formation of lanes or lines of pedestrians are a very common self-organization phenomenon observed when there is moderate to high flow of pedestrians. A study by Oeding (1963) observed that if the pedestrian density was high, the pedestrians spontaneously organized themselves into lanes of uniform walking direction. Weidmann (1993) and Lam (2002) suggested that the main reason for relatively minor loss of capacity in bi-directional movement was lane formation. As per Helbing (2001), pedestrians could move freely under low densities, but as repulsive interactions with other pedestrians began, the pedestrians tried to self-organize and formed separate lanes of uniform direction. Teknomo (2001) studied the crossing behaviour of pedestrians and observed lane like segregation. In an experimental study, Hoogerdoorn (2005) observed that pedestrians tend to form lanes while walking through bottlenecks. Saberi (2015) used empirical data to study the lane formation behaviour under bi-directional movement. In an experimental study, Feliciani (2016) attempted to understand the mechanism leading to formation of lanes. A study by Lee (2016) observed spontaneous lane formation that reduced the conflict and increased the travel speed. In 2017, Jin through different experimental setups (circular and open corridor) observed lane formation phenomenon under bi-directional flow. Xiong (2011), Wang (2014), Tao (2016), and Yuan (2017) used microscopic modelling approaches to understand the lane formation phenomenon.

Leader-follower relationship

Reuschel (1950) introduced the concept of leader-follower term in car-car leader-follower relationship. In case of pedestrians, leader-follower relationship or follow-the-leader is a self-organizing phenomenon that generally occurs under moderate or high flow condition when pedestrians are in lane formation mode. An experimental study by Hoogerdoorn (2005) observed that under bottleneck conditions, pedestrians followed the preceding pedestrians directly ahead in the same layer. Shi (2005) observed leader-follower relationship patterns towards the sides of the confined facilities which minimized the interaction with the opposite direction pedestrians. In 2007, Antonini used trajectory data to estimate the leader follower relationship between groups of pedestrians. Lemercier (2012), through an experimental study inside a corridor tried to analyze the following behaviour of the pedestrian without overtaking. Ko (2013) in a crosswalks related study tried to model the leader-follower behaviour under low and high densities. A study by Rastogi (2013) on sidewalk facilities observed follow the leader occurrence near the sides under heavy bi-directional flow. Haghani (2017) analyzed follower the leader behaviour in case of escape from an emergency and found that pedestrians without leader follower behaviour took more time to exit. Zhao (2017) through experiments found that the leader follower relationship in pedestrians was similar to the ones observed in case of cyclists and vehicle users. Li (2020) in an attempt to understand the effect of group behaviour on the pedestrian choice for vertical facilities, observed leader-follower relationship between groups of pedestrians.

Lane shifting

The lane changing phenomenon was introduced by Sparmann (1978) in case of vehicles. Lane shifting or lane changing is a common phenomenon that occurs when a fast moving vehicle tries to overtake a slow moving vehicle in front. However, in the case of pedestrians, lane shifting is a very common phenomenon where a pedestrian keeps on shuffling lanes to either overtake a pedestrian, move away from a crowd or avoid collision with the oncoming pedestrians from the opposite direction. Shuaib (2016) introduced the term lane change behaviour to predict the oncoming behaviour of pedestrians from the opposite direction and decide on whether to change the lane or not. Apart from the study by Shuaib (2016), more field data investigations related to lane shifting are lacking.

Overtaking

Overtaking or surpassing is a common phenomenon in reality where pedestrians either shift their lane to overtake slower pedestrians in the front or walk on the same lane to bypass the slower pedestrians. Thus pedestrians, who are facing obstructions in form of slower moving pedestrians in the front, generally try to evade the slower pedestrians and move at their own desired speed. Such overtaking behaviour is generally observed at locations where pedestrians are in a rush to reach their destinations. In the process of overtaking, pedestrians tend to seek sufficient space to avoid getting hurt from the boundary walls or colliding with other pedestrians. Figure 2.6 shows a typical overtaking maneuver of a pedestrian.

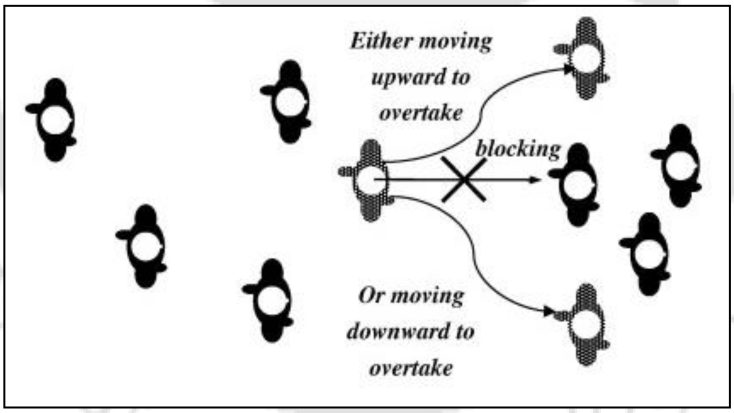


Figure 2.6. Action of overtaking (*Source: Yuen, 2012*)

Thompson (1995) proposed the possibility of incorporating the overtaking behaviour in pedestrian modelling. Yuen (2012) tried to analyze the impact of overtaking behaviour among pedestrians moving in uni-directional flow by avoiding the blocking pedestrians in the front. Using experimental setup and simulation, Hu (2015) tried to visualize the effect of overtaking under bi-directional flow. Zhang (2018, 2019) proposed an optimization model for overtaking under uni-directional pedestrian flow and found that pedestrians moving at speeds greater than 60m/min preferred to evade and overtake the slower moving pedestrians in the front. Liu (2019) observed similar overtaking behaviour over stairways while both ascending and descending.

Faster-is-slower effect

Helbing (2013) defined faster-is-slower effect as “certain processes (in evacuation situations, production, traffic dynamics, or logistics) take more time if performed at high speed”. The phenomenon is also known as “freezing by heating” effect (Stanley, 2000), where pedestrians who panic are slower to exit and those who are calmer exit faster. Previous studies tried to model faster is slower effect in case of exit during emergency, where if the pedestrians who tried to overtake others and escape through a corridor, led to slower escape and panic amongst others. Studies by Parisi (2007), Sticco (2017) and Chen (2018) tried to model the faster is slower effect under different corridors and exit points. However, the faster is slower effect or slower is faster effect is a rare phenomenon which can occur over different pedestrian facilities (at-grade and grade separated). It occurs when a pedestrian decides to shift lane and overtake, but while moving through the motion is obstructed by pedestrians from opposite direction or a group of pedestrians in the front (moving in the same direction as the subject pedestrians), and thus the subject pedestrian needs to shift back to his/ her original lane.

Squeezing effect

Squeezing effect is a self-organization phenomenon that occurs when pedestrians in the minor flow direction are forced to shift to one side of the walkway due to the major flow in the opposing direction. In squeezing effect, the subject pedestrian can be a single pedestrian or a lane of pedestrians walking together. Rastogi (2013) observed squeezing effect towards the center of the facility as compared to the sides due to bi-directional flow condition. Chandra (2014) observed squeezing phenomenon more on the sidewalk facilities than the wide-sidewalks, due to which more pedestrians were observed to walk in the available area leading to higher densities.

Some important observations related to microscopic flow characteristics of pedestrians were:

- Majority of the studies used gender, age and luggage condition to define the individual pedestrian speeds.
- The difference between male and female pedestrian speeds on sidewalks, walkways, crosswalk, stairways (ascending) and stairways (descending) were 7.7m/min, 7m/min, 6.6m/min, 5.6m/min and 7.6m/min respectively.
- The speed across different facilities were observed to decrease with the age of a person.
- The presence of luggage reduced the walking speeds depending on the slope of the facility and dimension of the luggage.

- Depending on the use of hand held devices (i.e., using phone, texting or calling), the reduction in walking speed was significant. Moreover, the use of mobiles also changed the overall walking pattern of the pedestrians and their interaction with the environment.
- The travel time and walking speed was severely affected by the direction of movement over facilities especially with grade.
- The formation of groups impacted the walking speed in comparison to pedestrians walking alone. The reduction ranged between 12-20% depending on the composition and size of group.
- Self-organization phenomenon such as lane formation, leader-follower relationship, lane shifting, overtaking, faster-is-slower effect, and squeezing effect impacted the overall walking behaviour of the pedestrians over different facilities.

2.4. Review of data collection techniques

Various researchers across the globe used either qualitative (perception survey or questionnaire survey), quantitative (videographic survey), controlled and manual counting data collection techniques in order to come up with practical solutions for actual field conditions. Figure 2.7 shows the line diagram of the different data collection techniques.

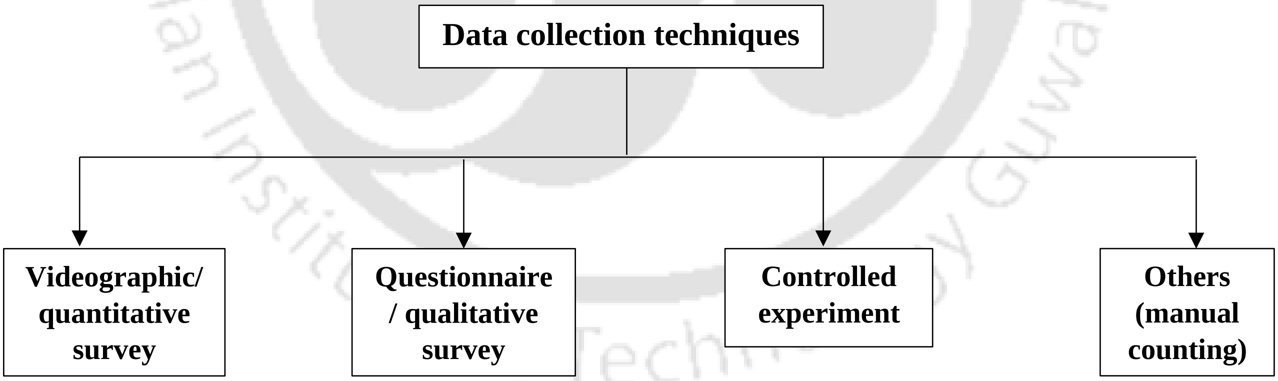


Figure 2.7. Pedestrian data collection techniques

The different data collection techniques help in understanding the walking behaviour of pedestrians, developing macroscopic and microscopic models as well as introduce LOS standards for the different pedestrian facilities. From previous literature, it was observed that majority of the studies either used qualitative or quantitative data collection techniques separately, and very few studies combined both the techniques. Different factors such as space, flow, speed, land use type, obstruction (in the form of vendors/beggars), traffic and pedestrian volume, safety and security, surface conditions, width and overall environment were used for data collection.

2.4.1. Parameter extraction using videographic data collection technique

The videographic or quantitative data collection technique is the most primitive method of data collection. In this method, the camera is step up at a vantage point for recording the pedestrians' movement. The advantage of collecting data using videographic technique is that it is a permanent data collection technique where the minutest details related to pedestrians can be extracted easily. Even though traffic extraction software is easier to use, it does not allow extraction of minute details of the pedestrians. Researchers across the globe preferred using one of the most primitive and reliable methods of data collection, i.e., videographic technique to collect data over different pedestrian facilities. Table 2.4 shows the different facilities over which data was collected using videographic technique to extract the various required parameters.

Table 2.4. Videographic data collection and parameters considered over different facilities in past studies

Type of facility	Author	Parameters considered
Sidewalk	Polus (1983), Mori (1987), Tanaboriboon (1991), Kwon (1998), Sisiopiku (2006, 2007), Petritsch 2006), Jensen (2007), Al-Azzawi (2007), Talevska (2012), Christopoulou (2012), Kim (2013), Tuydes-Yaman (2014), Daniel (2016), Marisamynathan (2016), Sahani (2017), Cepolina (2019)	Density, space, flow rate, speed, v/c ratio, obstruction, delay, width, vehicle volume, demographics
Walkway	Fruin (1971), Gerilla (1995), Shams-E-Rabbi (2018)	Density, space, flow rate, pedestrian speed, width, v/c ratio, demographics
Stairway	Fruin (1971), Tanaboriboon (1991), Cheung (1997), Lam (2000), Hongfei (2009), Liu (2008), Fujiyama (2011), Shah (2017), Liu (2019)	Speed, space, density, flow rate, travel time, direction, gradient, demographics
Crosswalk	Tanaboriboon (1991), Zhang (2003), Hubbard (2009), Alhajyaseen (2010), Asadi-Shekari (2014), Rastogi (2014), Marisamynathan (2017), Sahani (2017), Das (2018)	Space, flow rate, delay, pedestrian volume, vehicle volume, demographics, width, delay, number of lanes
Overpass	Rasanen (2007), Rizati (2013), Hasan (2017), Patra (2020)	Demographics, direction, speed, flow, density, group size, mobile use
Underpass	Hankin (1958), Zhang (2009), Ming (2013), Cui (2015)	Speed, geometric conditions (width, slope), flow volume, demographics, gender ratio, travel behaviour

Table 2.4 shows that majority of studies using videographic data collection technique were conducted over sidewalks, walkways, stairways and crosswalk facilities. The macroscopic factors such as speed, flow rate, density and space were the most common parameters which

were used for data collection across all facilities. Moreover, very few studies have been conducted over overpass and underpass facilities using videographic data.

2.4.2. Parameter extraction using questionnaire data collection technique

In order to understand the current existing conditions and improve the facilities accordingly, as well as predict the LOS, the researchers used questionnaire survey technique. Interviewer-administered questionnaire survey is the most common type of qualitative survey technique. The result of such studies provide information on the existing facilities and how they can be improved to attract more pedestrians. Table 2.5 shows the different studies conducted using questionnaire survey technique.

Table 2.5. Questionnaire data collection and parameters considered over different facilities in past studies

Type of facility	Author	Parameters considered
Sidewalk	Jaskiewicz (2000), Landis (2001), Muraleetharan (2003), Bian (2007), Dandan (2007), Ferreira (2007), Parida (2008), Hidayat (2011), Bahari (2012), Kang (2013), Kim (2013), Gokhale (2013), Martokusumo (2013), Rahman (2015), Babu (2016), Arshad (2016), Bivina (2018), Zannat (2019), Rodriguez-Valencia (2020),	Surface, obstruction, width, accessibility, safety, comfort, environment, movement easiness, traffic noise pollution, pleasure, road signs, demographics
Walkway	Sarkar (2003), Rahaman (2006), Zakaria (2014)	Safety, security, comfort, convenience, accessibility, environment
Stairway	Lee (2003)	Safety, conflict, accessibility, environment
Crosswalk	Miller (2000), Baltes (2002), Muraleetharan (2005), Petritsch (2005), Lee (2005), Muraleetharan (2007), Kim (2011), Saha (2011), Archana (2013), Yadav (2015), Mukherjee (2019), Rankavat (2020)	Safety, environment, accessibility, traffic control, actual risk, perceived risk, demographics
Overpass	Wu (2014), Sangphong (2014), Demiroz (2015), Das (2015), Rankavat (2016), Malik (2017), Oviedo (2017), Anciaes (2018), Hasan (2018), Truong (2019), Landa-Blanco (2020)	Demographics, security, safety, overpass dimensions (height, width, length), number of steps, detour distance, phone use, hawker's presence, security, entry access, cleanliness, time saving, fine imposed, illumination
Underpass	Saha (2013), Abojaradeh (2013), Pasha (2015), Das (2015)	Demographics, slope, length, surface, physical dimensions

From Table 2.5 it is observed that the questionnaire technique was quite common among researchers studying sidewalk, crosswalk and overpass facilities. The most common factors used while data collection were demographic characteristics along with user characteristics such as surface, comfort, accessibility, width, obstruction, safety and security.

2.4.3. Parameter extraction using controlled techniques

Past researchers tried to model the behaviour of pedestrians that are difficult to attain on the field using controlled experiment conditions. Appointed pedestrians were asked to move through different sections of corridors, viz. straight corridor, different angles (right angle and oblique angles), bottlenecks, queuing areas, and the data was recorded using videographic techniques. Further using the data, macroscopic and microscopic simulation studies were conducted in order to understand the behaviour of pedestrians under different density conditions. Table 2.6 shows the different studies conducted under controlled environment and the objective of the studies.

Table 2.6. Use of controlled data collection technique

Author	Facility	Sample size	Study objective
Daamen (2003)	Narrow bottleneck	60 (morning), 80 (evening)	Walking behaviour and interaction
Helbing (2007)	Corridors, bottlenecks, and intersections	NA	Empirical flows under normal and panic situations
Chattaraj (2009)	Straight corridor	34	Walking behaviour across cultures
Seyfried (2009)	Bottleneck	60	Impact of width of flow
Sun (2014)	Passageway	50	Weaving behaviour under high density
Das (2016)	Straight corridor	NA	Gender mix single file pedestrian motion
Guo (2016)	Ring-shaped corridor	100	Impact of uni and bi-directional flow
Sharifi (2017)	Passageway, corners (right and oblique), doorways, bottlenecks	NA	Walking behaviour of disabled pedestrians
Zeng (2018)	Circular corridor	60	Step length and step frequency
Rahman (2019)	Angled-corridors (60°, 90°, 135°)	60	Characteristics and speed of pedestrians
Hu (2020)	Circle	72	Multi-directional movement analysis as individuals or groups
Li (2020)	Bottleneck	86	Flow under different movement motivations
Aghabayk (2020)	Intersecting angles (30°, 90° and 150°)	89	Interaction and walking speeds at outflow
Zhang (2020)	Corridor	20	Behavior of individuals and groups

From Table 2.6 it is observed that the studies related to controlled experiments were mainly conducted on a sample size of around 50-100 pedestrians. The studies aimed at understanding the walking behaviour of the pedestrians based on gender, culture, direction, step length, speed, and group patterns.

2.4.4. *Other data collection techniques*

The earliest studies used manual counting method to calculate the flow of pedestrians across a section using manual clicker and tally mark sheets. Some major factors that should be considered while doing such data collection technique are:

- The time period when the data is collected should coincide with the peak hour data.
- The locations selected for data collection must be carefully selected to ensure total existing demand.

The main problem with this data collection technique is that it is quite labour intensive and detailed information cannot be gathered through it.

Some important observations related to data collection techniques are:

- Majority of studies using videographic data collection technique were conducted over sidewalks, walkways, stairways and crosswalk facilities. The most common parameters used were as speed, flow rate, density and space.
- Very few studies were conducted over overpass and underpass facilities using videographic data.
- Questionnaire technique was common over sidewalk, crosswalk and overpass facilities. Most of the studies used demographic characteristics, along with user characteristics such as surface, comfort, accessibility, width, obstruction, safety and security.
- The controlled experimental studies used gender, culture, direction, step length, speed, and group patterns for studying pedestrian behaviour.
- The manual counting data collection method is labour intensive and minute information are not captured.

2.5. Study of pedestrian movement characteristics over different pedestrian facilities

The following section discusses about the different studies related to pedestrian flow characteristics which have been conducted over grade separated (FOB, skywalk, subway stairways/ escalator) and at-grade (sidewalk, walkway, crosswalk) facilities.

2.5.1. *Pedestrian behaviour over grade-separated facilities*

Grade-separated pedestrian facilities are constructed to have complete segregation of pedestrian and vehicular interaction. These facilities are generally constructed in urban settings where pedestrian crossing signals may cause congestion or accident. The facilities allow reduction in pedestrian crash at locations where there is a high chance of interaction between the pedestrians and the vehicular traffic. The grade-separated facilities are primarily of two types, underpass (i.e. subway) and overpass (i.e. foot over bridge and skywalk). The grade-separated facilities consist of a vertical connectivity (in the form of stairway, ramp, escalator, and elevator) which connects the mid-block (or walkway) section of the overpass or underpass to the road level. The behaviour of the pedestrians over the vertical connectivity and mid-block sections are quite different.

The connection between the overpass and underpass as discussed is achieved through the vertical connectivity in the form of manual vertical connectivity (stairways or ramps), and automated vertical connectivity (escalators and elevators). Depending on the availability of manual or automated vertical connectivity, the choice and behaviour of the pedestrians vary significantly.

2.5.1.1. Overpass (Foot over bridge and Skywalk)

The overpasses or elevated walkways are mainly of two types, namely, foot over bridges (which allow easy crossing from one side of the road to the other) and skywalks (which enable lateral and longitudinal movements and can be the best substitute to the sidewalks and crosswalks). Table 2.7 discusses about the empirical studies carried out by different researchers across the globe related to FOB facilities.

Table 2.7 shows that majority of the studies related to elevated facilities were conducted in Asian countries and used logistic regression (binary, multiple and mixed) to predict the pedestrian choice between the different crossing facilities. In addition, questionnaire was the most preferred survey technique used by different researchers for modelling purposes. Apart from demographic characteristics, variables such as frequency of use, safety, security, hawker’s presence, cleanliness, number of steps and type of facility available were the most commonly used for questionnaire studies.

Table 2.7. Empirical studies conducted over FOB facilities

Author	Type of study	Variables used	Model/ Method used
Abojaradeh (2013), Wu (2014), Sangphong (2014), Demiroz (2015), Das (2015), Rankavat (2016), Malik (2017), Oviedo-Trespalacios (2017), Anciaes (2018), Landa-Blanco (2020)	Q	Age, gender, safety-security, awareness, hawker's presence, cleanliness, accessibility	Logistic regression (binary, multiple linear, or ordinal)
Patra (2020)	V	Age, Gender, Luggage, No. of adults traveling together, mobile phone use	Binary logit
Rasanen (2007), Rizati (2013), Hasan (2014, 2017, 2020)	V & Q	***Videographic factors:*** Hourly traffic volume, width of the crosswalk, the existence of median, distance of FOB from the illegal crossing point, time to cross FOB and crosswalk ***Questionnaire factors:*** Age, gender, frequency of use, purpose of trip, safety-security, reason for not using facility	Logistic regression (binary, multiple linear, and mixed)
Truong (2019)	O	Gender, age, weather, overpass height and width, mean illegal crossing	Binomial regression

Note: *V- Videographic, Q- Questionnaire, O- Observational*

2.5.1.2. Underpass (Subway)

A subway or underpass is an underground pedestrian facility, which allows pedestrians to reach to the other side of the road safely. The main benefit of providing a subway is that pedestrians need to go down first and then climb up. This psychological tendency to avoid ascending stairways arrives when a pedestrian has to use an elevated facility. However, the main problem with a subway is that if it is not properly maintained and adequate safety-security is not ensured, then it may be misused in many ways and pedestrians tend to avoid such facilities. Table 2.8 discusses about the different studies related to underpass facilities.

Table 2.8. Past empirical studies related to underpass facilities

Author	Type of study	Variables used	Model/ Method used
Hankin (1958), Zhang (2009), Ming (2013), Cui (2015)	V	Speed, geometric conditions (width, slope), flow, demographics, gender ratio, travel behaviour, trip duration	Simulation of emergency evacuation
Saha (2013), Abojaradeh (2013), Pasha (2015), Dass (2015)	Q	Demographics, slope, length, surface, physical dimensions	AHP, MLR, Factor analysis

Note: *V- Videographic, Q- Questionnaire*

2.5.1.3. Vertical connectivity (Stairways and escalators)

Stairways and escalators are the facilities that allow vertical movement and are used to ascend or descend, to and from grade-separated facilities (i.e., overpasses and underpasses). Whereas, stairways allow easy movement only for a particular group of pedestrians (e.g. young adult male/ female) for whom ascending or descending is relatively easy; escalators, on the other hand provide easier accessibility and comfort to a wider range of pedestrians (e.g. elderly, and children). Only properly designed stairways (with low riser height and low gradient) allow easy access for all groups of pedestrians. Table 2.9 shows the different studies which have been conducted across the globe based on stairways and escalators or both.

Table 2.9. Studies conducted over stairway and escalator pedestrian facilities

Facility	Direction	Author	Variables used	Regime used	Model used
Stairway	Uni- and bi-	Fruin (1971), Templer (1978), Tanaboriboon (1991), Weidmann (1993), Sarkar (2001), Lee (2006), Hongfei (2009), Chen (2010), Choi (2013), Chen (2017), Koster (2019). Liu (2019)	Speed, flow, density, space, FFS, jam density	Single, two and multi	Linear, exponential, polynomial
	Bi-	Fujiyama (2004), Yang (2012), Shah (2013, 2015, 2016, 2017), Choi (2014), Ye (2020)	Speed, flow, density	Single and multi	Linear, logarithmic
Stairway and escalator	Uni- and bi-	Daly (1991), Cheung (1997), Lam (2000), Lee (2005), Daamen (2007), Eves (2008), Kinsey (2010), Andersen (2011), Suri (2014), Zacharias (2015), Patra (2017), Belletteire (2019), Malveira (2019)	Speed, flow, density, space, FFS, jam density	Single and two	Linear

The findings from Table 2.9 indicate that other than very early studies which considered both uni- as well as bi-directional movement; most of the recent studies were done considering bi-directional movement of pedestrians over the stairways. Speed and flow were the preliminary parameters that were measured across all the studies. Moreover, single regime approach was mostly preferred while a few studies also used two or multi regime approach.

Most of the above-mentioned studies were conducted from subway, metro station or railway station stairways and escalators under experimental or actual field conditions. The aim of these studies were to observe how the pedestrian behaviour varied with different demographic factors (such as gender, age, luggage carrying condition, body dimension of pedestrians), geometric dimensions (such as step width, number of steps, tread and riser dimensions, landing) or for development of macroscopic relationships. The studies which were conducted over both the facilities, tried to assess the choice pedestrians made between the two facilities and for comparison of walking speeds. Some studies also tried to simulate the pedestrian walking motion over stairways facilities. Rarely any studies have been conducted in India for understanding pedestrian behaviour over stairways or escalators for FOBs or skywalks, which are not located inside railway/ metro stations.

2.5.2. Pedestrian behaviour on at-grade facilities

2.5.2.1. Sidewalk (or footpath or footway) and walkway

A sidewalk or footpath is a raised path along the roadside which is separated from vehicular traffic by a kerb, do not allow bicycles or other users, accommodate the highest volume of pedestrians, have a width between 1.5 to 5 m and may have slight changes in grade. On the other hand, walkway is a pedestrian facility that is located far away from the vicinity of motorized traffic in recreational or shopping areas where pedestrians can move around freely, without the intrusion of motorized vehicles. The walkway is different from the sidewalk as it is unraised and wider than sidewalks, with complete segregation from motorized traffic. Table 2.10 shows the different studies conducted over sidewalks and walkways.

Table 2.10. Pedestrian behaviour studies conducted over sidewalk and walkway facilities

Facility	Direction	Author	Variables used	Regime used	Model used
Sidewalk	UD and BD	Oeding (1963), Older (1968), Navin (1969), Koushki (1993), Gerilla (1995), Nazir (2012), Rahman (2012), Das (2015), Brahmbhatt (2015), Daniel (2016), Cepolina (2018)	SP, FL, DN, SC, FF, JD	Single	Linear
	BD	Al-Azzawi (2007), Tipakornkiat (2012)	SP, FL, DN, SC		Linear, logarithmic
		Koushki (1988), Morrall (1991), Sarsam (2015), Bargegol (2015)	SP, FL, DN, FF		Linear
		Al-Masaeid (1993), Kwon (1998), Christopoulou (2012), Shafabakhsh (2013), Shoaib (2015), Bargegol (2015), Rungta (2016)	SP, FL, DN		Linear, exponential
Walkway	UD and BD	Tanaboriboon (1986), Virkler (1994), Nazir (2014), Corbetta (2016), Shams-E-Rabbi (2018)	SP, FL, DN, SC, FF, JD	Single, two	Linear, exponential
		Young (1999), Moussaïd (2010), Corbetta (2016)	SP, FL, DN, SC		Exponential

Note: *SP- speed, FL- flow, DN- density, SC- space, FF- FFS, JD- jam density, UD- uni-direction, BD-bi-direction*

From Table 2.10 some important observations related to sidewalk studies are:

- Even though some studies were focused on capturing uni-directional pedestrian movement, most of the studies were conducted for bi-directional movement.
- Speed, flow and density were the most key parameters that were measured in all the studies; while space and free flow speed were also measured by some researchers.
- The parameters were preferably modelled using single regime approach.
- The linear speed and density relationship was mostly developed in all the studies, while some studies proposed logarithmic or exponential relationship for better fitting of the data.
- Most of the studies on the sidewalk were conducted in countries like India, Bangladesh and Iran; while some researchers in the UK, USA and Germany also studied the facility.

From Table 2.10 some important observations related to walkway studies are:

- It was observed that most of the studies over walkway facility were conducted for both uni- as well as bi-directional flow in countries like the USA, UK, France and Netherlands; while few studies had also been conducted in Singapore and Bangladesh.
- Speed and flow were the basic parameters that were measured for most of the studies.
- Exponential as well linear speed-density relationships were developed for such studies.

2.5.2.2. Crosswalk

Crosswalks are at-grade facilities that are provided for easy and safe dispersal of pedestrians from one side of the road to the other. These crosswalks/ crossings can be located either at intersections or at midblock with either presence of signals or can be unsignalized with/ without zebra crossings. Crosswalks are more critical than sidewalks due to greater pedestrian-vehicle interaction.

Various researchers (O'Flaherty, 1972; Wilson, 1980; Griffiths, 1984; Tanaboriboon 1994; and Bowman, 1994) had carried out early studies on crosswalk for bidirectional pedestrian movement, and speed was the only parameter measured. The study by Tanaboriboon (1994) found that illegal signalized crossings were nearly 30-45% at different locations in China and was a significant reason for pedestrians being killed regularly, yet pedestrians were more interested in crossing at grade instead of using the overpasses or underpasses. Later, Tarawneh (2001), Hamed (2001), Keegan (2003), Zhao (2003), Goh (2004), Ibrahim (2005), Gates (2006), Montufar (2007), Shi (2007) and Lee (2008) measured both speed and flow parameters for crosswalks. In Malaysia a study by Ibrahim (2005) found the waiting time to range between 7-23s depending on whether vehicles were moving alone or in a platoon; while in China, Shi (2007) observed that the average waiting time ranged between 6-8 seconds. In Canada, Montufar (2007) observed that crossing speed of pedestrians also varied from season to season. Parameters such as pedestrian volume, group size and stopping times and their effect on crossing speed were well explored in China and Malaysia. It could be seen that average crossing speed for Chinese or Malaysian pedestrian was between 78-91 m/min and those in the USA or Canada was 80 m/min. Recently, Alhajyaseen (2010, 2011), Serag (2014), Bargegol (2014), Mako (2015), Shabaan (2019), Hassouna (2020) and Torres (2020) performed studies on signalized and unsignalized crosswalks for estimating speed parameter for bi-directional pedestrian movement.

Sahani (2013), Kadali (2013, 2014), Jain (2014), Ferenchak (2016), and Asaithambi (2016) conducted similar studies in India over crosswalk and mid-block crossings respectively, and gap acceptance behaviour was mainly measured under mixed traffic condition. The study by Kadali (2013) observed the average accepted gaps to cross intersections were 4.75 s, 3.35 s and 3.50 s by elderly, middle-aged and young pedestrians. The before-after study by Asaithambi (2016) showed that 4.65s and 7.07s were the average waiting times, before and after the installation of a signal. Marisamynathan (2018) modelled the crossing behaviour of pedestrians and safety at signalized crosswalks. Bansal (2019) studied the pedestrian speed at signalized intersections under heterogeneous traffic conditions.

Some important conclusions related to pedestrian movement characteristics over different pedestrian facilities are:

- *Grade-separated facilities:*
    - Majority of the studies related to elevated walkways used questionnaire survey, while some studies used both videographic and questionnaire surveys techniques.
    - In India, two studies (Rankavat, 2016 and Patra, 2020) were conducted to compare the pedestrians' choice between using FOB and at-grade facility (crosswalk).
    - No studies have been conducted to understand the walking behaviour of pedestrians over mid-block as well as stairway sections of FOBs using both questionnaire as well as videographic survey techniques.
    - No studies have been conducted over skywalk facilities.
    - The studies related to underpasses measured demography, geometric conditions, flow, and trip duration to model the walking behaviour using both videographic and questionnaire techniques.
    - The studies related to stairways tried to understand the impact of different geometric dimensions and demographic factors on the movement characteristics of pedestrians, located at subways, metro stations or railway stations.
    - No studies have been conducted over stairway facilities for FOBs or skywalks, which are not located inside railway stations.
- *At-grade facilities:*
    - Most of the studies related to sidewalks were conducted in Asian countries (India, Bangladesh and Iran) for bi-directional movement based on speed, flow and density using single regime approach. The linear speed-density relationships were developed in all the studies.

- Uni- and bi-directional movement studies were conducted over walkway facilities mainly in developed countries (USA, UK, France and Netherlands). Speed and flow were the fundamental parameters measured, while both exponential and linear relationships were developed.
- The studies related to crosswalks were mainly conducted in Asian countries (China and India), where speed, flow, waiting time, gap acceptance behaviour and speed were studied.

2.6. Study on Pedestrian Level of Service (PLOS)

The level of service (LOS) as per Highway Capacity Manual (US-HCM, 2010) is explained as "a quantitative stratification of a performance measure or measures that represent the quality of service, measured on an A-F scale, with LOS A representing the best-operating conditions from the traveler's perspective and LOS F the worst. LOS evaluates the performance of a facility and the need to redesign it. Various researchers across the globe have carried out several studies in developing LOS for different types of facilities. The different studies either used quantitative or qualitative methods for conducting the survey and it was observed that a combination of both the studies could reflect the actual field conditions. Various factors such as flow rate, area module, speed, adjacent land use, obstruction, volume, safety, surface, width, etc. were used in developing the LOS for different types of facilities.

Table 2.11 provides an overview of the studies that were conducted over different pedestrian facilities (such as sidewalks, walkways, stairways, crosswalks and multiple facilities) by various researchers in order to develop LOS for such facilities based on either quantitative or qualitative survey technique. Table 2.11 shows the studies related to pedestrian level of service across different facilities. Some important observations related to LOS studies are:

- Majority of the studies were conducted on sidewalk/ footpath; while some studies were focussed on walkways and stairways.
- Most important factors for quantitative survey were flow rate and space.
- Researchers generally tried to categorize LOS ranges between 4-6 (quantitative) and 5-6 (qualitative) categories.
- Indo-HCM (2018) developed LOS for Foot Over Bridges (FOBs) based on quantitative survey considering five FOB locations.
- No study on skywalk LOS development was carried out.

Table 2.11. LOS related studies conducted over different facilities using quantitative and qualitative techniques

Facility	Author	Data collection technique	Measure of effectiveness (MOE)	LOS ranges defined
Sidewalk	Polus (1983), Tanaboriboon (1989), Kim (2006), Televska (2012), Kim (2014), Rastogi (2014), Raghuwanshi (2016), Cepolina (2018)	Quantitative	***Most Studies:*** Flow Rate, Space ***Some Studies:*** Density, Speed, V/C ratio	4-6
Walkway	Gerilla (1995), Sahani (2016, 2017)			6
Stairways	Fruin (1971)			6
Sidewalk	Khisty (1994), Dixon (1996), Jaskiewicz (2000),Gallin (2001), Muraleetharan (2007), Asadi-Shekari (2012), Meng (2014), Marisamynathan (2018), Parvathi (2018), Bivina (2019), Zannat (2019)	Qualitative	Perception Score	5-6
Walkway	Sarkar (2003), Rahaman (2006), Zakaria (2015)			
Stairways	Lee (2006)			
Sidewalk, Stairways, FOB	US-HCM (2010), IRC-103 (2012), Indo-HCM (2018)	Quantitative	Flow Rate, Space	6
		Qualitative	Perception Score	5-6

2.7. Modelling approaches related to pedestrian behaviour over different facilities

This section describes the different types of modelling approaches of pedestrian motion, namely dynamic modelling, continuous modelling and discrete modelling.

2.7.1. Dynamic modelling approach

Dynamic models based on Navier-Stokes or Boltzmann equations consider each pedestrian as gas or fluid. These models are macroscopic in nature and provide rigorous mathematical analysis of motion. Henderson (1971) described pedestrian crowds with Navier-Stokes equation and considered energy and momentum to be collisional invariants. Helbing (1991) improved on Henderson’s approach and mathematically developed a fluid dynamics model based on a Boltzmann-like gas-kinetic constant. Development of walking lanes and jams were observed as in reality. The main drawbacks were the role of pressure, specific influence of internal friction and origin of temperature as in fluid dynamics, which could not be defined for pedestrians.

Pauls (1995) presented a model where pedestrians were represented as particles of liquid and hydromechanics dynamics was hence applied. The model could not simulate a person's movement properly. A lattice gas model was proposed by Muramatsu (1999, 2000), where a pedestrian was represented as a gas particle. Results of two-way flow was found to be similar to cellular automata model, but four-way flow was quite dissimilar.

Hughes (2002) derived continuity equations of motion conservation based on fluid mechanics and Jiang (2010) developed a higher order model of fluid dynamics that consisted of two-dimensional Euler equations with relaxation. Both the models could capture macroscopic characteristics to some extent, but could not clearly resolve the behaviour of pedestrians, as the task to which pedestrians responded was not clearly defined. Colombo (2012) assumed each individual to move towards a fixed target, deviating from the best path according to the instantaneous crowd distribution based on mathematical equations. Boundedness of crowd density could be seen, but the detailed individual behaviour could not be predicted.

Dynamic models as seen above only provide information about pedestrian motion at macroscopic level, but not at individual pedestrian interaction level.

2.7.2. Discrete modelling approach (Cellular automata model)

The Cellular Automata (CA) model is a discrete particle-hopping model in which a set of local rules describe the behaviour of entities within local neighbourhood of cells. CA microsimulation has emerged as a tool for simulating traffic flow and modelling transportation network. Nagel (1992) put forward a CA car-following model to analyze vehicle movement using two steps of vehicle velocity update and movement. Blue (1997) developed an approach of modelling pedestrian movements based on CA rule set that could imitate actual pedestrian goals such as minimizing distance travelled and avoiding conflict with others. The approach was valid only for pedestrians in a large open space such as a rail or bus terminal, shopping mall or office lobby where conflicting movement at high volumes tend to cause congestion and reduce overall flows with constant arrival rates that was not applicable on sidewalks, street corners or traffic crossing lanes.

In the CA model developed by Blue (1997), a pedestrian entity finds its way from origin (i_0, j_0) to a destination cell (i_d, j_d) as shown in Figure 2.8 by following local behavioural rules as given below:

i. The entity enters matrix at time T_i at an origin cell (i_0, j_0) and assigned an entity number (e_n), until it reaches the opposite side at its destination cell (i_d, j_d).

ii. In the next time step T_{i+1}, entity selects a cell towards (i_d, j_d). If $j_d - j_0 = 0$, the entity moves to a cell directly ahead (i_{0+1}, j_0). If that cell is occupied by another entity, the entity 'adjusts' its path by choosing with equal probability either diagonal cell ahead $(i_{0+1}, j_{0\pm1})$ without going off the matrix. If the three forward cells are occupied, the entity 'sidestep'.

iii. For sidestep, when $j_d - j_0 = 0$, the entity chooses with equal probability either cell to the side $(i_0, j_{0\pm1})$ without going off the matrix. If the cell is occupied, the entity bumps the occupant.

iv. If $j_d - j_0 \neq 0$, the entity chooses to move to the cell diagonal ahead and towards its destination cell (i_{0+1}, j_{0+1}). If this cell is occupied, it adjusts its path by choosing the cell directly ahead (i_{0+1}, j_0). If that cell is occupied, the entity tries to sidestep.

v. For the sidestep when $j_d - j_0 \neq 0$, it chooses the cell to the side closest to the destination $(i_0, j_{0\pm1})$ without going off the matrix. If that cell is occupied, the entity 'bumps' the occupant.

vi. In bumping, the bumper leaves its space and occupies the desired cell to the side. The bumped entity moves to the side closest to its destination or arbitrarily to either side if $j_d - j_0 = 0$. This entity bumps the occupant if the desired cell is occupied. A bumped entity may leave the matrix if it is bumped off it. Bumping is recursive and may result in several bumps before and entity finds an empty cell or leaves the matrix.

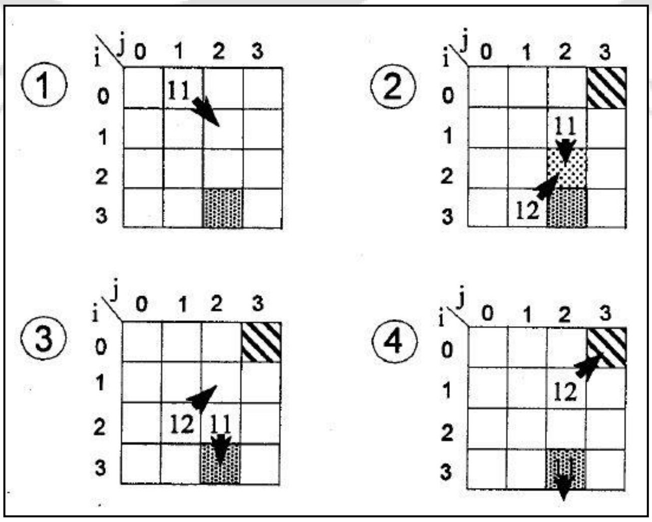


Figure 2.8. Illustration of pedestrian movements in four consecutive time steps (*Source: Blue, 1997*)

After the development of the Blue (1997) model under normal situation, various researchers had tried to apply CA model under both normal as well as evacuation situations. Blue (1998, 1999, 2000 and 2001) tried to modify the original model developed under normal situation, and considered uni-directional flow, bi-directional flow and four-directional flow for different cell sizes in order to observe the movement of pedestrians on the lattice. Reasonable emergent fundamental parameters were observed using a few simple rules.

Fukui (1999), Dijkstra (2001), Weifeng (2003), Yue (2007, 2010), Chen (2010, 2014) Lammel (2015), Jin (2017), Padovani (2018), and Dias (2018) did similar studies for normal situation. They tried to apply CA rules on different cell sizes by introducing a few rules like back-stepping, right-hand parameter, orientation for multi-directional movement. Some interesting observations that could be made were that critical density increased with probability of increased back stepping, that critical density depend on system size and that phase transitions occurred at critical densities.

Evacuation scenarios were studied by Burstedde (2001), Kirchner (2003), Wei-Guo (2003, 2005, 2006), Varas (2007), Guo (2008), Sarmady (2011), Li (2014), and Ruiz (2019) using CA model for different cell sizes. They observed floor field concept, friction parameter, panic parameter, repulsive force of personal space, etc. into the model in order to define movement of pedestrians on the lattice. Common features that could be observed for evacuation situation were collective phenomenon, oscillation at doors, and faster-is-slower effect.

2.7.3. Continuous modelling approach (Social force model)

The social force model for pedestrian movement is a continuous model based on concepts adopted from the social fields as described by Lewin (1951). One of the first force based models was developed by Hirai (1975), inspired by a similar model of the motion of shoals of fish presented by Suzuki (1973). Okazaki (1979) proposed a model inspired by forces between magnets. These models had restricted applicability, as there was limited computational power. Helbing (1995), proposed the Social Force Model (SFM) for a normal situation, where computational power was no longer a major obstacle to applicability. The social force is not a force exerted by the environment on the pedestrian’s body, but rather a quantity that describes the concrete internal motivation to act. The model was formulated (as shown in Figure 2.9) based on three effects:

i. The will to reach a certain destination comfortably through the shortest path.

ii. The repulsive or territorial effect to keep a certain distance from other pedestrians and maintain a private sphere, which depends on the pedestrian density and desired speed.

iii. The attractive effect by which pedestrians are sometimes attracted to other pedestrians or objects (e.g., window displays).

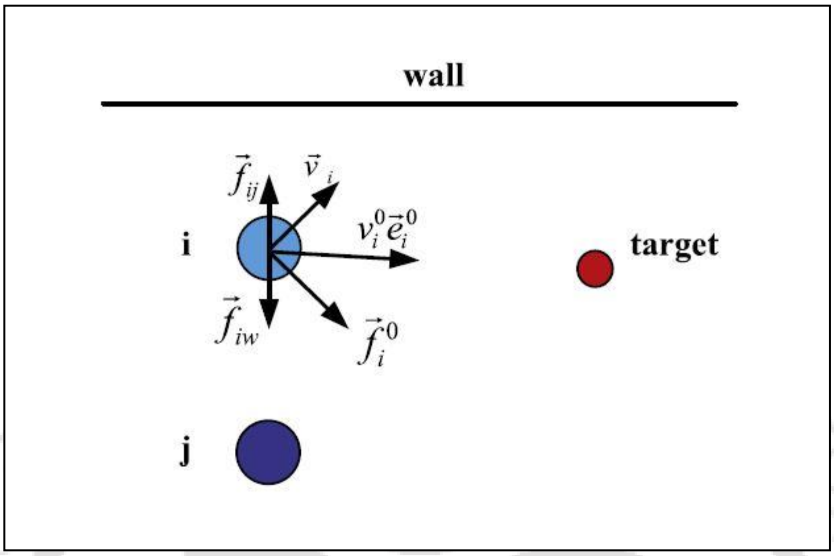


Figure 2.9. Social forces acting on a pedestrian (*Source: Yang, 2014*)

In Figure 2.9, f_i^0 represents the driving force, f_{ij} represents the interaction force between pedestrians 'i' and 'j', and f_{iw} represents the interaction force between the pedestrian 'i' and wall 'w'.

The Equation 2.2 given below developed by Helbing (1995), suggests that the change of actual velocity $V_\alpha(t)$ of a pedestrian α is given by a vectorial quantity $f_\alpha(t)$. A fluctuation term is also considered which takes into account random variations of the behaviour due to deviation from the usual rules of motion.

$$\frac{dV\alpha}{dt} = f_\alpha(t) + fluctuations \qquad .... \mathbf{Eq.2.2}$$

The social force terms as per Helbing (1995, 1998) can be described as follows:

i. A pedestrian wants to walk into a desired direction e_α with a certain desired speed V_α^0. The deviation of actual velocity V_α from desired velocity V_α^0 (=V_α^0 * e_α) due to necessary decelaration leads to a tendency f_α^0 to approach V_α^0 again within a certain relaxation time τ_α. This can be explained as an acceleration term.

$$f_\alpha^0 (V_\alpha, V_\alpha^0 e_\alpha) = \frac{V_\alpha^0 e_{\alpha} - V_\alpha}{\tau_\alpha} \qquad .... \mathbf{Eq.2.3}$$

where, f_α^0 is the measure for "pressure of time" and means of "motivation to move ahead".

ii. Motion of pedestrian α is influenced by other pedestrian β, and α keeps a certain distance that depends on the pedestrian density and desired speed V_α^0. Here the private sphere interpreted by territorial effect ($f_{\alpha\beta}$), plays a vital role. The repulsive effect of other pedestrian β can be interpreted as.

$$f_{\alpha\beta}(r_{\alpha\beta}) = -\nabla_{r\alpha} V_\beta [b(r_{\alpha\beta})] \qquad \ldots\ldots\ldots\ldots\ldots\ldots \textbf{Eq.2.4}$$

It is assumed that repulsive potential V_β defines the interaction potential which influences the behaviour of each pedestrian. For V_β, it is assumed that a monotonic decreasing function in 'b' with equipotential lines having the form of an ellipse is directed towards direction of motion (refer Figure 2.10).

Figure 2.10. (a) Decrease of repulsive interaction potential $V_\beta(b)$ with b, (b) Elliptical equipotential lines of V_β for different values of b (*Source: Helbing, 1998*)

Where, b is the semi-minor axis of ellipse and is given by:

$$2b = \sqrt{[(r_{\alpha\beta}) + (r_{\alpha\beta} - V_\beta \Delta t e_\beta)]^2 - (V_\beta \Delta t)^2} \qquad \ldots\ldots\ldots\ldots\ldots \textbf{Eq.2.5}$$

and, $s_\beta = V_\beta \Delta t$, which is the step width of pedestrian β; $r_{\alpha\beta} = r_\alpha - r_\beta$.

iii. A pedestrian keeps a certain distance from borders (i.e. buildings, walls, streets, obstacles). The border 'B' evokes a repulsive effect which is a monotonic decreasing potential V_B.

$$f_{\alpha B}(r_{\alpha B}) = -\nabla_{r\alpha} V_B [(r_{\alpha\beta})] \qquad \ldots\ldots\ldots\ldots\ldots \textbf{Eq.2.6}$$

where, $r_{\alpha B} = r_\alpha - r_B^\alpha$, and r_B^α denotes the location of the piece of the border B that is nearest to the pedestrian α.

iv. Fellow pedestrians or objects (window displays) sometimes attract pedestrians. These attractive effects $f_{\alpha i}$ at place r_i can be modelled by attractive, monotonic increasing potential W_i.

$$f_{\alpha i}(r_{\alpha i}) = -\nabla_{r\alpha} W_i [(r_{\alpha i})] \qquad \text{………..……} \ \textbf{Eq.2.7}$$

where, $r_{\alpha i} = r_\alpha - r_i$

The social force (total motivation) is given as:

$$\boldsymbol{f_\alpha(t) = f_\alpha^0 (V_\alpha, V_\alpha^0 e_\alpha) + f_{\alpha\beta}(r_\alpha - r_\beta) + f_{\alpha B}(r_\alpha - r_B) + f_{\alpha i}(r_\alpha - r_i)} \qquad \text{……..} \ \textbf{Eq.2.8}$$

It can be seen from Equation 2.8 that the social force is dependent on the desire to move ahead, the repulsive effect of pedestrians, the repulsive effect of boundary and the attractive effect of pedestrians / objects.

Various researchers tried to implement the SFM for normal as well as emergency/ evacuation situations by introducing new parameters or by modifying existing parameters. Helbing (2000), Parisi (2005, 2007), Ko (2012), Ma (2013), Yang (2014), Gao (2016), Jiang (2020) and Zhou (2020) incorporated behaviour, such as panic (nervousness factor), self-stopping mechanism, collision avoidance, view radius, degree of occupants competitiveness, etc. into the social force model under emergency/ evacuation situations, in order to analyze pedestrian interactions at microscopic level. Patterns such as clogging, faster-is-slower, leader-follower relationship at high density, escape time being dependent on view radius were observed as well.

Lakoba (2005), Seyfried (2006), Parisi (2009), Xi (2010), Yuen (2012), Shuaib (2013), Zeng (2014), Johansson (2015), Farina (2017), Huang (2018), Krbálek (2018), Prédhumeau (2019) and Ma (2019) conducted SFM studies under normal situation. They tried to incorporate parameters like memory effect, familiarity factor, respect area, connection range, visible area, overtaking behaviour, prediction factor and waiting pedestrians into the SFM to predict the pedestrian movement. Some common features that could be observed were faster-is-slower effect, self-slowing mechanism instead of sudden stop, reduction of pushing behaviour, lane formation, etc.

On comparing SFM with CA model, it can be concluded that SFM has the advantage of giving a realistic description of individual movements in fine resolution at microscopic level considering individual pedestrian intentions, desired velocities and pair interactions. Moreover, features like self-organizing phenomenon, lane formation, segregation, zipper effect can be well portrayed through SFM, and it is quite flexible while considering the geometry of the facility as well. Also commercial software tool Viswalk (PTV, 2013) based on SFM for pedestrian simulation has a better graphical user interface that can be used for modelling.

Some important observations related to different modelling approaches related to pedestrian behaviour over different pedestrian facilities are:

- Dynamic models provide information about pedestrian motion at macroscopic level only, and not individual pedestrian level.
- Continuous model (social force model) gives a more realistic description of individual movements at microscopic level in comparison to discrete model (cellular automata). The self-organizing phenomenon can be well portrayed through SFM.

2.8. Viswalk simulation using Social Force Model

Viswalk was developed by PTV (2013) and is used in the research in this dissertation.

2.8.1. General

Viswalk enables us to simulate and model the human walking behaviour using a microscopic, time discrete, and behaviour based simulation model. The simulation is based on the Social Force Model (SFM) developed by Helbing (1995). The transport planners use the powerful software tool to simulate and analyze pedestrian flows. Viswalk offers two different ways to model pedestrian flow. The first is to specify no interaction between pedestrians and the second possible way is to use the vehicle-flow model specified in Viswalk based on Weidmann (1993). The pedestrians are categorized in different pedestrian types and pedestrian classes. Within a pedestrian type, the pedestrians have similar walking behaviour. For each pedestrian type, the maximum acceleration, the appearance of the pedestrian and behaviour parameters are defined. The behaviour parameter includes the parameters of the social force model and global parameters such as *use_ cache* and *grid_ size*. Pedestrian types with similar walking behaviour can form a pedestrian class. Examples of pedestrian types are men and women, while examples of pedestrian class are adults and child.

The compositions of pedestrians are defined with a desired speed distribution as a cumulative speed distribution function and ratio of each pedestrian type. The demand of pedestrians can be defined in two different ways in Viswalk, either by defining the inputs and outputs manually or defining the flow between origins and destinations with an O-D matrix. In the model, pedestrians are created at selected pedestrian area with random points in time according to pedestrian compositions and input volumes.

2.8.2. Viswalk related parameters

In Viswalk, the parameters of the social force model are used for simulation. In addition to the parameters of the social force model, some new parameters have been included in Viswalk to reduce the calculations in the model. Different values of the parameters can be set for different areas, which allow customized behaviour of the pedestrians at complex passages. The parameters of the social force model in Viswalk can be divided into two groups: parameters by pedestrian type (which affect only the defined pedestrian type) and global parameters (which influence all pedestrian types). All the pedestrian type parameters are briefly described in Table 2.12.

Table 2.12. Pedestrian type parameters in Viswalk

Parameter	Implication
Tau (in sec)	• It refers to relaxation time in seconds. • Lower value of tau indicates higher acceleration.
Lambda_mean (λ_m)	• It is used to adjust the weight that defines how the force from other persons and objects would affect the subject pedestrian. • Higher value implies that forces from other persons behind the pedestrian have less influence on the subject pedestrian than forces from other persons in front of the subject pedestrian.
A_soc_isotropic (A_i) *and B_soc_isotropic* (B_i)	• A_i and B_i along with λ_m form the repulsive force between the pedestrians.
A_soc_mean (A_m), *B_soc_mean* (B_m) *and VD*	• A_m decides the strength of the force in metres per square second. • B_m determines the ranges of force in metres. • A_m and B_m along with VD (in seconds) forms the other one of the two repulsive forces.
noise	• It relates to the random force which adds to calculated social force if the actual walking speed of a pedestrian is below desired speed • Higher noise represents stringer random force
react_to_n	• It refers to the total number of surrounding pedestrians to be considered for social force calculation
queue_order and queue_straightness	• The two parameters together control the shape of the queue
side_preference	• Detemines the preference of the subject pedestrian to pass the other pedestrians from the right or left side.

Global parameters such as grid_size, routing_large_grid, use_cache, routing_step, routing_accuracy, routing_cell_size, and dynamic_potential_cell_size are used to reduce the calculation time.

Another significant parameter, which has a direct impact on the speed of pedestrians is Desired Speed Distribution. As the name suggests, it signifies the speed distribution that the pedestrian is willing to reach. This kind of distribution can either be a linear function between a lower and an upper bound, or for higher accuracy, could be an S-Curve with data-points input from the collected data.

2.8.3. Simulation parameters in Viswalk

In order to minimize the simulation time and extract the best possible results, the simulation parameters shown in Table 2.13 are generally used.

Table 2.13. List of simulation parameters

Parameter	Definition
Simulation period	Simulation time in seconds.
Simulation resolution	Specifies how often pedestrian positions are recalculated within a simulation second. Value range between 1 and 20. For example, simulation resolution 1 means pedestrian moves once per simulation second.
Random seed	This value initializes a random number generator. If we vary the random seed the flow will change.
Number of runs	Refers to the number of simulation runs, and its value ranges between 5 and 20.
Random seed increment	Difference between random seeds when we perform multiple simulations run.
Simulation speed	Indicates simulation seconds per real time second. Value 1 means simulation is run in real time.
Number of cores	Number of processor cores used during simulation.

2.8.4. Evaluation of simulated pedestrian parameters

There are different evaluation modes available in Viswalk for assessing the simulated data. We can either present it in separate windows using GUI, or separate output files or databases using COM interface. One evaluation type is pedestrian flow data measurement, which can be interpreted as the number of pedestrians crossing the particular section over a specified amount of time. This can be achieved by creating a measurement area and extracting the SrcVol (Source Volume) attribute from it. Another important type of evaluation is pedestrian record. The user specifies which of the parameter needs to be evaluated and thus the program, by itself, collects the data at every time step.

2.8.5. Pedestrian performance measurements

This section describes the pedestrian performance measurements that can be obtained from the Viswalk and what evaluation possibilities the software provides in numerical outputs.

- **Travel time:** Measures travel time between origins and destinations. Since the origins and destinations are set to pedestrian areas. User can have defined evaluation time during which measurement shall be conducted.
- **Area measurements:** The location and size of a measurement area is user defined and provides information about pedestrians within the measurement area. The user also defines which outputs from area that should be collected from a list of numerous outputs.
- **Pedestrian record:** It is an evaluation feature that records data per time step and is obtained per pedestrian. User can define both for which pedestrian types and time steps record should be retrieved.

2.8.6. Pedestrian simulation model construction

Vissim provides an intuitive and user-friendly environment for simulation model creation. All of the models created for a study are generated using Viswalk approach for pedestrian traffic mode. The main steps involved in model creation are:

- Pedestrian Features (namely: Areas, Obstacles, Stairs and Ramps), Pedestrian Inputs and Pedestrian Routes are implemented.
- Performance measurements are done for parameters like Travel Time and Measurement Area feature (flow and average speed).
- In Base Data, Pedestrian Types are created for each of the pedestrian age group, Pedestrian Classes comprising of appropriate Pedestrian Types, Walking Behavior for each of Pedestrian Types and Area Behavior types for different areas wherever required.
- Pedestrian Compositions option in the Base Data menu provides us the ability to assign relative flows of the Pedestrian Types. The composition of each pedestrian input is edited according to the calibration data. Desired Speeds Distribution are assigned to each of the Pedestrian Type.
- Pedestrian Areas are created precisely by editing the text input files. Each area is then assigned an Area Behavior (comprising of the Walking Behavior parameters).
- In order to facilitate movement over the model, the areas are designated as Origin and Destinations using the OD matrix. Areas need overlapping for allowing smooth flow. Unwalkable areas due to different reasons (like presence of railings) are defined as obstacles over areas.

2.8.7. *Past studies conducted using Viswalk simulation*

Table 2.14 shows the past studies which have been conducted over pedestrian facilities using Viswalk modelling approach.

Table 2.14. Studies related to Viswalk simulation

Author	Study objective
Ishaque (2005)	Developed relationship between walking speed, flow and density
Yu (2006)	Searched for the best combination of parameters to minimize sum of squared error using genetic algorithm
Johansson (2008)	Studied impact of hybrid method to calibrate pedestrian model
Kretz (2008)	Calibrated and validated the social force model
Galiza (2010)	Studied the effect of elderly pedestrians in the composition
Galiza (2011)	Studied the effect of older pedestrians on space and speed
Zanlungo (2011)	Used genetic algorithm in order to calibrate collision avoidance
Ko (2013)	Simulated the effect of elderly pedestrians on the total flow
Roca (2014)	Applied assignment methods developed for vehicular traffic in pedestrian simulation
Seer (2014)	Validated using comprehensive real world motion data
Bamberger (2015)	Studied cross flow of crowd at school
Arman (2015)	Gap acceptance study in Iran
Benner (2017)	Calibrated trajectory data using Viswalk
Kretz (2019)	Identified inflection point in speed-density model
Arman (2019)	Investigated pedestrian crossing safety at mid-block and un-signalized intersection

Some important observations related to Viswalk simulation using social force model are:

- The most significant pedestrian type parameters are tau, lambda_mean, A_soc_isotropic, B_soc_isotropic, A_soc_mean, B_soc_mean, VD, and noise.
- The simulation parameters frequently used are simulation period, simulation resolution, random seed, number of runs, and simulation speed.
- The pedestrian performance is generally measured in terms of travel time, area measurement and pedestrian record.
- The past studies related to viswalk simulation mainly calibrated and validated the models under different geometries. Some studies also studied effect of elderly, and crossing behaviour under different scenarios.

2.9. Application of advanced soft computing techniques in transportation sector

The application of soft computing has become an integral part of the transportation sector. Whereas past studies mainly used different regression modelling approaches, recently there has been shift towards using soft computing approaches (such as random forest, decision trees, neural networks, etc.). The different machine learning techniques help in predicting better outcomes in comparison to earlier modelling approaches. The common evaluation metrics used are MAE, MAPE, RMSE, and R^2). Table 2.15 shows the application of different advanced soft computing techniques in the transportation-engineering domain.

Table 2.15. Application of soft computing techniques in transportation sector (*Source: Banerjee et al., 2020*)

Author	Study type	Soft computing technique	Evaluation metrics
Zhang (2015), USA	Travel time prediction	RT, GBM, RF	MAPE
Ding (2016), China	Driver's stop-or-run behaviour	GBM	R^2
Yang (2017), China	Short-term traffic forecast	GBM, SVM and BPNN	MAPE, MAE
Mousa (2018), USA	Lane changing maneuvers	DT, RF, GBM and XGB, Grid search, 10-fold CV	AUC
Alajali (2018), Australia	Traffic prediction at intersection	GBRT, RF and XGB	MSE and MAE
Tran Vinh (2019), Indonesia	Travel mode choice	GBM, DNN, Hyper-parameter, CV	Relative importance plot
Cheng (2019), China	Travel time prediction of freeway	GBDT, BPNN, SVM	MAD, MAPE, RE
Cheng (2019), China	Travel mode choice	RF, SVM, AdaBoost, MNL	Accuracy and MAPE

Table 2.15 showed that all the soft computing related studies were conducted for vehicular traffic. Different researchers studied travel time prediction, travel mode choice and lane changing behaviour. As per past studies related to transportation engineering (refer Table 2.15), better prediction accuracy was obtained using Boosting based algorithms on different study domain. Similar to other domain, in pedestrian-based researches, the use of such advanced algorithms is not well explored.

2.10. Outcomes of literature review

- Study on elevated facilities have not been well explored under Indian scenario.

- Fundamental diagrams related to mid-block and stairway sections of elevated walkways have been less explored.
- The studies conducted in India focussed on comparing between choice of using elevated walkways and at-grade facilities.
- Thorough study on walking behaviour and pattern which differ on elevated pedestrian facilities have been less explored in India.
- Study on the development of qualitative and quantitative Level of Service (LOS) for elevated pedestrian facilities are limited and hence needs more focus.
- Study of self-organizing walking behaviour (such as group formation, lane formation, leader follower relationship, lane shifting, overtaking, squeezing effect and faster-is-slower effect) need more exploration under Indian perspectives.
- The application of microscopic simulation models in order to understand behaviour at individual as well as group pedestrian levels, under Indian context have been limited.
- Only limited application of advanced soft computing approaches has been explored for pedestrian studies.

2.11. Concluding remarks

In the present chapter an attempt was made to understand the different relevant literatures related to pedestrian walking behaviour studies. Initially a discussion was made on the different types of pedestrian facilities (at-grade and grade-separated). Thereafter, fundamental characteristics of pedestrians were discussed (macroscopic: flow, speed, density, area module and relationships between them; and microscopic: individual and group behaviour). A detailed discussion was made on the different types of pedestrian data collection techniques. Further, relevant literatures were discussed related to pedestrian level of service over different facilities using quantitative and qualitative methods. The different pedestrian behaviour modelling approaches were discussed along with the importance of Viswalk simulation. The applications related to soft computing techniques in transportation sector were discussed as well. Finally, the gaps in the literature were identified. The next chapter discusses about the methodology of data collection and extraction.

CHAPTER 3

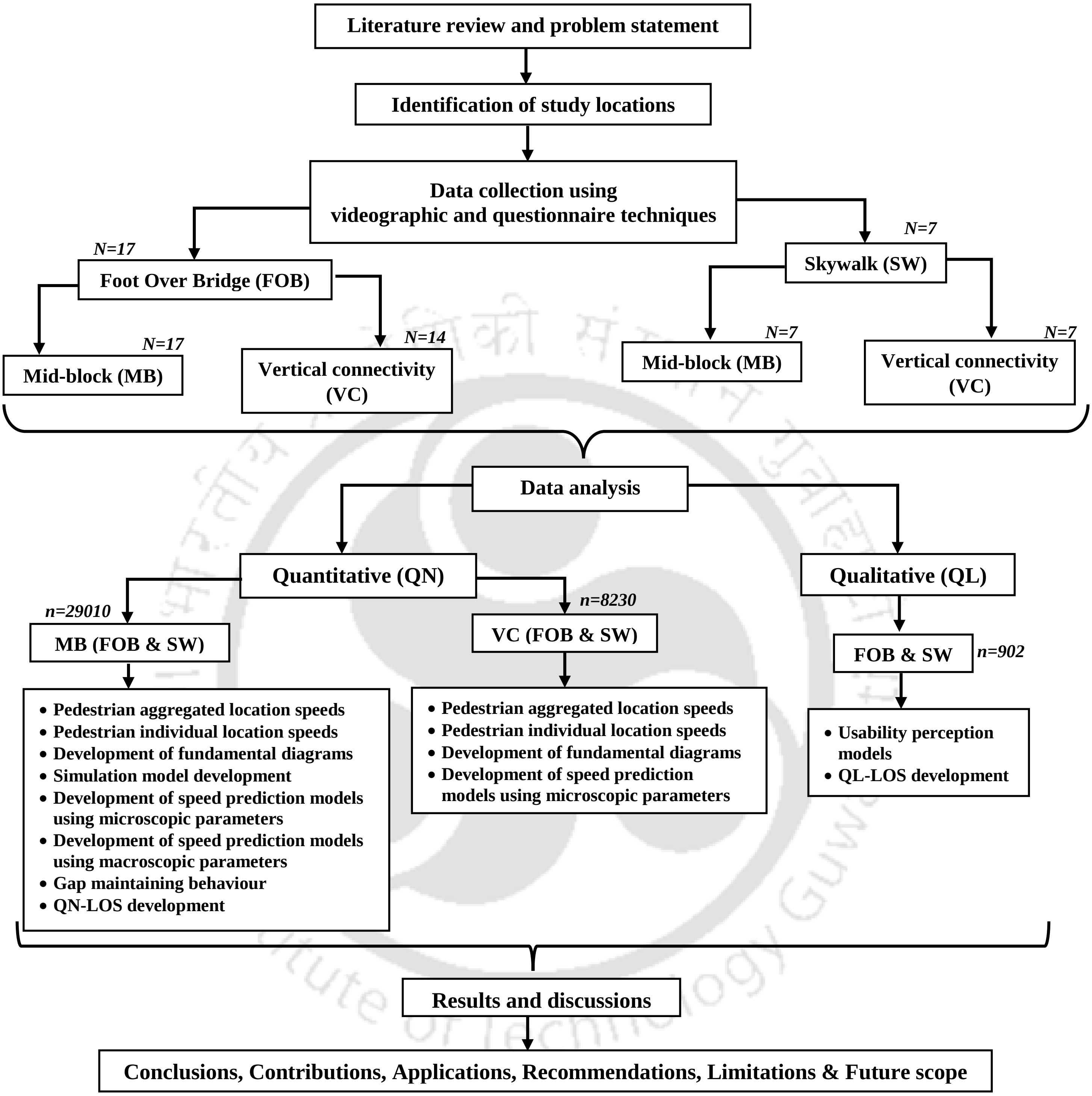
METHODOLOGY OF DATA COLLECTION AND EXTRACTION

3.1. General

The present chapter discusses the study areas selected for data collection and the technique of data extraction. The data was collected using both videographic and questionnaire survey techniques for the different elevated facilities (Skywalks and Foot Over Bridges: FOBs) across six Indian cities covering varied geographical locations. The videographic data was collected for peak and off-peak hours for fifty-one hours for mid-block sections of FOBs and skywalks; and twenty-one hours for their stairway sections. Similarly, for the perception or questionnaire survey, a total of 902 respondents were surveyed for both the facilities combined together. The two different data collection approaches (videographic and questionnaire) aimed to gather all possible variations to develop pedestrian behavior models and develop the level of service criteria for the elevated walkways. Figure 3.1 shows the flow chart of the entire thesis from literature review to data collection, extraction, analysis, results and final conclusions.

3.2. Preliminary planning of data collection and site selection

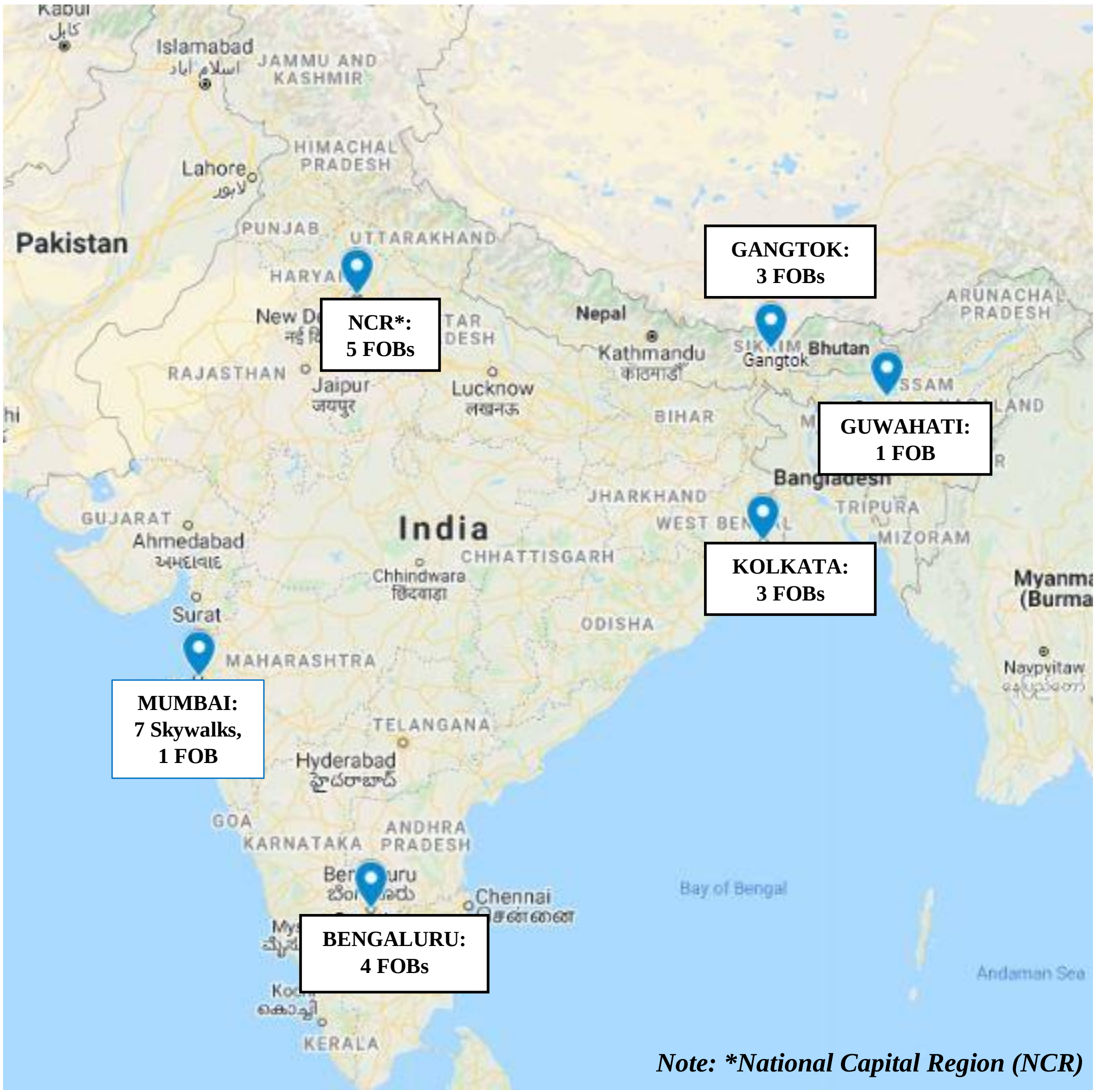
To capture the variability in walking behavior among pedestrians across different cultures, beliefs, languages, customs and physical body dimensions, it was decided to collect data from the various elevated facilities across northern, eastern, southern, western, and north-eastern regions of India. Moreover, to develop fundamental macroscopic and microscopic relationships among different flow characteristics, it is imperative to collect data over facilities with different geometric configurations. Primarily two different elevated facilities were finalized for data collection, i.e., skywalks and foot over bridges (FOBs). After the final selection of the cities (namely, Gangtok, Mumbai, National Capital Region: NCR (Delhi), Kolkata, Bengaluru, and Guwahati), each and every possible elevated pedestrian facility was visited. In total, 28 FOB and 12 skywalk locations were visited prior to data collection.



*(*__Note:__ N- Number of survey locations, n- number of samples)*

Figure 3.1. Flow chart of the entire research work presented in this thesis

Finally, those elevated walkway locations were selected, which had an adequate flow of pedestrians throughout the day and were connecting from one side of the road to the other side through a minimum single entry-exit points. Thus, 17 FOB locations and 7 skywalk locations were selected for data collection (both quantitative as well as qualitative), which had different flow levels throughout the day (i.e., peak and off-peak hours), as shown in Figure 3.2.



*Note: *National Capital Region (NCR)*

Figure 3.2. Cities covering different data collection locations across India

The videographic data was collected over both the mid-block and stairway sections. The foot over bridges were provided with either stairway alone or along with escalators, lifts, and ramps; while in the case of skywalks, stairways were the only vertical connectivity available. Similarly, the interviewer-administered questionnaire survey of the present pedestrians in the neighbourhood of the facility was conducted at each survey location.

3.3. Site selection and description of study locations

After visiting the different FOBs and skywalks across various cities, only those elevated pedestrian facilities which had varied geometric features and adequate flow of pedestrians throughout the day were shortlisted. Table 3.1 shows the details of the different locations selected along with their GPS co-ordinates.

Table 3.1. Geometric features of the elevated facilities

City	***Location (ID)***	***GPS co-ordinates***	***Duration of data collection***	***Land use type***	***Total length (in m)***	***Mid-block width (in m)***	***Number of steps***	***Stair width (in m)***	***Tread (in cm)***	***Riser (in cm)***	***No. of entry-exits***	***Vertical movement facility***
Gangtok	STNM Hospital *(F1)*	27.3314, 88.6139	8.00am-11.00am	CL	42.6	2.5	43	1.8	30	16	2	St
	Metro point *(F2)*	27.3305, 88.6130	3.30pm-6.30pm	CL	18.8	2.5	43	1.8	30	16	2	St
	M.G. Marg *(F3)*	27.3303, 88.6124	8.00am-11.15am	SG	18.5	2.4	43	1.8	30	16	3	St
Mumbai	IIT Bombay *(F4)*	19.1254, 72.9168	3.30pm-6.15pm	EL	46.5	3.6	52	1.6	32	17	2	St
	Andheri East *(S1)*	19.1197, 72.8486	7.30am-11.00am	CL	581	3.9	44	1.4	34	18	7	St
	Goregaon West *(S2)*	19.1633, 72.8483	3.00pm-6.00pm	CL	625	4.4	49	1.6	30	17	5	St
	Ghatkopar West *(S3)*	19.0847, 72.9073	7.45am-11.00am	RL	315	3.7	42	1.4	30	14	5	St
	Bandra East *(S4)*	19.0552, 72.8440	3.30pm-6.30pm	CL	970	4.5	51	1.5	28	14	7	St
	Vile Parle West *(S5)*	19.1006, 72.8393	7.30am-10.45am	EL	460	4.0	57	1.4	28	14	5	St
	Santa Cruz East *(S6)*	19.0806, 72.8446	3.45pm-6.30pm	SG	685	3.6	42	1.0	32	14	5	St
	Kalyan West *(S7)*	19.2368, 73.1317	3.15pm-6.15pm	SG	1287	4.4	54	1.9	32	17	8	St
Kolkata	Ultadanga *(F5)*	22.5914, 88.3931	8.00am-11.15am	CL	42.4	3.1	41	2.4	26	20	4	St
	Lake Town *(F6)*	22.6007, 88.4079	3.45pm-6.30pm	RL	42.2	2.9	19	2.9	30	15	6	St, R
	Sealdah *(F7)*	22.5648, 88.3683	8.00am-11.00am	CL	36.9	2.4	53	2.1	30	15	3	St
National Capital Region (NCR)	Anand Vihar *(F8)*	28.6565, 77.3174	3.15pm-6.15pm	PTT	61.5	5.7	48	2.3	30	16	4	St, E
	Akshardham *(F9)*	28.6187, 77.2798	7.45am-10.55am	PTT	66.5	2.2	48	2.3	31	16	4	St, E
	ITO *(F10)*	28.6278, 77.2439	3.45pm-6.45pm	CL	39.2	2.6	117	2.2	31	2	4	R*, E
	Maharani Bagh *(F11)*	28.5759, 77.2639	7.30am-10.30am	RL	41.3	2.6	115	2.8	30	2	4	R*, E
	Vaishali *(F12)*	28.6505, 77.3390	8.00am-11.15am	PTT	88.1	3.5	50	3.7	30	14	4	St, L
Bengaluru	Tin factory *(F13)*	12.9969, 77.6690	3.00pm-6.00pm	CL	49.8	2.6	50	2.1	25	12	2	St
	Yeshwantpur *(F14)*	13.0196, 77.5526	8.00am-11.00am	PTT	31.1	3.1	54	1.1	26	9	4	St, L
	Marathahalli *(F15)*	12.9570, 77.7017	3.00pm-6.00m	CL	32.1	3.4	44	1.5	32	16	4	St, L
	Christ University *(F16)*	12.9364, 77.6060	7.30am-10.45am	EL	21.2	2.8	39	3.1	29	14	4	St, L
Guwahati	Maligaon *(F17)*	26.1591, 91.6967	8.15am-11.15am	CL	33.8	2.6	55	1.2	28	8	4	St

Note:* *Location: *F- FOB, S- Skywalk*
Land use type: *CL- Commercial, PTT- Public Transport Terminal, RL- Residential, EL- Educational, SG- Shopping*
Vertical connectivity: *St- Stairway, L- Lift/ elevator, R- Ramp, R*- Ramp like stairway, E- Escalator*

From Table 3.1, it could be observed that the measured length and actual walkable width (with buffer distance) of the FOBs across selected locations varied between 18.5-88.1m and 2.2-5.7m, respectively. The measured length of the skywalks ranged between 315-1287m, and the available total walkable width varied between 3.60-4.50m. These data were consistent with the guidelines prescribed by IRC: 103 (2012), towards the minimum required walkable width of 1.8m. Depending on the riser dimension, i.e., the vertical distance between two successive steps

(Irvine et al., 1990), the number of steps keeps on varying across the different locations. The dimension of the tread, i.e., the horizontal top portion of a step where foot rests (Irvine et al., 1990), ranged between 25-32 cm.

Ideally, the suggested riser and tread dimensions as per IRC: 103 (2012) should be 15cm and 30cm, respectively. The locations in Delhi (i.e., ITO and Maharani Bagh) had stairways, which were similar to ramps with tread and riser dimensions of 30cm and 2cm, respectively. Table 3.1 also indicates that most of the FOBs other than those in Bengaluru and Delhi lacked either ramps/ lifts/ escalators. Due to a lesser number of FOBs in Guwahati, only one FOB was found suitable for this study. Similarly, in the case of Mumbai, the FOB situated outside the Indian Institute of Technology (IIT) Bombay campus was only considered due to its frequent usability.

The data collection was initiated with videographic survey technique in the city of Gangtok, the capital of the state of Sikkim, in October 2015. Thereafter, videographic, as well as questionnaire data were collected from the cities of Mumbai (in December 2016), Kolkata (in March 2017), Delhi and Bengaluru (February 2018), and Guwahati (July 2018). The subsequent section provides details on the locations where data were collected from each city.

3.3.1. Gangtok (Sikkim)

From the North-Eastern city of Gangtok, three FOBs were selected for video data collection. All three locations, namely: M.G.Marg, S.T.N.M. Hospital, and Telephone Exchange/ Metro FOBs were located over NH 31A passing through the main city. All the FOBs were connected using the stairways only. Table 3.1 provides a detailed description of the geometric features along with GPS co-ordinates of the facilities. Initially, it was planned to study pedestrian movement behaviour over the mid-block sections only, thus the data was not collected over the stairways. Moreover, the questionnaire survey was also not conducted for the city. Figure 3.3 shows the three different locations across Gangtok city. The mid-block sections are shown in Figure 3.4.

Figure 3.3. Videographic data collection locations in Gangtok

Fig. (a). M.G. Marg mid-block (F1)

Fig. (b). STNM Hospital mid-block (F2)

Fig. (c). Metro Point mid-block (F3)

Figure 3.4. Gangtok FOBs (F1-F3)

3.3.2. Mumbai (Maharashtra)

In December 2016, the city of Mumbai was visited and data for both skywalks as well as FOBs were collected using both questionnaire as well as videographic survey techniques. In India, the skywalk facilities were available only in the city of Mumbai for easy access of pedestrians from one zone to another over longer distances. All the seven skywalks selected were connected with railway stations on one side and had different entry-exit points from where pedestrians could easily access the skywalks. A major limitation in the construction of such facilities was the vertical connectivity, which was in the form of stairways only (with narrow walkable width). Also, security measures in the form of CCTV cameras or security personnel were missing in majority of the locations; while many vendors and beggars were present over such facilities. However, all-weather shade was provided all along the facilities. The questionnaire/ perception survey were conducted across all skywalk locations to understand the pedestrians' choice of using skywalk facilities under the existing conditions. Moreover, videographic data was collected for both the mid-block sections as well as stairway sections for all the locations. The different locations from where the data were collected were Andheri East, Goregaon West, Ghatkopar East, Bandra East, Vile Parle West, Santa Cruz West, and Kalyan West (refer Table 3.1 for details).

In Mumbai even though there are many FOBs that are available, yet most of them are sparsely unused. A major reason is that the position of such elevated facilities are near locations where the pedestrian movement is very less or there is provision of legal/ illegal at-grade opening within 10-15m from the facility. Thus, majority of the pedestrians prefer to cross at-grade instead of using the facilities, as median guardrails are unavailable. Also, the provision of only stairways demotivates pedestrians to use the FOB facilities. To understand how pedestrians in the city of Mumbai use the FOB facilities and also to capture their perception, the FOB outside IIT Bombay main gate was selected. This was the only facility that was frequently used by the pedestrians, as the at-grade crossing was completely blocked. Figure 3.5 shows the locations of the selected skywalks and FOBs for this study. Subsequent figures (Figure 3.6-Figure 3.13) show the mid-block and stairway sections of different skywalks and FOBs.

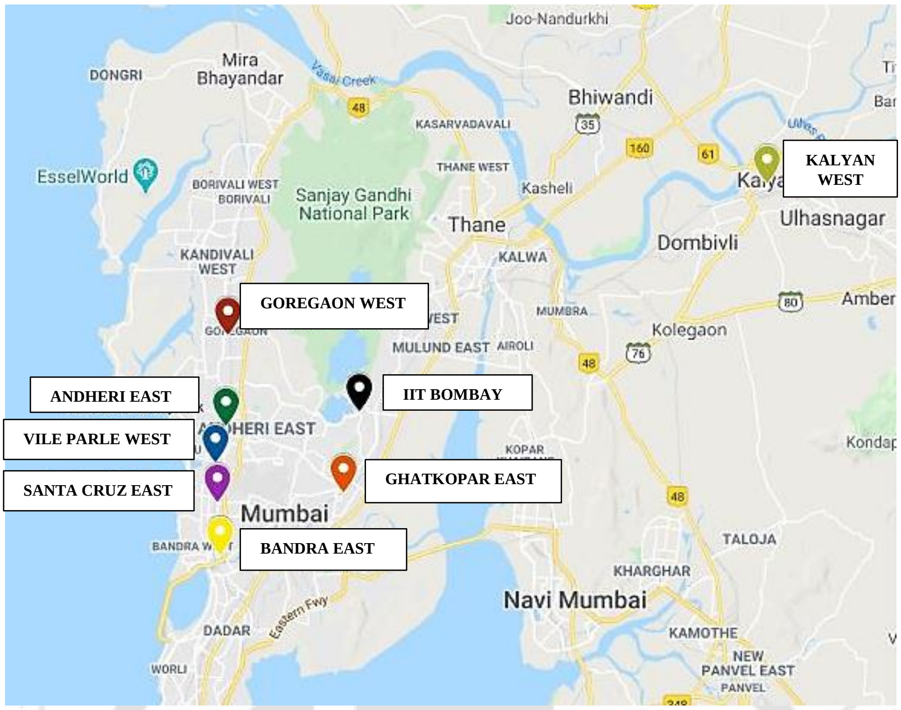


Figure 3.5. Questionnaire survey and videographic data collection locations in Mumbai

Fig. (a). Mid-block (S1) **Fig. (b).** Stairway (S1)

Figure 3.6. Andheri skywalk (S1)

Fig. (a). Mid-block (S2) **Fig. (b).** Stairway (S2)

Figure 3.7. Goregaon skywalk (S2)

Fig. (a). Mid-block (S3) **Fig. (b).** Stairway (S3)

Figure 3.8. Ghatkopar skywalk (S3)

Fig. (a). Mid-block (S4) **Fig. (b).** Stairway (S4)

Figure 3.9. Bandra skywalk (S4)

Fig. (a). Mid-block (S5) **Fig. (b).** Stairway (S5)

Figure 3.10. Vile Parle skywalk (S5)

Fig. (a). Mid-block (S6) **Fig. (b).** Stairway (S6)

Figure 3.11. Santa Cruz skywalk (S6)

Fig. (a). Mid-block (S7) **Fig. (b).** Stairway (S7)

Figure 3.12. Kalyan skywalk (S7)

Fig. (a). Mid-block (F4) **Fig. (b).** Stairway (F4)

Figure 3.13. IIT Bombay FOB (F4)

3.3.3. Kolkata (West Bengal)

In Kolkata, many FOBs were constructed, but only a few are under usable condition. After visiting many locations, Ultadanga, Lake Town and Sealdah FOBs were selected for final data collection using both questionnaire as well as videographic techniques. None of the facilities had escalators or elevators. Moreover, poor maintenance was observed at most of the locations and majority of the FOBs had vendors and beggars over the mid-block sections. Subsequent Figure 3.14-Figure 3.17 show the mid-block and stairway sections of the different FOBs.

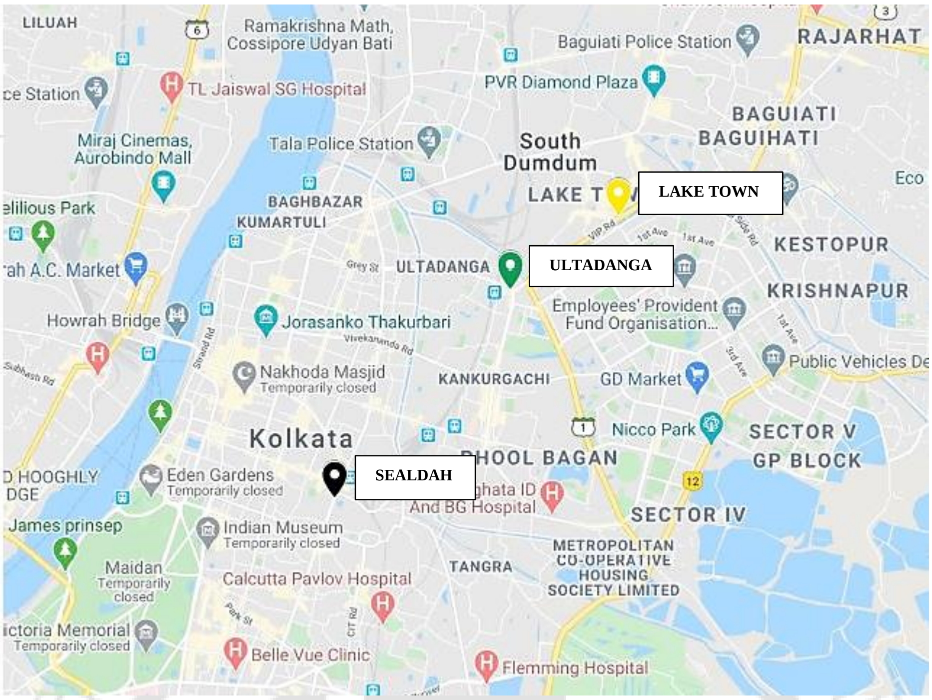


Figure 3.14. Questionnaire survey and videographic data collection locations in Kolkata

Fig. (a). Mid-block (F5) **Fig. (b).** Stairway (F5)

Figure 3.15. Ultadanga FOB (F5)

Fig. (a). Mid-block (F6) **Fig. (b).** Stairway (F6)

Figure 3.16. Lake Town FOB (F6)

Fig. (a). Mid-block (F7) **Fig. (b).** Stairway (F7)

Figure 3.17. Sealdah FOB (F7)

3.3.4. National Capital Region (NCR)

The entire NCR region comprises of several FOBs spread across different localities. In order to capture the variability among pedestrian behaviour, data was collected at Anand Vihar FOB (a location adjacent to the bus terminal, train station, and metro station) which had a huge rush of pedestrians throughout the day. Similarly, other FOBs selected were located at Akshardham, Maharani Bagh, ITO, and Vaishali. Majority of the FOBs were having access to either an escalator or a lift (elevator), apart from the stairways. At Maharani Bagh and ITO, ramp-like stairways were provided, which allowed easier vertical movement for the pedestrians. For all the five locations, videographic and questionnaire data were collected for both the mid-block and the stairway sections (refer to Figure 3.18-Figure 3.23). A major concern across all FOBs was the poor maintenance of the infrastructures available.

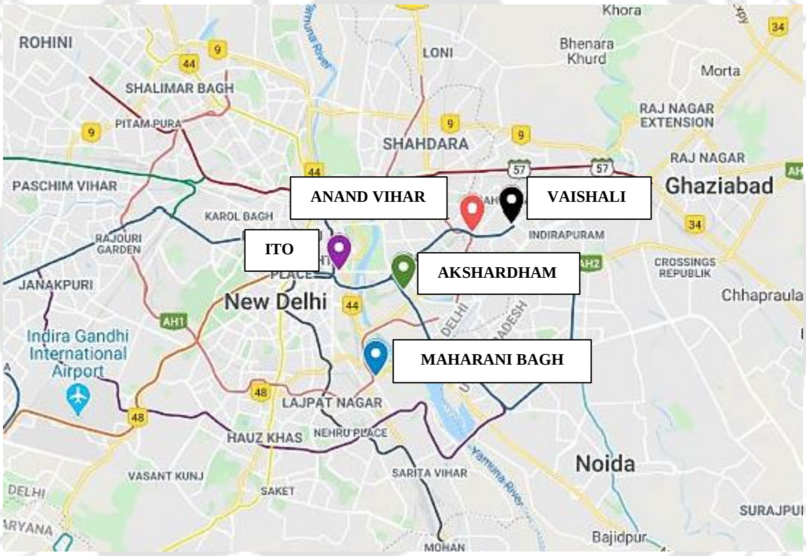


Figure 3.18. Questionnaire survey and videographic data collection locations in NCR

Fig. (a). Mid-block (F8) **Fig. (b).** Stairway (F8)

Figure 3.19. Anand Vihar FOB (F8)

Fig. (a). Mid-block (F9) **Fig. (b).** Stairway (F9)

Figure 3.20. Akshardham FOB (F9)

Fig. (a). Mid-block (F10)

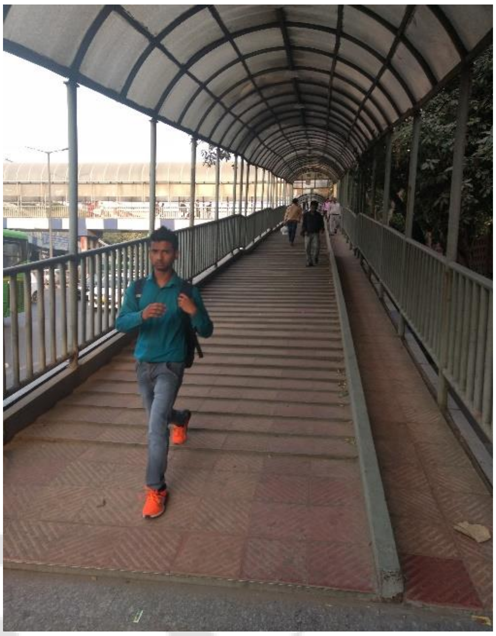


Fig. (b). Stairway (F10)

Figure 3.21. ITO FOB (F10)

Fig. (a). Mid-block (F11)

Fig. (b). Stairway (F11)

Figure 3.22. Maharani Bagh FOB (F11)

Fig. (a). Mid-block (F12) **Fig. (b).** Stairway (F12)

Figure 3.23. Vaishali FOB (F12)

3.3.5. Bengaluru (Karnataka)

From the city of Bengaluru, data collection was done across four different FOBs, namely, Tin Factory, Yeshwantpur, Christ University, and Marathahalli. All the FOBs were provided with lifts for vertical connectivity apart from stairways. In some cases, the lifts were under repair or not working. Moreover, vendor/ beggar presence and poor maintenance were critical issues that existed for the majority of the FOBs. The locations of data collection are shown in Figure 3.24-Figure 3.28.

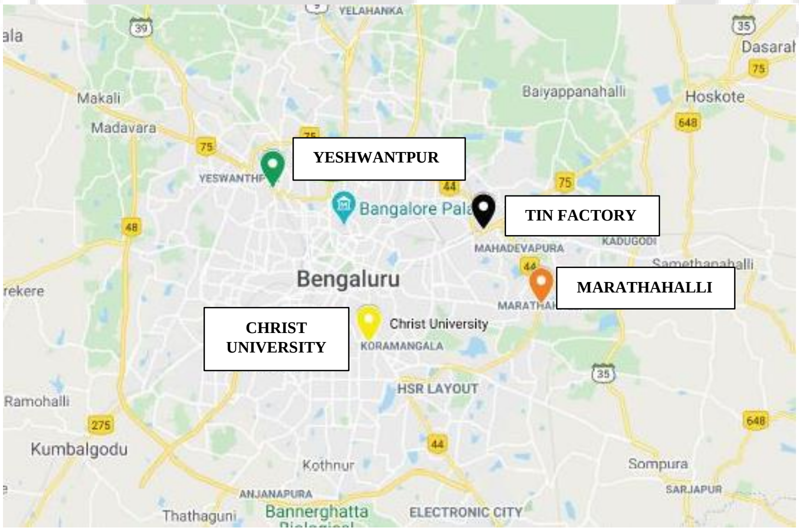


Figure 3.24. Questionnaire survey and videographic data collection locations in Bengaluru

Fig. (a). Mid-block (F13) **Fig. (b).** Stairway (F13)

Figure 3.25. Tin Factory FOB (F13)

Fig. (a). Mid-block (F14) **Fig. (b).** Stairway (F14)

Figure 3.26. Yeshwantpur FOB (F14)

Fig. (a). Mid-block (F15) **Fig. (b).** Stairway (F15)

Figure 3.27. Marathahalli FOB (F15)

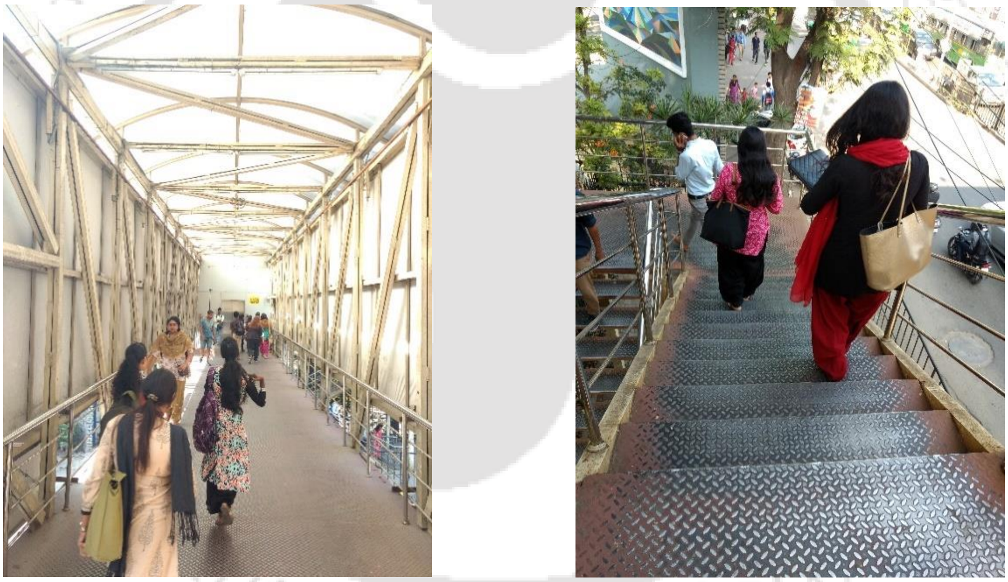


Fig. (a). Mid-block (F16) **Fig. (b).** Stairway (F16)

Figure 3.28. Christ University FOB (F16)

3.3.6. Guwahati (Assam)

In the city of Guwahati, elevated pedestrian facilities are not common. In total there are 3 FOBs, out of which only one was renovated and converted to mechanized FOB (i.e., with lifts) and used frequently. Maligaon FOB was chosen for data collection, as it was expected that more pedestrians would be interested to use the newly constructed FOB. Moreover, this was the only FOB which had elevator facility for elderly and specially challenged pedestrians, and surveillance cameras with security personnel were deployed. Videographic as well as questionnaire survey was recorded over mid-block as well as stairway sections to understand the walking pattern as well as the perception of the pedestrians. Some design issues observed were narrow stairway width and low height of the clearance between the steps and shade. Figure 3.29-Figure 3.30 show the FOB details at Guwahati.

Figure 3.29. Questionnaire survey and videographic data collection location in Guwahati

Fig. (a). Mid-block (F17) **Fig. (b).** Stairway (F17)

Figure 3.30. Maligaon FOB (F17)

3.4. Data collection

The different data collection techniques which are generally used are qualitative survey (perception or questionnaire), quantitative survey (videographic), controlled experiments and manual counting. In the current study, videographic and interviewer-administered questionnaire survey techniques were used. Prior to data collection, all the locations were visited and the most suitable positions to set up the cameras were identified. Thereafter, police permissions were taken from both the city headquarters as well as the local police stations. The surveyors were trained prior to visiting the field about the different needs of the study as well as the necessary precautions to be taken. In total, 3-4 surveyors helped during the data collection, where two of them were positioned near the cameras (at the mid-block section and stairway section), and the other surveyor(s) helped in conducting the questionnaire survey.

The videographic survey was conducted for approximately three hours on weekdays at each location covering both peak and off-peak hours, and the questionnaire survey was conducted only after the cameras were set up, recordings were started and the location details were noted.

3.4.1. Videographic based data collection

To capture the pedestrian movement behaviour at the macro as well as micro levels, the videographic data collection technique was used. It not only provides a permanent record of the data collected, but also allows more precise data extraction as per the need of the study. High-resolution handycams (*make: Sony and Panasonic*) were used to collect the data (refer Figure 3.31).

Figure 3.31. High-resolution cameras used for data collection

The cameras were mounted on tripod stands and fixed at the height of more than 10ft with a top-frontal camera angle focusing on the pedestrians. Two cameras were fixed (refer Figure 3.32), one near the stairway section (either top or bottom of the stairway depending on the suitable position available) and other near the mid-block section (at least at a distance of 15-50m away from the stairway section). In some cases, where the length of the FOBs was shorter (as in the case of Gangtok), the mid-block cameras were fixed near the stairways. Both the cameras were synchronized well and video recording were started at the same instant. Continuous video data were collected for approximately three hours at each location covering both peak and off-peak hours. In order to capture the pedestrian movement over the study section (trap area), the entry and exit points/ sections were marked with reflective tapes. The rectangular trap length was fixed between 10-12m and the effective width for all locations were measured. The effective width was calculated after deducting the buffer/ shy away from distance from the total width, as per Table 3.2.

Table 3.2. Estimated shy-away distances in the Indian context (*Source: Indo-HCM 2018*)

Obstacle	**Shy distance (m)**
Wall	0.4 - 0.6
Guardrails	0.4 - 0.6
Hawkers	0.3 - 0.5
Bench	0.3 - 0.5

Fig. (a). Mid-block **Fig. (b).** Stairway

Figure 3.32. Camera position over different sections

3.4.2. Pedestrian questionnaire survey

To understand the perception of the pedestrians towards the existing condition of the elevated facilities as well as to develop the Level of Service (LOS) standards, an interviewer-administered questionnaire survey was conducted at each location (refer Figure 3.33). Random respondents were selected and requested by the interviewers to participate in the survey, and those willing to participate in the entire interview process were selected. The participation rate was low (i.e., out of approximately twenty random pedestrians, only one participated when requested).

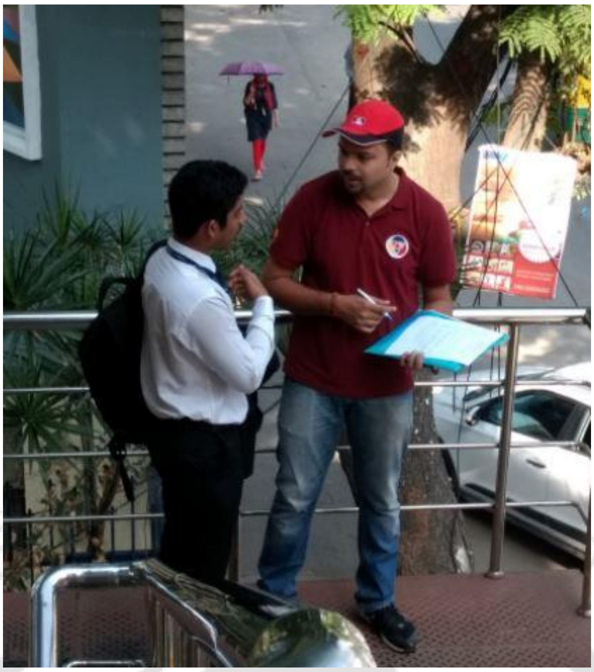


Figure 3.33. Questionnaire survey being conducted on the elevated facility

The questionnaire prepared included five broad sections (A to E) representing the demography of respondents, the existing condition of elevated facilities, preference of use of elevated facilities by respondents, future usability improvements of facility required, and field observations (refer Table 3.3).

As presented in Table 3.3, Section A of the questionnaire included the demographic characteristics such as gender (*male, female*), age *(≤10, 11-20, 21-40, 41-60 and ≥60)*, presence of luggage (*yes/ no*), person with disability (*yes/ no*), profession (*businessman, homemaker, retired, self-employed, service, student and others*), purpose of trip (*work, education, shopping, change of mode, returning home, jaywalking and others*), and frequency of daily use of the elevated facility (*first time, occasionally, once, twice or more than twice*). Similarly, Section B focused on the existing condition of elevated facilities, i.e., factors were chosen based on IRC: 103 (2012). The different factors chosen were based on either physical factors or user factors. The physical factors chosen were the width (*effective walkable width available over the mid-block sections and on stairways*), surface condition (*in terms of broken/ slippery tiles or well-maintained surface*), and obstruction (*in the form of vendors, beggars, and standing pedestrians*). Similarly, the user factors chosen were end connectivity (*in form of entry/ exits along with type of vertical connectivity available*), safety and security (*in terms of CCTV cameras and security personnel*), comfort (*in form of lighting, shade, proper guard rails, sitting benches, and drinking water availability*) and the walk environment (*surrounding existing conditions in form of maintenance and cleanliness*). All the factors were rated on a scale of five, with ‘1’ representing ‘very poor’ condition and ‘5’ representing ‘very good” condition. Obstruction was rated from ‘1’ representing ‘many’ to ‘3’ representing ‘none’.

The preference of pedestrians to use the elevated pedestrian facility under the existing conditions (*no/ yes*) was noted in Section C (refer to Table 3.3). In section D, the pedestrians were further asked whether future usability of the facility would improve (*no/ yes*) with the removal of the obstruction, improvement in security, improvement in end connectivity, installation of escalator/ elevator/ ramp, regular maintenance and cleanliness, and redesigning of the facility (refer Section D of Table 3.3). The respondents could choose either one or more factors, which they felt, could enhance their future usability of using the elevated facilities. The complete questionnaire survey sheet is attached in Annexure I.

Table 3.3. Brief description of the questionnaire survey (refer Annexure I)

Section	Title	Description
A	*Demography*	**Gender** *(0: Female, 1: Male)*, **Age** *(0: ≤10; 1: 11-20; 2: 21-40; 3: 41-60 and 4: ≥60)*, **Luggage** *(0: With, 1: Without)*, **Person with disability** *(0: With, 1: Without)*, **Profession** *(0: Businessman, 1: Homemaker, 2: Retired, 3: Self-employed, 4: Service, 5: Student, 6: Other)*, **Trip purpose** *(0: Work, 1: Education, 2: Shopping, 3: Mode change, 4: Returning home, 5: Jaywalking, 6: Others)*, **Frequency of daily use** *(0: First time, 1: Occasionally, 2: Once, 3: Twice, 4: More than twice)*
B	*Existing conditions*	**Width, Surface, Connectivity, Safety and Security, Comfort, Walk Environment** *(1: Very Poor, 2: Poor, 3: Satisfactory, 4: Good, 5: Very Good)*, Obstruction *(1: Many, 2: Some, 3: None)*
C	*Preference of use*	**Preference of using elevated walkway under existing conditions** *(0: Do not prefer, 1: Prefer)*
D	*Future usability dependents*	**Obstruction removal or relocation** *(0: No, 1: Yes)*, **CCTV installation and security personnel deployment** *(0: No, 1: Yes)*, **Vertical end connectivity** (lift/ escalator/ ramp) **installation and maintenance** *(0: No/ 1: Yes)*, **Horizontal end connectivity improvement** *(0: No/ 1: Yes)*, **Regular maintenance** *(0: No, 1: Yes)*, **Redesigning** *(0: No, 1: Yes)*
E	*Field observations*	**Length of the elevated walkway** *(in meter)*, **Walkable width of the walkway** *(in meter)*, **Number of steps**, **Stairway width** *(in meter)*, **Tread dimension** *(in centimeter)*, **Riser dimension** *(in centimeter)*, **Land use type** *(0: Commercial, 1: Residential, 2: Public Transport Terminal, 3: Educational, 4: Shopping)*, **Type of facility for vertical movement** *(0:Stairway, 1: Escalator, 2: Lift, 3: Ramp)*, **Number of entry-exit points**

3.5. Data extraction

The recorded videos and the filled-in questionnaire sheets collected from the different study locations were manually extracted in the laboratory.

3.5.1. Videographic data extraction

The manual data extraction technique, even though time-consuming, is reliable as the micro-level analysis can be done easily. Considering the detailed pedestrian descriptions (such as age, gender, luggage condition, mobile use, group formation, and other behavioural aspects), it is suitable to use a manual extraction technique rather than an automatic technique. Moreover, in order to confirm the individual or group behaviour, the manual method plays an important role. The pedestrian data were manually extracted from the recorded videos by playing the data on Media Player Classic Home Cinema software. Screen marker software was used to mark the pedestrian entry-exit points in the section. The extracted data was stored in MS-Excel 2016.

Table 3.4 shows the different parameters that were selected to understand the pedestrian walking behaviour over the elevated pedestrian facilities for both mid-block as well as stairway sections. The parameters or behaviours were categorized based on face value from the recorded videos. The main intention of classifying the pedestrians based on different parameters was to understand their impact over walking speed.

Table 3.4. Parameters extracted from videographic data

Parameter	**Categories and definitions**
Gender	0: Female, 1: Male
Age	0: ≤10, 1:10-20, 2: 20-40, 3:40-60, 4: ≥60
Luggage	0: With (backpack, trolleys, side bags, child), 1: Without
Mobile	0: With, 1: Without
Group size	0: Single, 1: Two, 2: Three, 3: Four or more
Direction of movement	0: Towards camera, 1: Away from camera
Specially abled	0: With, 1: Without
Flow (m/min)	Number of pedestrians passing a given point per unit time, expressed as pedestrians per 15 minutes or pedestrians per minute or pedestrians per hour; "point" refers to a perpendicular line of sight across the width of walkway (as per Indo-HCM 2018).
Flow Rate (ped/min/m)	It refers to the average flow of pedestrians per unit width of effective walkway.
Speed (m/min)	It refers to the average walking speed of pedestrians over the study section.
Density (ped/m^2)	It represents the average number of pedestrians within a specified area.
Area module (m^2/ped)	It refers to the average area provided for each pedestrian in a walkway or queuing area, and is inverse of density.
Free Flow Speed (FFS) condition	When the subject pedestrian maintains a time headway ≥6sec with the subsequent pedestrians moving in the same direction, and no pedestrians are coming from the opposite direction.
Lane formation (LF)	When the subject pedestrian follows a lane or line of pedestrians throughout the entire section.
Leader follower relationship (LFR)	The phenomenon is observed when two pedestrians are in lane formation and the time headway between them is ≤2 sec.
Faster is slower effect (FSE)	The phenomenon is generally observed when the subject pedestrian attempts to change lane and overtake the slower moving pedestrians in the front, but is forced to shift back to original lane due to heavy oncoming flow from opposite direction or lack space.

Squeezing effect (SE)	The condition is observed when the subject pedestrian is in the minor flow direction and is forced to shift to either side of the walkway due to major flow from the opposite direction.
Lane shifting (LS)	When a subject pedestrian shifts from the current lane to either overtake slower pedestrians or to avoid collision with the pedestrians coming from the opposite direction.
Surpassing/ Overtaking	The condition when the subject pedestrian surpasses or overtakes the slower pedestrian in front. The phenomenon can be observed under two conditions where the subject pedestrians is: i. forced to shift the lane to overtake the slower pedestrians. ii. surpass the slower pedestrian/s without lane shifting.

The different walking behaviour observed from the extracted video are shown below in Figure 3.34-Figure 3.41. These figures show the pedestrians with different age categories, luggage condition, mobile use, group size, specially/ differently-abled, lane formation with and without leader-follower relationship, squeezing effect, and overtaking behaviour.

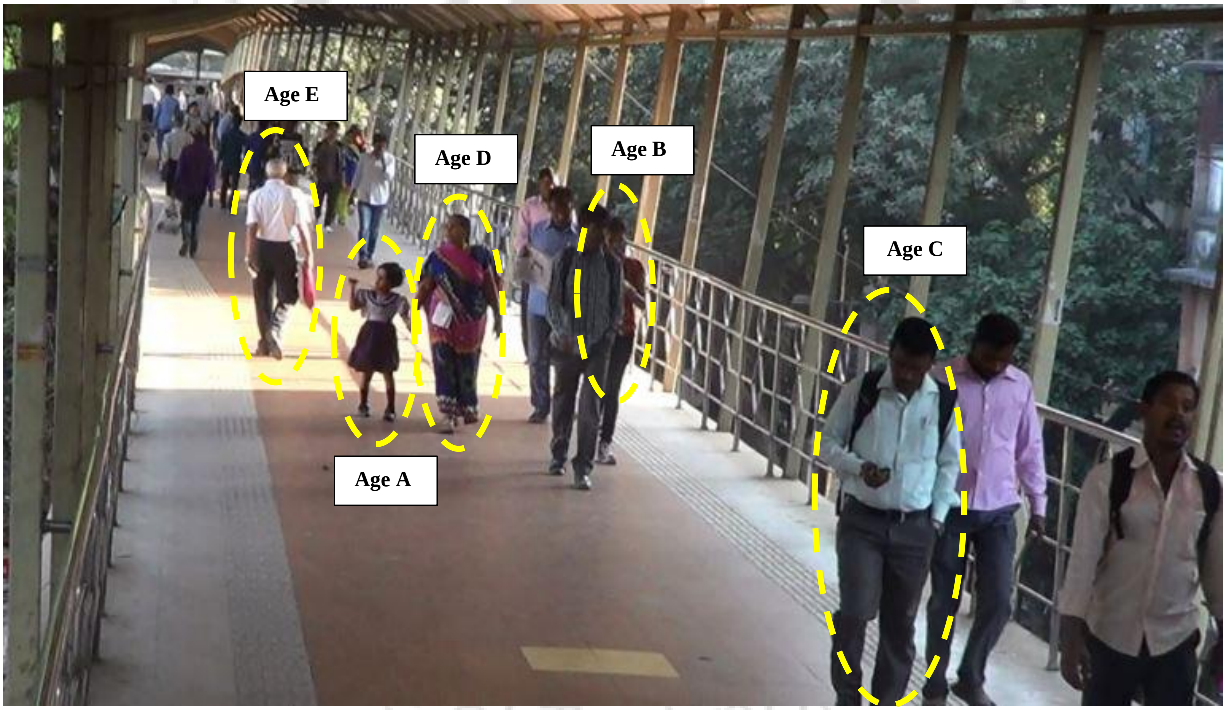


Figure 3.34. Different age categories of pedestrians

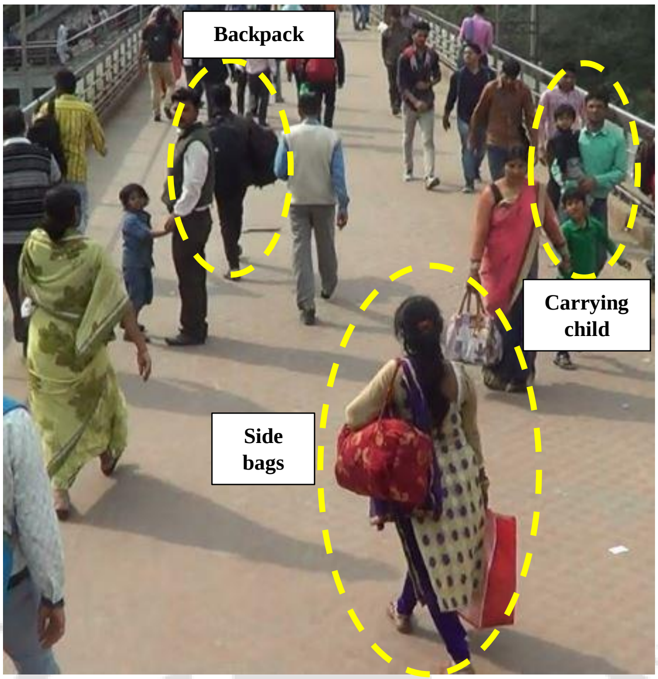


Figure 3.35. Pedestrians carrying backpack, side baggage and child

Figure 3.36. Pedestrian using mobile and carrying side luggage

Fig. (a) Two pedestrians **Fig. (b)** Three pedestrians **Fig. (c)** Four or more pedestrians

Figure 3.37. Different group sizes

Figure 3.38. Specially abled pedestrians using walking sticks and wheel chairs

Fig. (a). Without leader-follower **Fig. (b).** With leader-follower

Figure 3.39. Lane formation

Figure 3.40. Squeezing effect

Fig. (a). Decides to overtake **Fig. (b).** Shifts lane **Fig. (c).** Overtakes

Figure 3.41. Overtaking behaviour with lane shifting

Apart from the factors listed in Table 3.4, the individual pedestrian stream speed (m/min), average speed per minute (m/min), average flow rate (ped/min/m) and pedestrian density (ped/m^2) were noted.

Six to eight pedestrians were randomly selected every minute for tracking through the trap length, and their entry and exit times through the trap area were noted. The trap length was divided by the travel time of the pedestrians to get the actual speed (m/min). The flow rate (ped/min/m) was calculated as the number of pedestrians crossing the entry section of the study area per minute by the effective width of the trap. Similarly, the density (ped/m^2) was calculated by counting the number of pedestrians within a trap area at every 20-second interval. Per minute three density readings were taken, and then the average value of density was calculated per minute.

3.5.2. Questionnaire data extraction technique

In total 959 (Skywalk: 386 and FOB: 573) pedestrians participated in the questionnaire survey, and later these samples were entered manually into excel sheets. For the final analysis, only 350 samples (for skywalks) and 552 samples (for FOBs) adequately filled questionnaire sheets were used, which exemplified a representative sample size. A 5-point Likert scale was used to understand how much a pedestrian strongly agreed or disagreed with a particular statement. The data was further used for final data analysis and statistical modelling purposes.

3.6. Concluding remarks

In the present chapter, the details about the data collection locations and extraction procedure were discussed. Videographic and questionnaire survey techniques were used to collect the data over FOB and skywalk facilities. In videographic data extraction, different macroscopic parameters (speed, flow rate, density and area module) and microscopic parameters (*individual characteristics:* gender, age, luggage condition, disability, and mobile use; *group characteristics:* group size, lane formation, leader-follower relationship, faster-is-slower effect, squeezing effect, lane shifting and overtaking) were extracted using manual extraction technique. In the case of questionnaire surveys, the data was extracted as per demography, existing conditions, preference of using the facility, future usability improvement, and field observations. The next chapter discusses about the pedestrian behaviour over the mid-block sections of skywalks and FOBs.

CHAPTER 4

PEDESTRIAN BEHAVIOUR ON MIDBLOCK SECTIONS OF FOB AND SKYWALK FACILITY

The current chapter discusses about the walking behaviour of pedestrians over mid-block sections of elevated walkways. The pedestrian aggregated and individual location speeds, fundamental diagrams, simulation model development, speed prediction models using microscopic and macroscopic speed data, and study of gap maintaining behaviour are discussed further. Figure 4.1 shows the outline of the chapter in block diagram format for the pedestrian characteristics on mid-block section of elevated facilities.

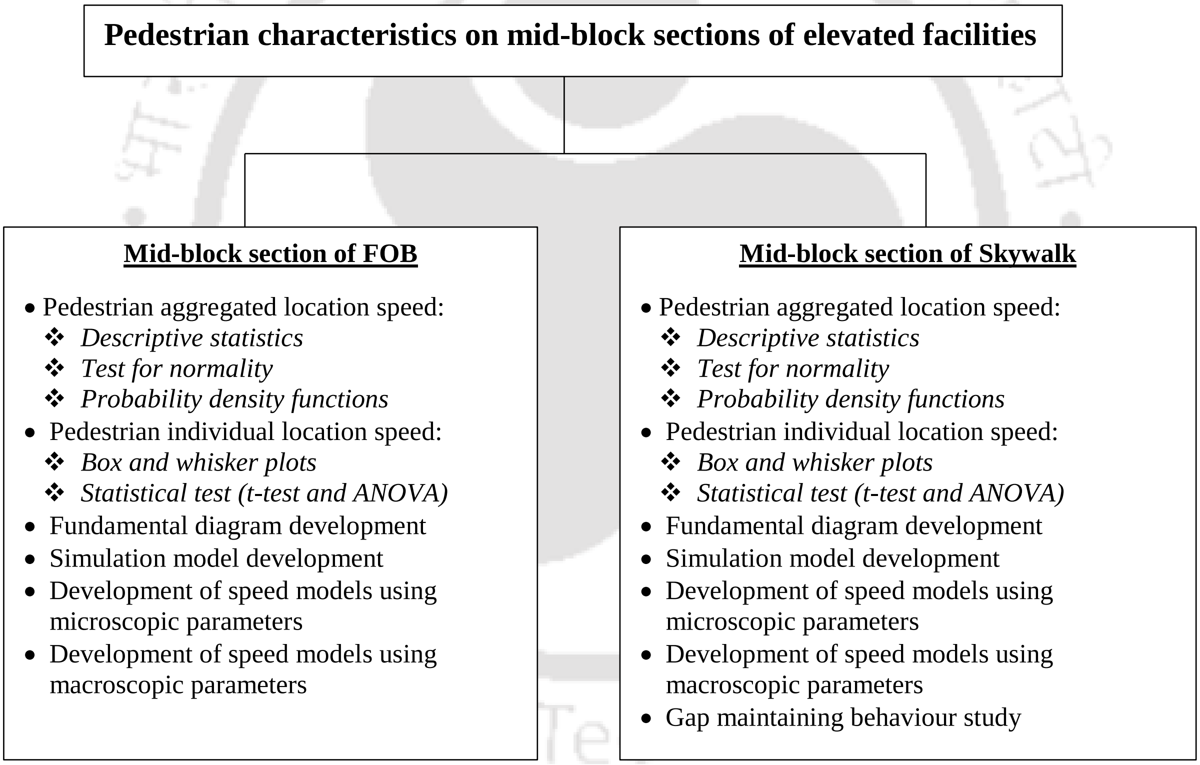


Figure 4.1. Block diagram for pedestrian behaviour on mid-block sections of elevated facility

4.1. Is pedestrian behaviour over mid-block section for FOB and Skywalk similar?

The mid-block data as discussed in the previous chapter, consists of 17 FOB locations and 7 skywalk locations. In order to decide whether to combine the mid-block data for both the facilities or keep them segregated, an initial t-test was conducted on the free flow speed data for all locations with comparable width where the dominant category with maximum data (*i.e., Gender: Male, Age: 21-40 years and Luggage condition: Without*) were selected. Table 4.1 shows the t-test (two sample assuming unequal variances) comparison between the two facilities. The t-test is carried out when a normal distribution is followed by the test statistic, and is performed to check whether a significant difference exists between two different data sets. When the t-statistical value is more than t-critical value, it can be said that a significant difference exists between the two data sets.

Table 4.1. t-test conducted among the FFS data for elevated facilities

Statistic	FOB	Skywalk
Mean	74.54	84.12
Variance	179.56	242.48
Observations	386	253
t-Statistical value	-6.19	
t-Critical two-tail	1.97	

The t-test result showed that the t-Statistical value was greater than the t-Critical value, i.e., significant difference existed between FOB and skywalk mid-block section users (*male, 21-40 years and without luggage*). Therefore, for further analysis, it was decided to segregate the mid-block data for both elevated facilities.

4.2. Determination of sample size requirement

A sample size refers to the selected portion of the total population where we expect to extract information about the entire population. The required sample size for mid-block sections of FOBs and skywalks is calculated using Krejcie and Morgan’s (1970) sample size estimation technique, which is used for population size (i.e., the count of number of pedestrians during the study period across all the locations), at 95% confidence level and 5% margin of error.

In order to study the walking behaviour of pedestrians over the elevated walkways, six to eight pedestrians (depending on pedestrian flow of that site) were randomly selected per minute and tracked throughout the study section length (10-15m). At some locations, per minute sample was low and at some other locations it was high. Sample size variation across different sites resulted due to their flow variation over the study period. The sample size requirement as per Krejcie and Morgan’s formula satisfied at individual locations as well. The maximum number of pedestrians observed at mid-blocks for the 17 FOB locations were 12,127 and the corresponding calculated sample size was 373. Similarly, for the 7 skywalks the maximum number of pedestrian observed were 31,005, which lead to a sample size of 379.

Further, the aggregated number of pedestrians observed for mid-block sections of FOBs and skywalks were 61,334 and 93,101, respectively. The minimum requirement of sample size were 382 and 384 as per Krejcie and Morgan (1970), which is much less than actual collected samples (17,107 and 10,535 for FOB and Skywalk respectively). It should be noted that the sample size requirement was fulfilled both at the aggregate and disaggregate levels.

4.3. Pedestrian characteristics on midblock section of FOBs

In total 17 FOB mid-block sections were used for final analysis. Table 4.2 shows the details of the geometric and demographic characteristics of the individual locations covered. The mean effective width and length of the mid-block section for all FOBs across different cities were 2m and 41.7m respectively. The average number of samples collected per location were 1006 with majority of the pedestrians using the FOB facilities being male pedestrians (~70%). Only in the case of F1 (51%) and F16 (58%), the female proportion was dominant. Also, pedestrians in the age category 21-40 years (63%) used the facilities more than the other age groups, followed by 41-60 years (22%). The proportion of pedestrians with and without luggage (52:48) were nearly same while using the mid-block sections. On an average 8% pedestrians used mobile phones while walking on mid-block sections across different locations, while mobile user proportion (14%) was the highest at F16, as majority of the users were young female pedestrians (84%). Across different sections, the group size of pedestrians walking alone was dominant (~80%), while pedestrians walking in the groups of two or three pedestrians were 15.5% and 4% respectively. In the case of F4 mid-block section, pedestrian group of two (~32%) or three (~13%) was quite high, as the facility was adjacent to an educational institute where majority of the users were students walking in groups.

In the further sub-sections, analysis was made over different mid-block sections of FOBs with combined and individual locations for understanding the impact of pedestrian flow characteristics over walking speed.

4.3.1. Pedestrian speed data aggregated from all FOB mid-block sections

In order to get an aggregated behaviour of pedestrians over different locations and understand the overall walking behaviour, the FOB mid-block data for all locations were combined together and used for studying descriptive statistics, normality and probability density functions.

Table 4.2. Details of FOB locations with demographic characteristics

Location	Geometry		Sample size	Demographic characteristics (in percentage)														
	Width (m)	Length (m)		Gender		Age					Luggage		Mobile Use		Group size			
				Male	Female	≤10	11-20	21-40	41-60	≥60	With	Without	With	Without	1	2	3	≥4
STNM (F1)	1.5	42.6	1423	49.1	50.9	0.4	1.5	74.3	21.6	2.2	51.4	48.6	6.5	93.5	79.7	17.6	2.2	0.5
Metro Point (F2)	1.5	18.5	1247	55.3	44.7	2.9	8.0	70.2	17.2	1.7	48.8	51.2	4.5	95.5	64.9	31.4	3.4	0.3
M.G.Marg (F3)	1.4	18.8	1426	67.3	32.7	1.7	1.7	70.1	25.6	0.9	35.2	64.8	6.7	93.3	84.7	13.5	1.5	0.3
IIT Bombay (F4)	2.6	43.3	887	75.5	24.5	1.0	12.4	76.2	8.4	2.0	54.0	46.0	9.2	90.8	48.4	31.7	13.2	6.7
Ultadanga (F5)	1.9	42.4	1230	74.9	25.1	3.2	11.0	60.0	21.7	4.1	62.1	37.9	7.4	92.6	88.5	9.9	1.3	0.3
Lake Town (F6)	1.9	42.2	805	64.5	35.5	3.1	13.4	48.9	24.3	10.3	58.0	42.0	10.4	89.6	77.4	17.5	3.4	1.7
Sealdah (F7)	1.4	36.9	699	71.7	28.3	4.5	8.9	40.6	36.6	9.4	29.9	70.1	3.9	96.1	75.3	18.4	4.3	2.0
Anand Vihar (F8)	4.7	61.5	1432	78.2	21.8	3.1	14.5	52.0	22.3	8.1	55.6	44.4	6.1	93.9	74.1	20.9	3.8	1.2
Akshardham (F9)	1.2	88.1	1167	71.6	28.4	0.1	0.6	90.7	6.8	1.8	76.3	23.7	9.2	90.8	96.7	3.3	-	-
ITO (F10)	1.6	39.2	861	81.3	18.7	0.2	1.9	62.9	29.9	5.1	63.5	36.5	11.5	88.5	88.7	9.9	1.2	0.2
Maharani Bagh (F11)	1.6	41.3	657	74.9	25.1	2.1	6.2	61.5	25.7	4.5	50.1	49.9	8.2	91.8	82.2	10.3	6.7	0.8
Vaishali (F12)	2.5	66.5	1208	76.2	23.8	1.4	11.3	65.1	18.9	3.3	58.7	41.3	12.1	87.9	82.6	12.4	3.3	1.7
Tin Factory (F13)	1.6	49.8	937	73.0	27.0	1.2	2.6	74.3	20.5	1.4	48.1	51.9	4.9	95.1	89.9	8.9	0.9	0.3
Yeshwantpur (F14)	2.1	31.1	695	85.8	14.2	0.9	5.6	49.5	38.0	6.0	34.0	66.0	5.3	94.7	88.6	8.1	2.3	1.0
Marathahalli (F15)	2.4	32.1	657	76.9	23.1	1.3	14.2	70.2	12.4	1.9	46.4	53.6	9.0	91.0	82.4	14.8	1.8	1.0
Christ University (F16)	1.8	21.2	689	42.1	57.9	0.1	25.7	57.9	13.8	2.5	74.2	25.8	14.1	85.9	83.5	11.9	3.2	1.4
Maligaon (F17)	1.6	34.0	1084	66.7	33.3	4.8	11.8	45.9	28.8	8.7	34.1	65.9	5.6	94.4	73.2	18.2	6.3	2.3
Overall	***2.0***	***41.7***	***1006***	***69.7***	***30.3***	***1.9***	***9.8***	***62.4***	***21.6***	***4.3***	***51.8***	***48.2***	***7.9***	***92.1***	***79.5***	***15.5***	***3.7***	***1.3***

4.3.1.1. Descriptive statistics for aggregated speed data

To determine the descriptive statistics of the mid-block speed data (i.e., mean, median, skewness and kurtosis), Table 4.3 was developed. The symmetry of the distribution is related to the skewness of the data, while the peak is represented by the kurtosis. Positive skewness values indicate that the data distribution lies to the right, while negative value indicates data distribution to the left. Similarly, a skewness value of 0 indicates that the data is normally distributed.

Table 4.3. Descriptive statistics of pedestrian speed over aggregated FOB mid-block data

	Mean (m/min)	**Median (m/min)**	**Variance**	**Standard Deviation**	**Minimum (m/min)**	**Maximum (m/min)**	**Skewness**	**Kurtosis**
Statistic	71.31	70.98	173.61	13.17	24.59	116.52	0.018	0.019
Standard Error	0.09	-	-	-	-	-	0.015	0.037

From Table 4.3, the mean speed above mid-block section of FOBs was approximately 71.31m/min, with minimum and maximum mean speed being 24.59m/min and 116.52m/min respectively. The skewness value of 0.018 showed that the data was positively skewed with more data towards the normal distribution.

4.3.1.2. Normality test for aggregated speed data

Histograms provide a rough estimation of whether the speed data is normal or not. Figure 4.2 was plotted to show the walking speed data distribution at 95% confidence level.

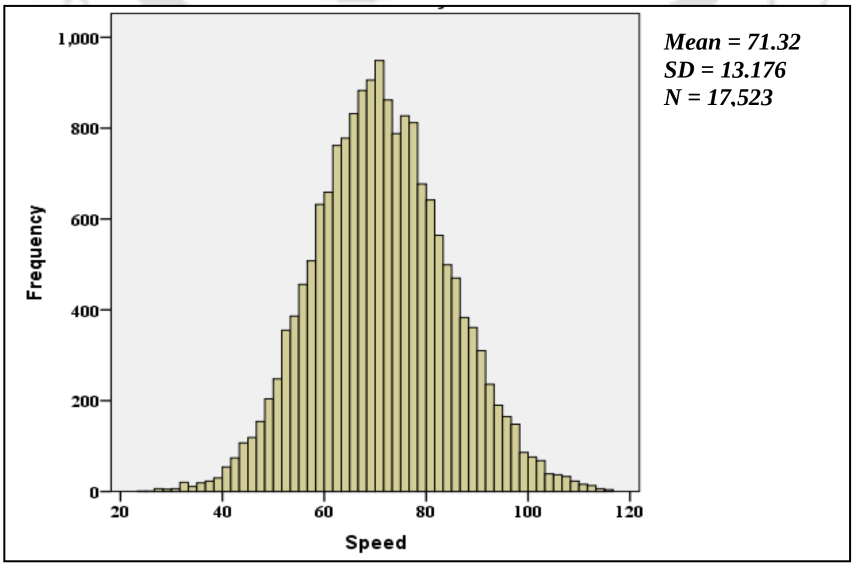


Figure 4.2. Histogram plot for FOB aggregated mid-block speed data

From Figure 4.2 it was observed that the data was normally distributed with mean and standard deviation of 71.32m/min and 13.18 respectively. Further, normality test was conducted in SPSSv20 using Kolmogorov-Smirnov (K-S) test. The test is designed to test the normality of the data by comparing to normal distribution with same mean and standard deviation. The data can be assumed to be normally distributed if the P-value is above 0.05 and thus the test is insignificant. The P-value was observed to be 0.113, which is greater than 0.05, and thus data was normal.

Moreover, normal Q-Q plot (refer Figure 4.3) was also used to determine the level of normality of the data. If the data are normally distributed, the data points will be closer to the diagonal line. If the data points stray from the line in an obvious non-linear fashion, the data are not normally distributed.

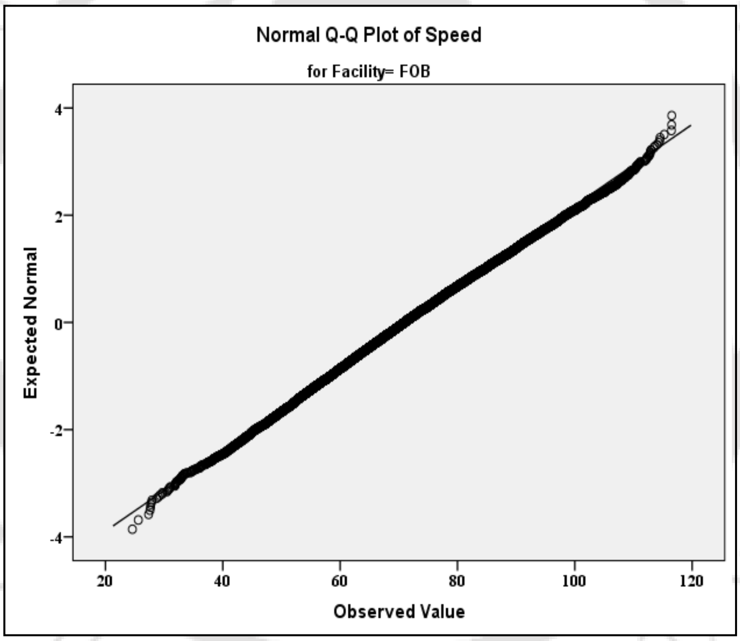


Figure 4.3. Normal Q-Q plot of aggregated walking speed for mid-block section of FOBs

It could be observed from the Q-Q plot that the data was normally distributed for walking speed over different mid-block sections.

4.3.1.3. Probability density functions for aggregated speed data

In order to understand the speed variation over mid-block sections of FOB facilities, probability density functions (i.e., a function whose value at any given sample in the sample space can be inferred as to offer a relative likelihood that the value of random variable would equal that sample) among pedestrians based on gender, age, luggage condition, mobile use and group size for all the locations combined together is presented below (refer Figure 4.4). The x-axis represents the mean walking speed (in m/min) and the y-axis shows the relative frequency.

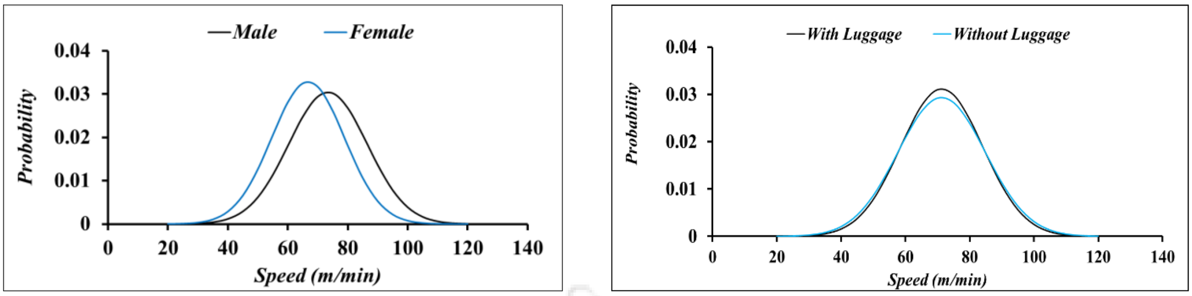


Fig. (a). Speed distribution based on gender

Fig. (b). Speed distribution based on luggage condition

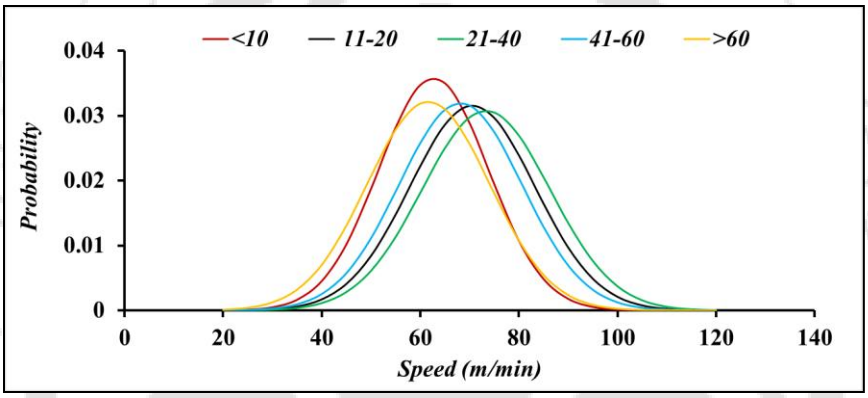


Fig. (c). Speed distribution based on age

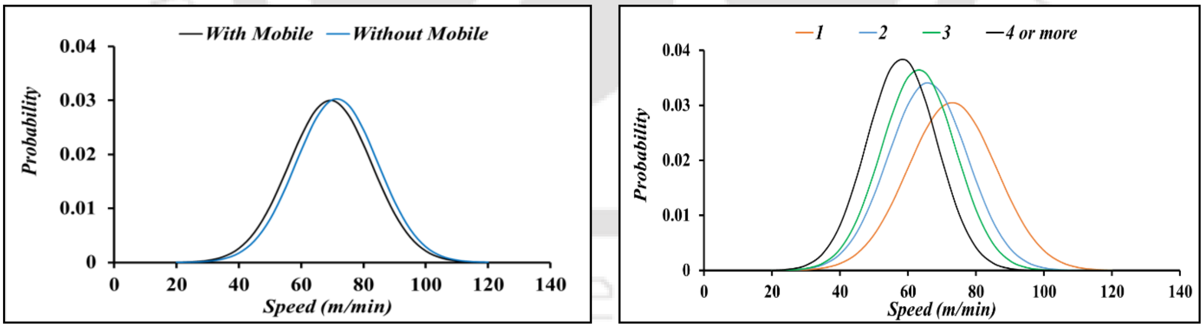


Fig. (d). Speed distribution based on mobile use

Fig. (e). Speed distribution based on group size

Figure 4.4. Speed distribution based on pedestrian gender, luggage condition, age, mobile use and group size

Figure 4.4(a) shows that the male pedestrians had a higher mean walking speed than female pedestrians by approximately 7m/min. The luggage distribution showed that pedestrians with and without luggage had similar walking speeds over FOB mid-block sections (Figure 4.4b).

The pedestrians in the age group of 21-40 years were found to have the highest average mean speed in comparison to other pedestrian age categories (refer Figure 4.4c). Similarly, child (≤10 years) and elderly (≥60 years) pedestrians had similar speed distributions with average speed around 62m/min. Figure 4.4(d) showed that the pedestrians without mobile phone had slightly higher walking speed than the ones using mobile (~2m/min). Group size (Figure 4.4e) showed that the pedestrians walking in groups of 4 or more had the lowest walking speeds in comparison to other groups.

4.3.2. Speed variation based on pedestrian characteristics for different FOB mid-block sections

4.3.2.1. Box and whisker plots of speed based on pedestrian characteristics

Figure 4.5-Figure 4.9 shows the box and whisker plots for the speed of different pedestrian categories based on age, gender, luggage, mobile usage and group size for all the seventeen FOB locations. The box and whisker plots show the lower (25th), median and upper (75th) quartile speeds along with skewness. The 25th percentile speed shows that 25% of the data are less than this value while the 75th percentile shows that 75% of the data are greater than this value. The skewness defines how symmetric or asymmetric the distribution is, and positive skewness indicates larger accumulation of lower speeds. In a positively skewed distribution, the mode is lower than the mean and median. Similarly, in a negatively skewed distribution, the mean is lower than the median because having very few low scores tend to shift the mean to the left. When the median is in the middle of the box, and the whiskers are same on both sides of the box, then the distribution is symmetric. Similarly, positively skewed distribution shows the median closer to the lower or bottom quartile, while negatively skewed distribution shows the median closer to the upper or top quartile. As per the standard terminology, the skewness is normally defined to the right or to the left. However, in the following figures, skewness to the right/ left will be shown as to the top/ bottom.

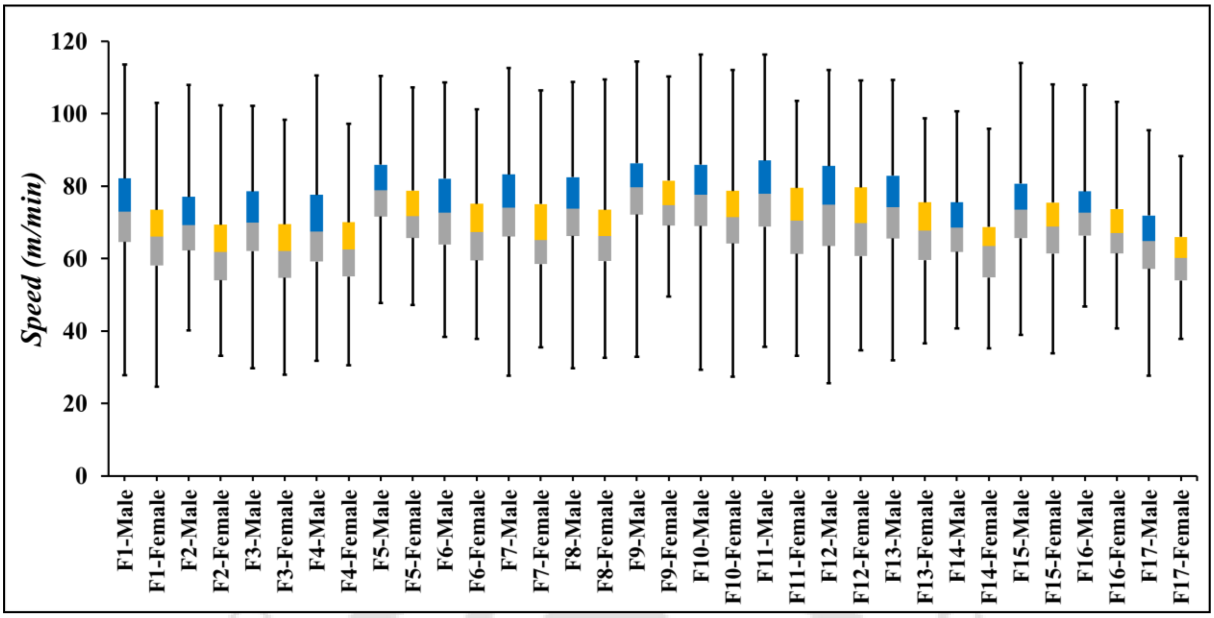


Figure 4.5. Effect of gender on speed variation for all FOB locations

From Figure 4.5 it is evident that female pedestrians had lower median speed than the male pedestrians for all the FOB mid-block locations. Previous studies over different pedestrian facilities also reported similar results where male pedestrians were observed to have higher speed (Polus, 1983; Morrall, 1991; Finnis, 2008; Rastogi, 2011; Chanda, 2014; Siddharth, 2018; Gore, 2020). The speed of male and female pedestrians at F10 was higher mainly due to the fact the location was a commercial area and pedestrians were in a hurry to reach their destinations quickly. In majority of the sites, symmetric distributions were observed, while in case of F2 and F16 positive skewness was observed, and in case of F10 negative skewness was found. At locations F2 and F16 the lower median speed was an indication of the greater percentage of female pedestrians using the facilities. In case of F10, majority of the users were male pedestrians (82%) who moved at relatively higher walking speeds.

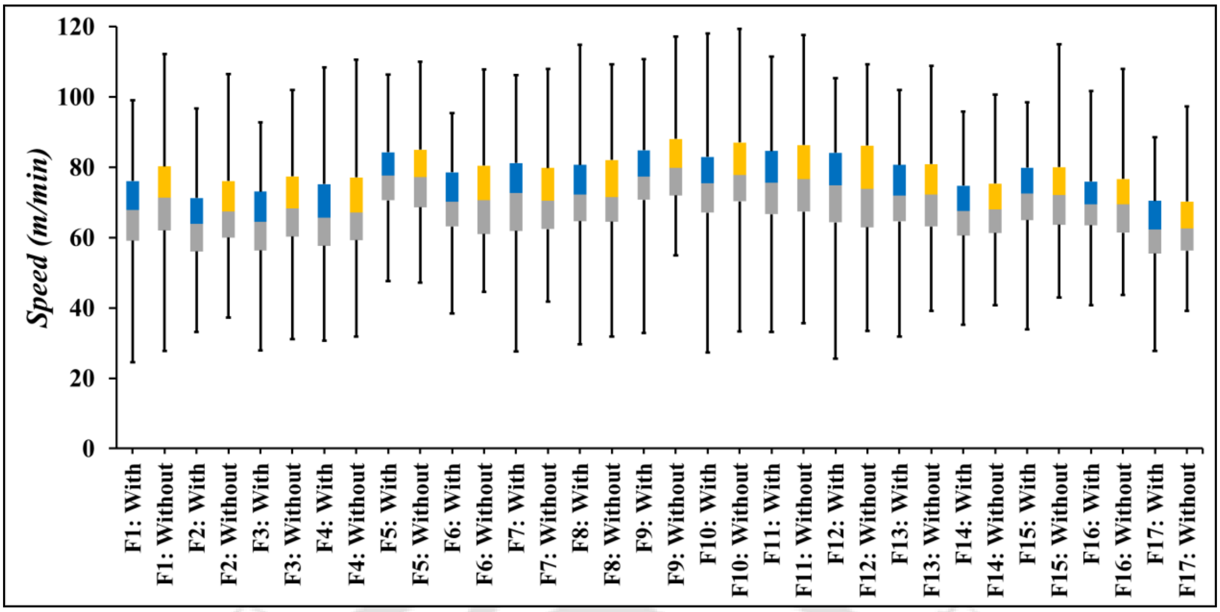


Figure 4.6. Effect of luggage on speed variation for all FOB locations

Figure 4.6 showed that the pedestrians without luggage had higher median walking speeds than the ones with luggage for all the locations. Previous studies by Young (1999), Laxman (2010), Ye (2012) and Huang (2019) also observed that luggage does impact the pedestrian walking behaviour. In case of F1 (with), F3 (with), F6 (with), F12 (with) negative skewness was observed; while in case of F6 (without), F9 (without) and F15 (without) positive skewness was visible.

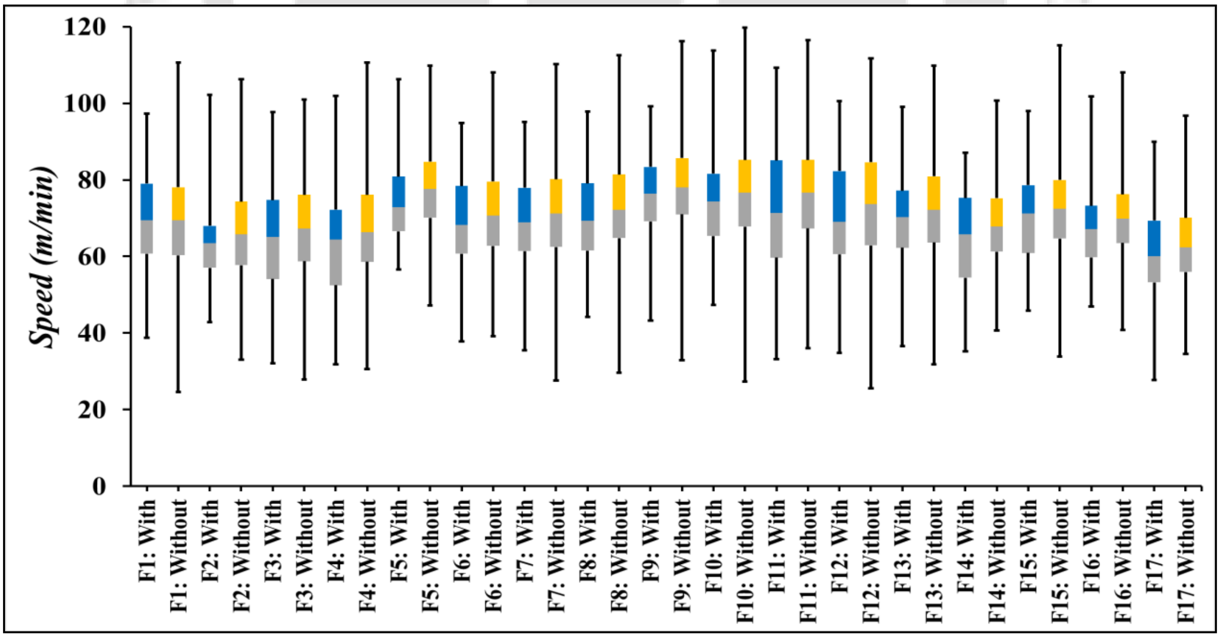


Figure 4.7. Effect of mobile use on speed variation for all FOB locations

From Figure 4.7, it was observed that at locations F2, F10 and F16 with mobile, positive skewness was observed, which indicated larger accumulation of lower speeds. This was mainly due to the fact that pedestrians at these three locations had the freedom to choose their walking speeds while using mobile due to comparatively lower flow rates. Similarly, at F3 (without mobile) and F9 (without mobile) negative skewness was observed due to both locations having higher flow rates, where pedestrians did not have the privilege to choose their walking speeds and were influenced by the group of pedestrians walking along with them. For all the sites the pedestrians not using mobile phones had significantly higher median speed than the ones using mobiles. The highest and lowest median speeds were observed at F12 (without mobile) and F15 (with mobile) respectively. The reason for such observation was that at site F12, the pedestrians were predominantly office goers who were more interested in reaching their destinations quickly (whether they were using mobiles or not); while in the case of site F15 the pedestrians were primarily travelling from or to their homes and were thus in a relatively relaxed mode. Similar to the current study, studies conducted by Loeb (2009), Mwakalonge (2015), Yoshiki (2017) and Lee (2020) also observed that pedestrians using mobile phones walked at lower speed in comparison to the ones without mobiles.

Figure 4.8 showed that at all the sites, the pedestrians in the age category of 21-40 years had the highest median speed, followed by the pedestrians in the age range of 41-60 years. The senior pedestrians (age ≥60 years) were observed to walk at lower speeds in comparison to other groups for all the sites. Studies by Sjöstedt (1967), Cresswell (1978), Wilson (1980), Bowman (1994), Tarawneh (2001), Gates (2006), Nazir (2012) and Pinna (2018) also showed that with the increase in age the pedestrian speed keeps on decreasing. Positive skewness, i.e., accumulation of lower speed was observed in the case of child pedestrians (≤10 years) for locations F1, F2, F4, and F7; and elderly pedestrians (≥60 years) for the locations F2, F3, F15 and F16. For all the other age categories, symmetric distributions were observed. Due to the lower sample size of pedestrians in the age group ≤10 years, box plots were not constructed for F9, F10 and F16 locations.

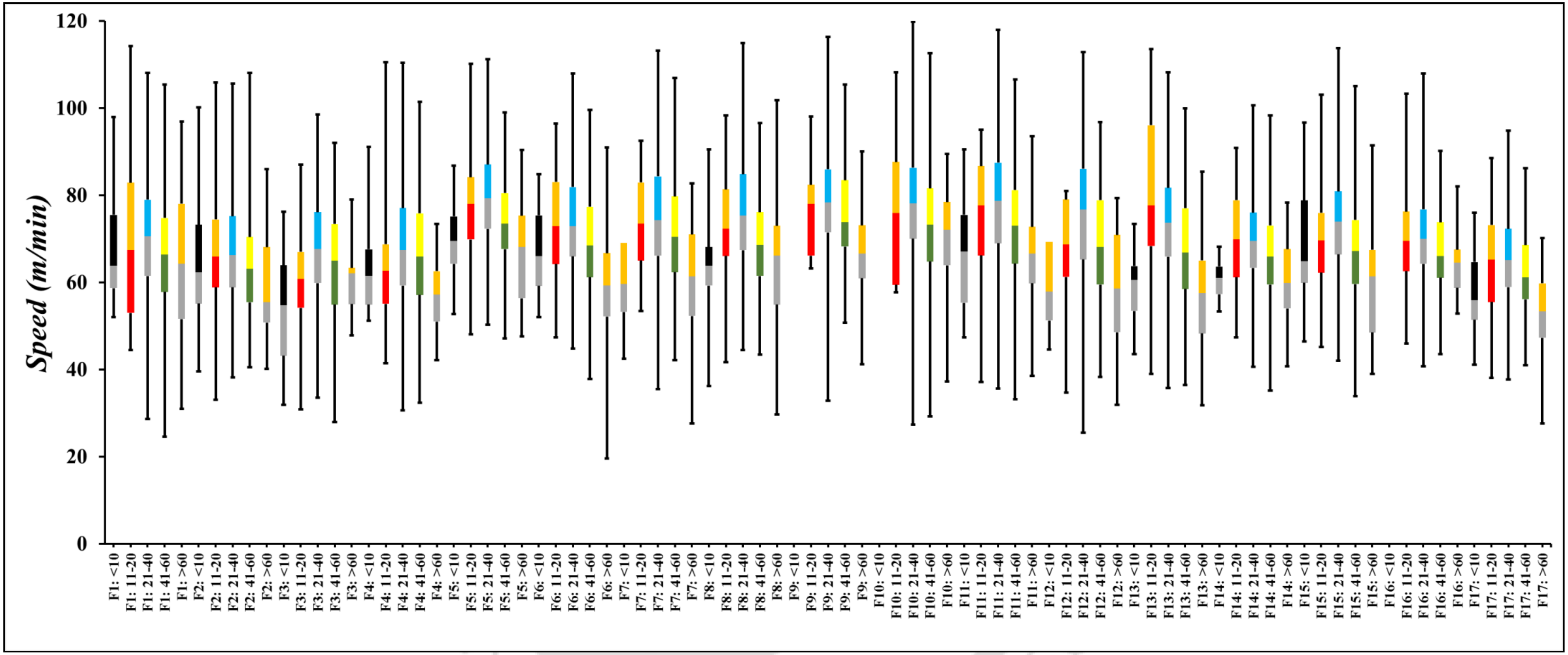


Figure 4.8. Effect of age on speed variation for all FOB locations

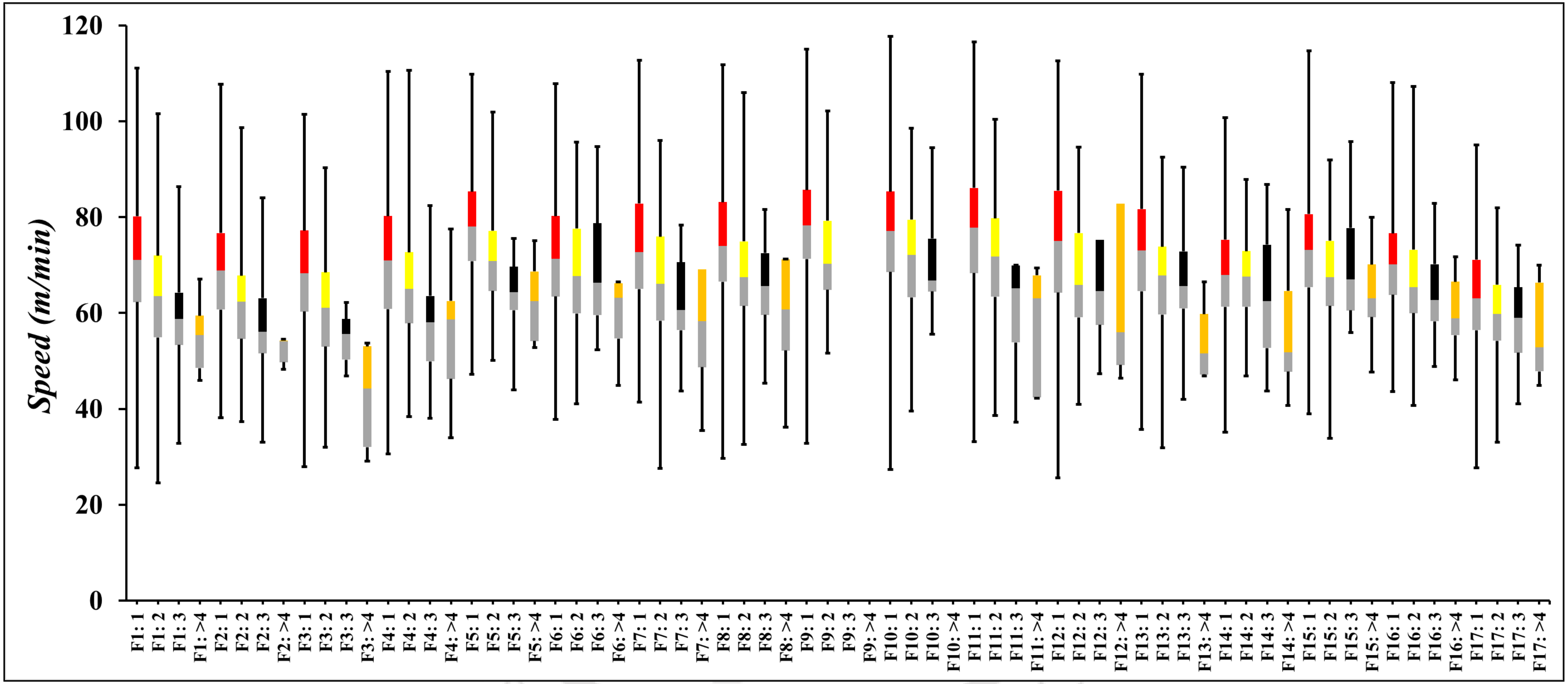


Figure 4.9. Effect of group size on speed variation for all FOB locations

The results from Figure 4.9 showed that the pedestrians travelling alone (i.e., in group size of 1) had the highest median speed in comparison to all other group sizes across all the other sites. The group size of 4 or more than 4 pedestrians had the lowest median walking speed across all locations. As per previous studies by Al-Masaeid (1993), Tarawneh (2001), Moussaid (2010), Rastogi (2011), Duives (2014) and Vanumu (2017), it was also found that the increase in group size significantly decreased the walking speed of the pedestrians and thus impacted the overall walking behaviour. Positively skewed distribution or accumulation of lower walking speeds were observed for pedestrians' group size of 3 or more for all the locations. Previous studies by Carey (2005) and Nakagawa (2007) also showed that with increase in group size the walking speed kept on decreasing. For group size of three (F9 location) and group size of four (F9 and F10 locations) box plots were not plotted due to lower sample size.

4.3.2.2. Statistical tests to identify the differences in pedestrian speed behaviour among different FOBs

Statistical tests (t-test and ANOVA single factor test) were also carried out between different pedestrian categories to understand whether significant difference existed between such categories. Single factor ANOVA test is performed to compare whether a significant difference exists between two or more than two different data sets. When the F-statistical value is greater than the F-critical value, and P value is lesser than 0.05, then significant difference exists between the data sets. The t-test (shown in Table 4.4) was performed on gender (male/ female), luggage (with/ without) and mobile phone (using/ not using), while ANOVA test (shown in Table 4.5) was performed on age categories (≤10, 11-20, 21-40, 41-60 and ≥60 years) and group sizes (1, 2, 3 and ≥4 pedestrians).

From Table 4.4 it was observed that for gender category, a significant difference existed between male and female pedestrian speeds at each site which was also reported by many researchers in the past for different facilities (Polus, 1983; Tarawneh, 2001; Nakagawa, 2007; Finnis, 2008; Chandra, 2013; Silva, 2014; Siddharth, 2018; Gore, 2020). Similarly, in case of luggage and mobile use, it was observed that significant difference existed between pedestrians with and without luggage for majority of the locations. Only at locations F4, F11 and F13 insignificant difference existed between the pedestrians carrying luggage or not.

Table 4.4. t-test results based on gender, luggage condition and mobile use for FOB facilities

Location ID	Type of pedestrian category								
	Gender			*Luggage*			*Mobile usage*		
	t-Stat	*t- Crit*	*Sig.*	*t-Stat*	*t-Crit*	*Sig.*	*t-Stat*	*t-Crit*	*Sig.*
STNM (F1)	*9.59*	1.96	SIG.	4.83	1.96	SIG	2.28	1.96	SIG.
Metro Point (F2)	*11.94*			5.71		SIG	2.39		
M.G.Marg (F3)	*11.19*			5.74		SIG	2.78		
IIT Bombay (F4)	*5.63*			1.67		ISIG	2.02		
Ultadanga (F5)	*9.48*			2.67		SIG	3.38		
Lake Town (F6)	*6.82*			2.58		SIG	2.29		
Sealdah (F7)	*7.78*			2.33		SIG	3.29		
Anand Vihar (F8)	*10.03*			2.58		SIG	2.33		
Akshardham (F9)	*5.57*			3.56		SIG	2.73		
ITO (F10)	*5.63*			4.05		SIG	2.41		
Maharani Bagh (F11)	*5.53*			1.51		ISIG	2.32		
Vaishali (F12)	*4.95*			2.14		SIG	2.43		
Tin Factory (F13)	*7.82*			0.41		ISIG	2.35		
Yeshwantpur (F14)	*5.22*			2.86		SIG	2.75		
Marathahalli (F15)	*5.64*			2.25		SIG	2.25		
Christ University (F16)	*6.68*			3.38		SIG	2.49		
Maligaon (F17)	*5.85*			2.28		SIG	2.71		

Note: *t-Stat: t-Statistical value, t-Crit: t-Critical value, Sig.: Significance, SIG: Significant, ISIG: Insignificant*

Table 4.5. ANOVA single factor test results for FOB mid-block sections

Location	Type of pedestrian category					
	Age			*Group size*		
	F-Stat	*F- Crit*	*Sig.*	*F-Stat*	*F-Crit*	*Sig.*
STNM (F1)	8.61	2.37	SIG.	38.19	2.61	SIG.
Metro Point (F2)	8.35	2.37		46.37	2.61	
M.G.Marg (F3)	*15.45*	2.37		36.45	2.61	
IIT Bombay (F4)	5.74	2.37		31.01	2.61	
Ultadanga (F5)	*35.61*	2.37		20.47	2.61	
Lake Town (F6)	9.15	2.37		6.72	2.61	
Sealdah (F7)	*18.37*	2.37		19.6	2.61	
Anand Vihar (F8)	*40.55*	2.37		31.61	2.61	
Akshardham (F9)	9.15	2.37		-	-	
ITO (F10)	9.92	2.37		5.60	2.61	
Maharani Bagh (F11)	*11.93*	2.37		13.26	2.61	
Vaishali (F12)	*25.47*	2.37		15.36	2.61	
Tin Factory (F13)	*19.31*	2.37		9.78	2.61	
Yeshwantpur (F14)	*10.33*	2.37		4.81	2.61	
Marathahalli (F15)	*29.12*	2.37		13.65	2.61	
Christ University (F16)	4.66	2.37		9.45	2.61	
Maligaon (F17)	*34.19*	2.37		11.62	2.61	

Note: *F-Stat: F-Statistical value, F-Crit: F-Critical value, Sig.: Significance, SIG: Significant, ISIG: Insignificant*

From Table 4.5 it was observed that both in case of age and group sizes, a significant difference existed between the different data sets. Previous studies on different facilities also showed that group size (Al-Masaeid, 1993; Carey, 2005; Nakagawa, 2007; Rastogi, 2011; Duives, 2014; Vanumu, 2017) and mobile phone use (New York Pedestrian Study, 2006, Loeb, 2009; Timmis, 2016; Crowley, 2019) had significant impact on the walking speed of the pedestrians. In case of F9, t-test was conducted for group size of 1 & 2 and significant difference was observed between these two group sizes.

4.3.3. Development of fundamental diagrams for FOB mid-block sections

Fundamental diagrams are the primary relationships which are established between the macroscopic parameters: speed, flow rate, density and area module (space). These relationships are used for predicting the free flow speeds (FFS: u_f), jam density (K_j), maximum flow rate (q_{max}) and capacity of the pedestrian facilities.

The observed relationship between the different macroscopic parameters, as shown in Table 4.6 provides the mathematical flow models developed for the various FOB study locations considered and a general model for combining all data together. Table 4.6 consists of the different speed-density, speed-flow rate, flow rate-density and flow rate-area module relationships along with the R^2 values for each location. The R-squared (R^2) or coefficient of determination value represents the proportion of variance for a dependent variable which is explained by an independent variable in a regression model. For example, if the R^2 of a model is 0.50, then the model input explains approximately half of the observed variation. The correlation coefficient (r) is represented by Equation 4.1.

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n(\sum x^2) - (\sum x)^2][n(\sum y^2) - (\sum y)^2]}} \qquad \text{........ } \mathbf{Eq.\ 4.1}$$

Table 4.6. Pedestrian flow models for FOB locations

Study Location	**Speed-Density**		**Speed-Flow**		**Flow-Density**		**Flow-Area module**	
	Relationship	***R^2 value***	***Relationship***	***R^2 value***	***Relationship***	***R^2 value***	***Relationship***	***R^2 value***
STNM (F1)	$v = 80.564 – 26.599*k$	0.471	$q = 3.028*u - 0.037*u^2$	0.799	$q = 80.564*k – 26.599*k^2$	0.752	$q = 80.564/M - 26.599/M^2$	0.802
Metro Point (F2)	$v = 79.841 – 47.979*k$	0.504	$q = 1.664*u - 0.021*u^2$	0.836	$q = 79.841*k – 47.979*k^2$	0.802	$q = 79.841/M - 47.979/M^2$	0.819
M.G. Marg (F3)	$v = 77.822 – 21.665*k$	0.468	$q = 3.591*u - 0.046*u^2$	0.783	$q = 77.822*k – 21.665*k^2$	0.745	$q = 77.822/M - 21.665/M^2$	0.788
IIT Bombay (F4)	$v = 79.529 – 67.798*k$	0.574	$q = 1.173*u - 0.015*u^2$	0.871	$q = 79.529*k – 67.798*k^2$	0.822	$q = 79.529/M - 67.798/M^2$	0.837
Ultadanga (F5)	$v = 84.178 – 23.801*k$	0.433	$q = 3.536*u - 0.042*u^2$	0.762	$q = 84.178*k – 23.801*k^2$	0.768	$q = 84.178/M - 23.801/M^2$	0.759
Lake Town (F6)	$v = 78.895 – 46.784*k$	0.437	$q = 1.686*u - 0.021*u^2$	0.751	$q = 78.895*k – 46.784*k^2$	0.738	$q = 78.895/M - 46.784/M^2$	0.772
Sealdah (F7)	$v = 80.895 – 36.793*k$	0.617	$q = 2.198*u - 0.027*u^2$	0.899	$q = 80.895*k – 36.793*k^2$	0.876	$q = 80.895/M - 36.793/M^2$	0.888
Anand Vihar (F8)	$v = 83.863 – 26.491*k$	0.353	$q = 3.165*u - 0.037*u^2$	0.757	$q = 83.863 *k – 26.491*k^2$	0.699	$q = 83.863/M - 26.491/M^2$	0.673
Akshardham (F9)	$v = 79.564 – 13.463*k$	0.495	$q = 5.909*u - 0.074*u^2$	0.824	$q = 79.564*k – 13.463*k^2$	0.772	$q = 79.564/M - 13.463/M^2$	0.809
ITO (F10)	$v = 82.671 – 56.079*k$	0.433	$q = 1.474*u - 0.028*u^2$	0.729	$q = 82.671*k – 56.079*k^2$	0.755	$q = 82.671/M - 56.079/M^2$	0.755
Maharani Bagh (F11)	$v = 78.224 – 57.443*k$	0.431	$q = 1.362*u - 0.017*u^2$	0.771	$q = 78.224*k – 57.443*k^2$	0.742	$q = 78.224/M – 57.443/M^2$	0.734
Vaishali (F12)	$v = 84.122 – 29.814*k$	0.476	$q = 2.821*u - 0.033*u^2$	0.811	$q = 84.122*k – 29.814*k^2$	0.767	$q = 84.122/M - 29.814/M^2$	0.793
Tin Factory (F13)	$v = 82.024 – 20.083*k$	0.419	$q = 4.084*u - 0.049*u^2$	0.767	$q = 82.024*k – 20.083*k^2$	0.735	$q = 82.024/M - 20.083/M^2$	0.702
Yeshwantpur (F14)	$v = 78.327 – 49.032*k$	0.511	$q = 1.597*u - 0.020*u^2$	0.832	$q = 78.327*k – 49.032*k^2$	0.787	$q = 78.327/M - 49.032/M^2$	0.811
Marathahalli (F15)	$v = 79.857 – 24.926*k$	0.388	$q = 3.204*u - 0.041*u^2$	0.772	$q = 79.857*k – 24.926*k^2$	0.717	$q = 79.857/M - 24.926/M^2$	0.732
Christ University (F16)	$v = 76.305 – 39.758*k$	0.409	$q = 1.919*u - 0.025*u^2$	0.778	$q = 76.305*k – 39.758*k^2$	0.707	$q = 76.305/M - 39.758/M^2$	0.722
Maligaon (F17)	$v = 74.256 – 31.851*k$	0.522	$q = 2.331*u - 0.031*u^2$	0.851	$q = 74.256*k – 31.851*k^2$	0.813	$q = 74.256/M - 31.851/M^2$	0.829
Overall	$v = 76.961 – 17.538*k$	***0.524***	$q = 4.388*u - 0.057*u^2$	***0.803***	$q = 76.961*k – 17.538*k^2$	***0.852***	$q = 76.961/M – 17.538/M^2$	***0.858***

where, *x* represents the observed value (in this case the observed flow rate), *y* represents the predicted value (in this case the predicted flow rate) and *n* represents the number of samples (i.e., the number of minutes per location considered). The R^2 obtained for speed-density ranges lied between 0.35-0.62, due to the scattered pattern of data around the best fit curve. Previous studies by Tipakornkiat (2012) and Rastogi (2013) also reported lower R^2 values due to similar reasons for different facilities.

Figure 4.10(a-d) were plotted for establishing speed-density, flow rate-density, speed-flow rate, and flow rate-area module relationships for the different FOB mid-block sections combined. The diagrams give an overall view of combined data from the existing condition of the mid-block section of the FOBs.

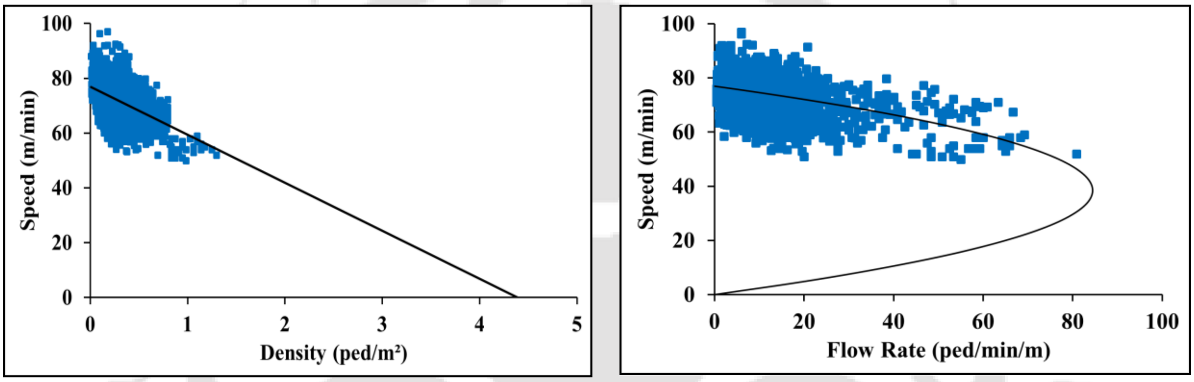


Fig. (a). Speed-Density relationship **Fig. (b).** Speed-Flow Rate relationship

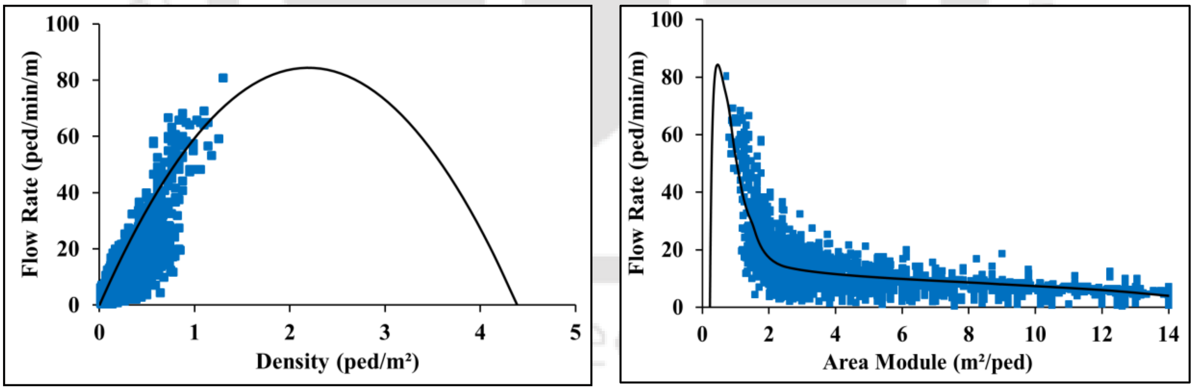


Fig. (c). Flow Rate-Density relationship **Fig. (d).** Flow Rate-Area Module relationship

Figure 4.10. Fundamental relationship diagrams of macroscopic parameters for combined data from all the sites

Table 4.7. Pedestrian flow characteristics for different FOB mid-block sections

Location	**Free Flow Speed (u_f), m/min**	**Maximum Flow Rate (q_{max}), ped/min/m**	**Area Module (M), at q_{max} (m^2/ped)**	**Optimum speed (m/min)**	**Optimum Density (ped/m^2)**
STNM (F1)	80.56	59.95	0.58	35.44	1.72
Metro Point (F2)	79.84	35.98	1.11	39.60	0.89
M.G.Marg (F3)	77.80	46.54	0.85	39.20	1.16
IIT Bombay (F4)	79.53	34.98	1.14	40.47	0.87
Ultadanga (F5)	84.17	59.39	0.67	42.11	1.45
Lake Town (F6)	78.89	33.25	1.43	39.82	0.84
Sealdah (F7)	80.89	40.01	0.99	41.82	0.99
Anand Vihar (F8)	83.86	66.23	0.61	41.27	1.66
Akshardham (F9)	79.56	81.83	0.40	34.84	2.39
ITO (F10)	82.67	30.43	1.31	43.10	0.76
Maharani Bagh (F11)	78.22	32.92	1.52	44.60	0.77
Vaishali (F12)	84.12	50.32	0.79	42.42	1.23
Tin Factory (F13)	82.02	58.59	0.68	41.92	1.43
Yeshwantpur (F14)	78.32	32.87	1.27	40.01	0.78
Marathahalli (F15)	79.85	51.16	0.78	39.62	1.28
Christ University (F16)	76.31	32.88	1.21	38.16	0.82
Maligaon (F17)	74.25	36.26	0.96	36.22	1.03

Figure 4.10(a) showed that the overall FFS for the different locations combined was 76.96m/min with the predicted jam density around 4.38ped/m^2. From Figure 4.10(c) the maximum flow rate predicted was 84ped/min/m occurring at an optimum density of 2.11ped/m^2. The optimum speed at the maximum flow rate was predicted to be 41.2m/min. Moreover, the area module predicted at maximum flow rate was 0.48m^2/ped.

Table 4.7 showed the pedestrian flow characteristics (i.e., FFS, q_{max}, area module at q_{max}, optimum speed and optimum density) for the different FOB locations. For F9, at maximum predicted flow rate (q_{max}) of 81.83ped/min/m, an area module of 0.40ped/m^2 was observed. The maximum space (1.52m^2/ped) was available at location F11 at a flow rate of 32.92ped/min. The optimum speed at maximum capacity across all locations ranged between 35-45m/min. The highest optimum density (2.39ped/m^2) was observed at location F9, as it was primarily a commercial area with narrow effective walkway width. As the observed data were available mostly for lower to moderate ranges of density, capacity values predicted by the fundamental relationships in Table 4.7 could have some variations.

4.3.4. Development of simulation model

In an attempt to develop a global simulation model which could replicate the walking behaviour over elevated walkways, commercially available software: PTV Viswalk 6.0 (2013) which uses Social Force Model (SFM) approach was used. The SFM model gives a realistic description of the individual movements at microscopic level as it considers intentions, desired velocities and pair interactions. The visible similarities (i.e. purpose of segregating pedestrian traffic from vehicular traffic, enhancing comfort and safety; geometric design standards, effect of vertical connectivity and lack of security on the pedestrian psychology) between the two types of elevated facilities (FOBs and skywalks) encouraged in developing a common global simulation model which could represent the walking behaviour of pedestrians over any elevated walkway. The development of the simulated model not only helps understanding the existing scenario over the walkways, but also helps to predict the capacity of the facilities if more pedestrians use the facilities in the future.

4.3.4.1. Preliminary data collection and extraction

As mentioned in the methodology chapter, data was collected over the mid-block and stairway sections of elevated walkway facilities. The aim of the data collection procedure was to capture variability in the pedestrian movement characteristics including the composition and flow levels. After data collection, the data was processed in the lab manually to extract different individual pedestrian characteristics such as age, gender, and luggage condition.

4.3.4.2. Model development

The model development includes creation of a simulation model using the geometry of the elevated walkway, feeding the pedestrian types as per extracted data, carrying out sensitive analysis of the different parameters, calibrating the model using genetic algorithm through COM interface in MATLAB, and validating the data with new data set.

Comparative analysis

In order to understand the effect of geometry on the pedestrians, the base model was developed using the configurations in Table 4.8.

Table 4.8. Pedestrian composition for model development

Location ID	Width (m)	Pedestrian types	Mean (km/hr)	Min (km/hr)	Max (km/hr)
F8	4.7	Male-with luggage	4.33	2.49	6.76
		Male-without luggage	4.45	2.72	6.83
		Female-with luggage	3.97	2.41	5.87
		Female without luggage	4.09	2.61	5.99

FOB geometry creation and development of walking behaviour model in Viswalk

Although in the current chapter, only mid-block data is discussed, however to replicate the elevated facility, Viswalk simulator was used for the entire FOB (including both mid-block and stairway sections). The global microscopic simulation model was created in the Viswalk software, as shown in Figure 4.11. The geometric details of the model were taken from the field data. Set scaling option was used to define the geometry of the study area. Two pedestrian types were created: man and woman with age, luggage condition and direction of movement. The different walking behaviour parameters along with desired speed distributions, pedestrian input volumes, routes, and compositions were provided for the functioning of the model. For model development 80% of data was used and 20% data was kept for validation.

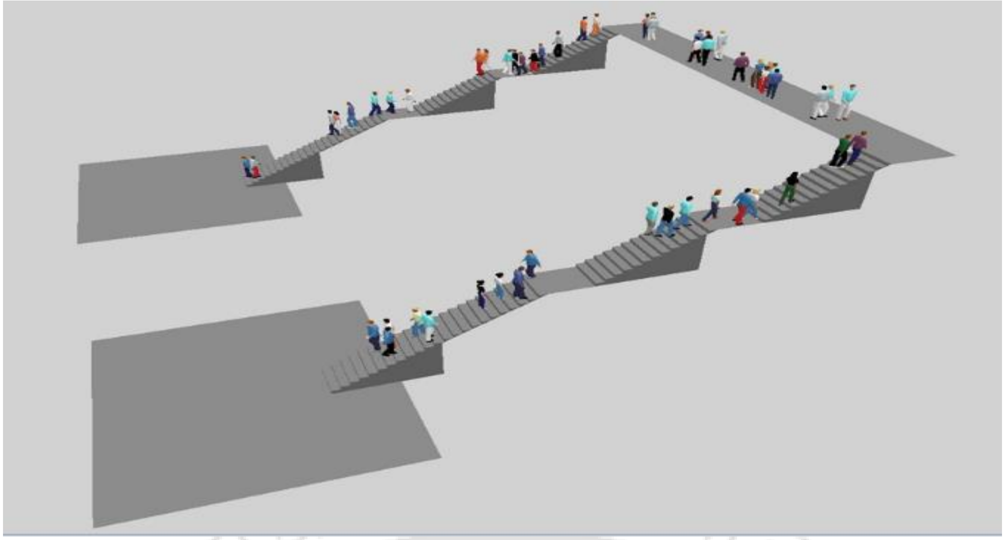


Figure 4.11. Developed global model for elevated walkways

Sensitivity analysis of Viswalk parameters

Sensitivity analysis was carried out to check the significant parameters which impacted the walking behaviour and thus simplified the computational workload on the optimization technique. In Viswalk there are different sets of walking behaviour parameters (refer Table 4.9). Previous literatures showed that parameters such as ReactToN, Noise and SidePref had least effect on the model and thus default values could be applied. Sensitivity analysis was carried out for the seven other parameters (Tau, ASocIso, BSocIso, Lambda, ASocMean, BSocMean, and VD) to check their relative impact on the model. Latin hypercube sampling technique was used to sample out ten different samples of the ranges given below.

Table 4.9. Walking behaviour parameters

Parameter	Value Range
Tau (s)	0.1-1
A_Soc_Isotropic (m/s^2)	0-10
B_Soc_Isotropic (m)	0-10
Lambda_mean	0.1-1
A_Soc_Mean (m/s^2)	0.1-1
B_Soc_Mean (m)	0-10
VD (s)	0-10

Simulations were run for each of the sample values keeping other parameters to their default values. Walking speed of pedestrians over a predefined measurement area were recorded and averaged out for each simulation run (a single set of parameters). These velocities were plotted against their respective parametric samples and presented in Figure 4.12(a-g).

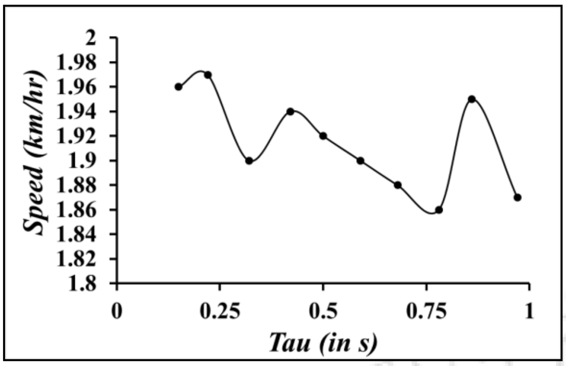


Fig. (a). Speed vs Tau

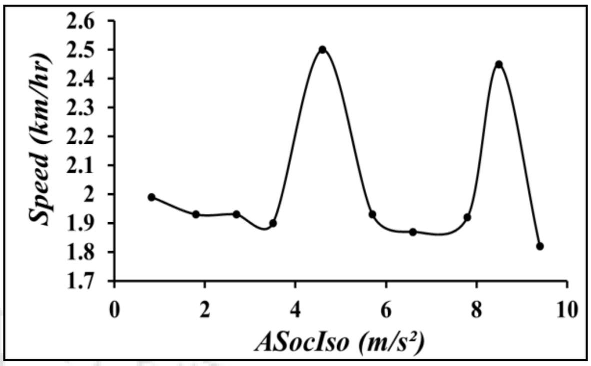


Fig. (b). Speed vs ASocIso

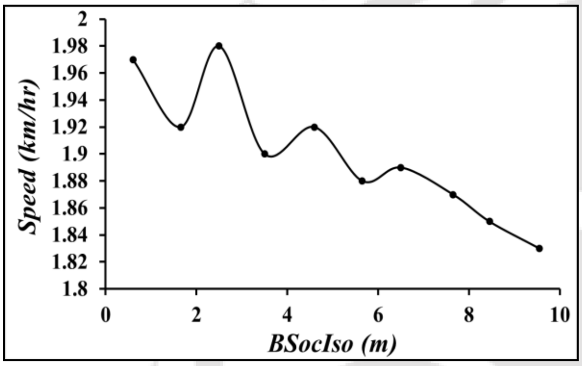


Fig. (c). Speed vs BSocIso

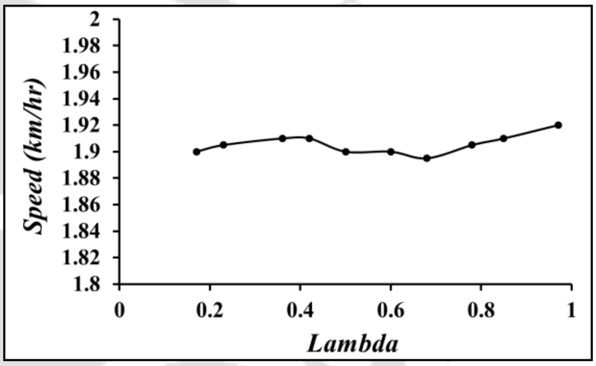


Fig. (d). Speed vs Lambda

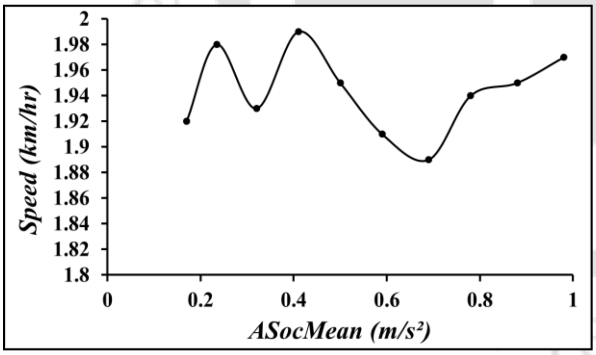


Fig. (e). Speed vs ASocMean

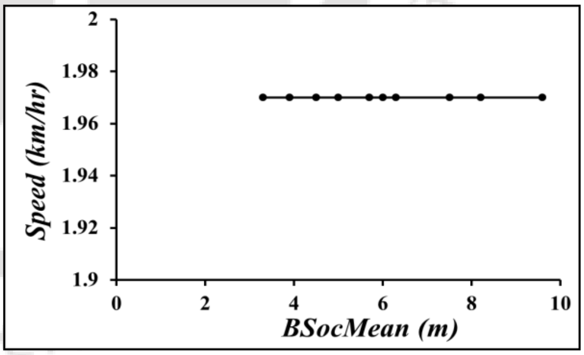


Fig. (f). Speed vs BSocMean

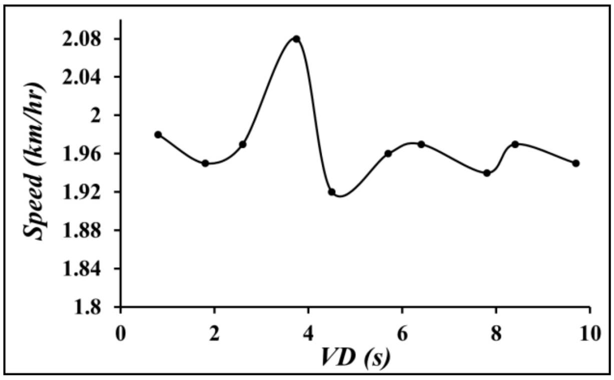


Fig. (g). Speed vs VD

Figure 4.12. Stream speed variation with different Viswalk parameters

From Figure 4.12 it was observed that Lambda and BSocMean were the least sensitive parameters and thus their default values were used. The other five parameters were used for further model calibration.

Calibration of the developed model

Calibration of the simulation model was done using a Genetic Algorithm (GA) through COM interface in MATLAB. The five sensitive parameters: Tau, ASocIso, BSocIso, ASocMean and VD were provided as input parameters to the GA while keeping the other parameters as default values. Fitness function comprised of a MATLAB code that ran the simulation for a particular period and calculated the Mean Absolute Percentage Error (MAPE) between the observed and simulated velocities of pedestrians. The lower and upper bound values for the parameters were also provided to GA.

Using GA, optimization was performed for an initial population size of 50 individuals and 200 individuals for 5 and 10 number of input variables respectively (MATLAB documentation, 2019). The number of generations was used as the stopping criteria. Figure 4.13 shows the variation of fitness function with the number of generations.

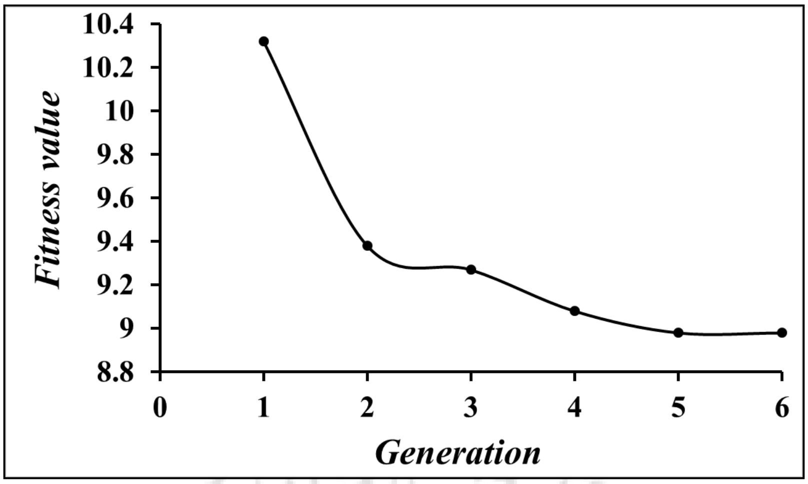


Figure 4.13. Fitness vs Generation

From Figure 4.13 it was observed that fitness function (MAPE) improved with the increase in the number of generations, and after six generations satisfactory results were obtained. The calibrated values of the sensitive parameters are shown in Table 4.10.

Table 4.10. Calibrated global parameters for elevated walkways

ASocIsotropic	**BSocIsotropic**	**ASocMean**	**Tau**	**VD**
0.4833	1.2264	0.1043	0.3	0.6427

Validation of the developed global model

The calibrated model was then evaluated with the remaining 20% field data including the input volumes, pedestrian compositions, and desired speeds. The optimal parameters obtained from the calibration was put in the model with new data set, MAPE of the model was computed and observed to be 8.98%.

The Lewis scale (Lewis, 1982), was used for interpretation of MAPE values. Table 4.11 shows the MAPE values along with the forecasting.

Table 4.11. Lewis scale interpretation based on MAPE

MAPE (%)	**Forecasting**
≤10	Highly accurate
10-20	Good
20-50	Reasonable
≥50	Inaccurate

As per Table 4.11 it was observed that the error (8.98%) was within required limits, and the model was able to predict well. Using the same developed global model, the other elevated walkway locations with different effective widths were validated as well. Table 4.12 shows the MAPE values for the different FOB locations.

Table 4.12. Validation of FOB facilities

Location ID	Width	MAPE (%)
F4	2.6	11.32
F5	1.9	9.84
F6	1.9	8.47
F7	1.4	14.22
F9	1.2	15.29
F10	1.6	7.34
F11	1.6	9.53
F12	2.5	13.91
F13	1.6	12.63
F14	2.1	8.07
F15	2.4	9.64
F16	1.8	8.42
F17	1.6	10.47

The MAPE values from Table 4.12 showed that the range of MAPE lied between 7.34-15.29%. This meant that the model was able to accurately predict the walking behaviour over different FOB facilities and the calibrated parameters could be used for development of elevated walkway simulation models. To improve the simulated model accuracy further, Viswalk model can be calibrated for each FOB separately. Using the global model parameters, planners and designer can design better elevated walkways, which can be utilized by maximum number of pedestrians.

4.3.5. Development of speed models over FOB mid-block sections using microscopic pedestrian behaviour parameters

Pedestrian walking speed is the most fundamental parameter which defines the walking behaviour of an individual pedestrian or a group of pedestrians. This behaviour is very complicated to predict as it depends on many microscopic individual and group characteristics. An individual pedestrian’s walking behaviour is greatly impacted by his/ her age, gender, luggage condition, use of hand held devices (mobiles), direction of movement, and whether the pedestrian is differently abled or not. Similarly, when a group of pedestrians are walking together then different group characteristics such as the size of the group (i.e., if the pedestrian is walking alone or in group of sizes 2, 3, 4 or more pedestrians), lane formation (i.e., whether the pedestrians are walking in dedicated lanes throughout the section), leader-follower relationship (i.e., whether the pedestrians are in lane formation and following the leader in front), squeezing effect (i.e., if the pedestrians are forced to shift to one side of the walkway due to oncoming major flow from opposite direction), faster-is-slower effect (i.e., when the subject pedestrian attempts to change lane and overtake slower pedestrians in the front, but is forced to shift back to original lane due to oncoming group of pedestrians from the opposite direction or lack of space), overtaking (i.e., if the pedestrian surpasses slower moving pedestrians in front) and lane shifting (i.e., if the pedestrian is constantly shifting lanes throughout the study section, to either overtake or avoid collision), influence the walking behaviour. In the current section an attempt is made to understand the impact of different individual (age, Gen: gender, Lug: luggage carrying conditions, Mob: mobile use and Dis: disability) and group (GS: group size, LF: lane formation, LFR: leader-follower relationship, LS: lane shifting, Over: overtaking, SE: squeezing effect and FSE: faster-is-slower effect) behavioural characteristics on the walking speed of the pedestrians over mid-block sections of FOB facilities. Accurate pedestrian walking speed prediction is important for the operation, management, and efficiency of different connecting infrastructure such as elevated walkways.

4.3.5.1. Descriptive statistics of the field FOB data

Table 4.13 shows the descriptive statistics of the seventeen different mid-block sections considered for the study. As discussed previously, male pedestrians in the age category 21-40 years were dominant across all locations, other than locations F1 and F16 where proportion of female pedestrians was higher. As discussed in section 4.2.1, luggage wise distribution was quite similar at all sites. The percentage of pedestrians using mobile was low (3.9-14.1%) except location F16 which had the highest percentage of pedestrians using mobile phones (14.1%). Apart from locations F2 and F4, where nearly 32% pedestrians walked in group size of two pedestrian, majority of other locations had pedestrians walking alone without groups. The proportion of disabled pedestrians ranged between 0.11-2.13%. At locations F4, F5, F11 and F15, high percentage of pedestrians were observed to walk in lane formation with locations F9 and F15 having the highest proportion of pedestrians in the leader-follower mode. Faster-is-slower effect and squeezing effect were rare phenomenon which were mainly observed at

Table 4.13. Demographic characteristics of walking behaviour over FOB mid-block sections

Characteristics		Locations																
		F1	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**F9**	**F10**	**F11**	**F12**	**F13**	**F14**	**F15**	**F16**	**F17**
Sample Size		1423	1247	1426	887	1230	805	699	1432	1167	861	657	1208	937	695	657	689	1084
Age (%)	*≤10*	0.4	2.9	1.7	1	3.2	3.1	4.5	3.1	0.1	0.2	2.1	1.4	1.2	0.9	1.3	0.1	4.8
	11-20	1.5	8	1.7	12.4	11	13.4	8.9	14.5	0.6	1.9	6.2	11.3	2.6	5.6	14.2	25.7	11.8
	21-40	74.3	70.2	70.1	76.2	60	48.9	40.6	52	90.7	62.9	61.5	65.1	74.3	49.5	70.2	57.9	45.9
	41-60	21.6	17.2	25.6	8.4	21.7	24.3	36.6	22.3	6.8	29.9	25.7	18.9	20.5	38	12.4	13.8	28.8
	≥60	2.2	1.7	0.9	2	4.1	10.3	9.4	8.1	1.8	5.1	4.5	3.3	1.4	6	1.9	2.5	8.7
Gen (%)	*Male*	49.1	55.3	67.3	75.5	74.9	64.5	71.7	78.2	71.6	81.3	74.9	76.2	73	85.8	76.9	42.1	66.7
	Female	50.9	44.7	32.7	24.5	25.1	35.5	28.3	21.8	28.4	18.7	25.1	23.8	27	14.2	23.1	57.9	33.3
Luggage (%)	*With*	51.4	48.8	35.2	54	62.1	58	29.9	55.6	76.3	63.5	50.1	58.7	48.1	34	46.4	74.2	34.1
	Without	48.6	51.2	64.8	46	37.9	42	70.1	44.4	23.7	36.5	49.9	41.3	51.9	66	53.6	25.8	65.9
GS (%)	*1*	79.7	64.9	84.7	48.4	88.5	77.4	75.3	74.1	96.7	88.7	82.2	82.6	89.9	88.6	82.4	83.5	73.2
	2	17.6	31.4	13.5	31.7	9.9	17.5	18.4	20.9	3.3	9.9	10.3	12.4	8.9	8.1	14.8	11.9	18.2
	3	2.2	3.4	1.5	13.2	1.3	3.4	4.3	3.8	0	1.2	6.7	3.3	0.9	2.3	1.8	3.2	6.3
	≥4	0.5	0.3	0.3	6.7	0.3	1.7	2	1.2	0	0.2	0.8	1.7	0.3	1	1	1.4	2.3
Mob (%)	*With*	6.5	4.5	6.7	9.2	7.4	10.4	3.9	6.1	9.2	11.5	8.2	12.1	4.9	5.3	9	14.1	5.6
	Without	93.5	95.5	93.3	90.8	92.6	89.6	96.1	93.9	90.8	88.5	91.8	87.9	95.1	94.7	91	85.9	94.4
Dis (%)	*With*	0.21	0.40	0.35	0.11	1.38	1.24	0.86	1.33	0.60	1.16	1.22	0.66	0.43	0.43	2.13	0.29	1.75
	Without	99.79	99.60	99.65	99.89	98.62	98.76	99.14	98.67	99.40	98.84	98.78	99.34	99.57	99.57	97.87	99.71	98.25
LF (%)	*With*	7.87	19.25	7.99	21.42	39.27	13.91	8.58	14.39	14.91	6.04	19.63	13.49	6.40	8.78	44.44	2.76	18.17
	Without	92.13	80.75	92.01	78.58	60.73	86.09	91.42	85.61	85.09	93.96	80.37	86.51	93.60	91.22	55.56	97.24	81.83
LFR (%)	*With*	5.48	1.36	4.35	3.04	18.86	6.71	6.58	4.96	13.37	3.25	6.70	5.30	4.06	5.61	20.09	1.45	5.81
	Without	94.52	98.64	95.65	96.96	81.14	93.29	93.42	95.04	86.63	96.75	93.30	94.70	95.94	94.39	79.91	98.55	94.19
FSE (%)	*With*	0.07	0.08	0.91	0.56	2.11	0.37	0.29	0.35	0.00	0.35	0.76	0.25	1.07	0.00	0.46	0.00	0.55
	Without	99.93	99.92	99.09	99.44	97.89	99.63	99.71	99.65	100.00	99.65	99.24	99.75	98.93	100.00	99.54	100.00	99.45
SE (%)	*With*	0.07	0.64	0.07	0.00	1.71	6.09	1.29	1.89	0.00	0.00	0.00	2.48	0.00	0.14	2.59	0.44	6.55
	Without	99.93	99.36	99.93	100.00	98.29	93.91	98.71	98.11	100.00	100.00	100.00	97.52	100.00	99.86	97.41	99.56	93.45
Over (%)	*With*	4.64	2.41	3.79	5.41	3.58	2.73	1.43	4.26	3.00	2.67	3.81	3.64	3.95	1.58	4.72	2.03	6.27
	Without	95.36	97.59	96.21	94.59	96.42	97.27	98.57	95.74	97.00	97.33	96.19	96.36	96.05	98.42	95.28	97.97	93.73
LS (%)	*With*	27.20	6.90	23.21	23.90	23.01	6.34	2.43	2.51	28.28	26.02	20.24	12.91	13.34	2.30	43.07	3.19	10.15
	Without	72.80	93.10	76.79	76.10	76.99	93.66	97.57	97.49	71.72	73.98	79.76	87.09	86.66	97.70	56.93	96.81	89.85
Speed (m/min)	*Mean*	69.04	66.27	67.29	67.28	77.34	71.08	71.49	73.00	77.72	76.26	75.70	73.77	72.53	68.31	70.48	69.95	63.44
	Median	69.04	65.62	67.11	66.14	77.43	70.27	71.28	72.09	77.58	76.37	76.15	73.13	72.13	67.75	70.92	69.39	62.56
	S.D.	13.47	11.95	12.77	13.63	11.27	12.15	12.99	12.81	10.28	12.68	13.84	15.35	13.37	10.86	5.49	10.27	11.13

F5, F6, F12, F15 and F17 locations. The percentage of pedestrians trying to overtake slower pedestrians by either changing lanes or walking in the same lane was 1.43-6.27% across all locations. Similarly, high percentage of lane shifting was observed at F1, F3- F5, F9-F11 and F15 locations. The highest mean speed observed considering all the individual and group pedestrian flow characteristics was at location F9, while the lowest was observed at F17.

4.3.5.2. Statistical test on walking behaviour over different FOB mid-block sections

A significance test was conducted using SPSSv20 for checking the p-values based on K-S hypothesis testing results. Table 4.14 shows the results of the K-S test.

Table 4.14. Significance test results for different considered variables of FOB sections

Section	Lane Shift	Overtake	LFR	LF	Mobile	Luggage	Gender	Age	Group size
F1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
F2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
F3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
F4	0.000	0.000	0.000	0.000	0.000	*0.141*	0.000	0.000	0.000
F5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
F6	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
F7	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
F8	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
F9	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
F10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
F11	0.000	0.000	0.000	0.000	0.000	*0.993*	0.000	0.000	0.000
F12	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
F13	0.000	0.000	0.000	0.000	0.000	*0.353*	0.000	0.000	0.000
F14	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
F15	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
F16	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
F17	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

***Note:** LFR- Leader-follower relationship, LF- Lane formation*

From Table 4.14, p-values were observed to be less than 0.05, thus significant difference exist between the different variables considered. In the case of locations F4, F11 and F13, no significant difference was observed in case of luggage.

Further correlation analysis was carried out to understand the relationship between the different variables considered. Correlation coefficient (*r*) shows the linear relationship between two variables. A value of *r* less than 0.3 indicates weak relationship. Table 4.15 shows the results of the correlation analysis. In order to develop the walking behaviour model, different variables were coded as: age *(0: <10, 1:11-20, 2: 21-40, 3: 41-60, 4: >60)*, gender, luggage *(0: with, 1: without)*, group size *(0: Single pedestrian, 1: Two pedestrians, 2: Three pedestrians, 3: Four* *or more pedestrians together)*, mobile use *(0: with, 1: without)*, disability *(0: with, 1: without)*, lane formation *(0: with, 1: without)*, leader-follower relationship *(0: with, 1: without)*, faster-is-slower effect *(0: with, 1: without)*, squeezing effect *(0: with, 1: without)*, overtaking *(0: with, 1: without)*, and lane shifting *(0: with, 1: without)*.

Table 4.15. Correlation analysis for all the variables considered for FOB sections

	Age	**Gen**	**Lug**	**GS**	**Mob**	**Dis**	**LF**	**LFR**	**FSE**	**SE**	**Over**	**LS**	**Speed**
Age	1.00	-0.10	0.07	-0.19	0.05	-0.08	-0.02	-0.01	0.00	-0.03	0.03	0.04	-0.11
Gen		1.00	-0.16	0.12	0.00	0.02	0.01	0.02	0.00	0.00	0.04	0.00	-0.22
Lug			1.00	0.03	0.01	-0.01	0.02	0.02	0.01	0.00	-0.01	0.00	-0.01
GS				1.00	0.06	0.01	-0.03	-0.01	0.01	0.02	0.04	0.06	-0.23
Mob					1.00	0.00	-0.02	-0.02	-0.01	0.00	0.00	-0.01	0.04
Dis						1.00	0.00	-0.01	0.00	0.02	-0.02	-0.01	0.12
LF							1.00	0.23	0.01	0.01	-0.03	-0.03	0.04
LFR								1.00	0.02	0.00	-0.03	0.02	0.02
FSE									1.00	0.00	0.00	0.04	0.02
SE										1.00	-0.01	0.01	0.06
Over											1.00	0.21	-0.13
LS												1.00	-0.06
Speed													1.00

Note: *Gen-Gender, Lug-Luggage, GS-Group size, Mob-Mobile use, Dis-Disability, LF-Lane formation, LFR-Leader follower relationship, FSE- Faster is slower effect, SE-Squeezing effect, Over-Overtaking, LS- Lane shifting*

As per Table 4.15, positive or negative relationship indicates how speed (dependent variable) increases or decreases with the independent variables. For example, a negative correlation coefficient (-0.22) for gender-speed relationship indicates that as gender changes from 0 (male) to 1 (female), the overall walking speed of the system decreases. A negative age-speed coefficient indicates that when more elderly pedestrians (>60 years) are using the facility, the overall walking speed is likely to decrease. Similarly, a positive mobile use-speed relationship indicates that when pedestrians are without mobile phones (coded as 1), their walking speed considerably increases. No significant relationship (-0.01) was observed between luggage and speed. The difference between mean walking speed for pedestrians with luggage and without luggage observed in the field was also negligible (0.3m/min).

However, as all the variables considered had a coefficient much less than 0.3, thus a very weak relationship exists between the different variable pairs. Considering pair-wise correlations of speed with the other independent variables, the results indicated uncorrelated relationship (≤0.30) between the dependent (speed) and the independent variables (variables other than speed). All these variables were therefore considered for the development of linear regression model for walking speeds of pedestrians.

4.3.5.3. Development of microscopic speed prediction model

In an attempt to understand the impact of different pedestrian characteristics (individual and group) on the walking behaviour, linear regression model (LRM) was used. In LRM a relationship is obtained between the scalar response (dependent variable) and one or more explanatory variables (or independent variables). For walking behaviour modelling, multiple linear regression was used to obtain the relationship between the walking behaviour parameters and the walking speed over the mid-block section of FOBs. In model development, 80% data was used and remaining 20% data was segregated for model validation. Table 4.16 shows the most significant variables which impact the walking behaviour over mid-block sections along with the coefficients.

Table 4.16. Coefficients for microscopic walking behaviour over FOB mid-block sections

	Reference category	**Estimate**	**Std. Error**	**t value**	**Pr(≥|t|)**
(Intercept)		47.261	2.034	23.228	≤ 0.001 ***
Age1 (11-20 years)	*Age (≤10 years)*	6.169	0.725	8.510	≤ 0.001 ***
Age2 (21-40 years)		6.299	0.668	9.425	≤ 0.001 ***
Age3 (41-60 years)		0.950	0.687	1.382	0.167
Age4 (≥60 years)		-5.672	0.799	-7.097	≤ 0.001 ***
Gender (Female)	*Gender (Male)*	-5.860	0.197	-29.690	≤ 0.001 ***
Luggage (Without)	*Luggage (With)*	-0.283	0.181	-1.562	0.118
Group_size (GS: 2)	*Group_size (GS: 1)*	-5.906	0.255	-23.298	≤ 0.001 ***
Group_size (GS: 3)		-9.563	0.509	-18.794	≤ 0.001 ***
Group_size (G: ≥4)		-12.611	0.892	-14.144	≤ 0.001 ***
Mobile (Without)	*Mobile (With)*	3.668	0.334	10.965	≤ 0.001 ***
Disability (Without)	*Disability (With)*	14.930	1.006	14.844	≤ 0.001 ***
Lane_formation (Without)	*Lane_formation (With)*	1.447	0.322	4.497	≤ 0.001 ***
Leader_follower (Without)	*Leader_follower (With)*	-0.071	0.466	-0.152	0.879
Faster_slower (Without)	*Faster_slower (With)*	4.758	1.292	3.682	≤ 0.001 ***
Squeezing_effect (Without)	*Squeezing_effect (With)*	5.706	0.778	7.335	≤ 0.001 ***
Overtaking (Without)	*Overtaking (With)*	-7.081	0.497	-14.239	≤ 0.001 ***
Lane_shift (Without)	*Lane_shift (With)*	-0.299	0.235	-1.273	0.203
Significance codes *'***'- 0; '**'- 0.001; '*'- 0.01; '.'- 0.05; ' '- 0.1*					

Table 4.16 showed the most significant variables which impacted the walking behaviour of the pedestrians over the FOB mid-block section. As per Table 4.16, age, gender, group size, mobile use, disability, lane formation, faster-is-slower effect, squeezing effect and overtaking behaviour were the most significant parameters affecting the walking speed behaviour over the FOB mid-block sections. The negative coefficient for female indicated that the walking speed of the female was lower than the male pedestrians. Moreover, when the pedestrians were moving in lanes their speeds were observed to be higher than those without lane formation. The age coefficient showed that with the increase in age the walking speeds increased. The pedestrians without disability were observed to have higher walking speeds and impacted the overall walking speeds. Similarly, pedestrians without leader follower relationship, without luggage and without lane shifting did not have significant impact on the overall walking behaviour.

4.3.5.4. Validation of microscopic speed prediction model

The remaining 20% of the test data set was used to make a comparison between the predicted and actual speeds using MAPE (measure of prediction accuracy of a forecasting method) and RMSE (used to measure differences between values predicted by the model and values observed) as per following Equations 4.2 and 4.3,

$$\textit{Mean Absolute Percentage Error (MAPE)} = \frac{1}{n}\sum_{t=1}^{n}\left[\frac{A_t - F_t}{A_t}\right] \qquad \text{.......} \ \textbf{Eq. 4.2}$$

where, A_t and F_t represents the actual and predicted values.

$$\textit{Root Mean Square Error (RMSE)} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(f_i - o_i)^2} \qquad \text{.......}\textbf{Eq. 4.3}$$

where, f_i and o_i are the predicted and observed values.

Using equations 4.2 and 4.3, the obtained MAPE and RMSE errors were 17.57% and 0.131 respectively. As per Lewis scale of interpretation, a MAPE value of 10-20% specifies that the model forecasting was good.

4.3.5.5. Application of microscopic speed prediction model

As per Table 4.16, if one wants to calculate the impact of any individual or group behaviour characteristic on the walking speed over mid-block section of FOBs, then Equation 4.4 can be used.

$$Walking\ Speed\ (MB\text{-}FOB) = 47.261 + 6.169*Age(11\text{-}20) + 6.299*Age(21\text{-}40) - 5.672*Age(\geq 60) - 5.860*Gen - 5.906*GS2 - 9.563*GS3 - 12.611*GS4 + 3.668*Mob + 14.930*Dis + 1.447*LF + 4.758*FSE + 5.706*SE - 7.081*Over \quad \text{.......... } \textbf{Eq. 4.4}$$

For example, two cases are discussed below where the speed of the pedestrian is calculated based on the behavioural characteristics.

Case 1: The subject pedestrian is a female in the age group of 21-40 years (i.e., Age group 2) without luggage, walking in group size of 2, with mobile, without disability, in lane formation and leader follower relationship, not in squeezing effect, does not shift lane or overtake. Then, predicted walking speed of that pedestrian would be 80.75m/min as per Equation 4.4.

Case 2: The subject pedestrian is a female in the age group of 41-60 years (i.e., Age group 3) with luggage, group size of 3 pedestrians, with mobile, without disability, in lane formation and leader follower relationship, not in squeezing effect, does not shift lane or overtake. Then, the walking speed of the pedestrian would be 58.07m/min as per Equation 4.4.

4.3.6. Development of speed models over FOB mid-block sections using macroscopic pedestrian behaviour parameters

In this section an attempt was made to predict the walking speed over FOBs using different pedestrian flow characteristics (individual and group pedestrian characteristics) along with geometric features using different tree-based machine learning algorithms. Previous researchers mainly used machine learning tools to predict the speed under controlled conditions, and regression modelling approach were mostly used in the studies related to sidewalks/ crosswalks. However, no such attempt was made over elevated walkways.

4.3.6.1. Site selection, data collection and data extraction for macroscopic speed modelling

In order to capture the factors affecting pedestrian speed, videographic data collection technique was used. The data were collected using high definition video cameras fixed over tripod stands at a height of approximately 4.5m from the ground. Firstly, the different FOB facilities were visited and the locations for final data collection were fixed accordingly. The duration of data collection over the mid-block section of the elevated facilities was approximately 3 hours, covering both peak and non-peak hours. For each location, the trap length varied between 10-12m and the effective width varied between 1.4-4.7m (mode details had been provided in previous chapter). The effective width was calculated after deducting the shy away or buffer distance from the actual width.

After the data collection, the data was processed in the lab using manual data extraction technique. As the aim of the study was to identify the factors affecting the pedestrian speed, individual microscopic parameters (such as age, gender, luggage condition, and mobile use) along with other macroscopic factors (such as average flow, and average density), and geometric factors (such as obstruction, land use type, time of data collection, length of facility, connectivity, and effective width) were considered while extracting the video data. The final data used was based on the discussion provided in Section 4.3.

4.3.6.2. Development of macroscopic speed prediction model

To obtain the essential parameters that determine the walking speed of pedestrians over elevated crossing facilities, in the current study different tree based modelling approaches (Gradient boosting machine, Light gradient boosting machine, Extreme gradient boosting, Adaboost regressor, Random forest, Extra trees regressor and Decision tree) were explored to predict the speed determinants of FOBs (regression: continuous outcome) through PyCaret 2.0 machine learning library using open-source programming language Python version 3.6.

4.3.6.3. Training and hyper-parameter tuning of model

In order to train the speed models PyCaret 2.0 machine learning library was utilized. The total sample was randomly split into 80% train and 20% test datasets. Comparing multiple models and tuning all type of hyper parameters could be time consuming; thus, initially a 10-fold Cross Validation (CV) was performed with default hyper-parameters to get a preliminary model with the best overall performance. The 10-fold CV models were trained with different tree-based models including ensembles. The models were trained, and the average performance of the CV was reported as shown in Table 4.17 using various regression metrics such as MAE, MSE, RMSE, R-square, RMSLE, MAPE and Training Time (TT). After training, the models were sorted based on the MAE criteria as this evaluation metric is robust and is not affected by outliers. The 10-fold CV result of FOB speed prediction models revealed that Light GBM topped in the overall performance (MAE: 9.52).

Table 4.17. FOB 10-fold cross validation model comparison summary

Model	MAE	MSE	RMSE	R^2	RMSLE	MAPE	TT (Sec)
Light Gradient Boosting Machine	**9.5222**	156.1118	12.4931	0.1821	0.1741	0.1412	0.1656
Gradient Boosting Regressor	9.9678	159.7075	12.6360	0.1633	0.1761	0.1430	0.4421
Extreme Gradient Boosting	10.1164	165.3125	128556	0.1339	0.1785	0.1450	0.2925
AdaBoost Regressor	10.2298	167.1052	129255	0.1245	0.1801	0.1476	0.1267
Random Forest	10.4801	177.0355	13.3036	0.0724	0.1843	0.1498	0.4159
Extra Trees Regressor	10.5308	178.0702	13.3659	0.0637	0.1851	0.1505	0.2789
Decision Tree	10.5314	178.7174	13.3664	0.0636	0.1851	0.1505	0.0198

4.3.6.4. Optimization of hyper-parameters for obtaining best fit model

To obtain the best performing model and to reduce overfitting, a random hyper-parameter search was performed. Random search is faster and computationally less expensive compared to complete grid search. For FOB speed model (using Light gradient boosting) the hyper-parameters used were number of leaves, maximum tree depth, learning rate, number of estimators, minimum split gain, regression alpha and lambda. The different hyper parameters used along with their range are presented in Table 4.18.

Table 4.18. Model hyper-parameter optimization

Model	Hyper-parameters
Light GBM	**num_leaves:** [10,20,30,40,50,60,70,80,90,100,150,200] **max_depth:** [10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110] **learning_rate:**[0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,1] **n_estimators:** [10, 30, 50, 70, 90, 100, 120, 150, 170, 200] **min_split_gain:** [0,0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9] **reg_alpha:** [0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9] **reg_lambda:** [0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9]

By default, PyCaret performs 10 random iteration over search space. Thus, to get highly optimized model the FOB models' hyper-parameters random iteration was set to 100. The training involved a 10-fold cross validation to get a better estimate (average) of the model performance. The MAE was selected as model evaluation metric. The FOB 10-fold CV hyper-parameter optimization results revealed an average MAE of 9.83 with a standard deviation of 0.18 (refer Table 4.19).

Table 4.19. Summary of tuned 10-fold CV FOB model performance

CV Folds	MAE	MSE	RMSE	R^2	RMSLE	MAPE
1	9.9122	157.8689	12.5646	0.1706	0.1771	0.1142
2	9.615	152.0792	12.332	0.1859	0.1676	0.1344
3	10.0371	161.5887	12.7118	0.1773	0.1735	0.1413
4	9.587	148.3798	12.1811	0.2091	0.1743	0.1413
5	9.9654	161.4407	12.7059	0.1914	0.1753	0.1412
6	9.7681	159.022	12.6104	0.1749	0.1793	0.1429
7	70.0032	156.811	12.5224	0.1616	0.1720	0.1421
8	9.5492	148.692	12.1939	0.2022	0.1701	0.1379
9	9.9868	156.9614	12.5284	0.1801	0.1739	0.1432
10	9.9733	160.7066	12.677	0.1555	0.1806	0.1471
Mean	**9.8397**	**156.355**	**12.5028**	**0.1809**	**0.1744**	**0.1416**
SD	**0.1817**	**4.72**	**0.1897**	**0.016**	**0.0038**	**0.0033**

The optimized model hyper parameters for FOB speed models are presented in the following Table 4.20.

Table 4.20. Optimized model parameters

Models	Model Hyper parameter
Light GBM Regressor	*num_leaves*: 20, *max_depth*: 20, *learning_rate*: 0:1, *n_estimators*: 90, *min_split_gain*: 0:2, *reg_alpha*: 0:1, *reg_lambda*: 0:1

4.3.6.5. Validation of macroscopic speed prediction model

Further, for obtaining model performance on unseen test dataset, the final model was tested on the remaining 20% test dataset. Table 4.21 shows the model performance summary on the test data set.

Table 4.21. Summary of FOB model performance estimated on the test dataset

Model	MAE	MSE	RMSE	R^2	RMSLE	MAPE
Light Gradient Boosting Machine	9.9602	156.3941	12.5058	0.1938	0.1760	0.1447

The performance summary revealed that the overall optimized LGBM speed prediction model *(based on MAE: 9.96)* performed well on the unseen/test dataset.

4.3.6.6. Application of the developed macroscopic model

The Light GBM was found to perform best on test dataset. The main advantage of tree based regressor is that it provides the global importance scores of each feature which explains the contribution of different predictors in the model. Still, these high end blackbox models lack interpretability as they do not provide the direction of impact, i.e., whether the model variables have positive or negative influence. Thus, to trust a blackbox model the understanding of inner workings are essential. Lundberg (2017) proposed the SHAP (SHapley Additive exPlanations) values method which is fast and offers a high level of interpretability for a model. In the present study, the "shap" library was utilized to interpret the existing trained models. The SHAP values were estimated for tuned Light GBM on the test data and were plotted using a summary plot (refer Figure 4.14). The summary plot not only provides the variable importance in descending order but also illustrates the positive/ negative relationship with the outcome variable. The y-axis shows different variables (top five predictors) while the x-axis shows SHAP values ranging from negative to positive. The feature value is illustrated with blue and red colour gradients. Red colour indicates high feature value, while blue indicates a low feature value.

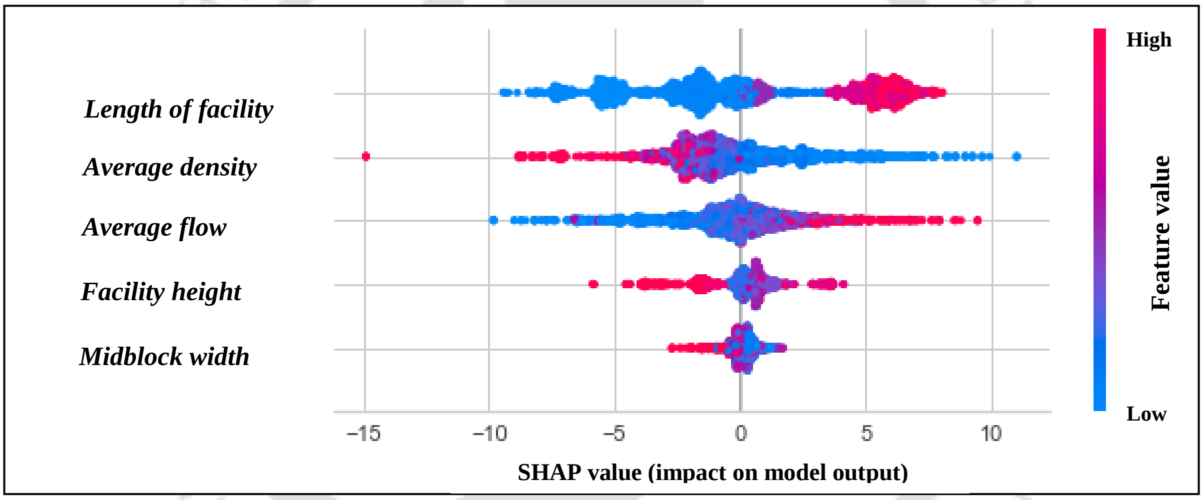


Figure 4.14. Variable impact of FOB walking speed model

The feature importance plot of FOB model illustrated crucial findings which influenced walking speed over FOBs (refer Figure 4.14). The most important feature was length of the facility which determines the walking speed. In FOBs, after climbing the stairs (in most of the FOBs considered, stairways were the only form of vertical connectivity), pedestrians feel tired. Due to this tiredness, the pedestrian speed was initially observed to be a little slower. However, with the increase in length of the FOB as the pedestrians approach the middle section, this impact on pedestrian speed towards the middle portion of the FOB (where the data was collected) does not show much variability in speed. From Figure 4.1.4, average density values had a wider range and negative relationship with walking speed. As the average density increased, the space for faster movement reduced and thus pedestrians' walking speeds also reduced. The impact of width and height of the facility on the pedestrian speed is not clear, and this necessitates data requirement over a wider range of facilities to establish a concrete relationship. The impact of the flow parameter reflected here is somewhat unclear or contradictory. Such behavior of flow is reflected as few sites for FOBs were in congested conditions (i.e. speed increases with increase in flow under congested regime), as opposed to most of the other sites which were in free flow condition with lower densities. Observation of pedestrian speed data over a wide range of densities in most sites might resolve this ambiguity.

4.4. Pedestrian characteristics on midblock sections of skywalk

In total 7 skywalk mid-block locations were used for analysis. Table 4.22 shows the demographic and geometric details for all the skywalk locations. The average width and length of mid-block sections observed were 2.7m and 600m respectively. The average number of samples collected per location was 1505. The percentage of male pedestrians observed was 77.1% across the seven skywalk locations. Pedestrians of age group of 21-40 years were in majority (64.9%), with 41-60 years and 11-20 years being 11.0% and 18.7%, respectively. The proportion of pedestrians carrying luggage was significantly higher (66.4%), with locations S1 and S3 having more than 85% users with luggage. The average percentage of mobile users was nearly 15%, with locations S2 and S5 having more than 21% pedestrians using mobile phones while walking. The data observed across all locations showed that majority of the pedestrians were walking alone without forming groups, while at location S7 nearly 39% pedestrians were observed to walk in groups of 2 or 3 pedestrians. Higher percentage of pedestrians walking in groups of 4 or more was observed at locations S4 (5.9%) and S5 (4.4%).

The mid-block data observed in Table 4.22 was further used for analysis including different statistical tests, fundamental diagram development, simulation modelling, and walking speed prediction modelling over skywalk facilities. Further, location S2 was used to understand the pedestrian gap maintaining behaviour over skywalk facilities.

4.4.1. Pedestrian speed data aggregated from all skywalk mid-block sections

To get an aggregated pedestrian behaviour over different skywalk midblock sections as well as understand the overall walking behaviour, the data across all the locations were combined together and used for studying the descriptive statistics, normality and probability density functions.

Table 4.22. Details of skywalk locations with demographic characteristics

Location	Geometry		Sample size	Demographic characteristics (in percentage)														
				Gender		Age					Luggage		Mobile Use		Group size			
	Width (m)	Length (m)		Male	Female	≤10	11-20	21-40	41-60	≥60	With	Without	With	Without	1	2	3	≥4
Andheri (S1)	2.5	581	2096	73.9	26.1	0.1	7.6	78.2	12.7	1.4	89.2	10.8	11.3	88.7	95.6	3.4	0.6	0.4
Goregaon (S2)	3.4	625	1622	93.0	7.0	0.6	3.6	76.2	16.6	3.0	66.2	33.8	21.2	78.8	75.5	19.3	3.6	1.6
Ghatkopar (S3)	2.7	315	1737	70.5	29.5	0.2	17.7	64.6	13.6	3.9	84.1	15.9	12.7	87.3	86.1	9.6	2.9	1.4
Bandra (S4)	2.7	494	1056	78.1	21.9	2.1	10.4	57.3	21.9	8.3	45.5	54.5	11.9	88.1	61.1	21.1	11.9	5.9
Vile Parle (S5)	3.0	460	1431	72.9	27.1	2.5	20.6	44.4	28.3	4.2	71.0	29.0	22.9	77.1	66.7	19.1	9.8	4.4
Santa Cruz (S6)	2.6	438	1329	71.0	29.0	1.1	10.3	66.3	17.5	4.8	65.6	34.4	13.1	86.9	76.6	20.2	2.0	1.2
Kalyan (S7)	2.0	1287	1264	80.4	19.6	1.3	6.5	67.2	20.2	4.8	43.2	56.8	10.3	89.7	57.9	31.2	7.5	3.4
Overall	***2.7***	***600***	***1505***	***77.1***	***22.9***	***1.1***	***11.0***	***64.9***	***18.7***	***4.3***	***66.4***	***33.6***	***14.7***	***85.3***	***74.2***	***17.2***	***5.5***	***2.6***

4.4.1.1. Descriptive statistics for aggregated speed data

Table 4.23 was used to determine the descriptive statistics of the skywalk mid-block data across the seven different locations.

Table 4.23. Descriptive statistics of skywalk mid-block data

	Mean (m/min)	Median (m/min)	Variance	Std. Deviation	Minimum (m/min)	Maximum (m/min)	Skewness	Kurtosis
Statistic	78.95	78.70	168.94	12.99	25.64	114.90	0.037	0.037
Standard Error	0.12						0.023	0.047

The descriptive statistics from Table 4.23 showed that the mean speed over the seven selected skywalk mid-block locations was 78.95m/min. The minimum and maximum speeds observed were 25.64m/min and 114.90m/min. The skewness value of 0.037 showed that the data was positively skewed with majority of the data towards normal distribution.

4.4.1.2. Normality test for aggregated speed data

Histogram was plotted to have a rough estimation about the normality of the data. Figure 4.15 shows the walking speed distribution over skywalk mid-block sections at 95% confidence level.

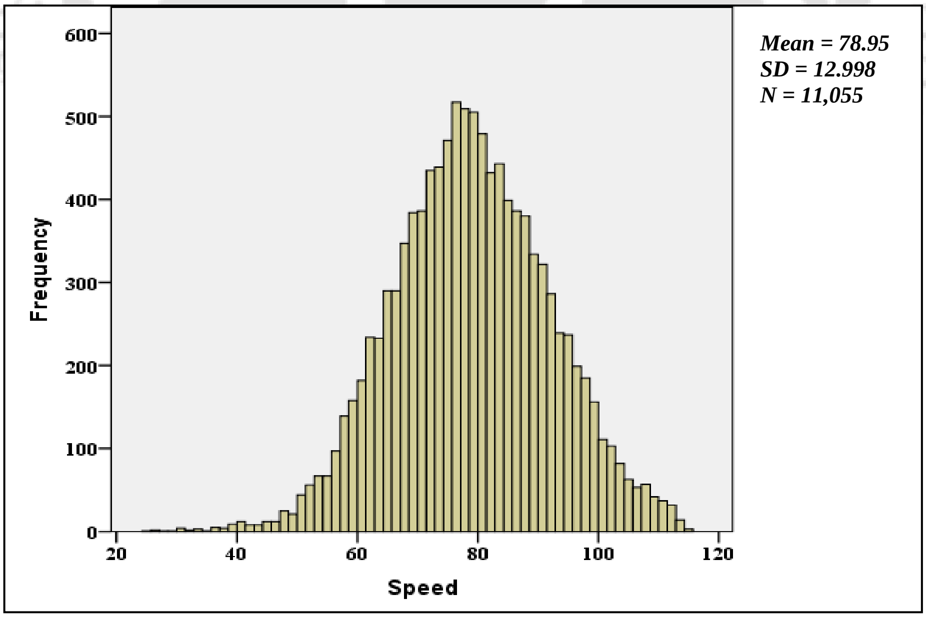


Figure 4.15. Histogram plot for skywalk mid-block speed data

Figure 4.15 showed that the data was normally distributed with mean and standard deviation of 78.95m/min and 12.99 respectively over the seven selected skywalk mid-block sections.

Further, normality test was conducted in SPSSv20 using K-S test statistics which showed that the significance (P-value) was 0.158. As the P-value was above 0.05, thus the test was insignificant and the data is normally distributed.

To determine the level of normality of the mid-block data, normal Q-Q plots were presented in Figure 4.16. It was evident that since data points were closer to the diagonal line, the data were normally distributed.

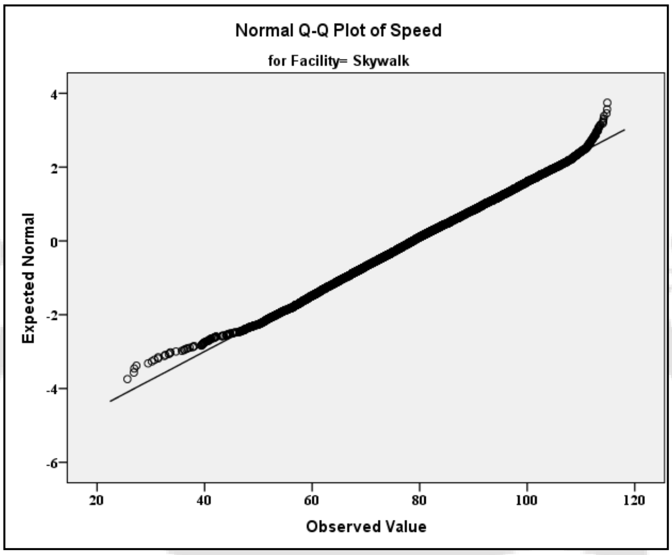


Figure 4.16. Normal Q-Q plot of aggregated walking speed for mid-block section of skywalks

4.4.1.3. Probability density functions for aggregated speed data

Probability density functions were plotted to understand the speed variation based on gender, age, luggage condition, mobile use and group size. Figure 4.17(a-e) shows the speed distributions over seven skywalk mid-block locations. The x-axis represents the mean walking speed (in m/min) and the y-axis shows the relative frequency.

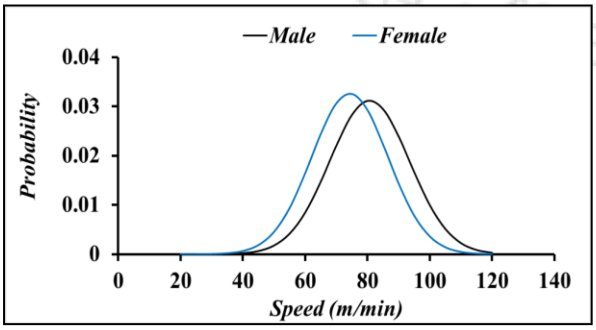


Fig. (a). Speed distribution based on gender

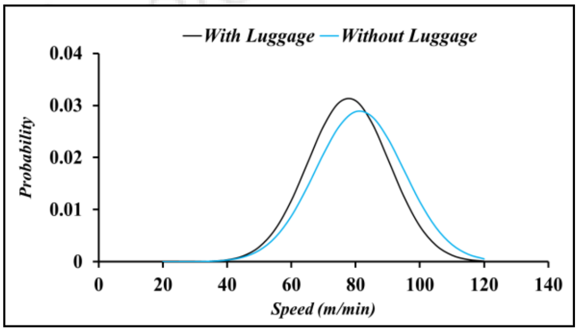


Fig. (b). Speed distribution based on luggage condition

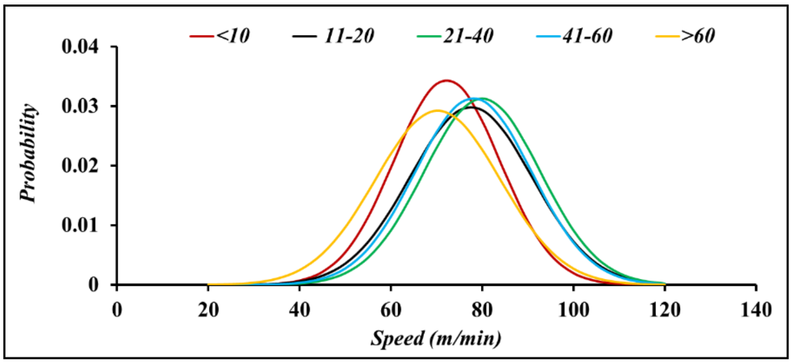


Fig. (c). Speed distribution based on age

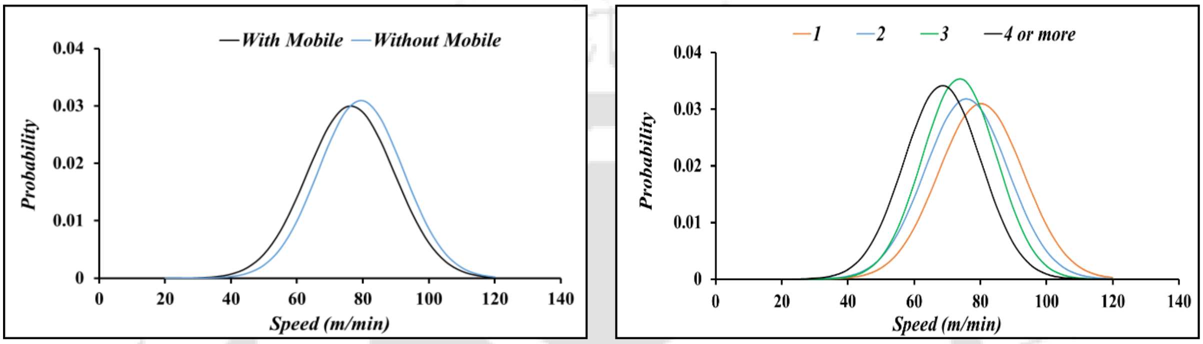


Fig. (d). Speed distribution based on mobile use

Fig. (e). Speed distribution based on group sizes

Figure 4.17. Speed distribution based on pedestrian gender, luggage condition, age, mobile use and group size

Figure 4.17(a) showed that the female pedestrians had lower walking speeds (by 6m/min) in comparison to the male pedestrians over skywalk mid-block sections. As per Figure 4.17(b), the pedestrians without luggage had higher walking speeds than the ones with luggage by 4m/min. The pedestrians in the age group of 11-20 years and 41-60 years had similar walking trends as observed in Figure 4.17(c). However, the pedestrians in the age group of 21-40 years had the highest mean walking speed of 80m/min. From Figure 4.17(d), the pedestrians using mobile phones had a 3m/min lower walking speed than those without mobile phones. As expected, the walking speed distribution for group size (Figure 4.17e) showed that the pedestrians mean walking speed kept on decreasing with the increase in the size of the groups.

4.4.2. Speed variation based on pedestrian characteristics for different skywalk mid-block sections

4.4.2.1. Box and whisker plots of speed based on pedestrian characteristics

To identify the lower, median and upper quartile ranges along with the skewness of the distribution based on gender, age, luggage, mobile use and group size for every mid-block locations, box and whisker plots were plotted. Figure 4.18-Figure 4.22 shows the box and whisker plots of the speed distribution for the seven skywalk mid-block locations.

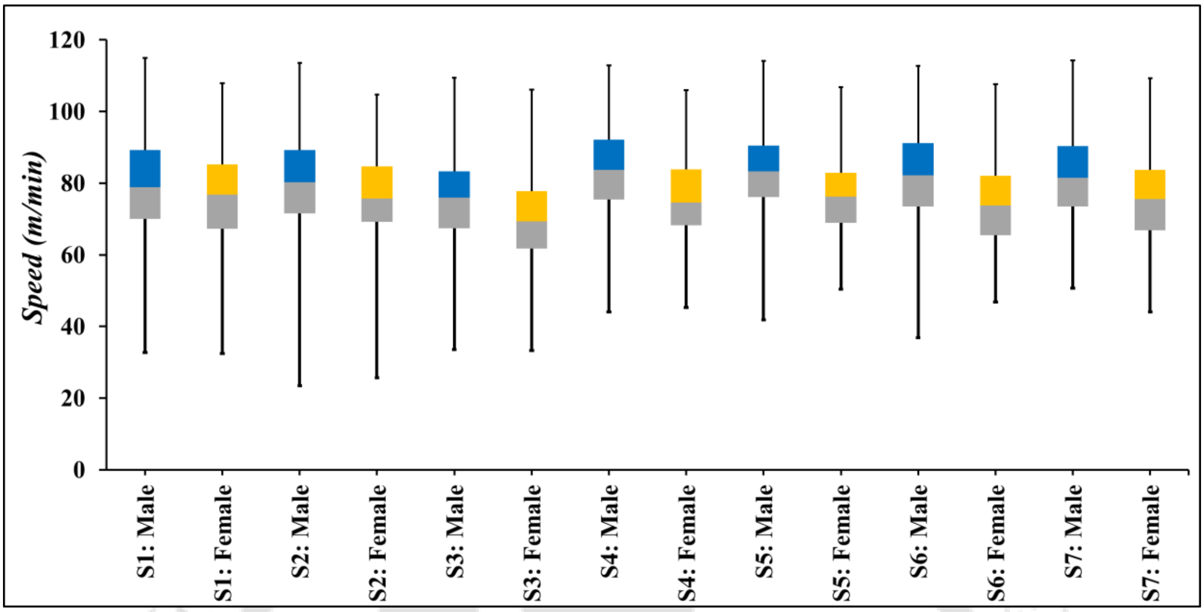


Figure 4.18. Effect of gender on speed variation for all skywalk locations

From Figure 4.18 it was observed that male pedestrian had higher median walking speeds in comparison to the female pedestrian across all skywalk locations. The highest median walking speed was observed at locations S4 and S5 as majority of the pedestrians were office goers or students travelling to their respective workplaces.

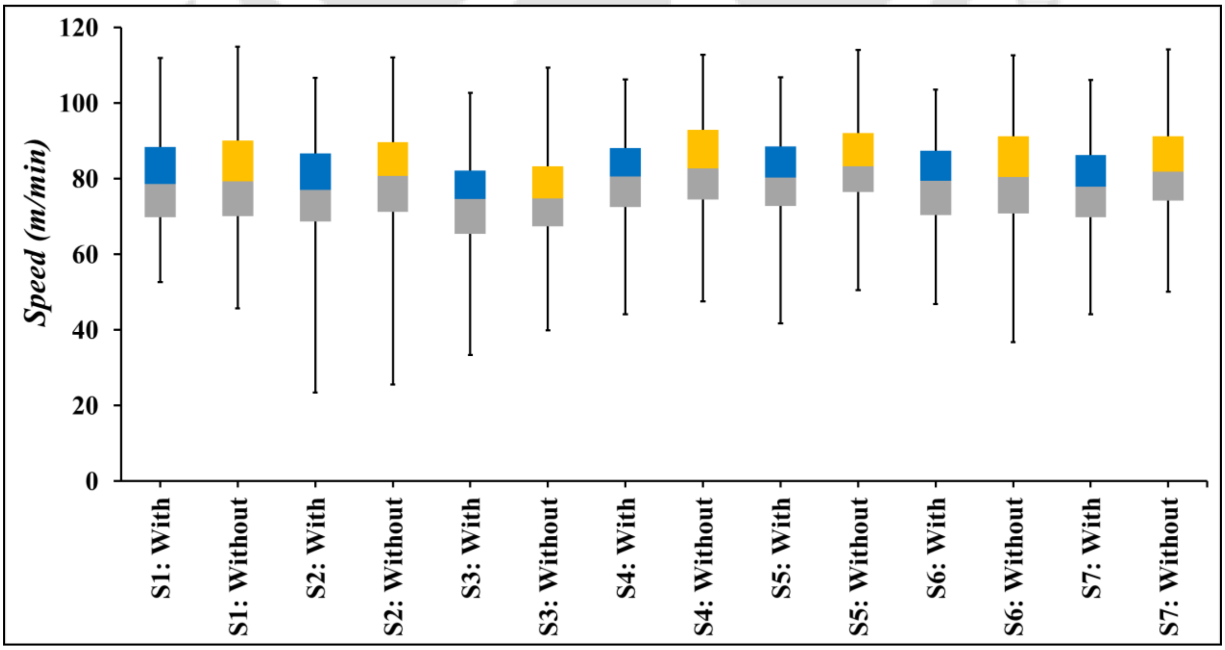


Figure 4.19. Effect of luggage condition on speed variation for all skywalk locations

Figure 4.19 showed that at locations S2 and S5 the median speed variation between pedestrians with and without luggage was 3m/min, while in the case of other locations not much difference was observed between the pedestrians with and without luggage.

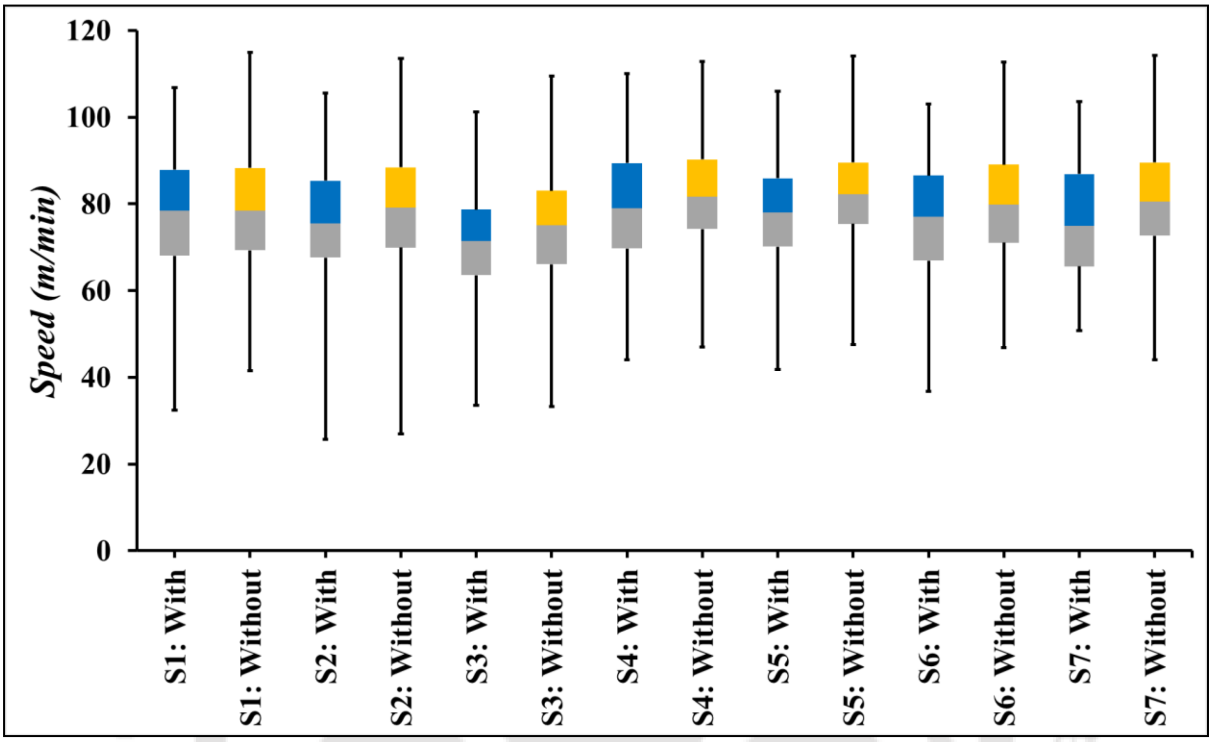


Figure 4.20. Effect of mobile use on speed variation for all skywalk locations

Apart from location S1, all other locations showed significance difference in the median walking speeds between pedestrian with and without mobile phones (as per Figure 4.20). The difference between the pedestrians' speed with and without mobile at S1 was insignificant as pedestrians were moving with the heavy flow during peak hour. The pedestrian without mobile were observed to walk at higher median speeds (by 2-6m/min).

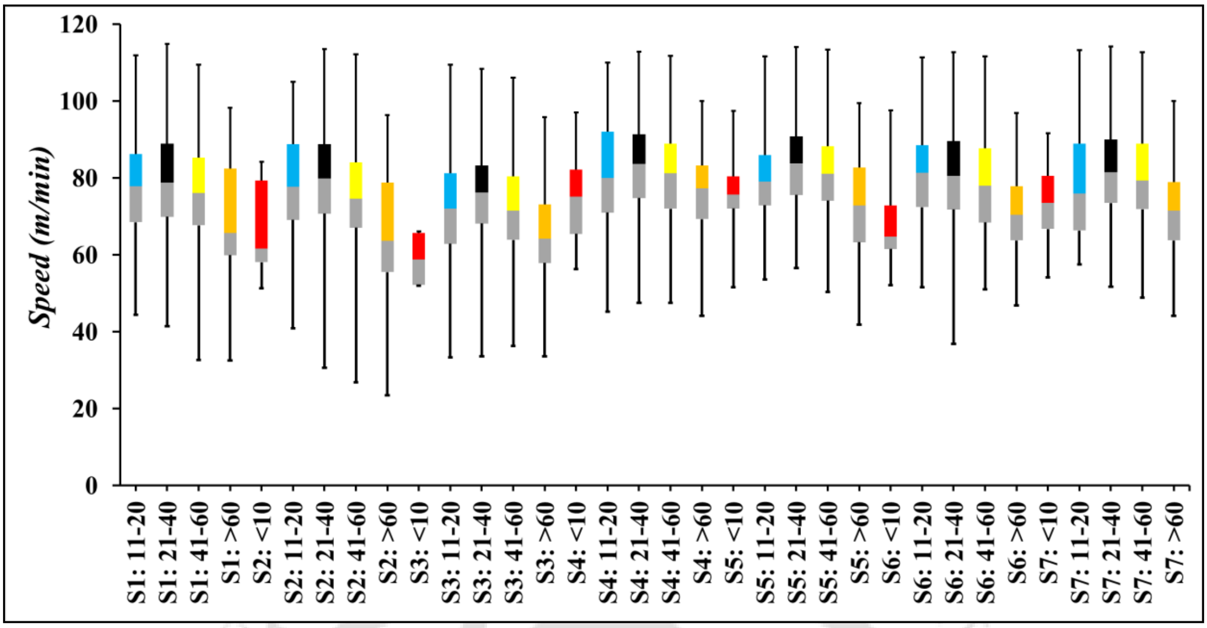


Figure 4.21. Effect of age on speed variation for all skywalk locations

From Figure 4.21, it was observed that across all the locations, age category of 21-40 years had the highest walking median speed among different age categories. The pedestrians in the age category ≤10 years and ≥60 years had the lowest median speed across different locations. At location S3, the pedestrians had lower walking speeds in comparison to the similar age groups in other locations, as S3 was majorly a residential location where pedestrians tend to walk in relaxed mode. Due to the low sample size of pedestrians in the age group ≤10 years, box plot was not constructed for S1 location.

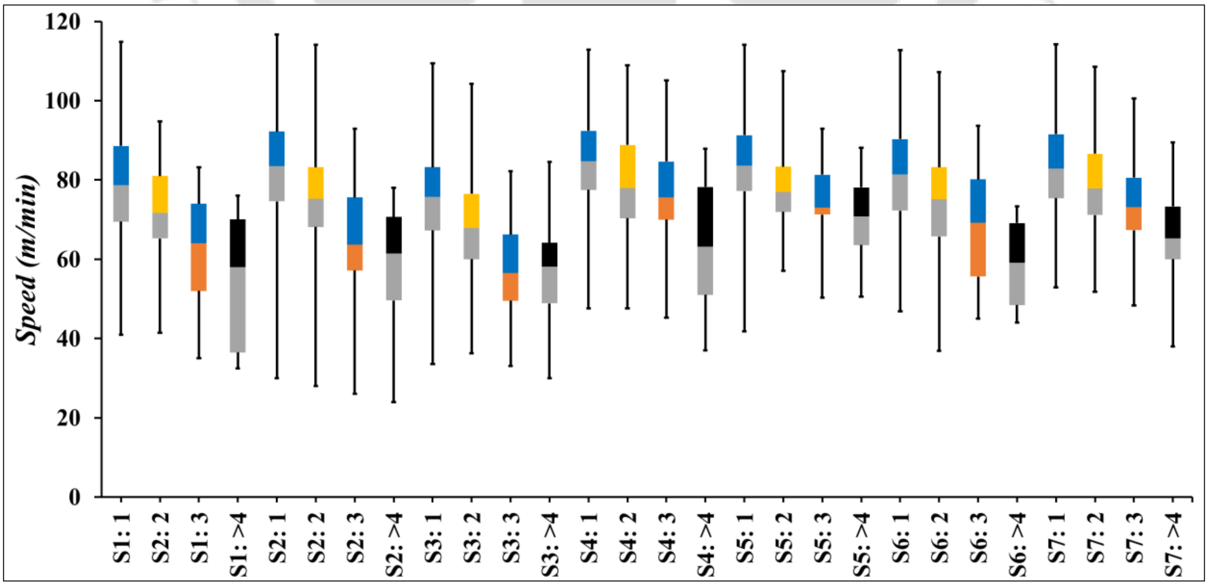


Figure 4.22. Effect of group size on speed variation for all skywalk locations

The group wise speed distribution (from Figure 4.22) showed that for all the locations, the drop in median speed from group size of a single pedestrian to four or more pedestrians was 9-16m/min.

4.4.2.2. Statistical tests to identify the differences in pedestrian speed behaviour among different skywalks

In order to understand whether significant difference existed between different pedestrian categories, statistical tests (t-test and ANOVA single factor test) were carried out over the mid-block section data. The t-test (shown in Table 4.24) was performed on gender (male/ female), luggage (with/ without) and mobile phone (using/ not using), while ANOVA test (shown in Table 4.25) was performed on age (≤10, 11-20, 21-40, 41-60 and ≥60 years) and group size (1, 2, 3 and ≥4 pedestrians).

Table 4.24. t-test results based on gender, luggage condition and mobile use for skywalk facility

Location	**Type of pedestrian category**								
	Gender			***Luggage***			***Mobile usage***		
	t-Stat	***t- Crit***	***Sig.***	***t-Stat***	***t-Crit***	***Sig.***	***t-Stat***	***t-Crit***	***Sig.***
Andheri (S1)	5.76	1.96	SIG	2.52	1.96	SIG	2.73	1.96	SIG
Goregaon (S2)	4.38			4.69			4.17		
Ghatkopar (S3)	8.99			2.47			4.04		
Bandra (S4)	9.59			3.82			2.89		
Vile Parle (S5)	11.34			5.30			5.51		
Santa Cruz (S6)	11.18			2.61			3.22		
Kalyan (S7)	7.62			6.62			4.01		

Note: *t-Stat: t-Statistical value, t-Crit: t-Critical value, Sig.: Significance, SIG: Significant*

The t-test results presented in Table 4.24 showed that significant difference existed between different gender, luggage and mobile user groups across all skywalk locations.

Table 4.25. ANOVA single factor test results for skywalk facility

Location	**Type of pedestrian category**					
	Age			***Group size***		
	F-Stat	***F- Crit***	***Sig.***	***F-Stat***	***F-Crit***	***Sig.***
Andheri (S1)	8.06	2.37	SIG	13.33	2.61	SIG
Goregaon (S2)	26.70			45.76		
Ghatkopar (S3)	23.45			37.67		
Bandra (S4)	7.74			38.75		
Vile Parle (S5)	13.98			49.89		
Santa Cruz (S6)	11.99			25.15		
Kalyan (S7)	14.05			33.46		

Note: *F-Stat: F-Statistical value, F-Crit: F-Critical value, Sig.: Significance, SIG: Significant, ISIG: Insignificant*

ANOVA test results presented in Table 4.25 showed that significant difference existed between the different age group and group sizes for all skywalk locations.

4.4.3. Development of fundamental diagram for skywalk mid-block sections

To observe the relationship between the different macroscopic parameters, Table 4.26 provides the different mathematical models developed for the 7 skywalk study locations. Later, a generalized model considering all the data from different skywalks was also developed. Table 4.26 presents the different speed-density, speed-flow, flow-density and flow-area module relationships along with R^2 values for each skywalk location.

Figure 4.23(a-d) were plotted for speed-density, flow rate-density, speed-flow rate, and flow rate-area module relationships for the seven different skywalk mid-block sections combined. These fundamental diagrams give an overall view of the existing condition of the skywalks.

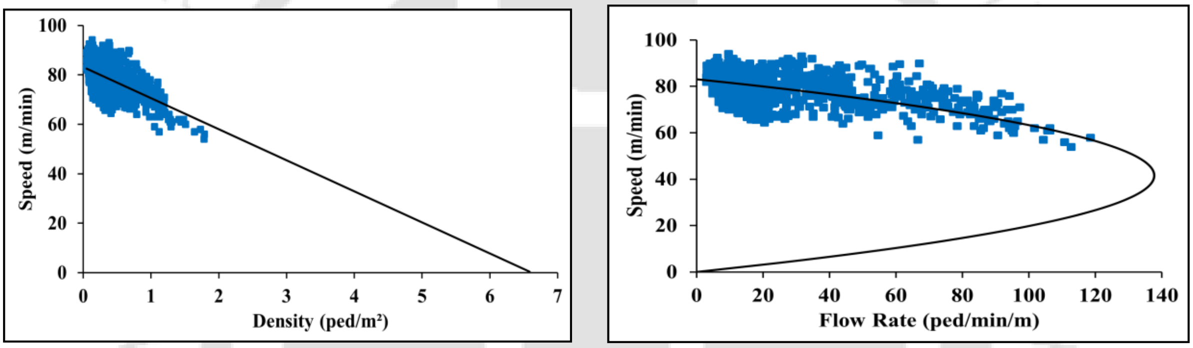


Fig. (a). Speed-Density relationship **Fig. (b).** Speed-Flow Rate relationship

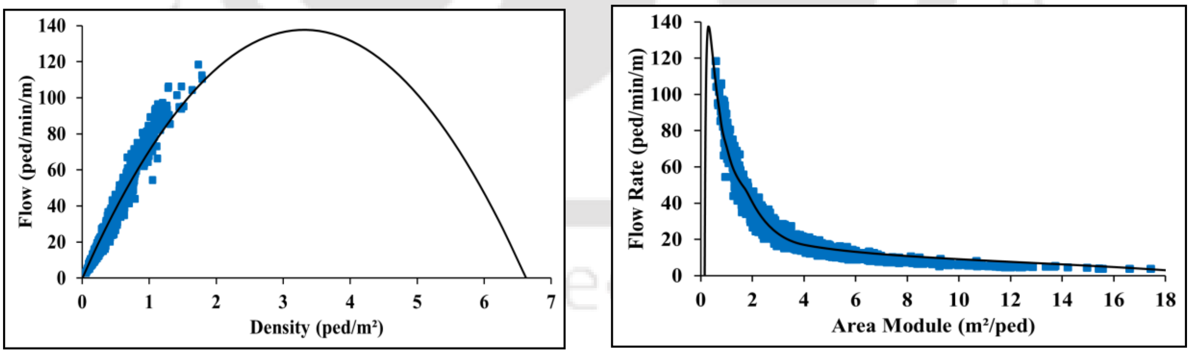


Fig. (c). Flow Rate-Density relationship **Fig. (d).** Flow Rate-Area Module relationship

Figure 4.23. Fundamental relationship diagrams of macroscopic parameters for combined data from all the sites

Table 4.26. Pedestrian flow models for skywalk locations

Study Location	**Speed-Density**		**Speed-Flow**		**Flow-Density**		**Flow-Area module**	
	Relationship	***R^2 value***	***Relationship***	***R^2 value***	***Relationship***	***R^2 value***	***Relationship***	***R^2 value***
Andheri (S1)	$v = 93.713 – 18.011*k$	0.623	$q = 5.203*u - 0.0555*u^2$	0.913	$q = 93.713*k – 18.011*k^2$	0.886	$q = 93.713/M - 18.011/M^2$	0.879
Goregaon (S2)	$v = 87.369 – 48.663*k$	0.485	$q = 1.795*u - 0.0205*u^2$	0.802	$q = 87.369*k – 48.663*k^2$	0.795	$q = 87.369/M - 48.663/M^2$	0.827
Ghatkopar (S3)	$v = 81.548 – 32.444*k$	0.471	$q = 2.513*u - 0.0308*u^2$	0.786	$q = 81.548*k – 32.444*k^2$	0.754	$q = 81.548/M - 32.444/M^2$	0.805
Bandra (S4)	$v = 89.438 – 23.505*k$	0.551	$q = 3.805*u - 0.0425*u^2$	0.868	$q = 89.438*k – 23.505*k^2$	0.842	$q = 89.438/M - 23.505/M^2$	0.853
Vile Parle (S5)	$v = 89.008 – 43.092*k$	0.519	$q = 2.065*u - 0.0232*u^2$	0.837	$q = 89.008*k – 43.092*k^2$	0.821	$q = 89.008/M - 43.092/M^2$	0.843
Santa Cruz (S6)	$v = 88.073 – 40.348*k$	0.487	$q = 2.182*u - 0.0247*u^2$	0.811	$q = 88.073*k – 40.348*k^2$	0.803	$q = 88.073/M - 40.348/M^2$	0.823
Kalyan (S7)	$v = 88.334 – 24.214*k$	0.596	$q = 3.648*u - 0.0413*u^2$	0.899	$q = 88.334*k – 24.214*k^2$	0.855	$q = 88.334/M - 24.214/M^2$	0.869
Overall	**$v = 83.133 – 12.547*k$**	**0.527**	**$q = 6.625*u - 0.0797*u^2$**	**0.853**	**$q = 83.133*k – 12.547*k^2$**	**0.838**	**$q = 83.133/M - 12.547/M^2$**	**0.844**

Figure 4.23(a) showed that the overall FFS for the different locations combined was 83.13m/min with the predicted jam density around 6.62ped/m^2. From Figure 4.23(c) the maximum flow rate predicted was 138ped/min/m occurring at an optimum density of 3.35ped/m^2. The optimum speed at the maximum flow rate was predicted to be 42.1m/min. Moreover, the area module predicted at maximum flow was 0.29m^2/ped.

Table 4.27 shows the pedestrian flow characteristics (i.e., FFS, q_{max}, area module at q_{max}, optimum speed and optimum density) for the different skywalk locations.

Table 4.27. Pedestrian flow characteristics for different skywalk mid-block sections

Location	**Free Flow Speed (u_f), m/min**	**Maximum Flow Rate (q_{max}), ped/min/m**	**Area Module (M), at q_{max} (m^2/ped)**	**Optimum speed (m/min)**	**Optimum Density (ped/m^2)**
Andheri (S1)	93.71	120.11	0.37	43.2	2.77
Goregaon (S2)	87.36	47.06	1.05	45.9	1.05
Ghatkopar (S3)	81.55	66.59	0.61	41.4	1.63
Bandra (S4)	89.44	85.07	0.52	45.8	1.89
Vile Parle (S5)	89.01	55.15	0.82	45.4	1.23
Santa Cruz (S6)	88.07	57.64	0.78	44.8	1.28
Kalyan (S7)	88.33	96.64	0.42	45.1	2.14

From Table 4.27, it was observed that for location S1, at a maximum predicted flow rate (q_{max}) of 120.11ped/min/m, an area module of 0.37m^2/ped was observed. The maximum space (1.05m$^{2/}$ped) was available at location S2 at a flow rate of 47.06ped/min. The optimum speed at maximum capacity across all locations ranged between 41-46m/min. The highest optimum density was predicted at locations S1 (primarily commercial area) of 2.77ped/m^2. As the observed data were available mostly for lower to moderate ranges of density, capacity values predicted by the fundamental relationships in Table 4.27 could have some variations.

4.4.4. Development of simulation model

The global simulated model developed in section 4.3.4 with similarities (i.e. purpose of segregating pedestrian traffic from vehicular traffic, enhancing comfort and safety; geometric design standards, and effect of vertical connectivity) between the two types of elevated facilities (FOBs and skywalks) which could represent the walking behaviour of pedestrians over any elevated walkway section, was used in the present section as well.

The data collected over the different skywalks were used for extraction of microscopic parameters such as age, gender and luggage conditions. The steps carried out during model development included creation of a global model (developed in section 4.3.4) which could replicate the walking behaviour over elevated walkways using PTV Viswalk software, feeding the pedestrian types into the model, carrying our sensitivity analysis of different Viswalk parameters, using genetic algorithm through COM interface for model calibration, and finally validating of the model using new data set.

Using the global calibrated model (developed in section 4.3.4.2) with the calibrated parameters (ASocIsotropic, BSocIsotropic, ASocMean, Tau and VD), validation was carried out for the skywalk sections having different walking widths. Table 4.28 shows the MAPE values for the different locations.

Table 4.28. Validation of skywalk facilities

Location ID	Width	MAPE (%)
S1	2.5	18.79
S2	3.4	5.93
S3	2.7	6.16
S4	2.7	8.24
S5	3.0	10.22
S6	2.6	8.71
S7	2.0	13.36

As per Lewis scale of interpretation, the MAPE value range (5.93-18.79%) in Table 4.28 were observed to be within required limits. This indicated that the model was able to predict the walking behaviour over skywalk facilities quite well and the calibrated parameters could be used for development of elevated walkway simulation models also. To improve the global simulated model accuracy further, Viswalk model can be calibrated for each skywalk separately.

4.4.5. Development of speed models over skywalk mid-block sections using microscopic pedestrian behaviour parameters

An individual pedestrian's walking behaviour is greatly impacted by his/ her age, gender, luggage condition, use of hand held devices (mobiles), direction of movement, and whether the pedestrian is differently abled or not. Similarly, when a group of pedestrians are walking together then different group characteristics such as the size of the group, lane formation, leader follower relationship, squeezing effect, faster-is-slower effect, overtaking and lane shifting influence the walking behaviour. In the current section an attempt was made to understand the impact of different individual behaviour characteristics (age, Gen: gender, Lug: luggage carrying conditions, Mob: mobile use and Dis: disability) and group behaviour characteristics (GS: group size, LF: lane formation, LFR: leader-follower relationship, LS: lane shifting, Over: overtaking, SE: squeezing effect and FSE: faster-is-slower effect) on the walking speed of the pedestrians over mid-block sections of skywalk facilities.

4.4.5.1. Descriptive statistics of the field skywalk data

Table 4.29 shows the descriptive statistics of the seven different mid-block sections considered for the study.

Table 4.29. Demographic characteristics of walking behaviour over skywalk sections

Characteristics		**Locations**						
		S1	***S2***	***S3***	***S4***	***S5***	***S6***	***S7***
Sample size		2096	1622	1737	1056	1431	1329	1264
Age (%)	*≤10*	0.1	0.6	0.2	2.1	2.5	1.1	1.3
	11-20	7.6	3.6	17.7	10.4	20.6	10.3	6.5
	21-40	78.2	76.2	64.6	57.3	44.4	66.3	67.2
	41-60	12.7	16.6	13.6	21.9	28.3	17.5	20.2
	≥60	1.4	3.0	3.9	8.3	4.2	4.8	4.8
Gen (%)	*Male*	73.9	93.0	70.5	78.1	72.9	71.0	80.4
	Female	26.1	7.0	29.5	21.9	27.1	29.0	19.6
Luggage (%)	*With*	89.2	66.2	84.1	45.5	71.0	65.6	43.2
	Without	10.8	33.8	15.9	54.5	29.0	34.4	56.8
GS (%)	*1*	95.6	75.5	86.1	61.1	66.7	76.60	57.9
	2	3.4	19.3	9.6	21.1	19.1	20.20	31.2
	3	0.6	3.6	2.9	11.9	9.8	2.00	7.5
	≥4	0.4	1.6	1.4	5.9	4.4	1.20	3.4
Mob (%)	*With*	11.3	21.2	12.7	11.9	22.9	13.1	10.3
	Without	88.7	78.8	87.3	88.1	77.1	86.9	89.7
Dis (%)	*With*	0.57	0.12	0.46	0.28	0.28	0.15	0.24
	Without	99.43	99.88	99.54	99.72	99.72	99.85	99.76
LF (%)	*With*	95.56	38.29	78.76	23.39	67.30	20.09	41.38
	Without	4.44	61.71	21.24	76.61	32.70	79.91	58.62
LFR (%)	*With*	26.96	13.26	2.59	9.66	24.53	3.99	20.17
	Without	73.04	86.74	97.41	90.34	75.47	96.01	79.83

FSE (%)	*With*	0.29	3.27	0.06	0.66	0.35	0.60	0.32
	Without	99.71	96.73	99.94	99.34	99.65	99.40	99.68
SE (%)	*With*	1.24	0.74	0.63	0.19	0.21	0.15	0.08
	Without	98.76	99.26	99.37	99.81	99.79	99.85	99.92
Over (%)	*With*	5.20	11.41	7.54	8.71	17.82	6.02	0.16
	Without	94.80	88.59	92.46	91.29	82.18	93.98	99.84
LS (%)	*With*	42.18	35.70	25.85	13.54	24.32	19.11	18.59
	Without	57.82	64.30	74.15	86.46	75.68	80.89	81.41
Speed (m/min)	*Mean*	78.90	78.30	74.43	81.94	81.56	79.49	80.61
	Median	78.44	78.31	74.65	81.55	81.11	79.34	80.23
	S.D.	13.72	13.89	12.32	12.22	11.15	12.79	12.08

From Table 4.29 it was observed that across all seven skywalk mid-block locations, male pedestrians in the age group of 21-40 years were the dominant group. At location S5, it was observed that 49% pedestrians were in the combined age group of 11-20 and 41-60 years. At location S2, 93% pedestrians were male with only 7% female pedestrians. In majority of the locations, pedestrians with luggage were significantly higher than the ones without luggage. However, at locations S4 and S7, approximately 55% pedestrians walked without luggage. Group size of two or more pedestrians were observed frequently at locations S4-S7. The group size of 4 or more pedestrian was highest at location S4. At location S1, the group size of two or more was less visible as pedestrians were moving in a crowd and it was difficult to distinguish the group size. Highest percentage of pedestrians using mobile (22.9%) was observed at location S5. The percentage of pedestrians with disability was quite low across all locations, except location S1. The lane formation phenomenon was observed to be extremely high at location S1 (95%), followed by S3 (79%) and S5 (67.3%). Leader follower relationship was mostly predominant in the locations S1, S5 and S7. Faster-is-slower and squeezing effects were rare phenomenon mainly observed at location S1. Overtaking behaviour was mostly observed at locations S2 (11.4%) and S5 (17.8%). The phenomenon of lane shifting was quite common among pedestrians across all the locations. The highest mean speed observed considering all the individual and group pedestrian characteristics was at location S4, while the lowest was observed at S3.

4.4.5.2. Statistical test on walking behaviour over different skywalk mid-block sections

A significance test was conducted using SPSSv20 for checking the p-values based on K-S hypothesis testing results. Table 4.30 shows the results of the K-S test.

Table 4.30. Significance test results for different considered variables of skywalks sections

Section	Lane Shift	Overtake	LFR	LF	Mobile	Luggage	Gender	Age	Group
S1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S2	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000	0.000
S3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S6	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S7	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Note: *LFR- Leader-follower relationship, LF- Lane formation*

From Table 4.30, p-values were observed to be less than 0.05 for all cases, thus significant difference existed between the different variables considered.

Further correlation analysis was carried out to understand the relationship between the different variables considered. A value of *r* less than 0.3 indicates weak relationship. Table 4.31 shows the results of the correlation analysis. In order to develop the walking behaviour model, different variables were coded as: age *(0: <10, 1:11-20, 2: 21-40, 3: 41-60, 4: >60)*, gender, luggage *(0: with, 1: without)*, group size *(0: Single pedestrian, 1: Two pedestrians, 2: Three pedestrians, 3: Four or more pedestrians together)*, mobile use *(0: with, 1: without)*, disability *(0: with, 1: without)*, lane formation *(0: with, 1: without)*, leader-follower relationship *(0: with, 1: without)*, faster-is-slower effect *(0: with, 1: without)*, squeezing effect *(0: with, 1: without)*, overtaking *(0: with, 1: without)*, and lane shifting *(0: with, 1: without)*.

Table 4.31. Correlation analysis for all the variables considered for skywalks sections

	Age	Gen	Lug	GS	Mob	Dis	LF	LFR	FS	SE	Over	LS	Speed
Age	1.00	-0.15	0.07	-0.05	0.02	-0.03	0.05	0.03	0.01	0.00	0.01	0.03	-0.06
Gen		1.00	-0.11	0.11	-0.02	0.02	-0.04	-0.01	0.00	0.00	0.05	0.01	-0.21
Lug			1.00	0.12	0.00	0.02	0.11	-0.01	0.02	0.03	-0.08	0.05	0.14
GS				1.00	0.01	0.01	0.07	-0.05	0.01	0.00	0.03	0.09	-0.20
Mob					1.00	0.01	0.03	0.05	0.01	0.00	0.06	0.00	0.09
Dis						1.00	0.00	-0.01	0.00	0.03	-0.01	0.00	0.06
LF							1.00	0.07	0.06	0.02	-0.03	0.06	0.12
LFR								1.00	0.16	0.04	0.06	0.08	0.08
FS									1.00	0.05	0.02	0.07	0.01
SE										1.00	0.01	0.08	0.05
Over											1.00	0.23	-0.20
LS												1.00	-0.09
Speed													1.00

Note: *Gen-Gender, Lug-Luggage, GS-Group size, Mob-Mobile use, Dis-Disability, LF-Lane formation, LFR-Leader follower relationship, FSE- Faster is slower effect, SE-Squeezing effect, Over-Overtaking, LS- Lane shifting*

As per Table 4.31, negative gender-speed and age-speed correlation coefficients indicate that when more female pedestrians are using the facility or more aged pedestrians (>60 years) are available, it leads to an overall decrease in the walking speed. A positive correlation coefficient (0.14) between luggage and speed indicates that the walking speed increases when more pedestrians are walking without luggage over skywalks mid-block sections. The linear regression model developed in Section 4.4.5.3 also indicates that luggage plays a significant role while pedestrians are using the mid-block sections of skywalks. Similarly, pedestrians without mobile phones or without disability tend to increase the overall walking speed over the skywalks. However, as all the considered variables had a coefficient of less than 0.3, thus a weak relationship existed between the different variable pairs. Considering pair-wise correlation of speed with the other independent variables, the results indicated uncorrelated relationship (≤0.30) between the dependent (speed) and the independent variables (variables other than speed). All these variables were therefore considered for the development of linear regression model for walking speeds of pedestrians over skywalk facilities.

4.4.5.3. Development of microscopic speed prediction model

In an attempt to understand the impact of different pedestrian characteristics (individual and group), linear regression model (LRM) was used. In the walking behaviour modelling multiple linear regression was used to obtain the relationship between the walking behaviour parameters and the walking speed over the mid-block section of skywalks. In model development 80% data was used and remaining 20% data was segregated for model validation. Table 4.32 shows the most significant variables which impacted the walking behaviour over mid-block sections along with the coefficients.

Table 4.32 showed the most significant variables which impacted the walking behaviour of the pedestrians' over the skywalk mid-block sections. As per Table 4.32, age, gender, luggage, group size, mobile use, disability, lane formation, leader-follower relationship, squeezing effect, overtaking and lane shifting behaviour were the most significant parameters affecting the walking speed behaviour over the skywalk mid-block sections. The pedestrians without luggage had a positive coefficient, which indicated that they had higher walking speed than the ones with luggage. Moreover, when the pedestrians were moving in lanes their speeds were observed to be higher than those without lane formation. The age coefficient showed that with the increase in age the walking speeds increased up to age of 60 years. The pedestrians without disability were observed to have higher walking speeds and impacted the overall behaviour.

Similarly, a pedestrian without ‘faster-is-slower effect’ did not have significant impact on the overall walking behaviour.

Table 4.32. Coefficients for skywalk mid-block walking behaviour

	Reference category	**Estimate**	**Std. Error**	**t value**	**Pr(≥|t|)**
(Intercept)		54.912	3.448	15.924	≤ 0.001 ***
Age1 (11-20 years)	*Age (≤10 years)*	5.182	1.191	4.352	≤ 0.001 ***
Age2 (21-40 years)		5.405	1.154	4.628	≤ 0.001 ***
Age3 (41-60 years)		2.861	1.174	2.437	0.015 *
Age4 (≥60 years)		-3.881	1.276	-3.040	0.002 **
Gender (Female)	*Gender (Male)*	-5.302	0.267	-19.832	≤ 0.001 ***
Luggage (Without)	*Luggage (With)*	3.543	0.237	14.893	≤ 0.001 ***
Group_size (GS: 2)	*Group_size (GS: 1)*	-4.340	0.318	-13.633	≤ 0.001 ***
Group_size (GS: 3)		-6.407	0.541	-11.863	≤ 0.001 ***
Group_size (GS: ≥4)		-9.777	0.781	-12.524	≤ 0.001 ***
Mobile (Without)	*Mobile (With)*	3.525	0.317	11.111	≤ 0.001 ***
Disability (Without)	*Disability (With)*	14.131	2.408	5.868	≤ 0.001 ***
Lane_formation (Without)	*Lane_formation (With)*	2.506	0.247	10.141	≤ 0.001 ***
Leader_follower (Without)	*Leader_follower (With)*	1.663	0.352	4.725	≤ 0.001 ***
Faster_slower (Without)	*Faster_slower (With)*	0.289	1.546	0.193	0.846
Squeezing_effect (Without)	*Squeezing_effect (With)*	8.600	1.643	5.233	≤ 0.001 ***
Overtaking (Without)	*Overtaking (With)*	-7.615	1.412	-18.462	≤ 0.001 ***
Lane_shift (Without)	*Lane_shift (With)*	-1.319	0.265	-4.975	≤ 0.001 ***

Significance codes: *‘***’- 0; ‘**’- 0.001; ‘*’- 0.01; ‘.’- 0.05; ‘ ’- 0.1*

4.4.5.4. Validation of microscopic speed prediction model

The remaining 20% of the test data set was used to make a comparison between the predicted and actual speeds using MAPE and RMSE metrics. The obtained MAPE and RMSE were 12.44% and 0.114 respectively. As per Lewis scale of interpretation, a MAPE value of 10-20% specifies that the model forecasting was good.

4.4.6. Development of speed models over skywalk mid-block sections using macroscopic pedestrian behaviour parameters

The macroscopic parameters (average flow and average density of the stream) along with geometric parameters (obstruction, land use type, length of facility, connectivity, and effective width) generally tend to influence the walking speed behaviour of pedestrians over different facilities. Similar to FOB mid-block sections, in the current study an attempt was made to predict the pedestrian walking speed over skywalk facilities using individual and group pedestrian characteristics along with geometric features using different tree-based machine learning algorithms.

4.4.6.1. Site selection, data collection and data extraction for macroscopic speed modelling

In order to capture the factors affecting pedestrian speed, the final data used for site selection, and data collection was based on Section 4.4. After the data collection, the data was manually extracted in the lab and processed. As the aim of the study was to identify the factors affecting the pedestrian speed, thus individual microscopic parameters (such as age, gender, luggage condition, mobile use) along with other macroscopic and geometric factors (such as obstruction, land use type, time of data collection, average flow, average density, length of facility, connectivity, and effective width) were considered while extracting the video data.

4.4.6.2. Development of macroscopic speed prediction model

To obtain the essential parameters that determine the walking speed of pedestrians over elevated crossing facilities, in the current study different tree based modelling approaches (GBM: Gradient boosting machine, LGBM: Light gradient boosting machine, XGB: Extreme gradient boosting, AdaBoost: Ada Boost regressor, RF: Random forest, ETR: Extra trees regressor and DT: Decision tree) were explored to predict the speed determinants of skywalks (regression: continuous outcome) through PyCaret 2.0 machine learning library using open-source programming language Python version 3.6.

4.4.6.3. Training and hyper-parameter tuning of model

In order to train the speed models PyCaret 2.0 machine learning library was utilized. The total sample was randomly split into 80% train and 20% test dataset. Comparing multiple models and tuning all type of hyper parameters could be time consuming; thus, initially a 10-fold CV was performed with default hyper-parameters to get the idea about overall best performing model. The 10-fold CV models were trained with different tree-based models including ensembles. The models included LGBM, GBR, XGBoost, AdaBoost, RF, ETR and DT. The models were trained, and the average performance of the CV was reported as shown in Table 4.33 using various regression metrics such as MAE, MSE, RMSE, R-square, RMSLE, MAPE and Training Time (TT). After training, the models were sorted based on the MAE criteria as this evaluation metric was robust and was not affected by outliers. The 10-fold CV result of skywalk speed prediction models revealed that GBR topped in the overall performance (MAE: 9.23).

Table 4.33. Skywalk 10-fold cross validation model comparison summary

Model	MAE	MSE	RMSE	R^2	RMSLE	MAPE	TT (Sec)
Gradient Boosting Regressor	**9.2327**	136.8887	11.6956	0.1715	0.1531	0.1231	0.2177
Light Gradient Boosting Machine	9.2616	136.3611	11.8019	0.1558	0.1543	0.1232	0.1382
AdaBoost Regressor	9.8466	154.4283	12.4186	0.0660	0.1616	0.1304	0.0747
Extreme Gradient Boosting	9.9957	162.098	12.7276	0.0172	0.1657	0.1326	0.2438
Random Forest	10.2621	169.9753	13.0347	-0.0303	0.1692	0.136	0.4022
Extra Trees Regressor	10.9459	165.4134	13.9749	-0.1853	0.1815	0.1448	0.2735
Decision Tree	11.4839	216.1147	14.6964	-0.3106	0.1919	0.1519	0.0144

4.4.6.4. Optimization of hyper-parameters for obtaining best fit model

To obtain the best performing model and to reduce overfitting a random hyper-parameter search was performed. Random search is faster and less computationally expensive compared to complete grid search skywalk model (Gradient Boosting Model), the hyper-parameters were loss, number of estimators, learning rate, subsample, criterion, minimum samples split, minimum samples leaf, maximum depth, and maximum features. The different hyper-parameters and their range are presented in Table 4.34.

Table 4.34. Model hyper-parameter optimization

Model	Hyper-parameters
GBR	**loss:** ['ls', 'lad', 'huber', 'quantile'] **n_estimators:** np:arange(10,200,5) **learning_rate:** np:arange(0,1,0:01) **subsample:** [0:1,0:3,0:5,0:7,0:9,1] **criterion:** ['friedman_mse', 'mse', 'mae'] **min_samples_split:** [2,4,5,7,9,10] **min_samples_leaf:** [1,2,3,4,5,7] **max_depth:** [10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110] **max_features:** ['auto', 'sqrt', 'log2']

By default, PyCaret performs 10 random iteration over search space. Thus, to get highly optimized model the skywalk models' hyper-parameters random iteration was set to 100. The training involved a 10-fold cross validation to get a better estimate (average) of the model performance. The MAE was selected as model evaluation metric. The skywalk 10-fold CV hyper-parameter optimization results revealed an average MAE of 9.22 with a standard deviation of 0.12 (refer Table 4.35).

Table 4.35. Summary of tuned 10-fold CV skywalk model performance

CV Folds	MAE	MSE	RMSE	R^2	RMSLE	MAPE
1	9.0746	132.7008	11.5196	0.1226	0.1461	0.118
2	9.1355	133.1924	11.5409	0.1922	0.1530	0.1237
3	9.3613	147.8658	12.16	0.1756	0.1716	0.1342
4	8.8664	123.2225	11.1006	0.1642	0.1384	0.1135
5	9.4767	143.502	11.9792	0.2017	0.1495	0.1208
6	9.1031	133.7385	11.5645	0.184	0.1480	0.1187
7	9.3650	139.8568	11.8261	0.1717	0.1536	0.1232
8	9.4480	138.7644	11.7798	0.1630	0.1600	0.1299
9	9.0116	131.8648	11.4832	0.1487	0.1543	0.1234
10	9.3917	141.6294	11.9008	0.2053	0.1575	0.1258
Mean	**9.2234**	136.6337	11.6855	0.1729	0.1532	0.1231
SD	**0.1197**	6.7195	0.2885	0.0238	0.0085	0.0056

The optimized model hyper parameters for skywalk speed models are presented in the following Table 4.36.

Table 4.36. Optimized model parameters

Model	Model hyper parameter
GBR	*loss*: huber, *n_estimators*: 175, *learning_rate*: 0:01, *subsample*: 0:3, *criterion*: friedman_mse, *min_samples_split*: 10, *min_samples_leaf*: 1, *max_depth*: 10, *max_features*: auto

4.4.6.5. Validation of macroscopic speed prediction model

Further, for obtaining model performance on unseen test dataset, the final model was tested on the remaining 20% test dataset. Table 4.37 shows the model performance summary on the test data set.

Table 4.37. Summary of skywalk model performance estimated on the test dataset

Model	MAE	MSE	RMSE	R^2	RMSLE	MAPE
GBR	9.2738	132.3588	11.5047	0.1627	0.1479	0.122

The performance summary revealed that the overall optimized GBR speed prediction model *(based on MAE: 9.27)* performed overall well on the unseen/test dataset.

4.4.6.6. Application of the developed macroscopic model

The GBR was found to perform best on test dataset. Similar to FOB sections, the SHAP values were estimated for tuned GBR on the test data for skywalk sections and were plotted using a summary plot (refer Figure 4.24). The summary plot not only provides the variable importance in descending order but also illustrates the positive or negative relationship with the outcome variable. The y-axis shows different variables (top five predictors) while the x-axis shows SHAP values ranging from negative to positive. The feature values are illustrated with blue and red colour gradients. Red colour indicates high feature value, while blue indicates a low feature value.

The feature importance plot of model (in Figure 4.24) illustrated that the top five parameters impacting the walking speed over skywalks were the average flow, average density, gender (male/ female), age (<10, 11-20, 21-40, 41-60, and >60 years), and length of the facility (refer to Figure 4). Males were found to be walking faster compared to female pedestrians. Moreover, the proportion of male pedestrians leads to higher stream speed. Similarly, pedestrians belonging to an age group of 21-40 (young adults) walked faster than any other age group. The old (>60 years) and young (<10 years) pedestrians are observed to negatively impact the relative stream speed. Thus with a higher proportion of old and young pedestrians, the overall stream speed would be significantly reduced. The total length of the facility although is found significant (with a positive relationship), however, its direction of influence on the walking speed is not clear. The impact of the flow parameter reflected here is somewhat unclear or contradictory. Such behavior of flow is reflected as few sites for Skywalks were in congested conditions (i.e. speed increases with increase in flow under congested regime), as opposed to most of the other sites which were in free flow condition with lower densities. Observation of pedestrian speed data over a wide range of densities in most sites might resolve this ambiguity.

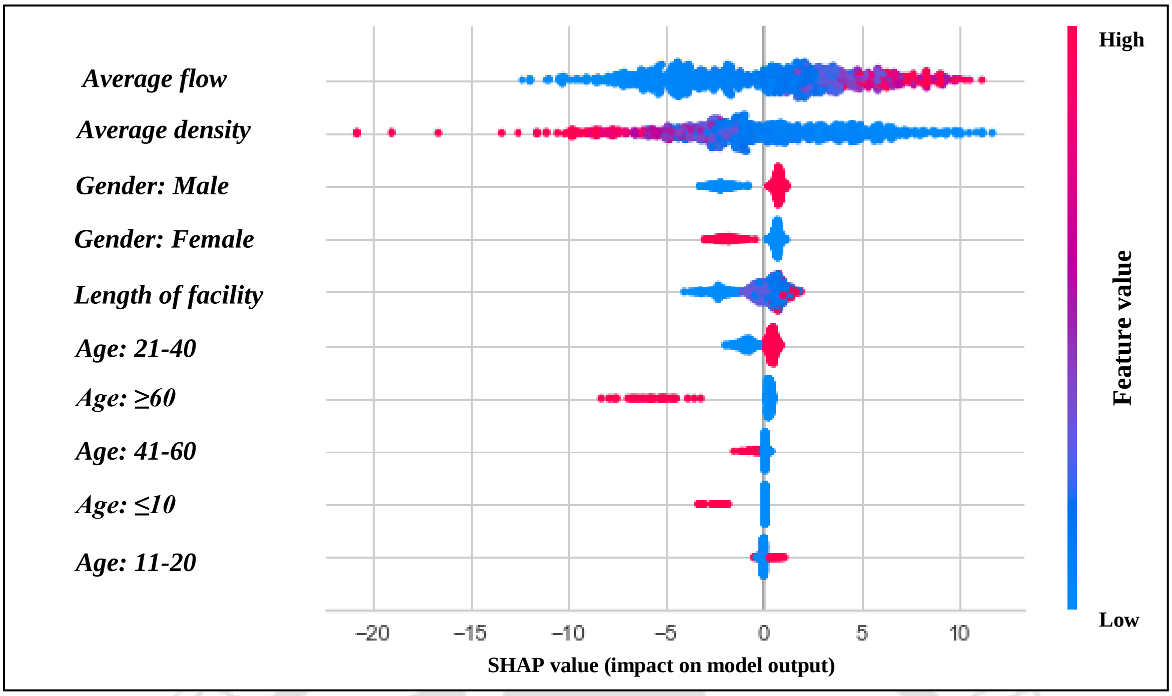


Figure 4.24. Feature importance plot for skywalk speed prediction

4.4.7. Understanding gap maintaining behaviour of pedestrians

A novel semi-manual data extraction technique was developed for extracting pedestrian position (subsequently speed and trajectory) data using front inclined camera angle as many times top-down angle is unavailable due to height restrictions. Vanishing point method was used to extract data for pedestrian body dimensions across vertical and pedestrian-specific trajectory planes. Using the trajectory and body dimension informations, the spacings maintained between pedestrians were estimated. Subsequently, JUPedSim software was used for extracting the fundamental macroscopic properties (speed, flow and density) from the pedestrian position data, and the results were compared using classical and voronoi approaches.

This semi-manual technique could be helpful in studying pedestrian gap maintaining behaviour and establishment of different threshold levels for the crowd management. Such approach can directly be applied to CCTV footage (which mostly gives front inclined views of camera) to ensure the social distancing in the current ongoing pandemic COVID-19. Further, the proposed approach can be made automated using the image processing tools for different applications like determination of pedestrian stream characteristics, level of services, safety evaluation and ensuring social distancing.

4.4.7.1. Data collection for gap maintaining behaviour study

Videographic data collection was conducted at an elevated pedestrian walkway accessing a suburban railway station Goregaon in the Western suburbs of Mumbai, India. Due to lack of vantage points at the top of confined walkway, a camera was fixed over a tripod of the height of 10ft (~3m) using a front camera angle. The camera was fixed towards the end of the walkway so that the tripod may not affect pedestrian movement. Figure 4.25 shows the location of the study section.

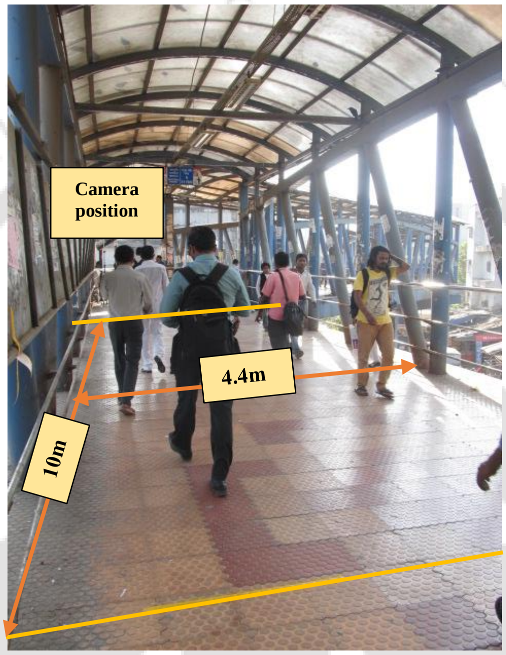


Figure 4.25. Camera position over mid-block section

4.4.7.2. Data extraction methodology

Although trajectories can be tracked using appropriate automatic face detection or pedestrian tracking systems, the systems require detection of the entire body of a pedestrian throughout the length of the selected section for extracting the body dimensions and trajectories of the pedestrians. This is difficult in sections with moderate or high pedestrian density. For this purpose, only manual tracking of pedestrian trajectory is possible. Also, from a top-frontal view, only heads of each pedestrian are visible throughout the section due to limited height availability in covered walkways. Hence, a semi-manual approach was adopted for pedestrian trajectory tracking from a frontal inclined view (from a limited height) video generally available from CCTV surveillance cameras. The semi-manual approach essentially consisted of (i) manual tracking and extraction of image co-ordinates of every pedestrian’s head at fixed time intervals, and (ii) marking and extracting the pedestrian details, such as body dimensions and other demographics characteristics (age, gender and luggage condition) of the pedestrians. Later, a software based algorithm calculated the real world pedestrian trajectories, positions and individual pedestrian's body ellipses. The area occupied and inter-pedestrian gaps were calculated using extracted trajectories. A camera calibration technique was used for converting video image coordinates to real world coordinates (coordinates with respect to a reference on the walkway). Figure 4.26 below shows the pictorial representation of the data extraction technique used. The calculation of trajectory extraction is provided in the subsequent paragraph.

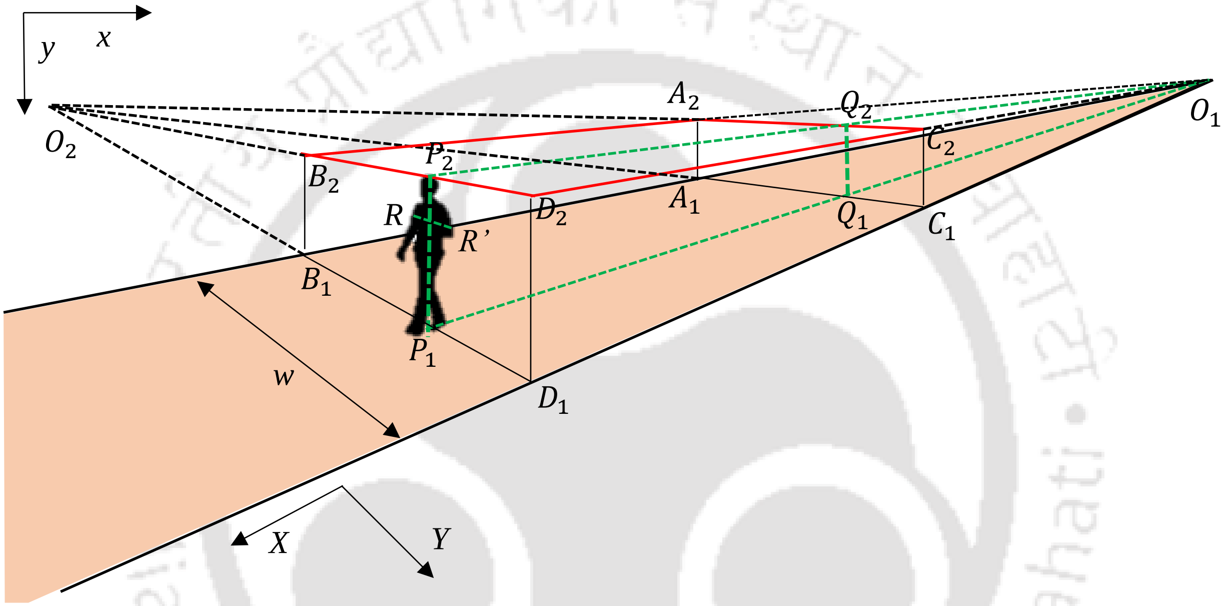


Figure 4.26. Pictorial representation of the extraction technique used *(Source: Banerjee et al., 2021)*

Several camera-calibration techniques are developed for converting image co-ordinates into real-world coordinates. The vanishing point methodology (Fung, 2003) was used in traffic data extraction researches (Munigety, 2014; Budhkar, 2015). This method requires marking the image coordinates of a point (say, P_1) in the video. This point lies on a plane on the ground, and the plane is calibrated by image coordinates of four points representing corners of a rectangle on the ground in the real world (say, rectangle $A_1B_1D_1C_1$ shown in Figure 4.26) with a known width ($B_1D_1 = A_1C_1 = w$). However, in semi-dense pedestrian traffic, pedestrians' feet (lying on the plane $A_1B_1D_1C_1$) are not always visible, though their head tops are visible. If the trajectory of the head of a pedestrian (P_2, which does not lie on $A_1B_1D_1C_1$) needs to be accurately marked; then, to convert the image co-ordinates into real-world coordinates, the trajectory points must lie on a plane, parallel to the ground surface and passing through the top-most point of head of a pedestrian. Such a plane will be unique to every pedestrian. Let

$A_2B_2D_2C_2$ be a rectangle in this a plane, marked in red in Figure 4.26. The points A_2, B_2, D_2 *and* C_2 are exactly above points A_1, B_1, D_1 *and* C_1 respectively in the real world, and their real-world lateral (*X*) and longitudinal (*Y*) coordinates are the same. If their lateral (*x*) and longitudinal (*y*) *image* coordinates are calculated, camera calibration can be conducted in a similar fashion and pedestrian trajectories can be calculated. For this purpose, coordinates of top and bottom point of a pedestrian, at the instance he/she crosses the end of the section (in this case, B_1D_1) needs to be determined and visible to an extractor. Let P_1 (bottom, foot) and P_2 (top, head) be these points denoting the pedestrian at the time-stamp of crossing the section. It is assumed that P_1 is exactly above P_2 in the real world, or ($Y_{P_1} = Y_{P_2}$, $X_{P_1} = X_{P_2}$). From existing information, the image coordinates are calculated by simple geometrical methods as follows:

i. The lines A_1B_1 and C_1D_1 intersect at the longitudinal vanishing point O_1, whereas the lines A_1C_1 and B_1D_1 intersect at the lateral vanishing point O_2. Equations of lines (on the screen) A_1B_1, C_1D_1, A_1C_1 and B_1D_1 are calculated using the equation of the line passing through two points each.

ii. Equation of line A_1B_1: $y = \left(\frac{y_{A_1} - y_{B_1}}{x_{A_1} - x_{B_1}}\right)x + \left(\frac{y_{B_1}x_{A_1} - x_{B_1}y_{A_1}}{x_{A_1} - x_{B_1}}\right)$,

This can be written in the form, $y = m_{A_1B_1}x + c_{A_1B_1}$, where *m* and *c* represent slope and y-intercept of the line.

iii. Similarly, the equation of the line C_1D_1: $y = \left(\frac{y_{C_1} - y_D}{x_{C_1} - x_{D_1}}\right)x + \left(\frac{y_{D_1}x_{C_1} - x_{C_1}y_{D_1}}{x_{C_1} - x_{D_1}}\right)$.

iv. But, O_1 is the vanishing point in the longitudinal direction and thus the point of intersection of lines A_1B_1 and C_1D_1 on the screen (in the field, these two lines are parallel to each other and do not intersect). Co-ordinates of O_1 can be calculated by simultaneously solving equations of lines A_1B_1 and C_1D_1.

v. Similarly, co-ordinates of O_2 can be calculated by simultaneously solving equations of lines A_1C_1 and B_1D_1.

vi. Equation of line P_1P_2, representing a standing person at the end of the section, can be calculated similar to step ii. This information is recorded when a pedestrian crosses the end of the section, and positions of his/her head and foot are marked by means of a mouse click.

vii. Line Q_1Q_2 represents pedestrian standing at the start of a section. Lines Q_1Q_2, B_1B_2 and D_1D_2 are parallel to line P_1P_2. Thus, their slopes are equal. Hence, $m_{P_1P_2} = m_{B_1B_2} = m_{D_1D_2} = m_{Q_1Q_2}$, already calculated in step vi. Intercepts of lines B_1B_2 and D_1D_2 can be evaluated by substituting co-ordinates of B_1 and D_1 respectively in slope-intercept form of a straight line equation. Thus, the equation of lines B_1B_2 and D_1D_2 can be calculated (i.e., equation of a line passing through a point and with a known slope).

viii. Equation of line O_2P_2 can be calculated since co-ordinates of O_2 and P_2 are known. B_2 and D_2 are points of intersection of the line O_2P_2 with lines B_1B_2 and D_1D_2 respectively. Therefore, co-ordinates of B_2 and D_2 can be evaluated by simultaneously solving equations of lines O_2P_2 with B_1B_2, and O_2P_2 with D_1D_2 respectively.

ix. Q_1 is the point of intersection of lines O_1P_1 with line O_2A_1 (or O_2C_1). Since coordinates of points P_1 and A_1 are known from initial data, and coordinates of points O_1 and O_2 are calculated in steps iv and v respectively, the equations of lines O_1P_1 and line O_2A_1 (or O_2C_1) can be evaluated as passing between respective points. Co-ordinates of Q_1 can be found by simultaneously solving equations of lines O_1P_1 and O_2A_1 (or O_2C_1).

x. Equation of line Q_1Q_2 passing through point Q_1 (co-ordinates calculated in Step xi) and with known slope (calculated in Step vii) can be found out. Further, since coordinates of the point P_2 is known from initial data, and co-ordinates of O_1 is calculated in step iv, the equations of the line O_1P_2 can be evaluated as passing between respective points. Q_2 is the point of intersection of lines O_1P_2 with line Q_1Q_2. Thus, coordinates of point Q_2 can be calculated by simultaneously solving equations of lines O_1P_2 and Q_1Q_2.

xi. Now, A_2 and C_2 are points of intersection of lines O_1B_2 with O_2Q_2, and lines O_1D_2 with O_2Q_2 respectively. Co-ordinates of points O_1 (Step iv), O_2 (Step v), B_2 and D_2 (step viii) and Q_2 (step x) all are calculated. Thus, equations of lines O_1B_2, O_1D_2 and O_2Q_2 can all be evaluated as passing between respective points. Co-ordinates of A_2 and C_2 can be found by simultaneously solving equations of lines O_1B_2 with O_2Q_2, and lines O_1D_2 with O_2Q_2 respectively.

xii. Lines A_1A_2 and C_1C_2 have slopes parallel to the line P_1P_2, and they pass through points A_1 and C_1 respectively (known co-ordinates from input data). Thus, their equations can be known. Since points A_2 and C_2lie on these lines respectively, they must satisfy the equation of the respective lines. The obtained co-ordinates in Step xi are thus verified during the evaluation process.

In this way, image co-ordinates of four points – A_2& C_2 (Step xi) and B_2 & D_2 (Step viii), which lie on a plane passing through the head of particular pedestrian, and parallel to the ground plane, can be calculated. This exercise is conducted for every pedestrian and the trajectory is evaluated by the following steps-

i. To evaluate the trajectory of every pedestrian, a MATLAB code is written wherein recorded pedestrian video can be played and paused at fixed intervals.

ii. For every pedestrian at every time-step, extractor clicks on the head of a pedestrian, and image coordinates (with a pedestrian number and frame number) are saved in a file (say, file *J*).

iii. As the pedestrian reaches the section B_1D_1, extractor marks on the head and foot of that pedestrian (represented by points P_1 and P_2 respectively in Figure 4.26) to calculate his/her height, and on points R and R' to calculate his/her shoulder width. Further, several buttons are provided in a module, to classify the pedestrian's age, gender or luggage category (refer Figure 4.27). All this information (image coordinates of points P_1, P_2, R and R', age gender and luggage category) along with the pedestrian number, are stored in a separate file (say, file *K*).

iv. Simultaneously, image co-ordinates of A_2, C_2, B_2 and D_2 are calculated for every pedestrian and stored in file *K*. Since the points P_1, P_2, R and R' all lie on the same plane (represented by the rectangle $B_2B_1D_2D_1$), thus actual height and width of a particular pedestrian can be accurately calculated.

v. Image co-ordinates in file *J* are converted to real-world trajectory co-ordinates by using calculated co-ordinates of A_2, C_2, B_2 and D_2. Data from file *K* (height, shoulder width, age, gender and luggage category) are assigned to the real-world trajectory co-ordinates.

Figure 4.27 shows the snapshot of the developed MATLAB software, which includes the pedestrians' details, toggle buttons, adjustment buttons and direction of travel (towards or away from camera).

Figure 4.27. Snapshot of developed software for the skywalk section data extraction

After getting the trajectories of every pedestrian, the body depth, speed of the pedestrian, and clearances maintained between two pedestrians at a particular time interval were calculated. The shoulder width of the pedestrian was obtained by the code. Body depth of pedestrian was calculated from the body ellipse area reported by an earlier Indian study (Singh, 2016) considering a constant body ellipse area.

4.4.7.3. Accuracy of obtained camera calibration technique

Since the process involved manual data extraction by means of a mouse click, human error in clicking precisely at a pedestrian's location needs to be investigated. The methodology adopted by an earlier study (Budhkar, 2016) was followed in this paper, and people of known heights were marked repeatedly by extractors. The standard deviation of error was about six pixels on the screen, synonymous with the previous literature. This corresponds to an error (standard deviation) of 0.039 m at the exit section (towards camera) and 0.11 m at the entry section. The error varied since these six pixels correspond to larger distances away from the camera than the points closer to the camera. As the height marking plane ($B_1B_2D_2D_1$ in Figure 4.26) was almost perpendicular to the camera, there was not much difference in error of marking heights and remain consistent at 0.055 m for a given height ($\sqrt{2}$ times 0.039 m, the standard deviation error at exit section). Although these errors cannot be eliminated, the magnitude of errors were significantly smaller as compared to the magnitude of obtained trajectory points or pedestrian details. Since the video recording does not utilize a camera with wide angle lens or a stereo camera, thereby corrections of fish eye effects or those constituting re-projection error are not applicable respectively.

4.4.7.4. Determination of clearance between pedestrians

Clearances

Lateral, longitudinal and diagonal clearances represent the minimum distance in the lateral direction, longitudinal and diagonal directions between two pedestrians respectively at a single time step (Figure 4.28).

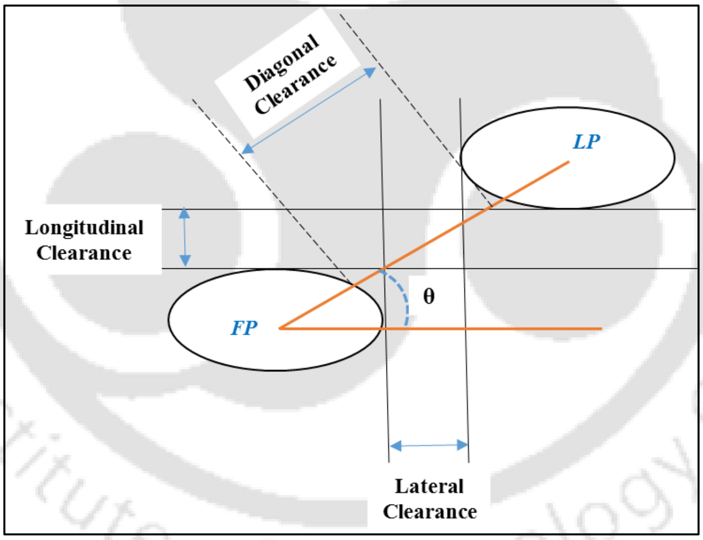


Figure 4.28. Clearances maintained by pedestrians (*Note:* LP- leading pedestrian, and FP- following pedestrian)

Theta (θ) represents the angle between the lines joining the centers of the body ellipses of any two pedestrians and horizontal axis (X-axis) which is graphically shown in Figure 4.28. Similarly, diagonal clearance (DC) is the minimum distance diagonally between two pedestrians at a single time step

Considering a case where there are two pedestrians, and leading pedestrian is to the left of the following pedestrian; then the coordinates of all four extreme points of the body ellipse for both the following pedestrian (FP) and leading pedestrian (LP) are as follows, refer Figure 4.29-Figure 4.30.

Lateral clearance

The longitudinal distance is calculated using Figure 4.29.

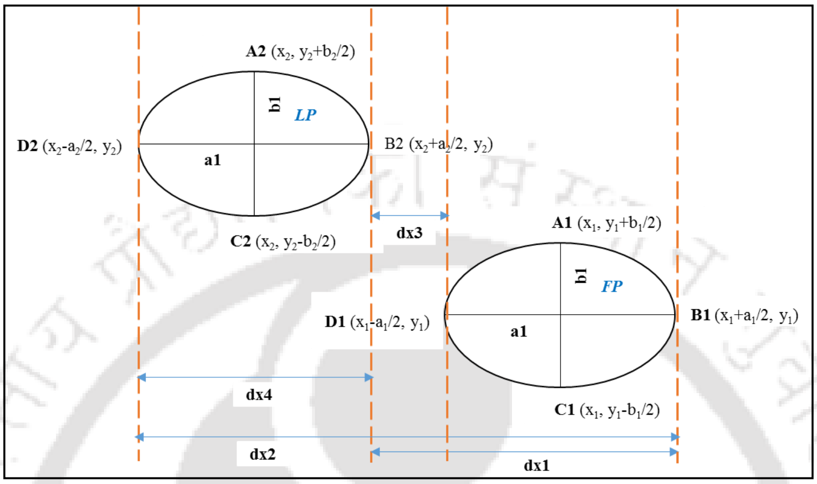


Figure 4.29. Lateral clearance maintained by leading and following pedestrians

From Figure 4.29, the Lateral Distance = min (dx_1, dx_2, dx_3, dx_4)

Longitudinal Clearance

The longitudinal clearance is calculated using Figure 4.30.

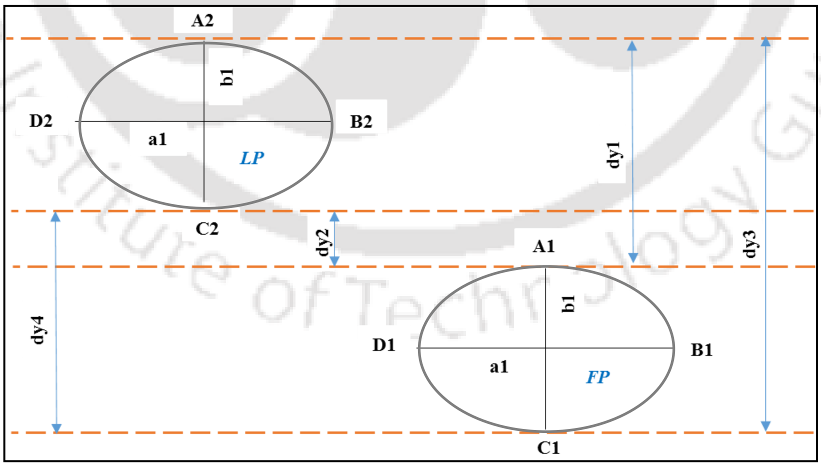


Figure 4.30. Longitudinal clearance maintained by leading and following pedestrians

Similar to the lateral distance, the longitudinal distance is represented as:

Longitudinal Distance = min (dy_1, dy_2, dy_3, dy_4).

Overlapping scenarios based on lateral positions

There can be two cases of overlapping for leading and following pedestrians. Case 1 refers to the positions of FP (denoted by 1) and LP (denoted by 2) where there is no lateral overlap between the two pedestrians, and Case 2 refers to the overlapping positions depending on whether the LP is to the left or right of the FP. Depending on the overlap between the LP-FP pair of pedestrians, the lateral clearance can be defined more precisely.

Case 1 (refer Figure 4.31)**:** When there is no lateral overlap between leading pedestrians (LP) and following pedestrian (FP). Then again, the leading pedestrian can be to the right or the left of the following pedestrian.

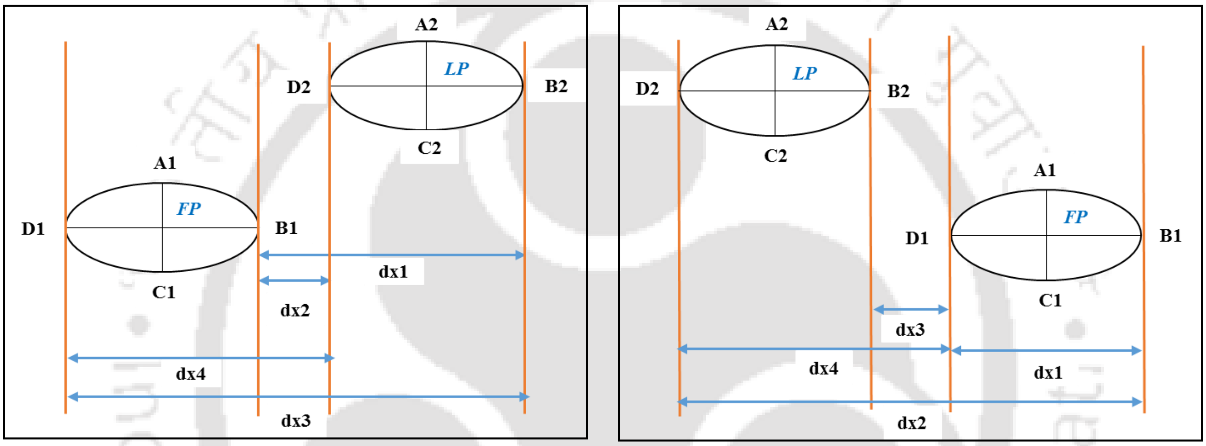


Figure 4.31. Lateral position when there is no overlapping and LP is (a) to the right and (b) to the left, of the FP

Case 2 (refer Figure 4.32)**:** When there is lateral overlap between leading pedestrians (LP) and following pedestrian (FP), the leading pedestrian can be to the right or left of the following pedestrian. If LP is to the right of FP, then $D_{1x} \leq D_{2x} \leq B_{1x}$ and when LP is to the left of FP, then $D_{1x} \leq B_{2x} \leq B_{1x}$. (refer to Figure 4.32, where B and D represents the coordinates of the FP: 1 and LP: 2)

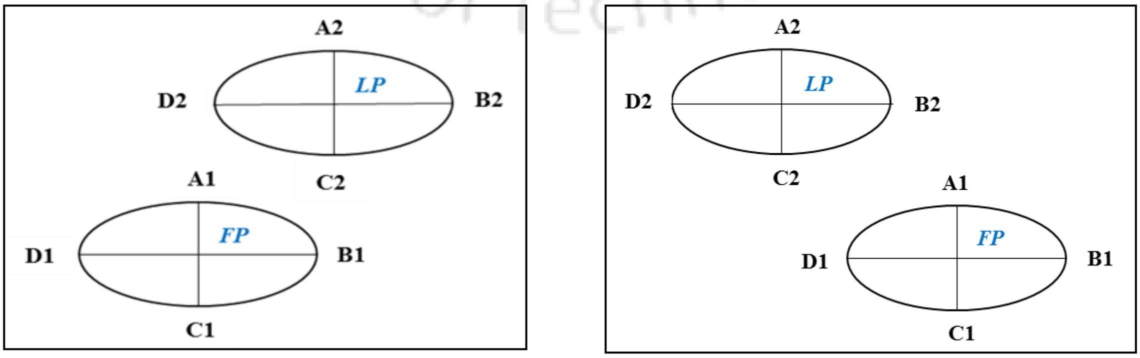


Figure 4.32. Lateral position when there is overlapping and LP is (a) to right and (b) to left, of the FP

4.4.7.5. Development of voronoi diagrams

The JPSreport, a tool of JuPedSim (Wagoum, 2015) was used for analyzing the trajectories and developing fundamental parameters (speed, flow and density). The working method of JPSreport is shown below:

i. ***Input files:*** Trajectory file (.txt), geometry file (.xml) and configuration file (.xml or .txt).

ii. ***Output files:*** Voronoi diagrams and profile of pedestrians.

Voronoi Density Algorithm

After getting voronoi cell coordinates from JPSreport output file, a c++ code was written which takes voronoi cell coordinates of each frame as input and gives voronoi density as output. The code was written using mathematical analysis discussed in the following subsections.

Voronoi Cell Area

Voronoi cell area was calculated using mathematical formula shown below (refer Equation 4.5) where *Xi* and *Yi* are *x* and *y* coordinate of i^{th} vertex of voronoi cell.

$$\text{Voronoi cell area } (A_i) = \frac{1}{2}\sum_{i=1}^{n-1} x_i y_{(i+1)} + x_n y_1 - \sum_{i=1}^{n-1} x_{(i+1)} y_i + x_i y_n \qquad \text{.......}\textbf{Eq. 4.5}$$

Density Algorithm

A c++ program was written which is a simplified version of voronoi density formula, given as below in Equation 4.6.

$$(\rho)_y = \Sigma(1/A_i)\,/\,A \qquad \text{........}\textbf{Eq.4.6}$$

4.4.7.6. Results of gap maintaining behaviour study

Spatial arrangement

Based on the spatial arrangement of different pedestrians, the variation of longitudinal distance between interacting pedestrian with theta were presented in the Figure 4.33. Pedestrian pairs were considered as interacting if their lateral and longitudinal gap were less than or equal to 0.25m and 1.5m respectively. It was seen for the Figure 4.33 that when the leading pedestrian comes in front of following pedestrian (i.e., theta value approaches 90°), FP maintains higher gap. When the angle between the LP and FP approaches zero, the FP comes beside the LP and both walk side by side, making the longitudinal distance tending to zero.

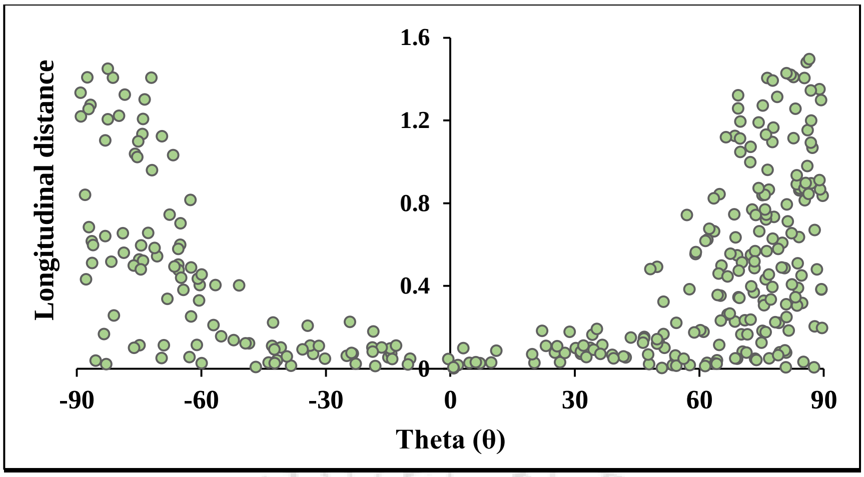


Figure 4.33. Longitudinal distance vs theta for interacting pedestrians

Figure 4.34 also demonstrate a similar fact, where the diagonal clearance increased with the increase of theta.

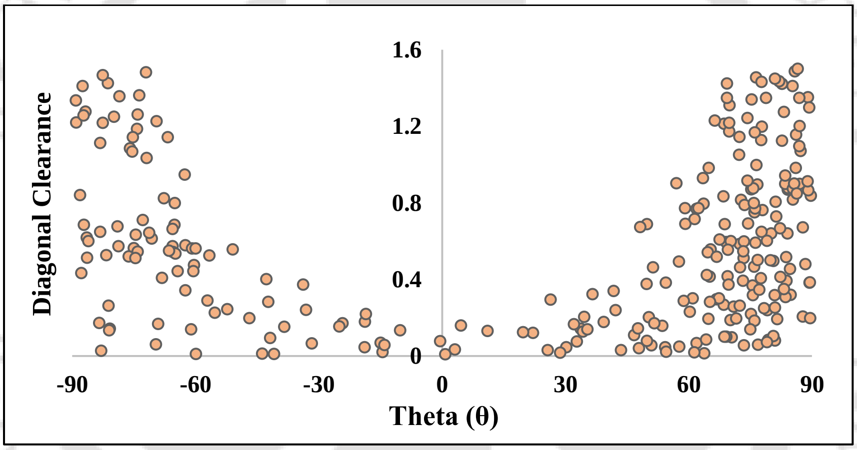


Figure 4.34. Diagonal clearance vs theta for interacting pedestrians

Lateral distance and theta were also plotted, however, no particular trend was observed. Such behaviour is observed as the pedestrians might be less affected by the spacing available with the side pedestrian beyond a minimum value.

Classical parameters vs voronoi parameters

In order to observe the stability between the classical and voronoi approaches, the speed, flow and density were presented in Figure 4.35-Figure 4.37.

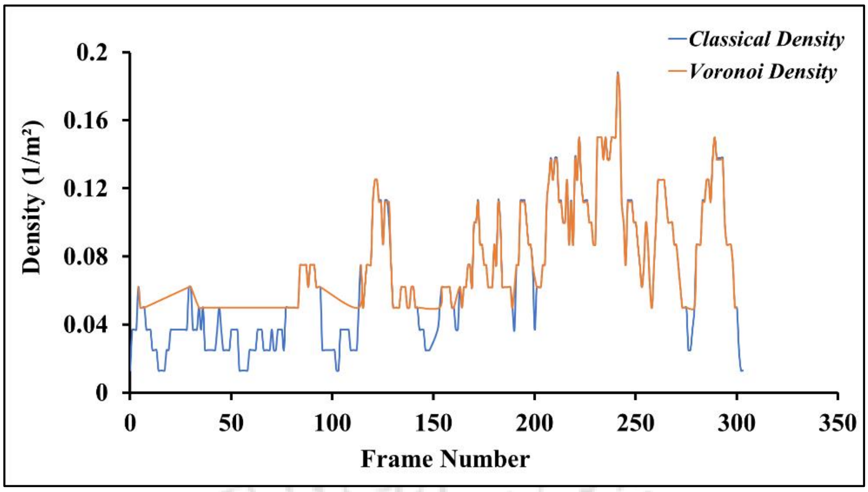


Figure 4.35. Classical density vs Voronoi density

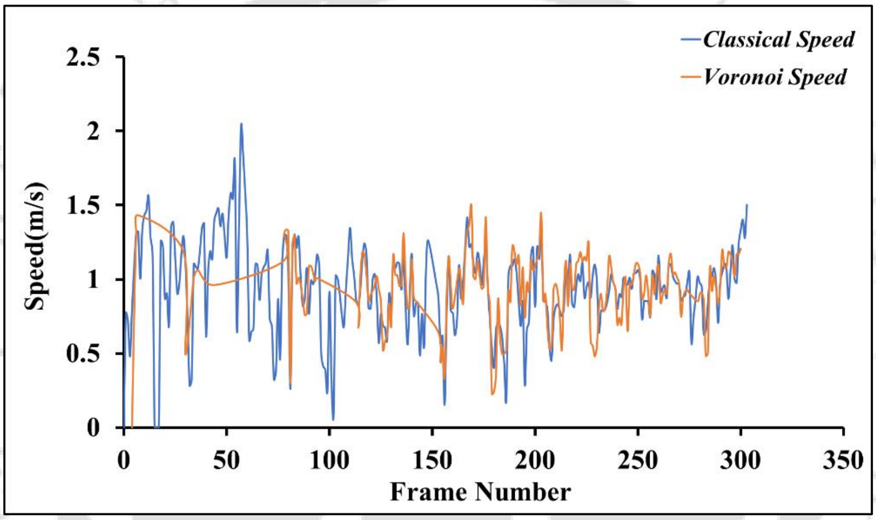


Figure 4.36. Classical speed vs Voronoi speed

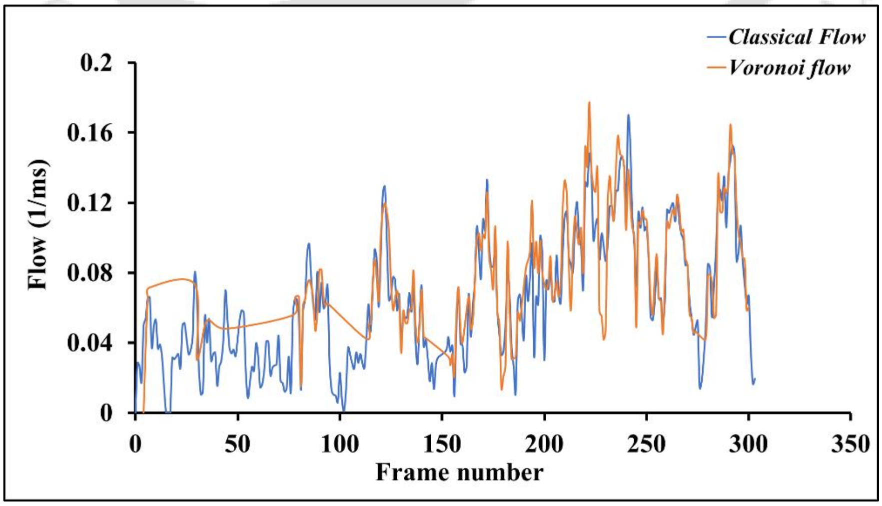


Figure 4.37. Classical flow vs Voronoi flow

Figure 4.35 showed that voronoi density curve (orange colour) had more stability than classical density curve (blue colour). Classical density curve had wider range and many local comparative dips showing more fluctuations than voronoi density curve. These fluctuations in classical approach of density might be because of binary counting of pedestrian at the edge of the observed section. Similar fluctuations could also be observed in the classical speed and flow values in comparison to voronoi speed and flow values (refer Figure 4.36 and Figure 4.37). Moreover, average classical speed and voronoi speed were observed to be 56.78 m/min and 56.09 m/min respectively, while average classical density and voronoi density were observed to be 0.068 ped/m^2 and 0.088 ped/m^2 respectively.

Voronoi diagram

Voronoi diagram was drawn for four different density data ranges and the voronoi cell formation was observed (refer to Figure 4.38). Previous researchers (Cepolina, 2018 and Zhang, 2013) had also used voronoi diagrams to identify pedestrian flow characterization for different corridors.

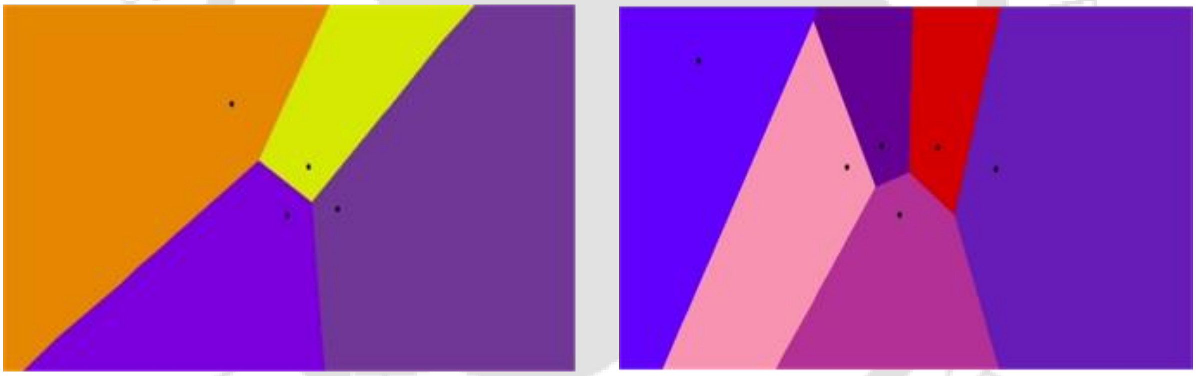


Fig. (a). Frame no. 5 ($\langle\rho\rangle v=0.05\ 1/m^2$) **Fig. (b).** Frame no. 118($\langle\rho\rangle v=0.075\ 1/m^2$)

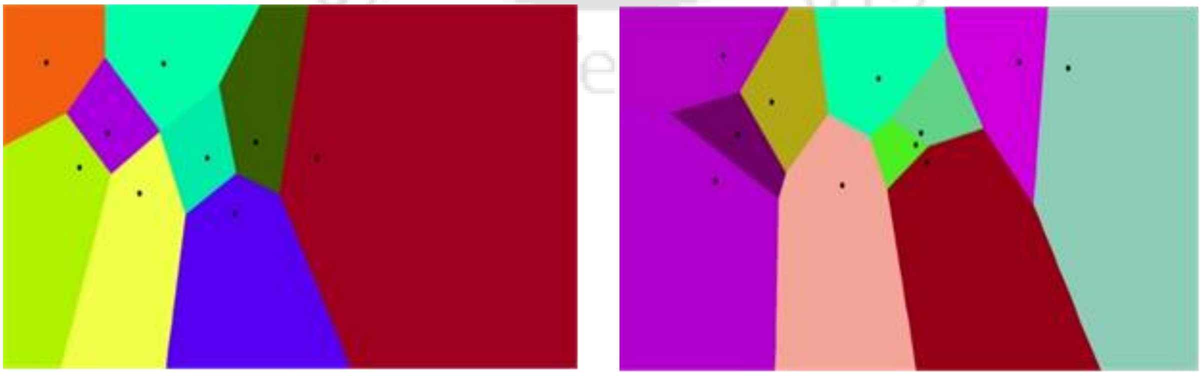


Fig.(c). Frame no. 120($\langle\rho\rangle v=0.112\ 1/m^2$) **Fig. (d).** Frame no. 211($\langle\rho\rangle v=0.137\ 1/m^2$)

Figure 4.38. Voronoi diagram and voronoi cell formation for four different density ranges

Figure 4.38(a-d) showed voronoi diagram for four different frames in which dots represent pedestrians. Different colour areas show voronoi cells with edge as boundary. Voronoi cell edge around a pedestrian is a set of nearer points from that pedestrian in comparison to other pedestrians**.** These diagrams show a better spatial arrangement and influence/ interaction zone of different pedestrians which can be used to study the impacts of different factors (such as age, gender, luggage condition, group movements, etc.) on pedestrian interaction.

4.4.7.7. Outcomes of gap maintaining behaviour analysis

The current study presented a methodology for the development of a semi-manual technique for pedestrian positions (subsequently trajectory), speed, and inter-pedestrian gap extraction from a top-frontal view video which is generally available from CCTV or other surveillance camera recordings. Study of these parameters play a vital role in pedestrian interaction behaviour study, their trajectory, social distancing enforcement, and detailed microscopic calibration of simulation models.

Further, data were collected using videographic technique (from top-frontal view and under moderate flow conditions) for 1034 set of pedestrians (826 male and 208 female) from a skywalk facility in a sub-urban station in Mumbai, India. The extracted data included the demographic characteristics (age, gender and presence/ absence of luggage) along with body dimensions (shoulder width and body depth) of pedestrians. Based on the elliptical area occupied by each pedestrian, the spacings (longitudinal, and lateral) were calculated. It was observed when the leading pedestrian was exactly in front of the following pedestrian, the following pedestrian maintained highest gap that any other position of the leading vehicle. Further, it was observed that the average latitudinal spacing, longitudinal spacing and diagonal clearance that a pedestrian maintains to walk comfortably are 0.25m, 0.90m and 1.07m respectively.

The study related to voronoi vs classical approach showed that voronoi density and speed data had lower fluctuations compared to corresponding classical data. Average classical speed and voronoi speed were observed to be 56.78 m/min and 56.09 m/min respectively. Average classical density and voronoi density were observed to be 0.068ped/m^2 and 0.088ped/m^2 respectively. It could be seen that the voronoi method provides a more stable data (minimize fluctuations) which suggest that for threshold determination (to define the level of crowd), stream parameter should be determined from the voronoi approach instead of the classical approach.

4.5. Concluding remarks

In the chapter an initial preliminary analysis (t-test) was conducted between the two facilities (FOB and Skywalk) using the dominant category data (*Gender: Male, Age: 21-40 years and Luggage condition: Without*). The result of the test showed that significant difference existed between the two facilities and thus it was decided to segregate the mid-block data for both facilities.

Thereafter, using the pedestrian aggregated speed data for FOB facilities the descriptive statistics, normality test, and probability density functions were analyzed. Thereafter, using speed variation based on pedestrian characteristics for different mid-block sections, box and whisker plots were presented and statistical tests (t-test and ANOVA test for gender, luggage condition, mobile use, age and group size) were conducted. Fundamental diagrams were plotted for FOB facilities to predict the free flow speeds (FFS: u_f), jam density (K_j), and maximum flow rate (q_{max}). A global simulation model was developed which could represent the pedestrian behaviour over different elevated walkways. Further, speed models which could predict the walking behaviour based on microscopic pedestrian behaviour (individual characteristics: age, gender, luggage, mobile use, disability; and group characteristics: group size, lane formation, leader follower relationship, lane shifting, overtaking, squeezing effect and faster-is-slower effect) over FOB mid-block sections were developed using linear regression model. Similarly, using macroscopic parameters (average flow and average density) along with geometric factors (such as obstruction, land use type, time of data collection, length of facility, connectivity from and connectivity to, effective width), an attempt was made to predict the walking speed using tree based model (Light GBM) over FOB facilities.

Similar to FOB mid-block sections, using aggregated data the descriptive statistics, normality tests and probability density functions were analyzed for skywalk mid-block sections. Thereafter, using the individual location speed data, box plots were made and statistical tests were conducted. The fundamental diagrams were developed for speed-density, speed-flow rate, flow rate-density and flow rate-area module. The developed global simulation model was used for validation of different skywalk locations. The microscopic parameters were used to model the speed of the pedestrians using linear regression model. Further, gradient booster regressor (GBR) tree based approach was used in estimating walking speeds based on macroscopic parameters and geometric factors. Finally, a novel semi-manual data extraction technique was developed for extracting pedestrian position (subsequently speed and trajectory) data using frontal inclined camera angle over a skywalk mid-block section to identify the gap maintaining behaviour of pedestrians.

CHAPTER 5

PEDESTRIAN BEHAVIOUR OVER VERTICAL CONNECTIVITY (STAIRWAYS) OF FOB AND SKYWALK

The stairways data as discussed in the methodology chapter consists of fourteen FOB locations and seven skywalk locations. The data for locations F1-F3 were collected only for the mid-block sections and not for stairways. The following sections in the present chapter discusses about the pedestrian flow characteristics on FOB and skywalk stairway locations considering ascending and descending directions. Further walking behaviour analysis is also conducted to understand the factors which influence the walking speed over the different stairways. Figure 5.1 shows the outline of the chapter in block diagram format for pedestrian behaviour over stairway sections of elevated walkways.

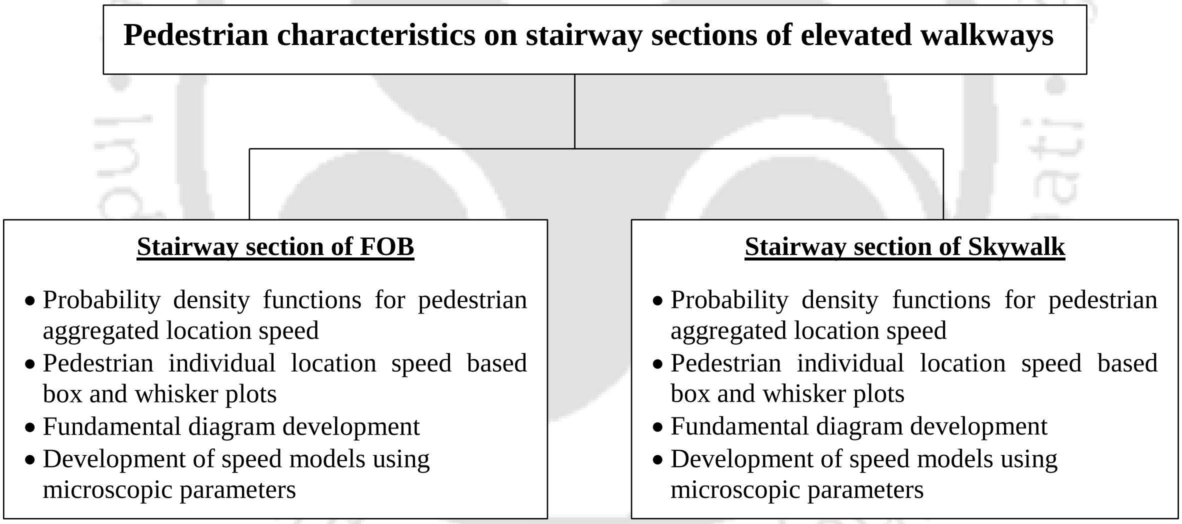


Figure 5.1. Block diagram for pedestrian behaviour on stairway sections of elevated walkways

5.1. Is the walking behaviour of pedestrians over stairway sections of FOBs and Skywalks same?

In order to investigate whether to combine the stairways data for both the facilities or keep them segregated, an initial significant test (t-test) was conducted between FOB and skywalk sections for ascending and descending directions, ascending direction between two facilities and descending direction between two facilities using free flow walking speed for dominant age group (*i.e., Gender: Male, Age: 21-40 years and Luggage condition: Without*). Table 5.1 shows the results of the significance test.

Table 5.1. t-test conducted among the FFS data for FOB and skywalk stairway sections

Facility	Direction	Mean (m/min)	Variance	Observations	t-Stat	t-Crit	Significance
FOB	*Ascend-Descend*	Asc (F): 29.66 Des (F): 35.32 Asc (S): 29.78 Des (S): 36.01	Asc (F): 116.61 Des (F): 165.95 Asc (S): 29.39 Des (S): 56.40	Asc (F): 271 Des (F): 309 Asc (S): 162 Des (S): 191	18.18	1.96	Significant
Skywalk	*Ascend-Descend*				23.63	1.96	Significant
FOB-Skywalk	*Ascend-Ascend*				0.44	1.96	Insignificant
FOB-Skywalk	*Descend-Descend*				1.12	1.96	Insignificant

Note: *Asc(F)-Ascending FOB, Des (F)-Descending FOB, Asc (S)- Ascending Skywalk, Des (S)-Descending Skywalk, t-Stat- t-Statistical, t-Crit- t-Critical*

The results from Table 5.1 showed that significant difference existed between ascending and descending directions for both FOB and skywalk facilities. However, no significant difference was observed between ascending direction for FOB and skywalk, as well as descending direction for FOB and skywalk facilities. As no difference was observed between ascending direction for both facilities and descending direction for both facilities, and to have a consistency with the previous chapter, analysis of FOB and skywalk stairways were presented separately. For development of speed models using microscopic parameters, the ascending direction data for both the facilities and descending direction data for both facilities were combined.

5.2. Determination of sample size requirement

The sample size calculation for stairways followed the similar estimation procedure as discussed for mid-block section (in chapter 4). Since there was significant difference between the ascending and descending directions of travel, the analysis followed this distinction. The total number of pedestrians observed in ascending direction were 16,707 during the study period, and the collected samples were 3,844 which were more than the calculated sample size requirement of 375 (as per Krejcie and Morgan, 1970). Similarly for the descending direction, the total observed pedestrians were 21,150 for which a sample of 4,445 was collected, and which was more than the calculated sample size requirement of 377 (as per Krejcie and Morgan, 1970). Similar to mid-block sections, the sample size requirements were fulfilled both at the aggregate and disaggregate levels.

5.3. Pedestrian characteristics on stairway sections of FOBs

In total 14 FOB stairway locations were used for final analysis. Table 5.2 shows the details of the geometric and demographic characteristics of the individual locations covered. The mean effective width, riser and tread dimensions across different FOB stairway sections were 1.75m, 0.15m and 0.29m respectively. Locations F10 and F11 had ramp like stairways with riser dimension of 0.02m and were thus not considered while calculating the riser dimension. The average number of samples collected per location in ascending and descending directions were 196 and 224 respectively. Across all locations, the proportion male pedestrians in comparison to female pedestrians was approximately 70%. The pedestrians in the age group of 21-40 years were the dominant pedestrian group in both the directions (approximately 60%). The proportion of pedestrians with luggage was approximately 42-44%, with highest percentage of pedestrians with luggage in both directions being at F9. In the ascending direction, the highest proportion of pedestrians using mobile was observed at location F15 (17%), while in descending direction F16 had the highest percentage (20%). Group size of single pedestrian was dominant across all locations in both the directions. Group size of 3 or more pedestrians was observed at locations F8 and F17.

In the following sub-sections, analysis was made over different stairway sections of FOBs with combined and individual locations for understanding the impact of pedestrian flow characteristics over walking speed.

Table 5.2. Details of FOB stairway locations with demographic characteristics

Location	**Geometry**				**Direction**	**Total Sample size**	**Sample size (in %)**														
							Gender		**Age**					**Luggage**		**Mobile Use**		**Group size**			
	Width (m)	**Riser (m)**	**Tread (m)**	**Slope (in °)**			***Male***	***Female***	***≤10***	***11-20***	***21-40***	***41-60***	***≥60***	***With***	***Without***	***With***	***Without***	***1***	***2***	***3***	***≥4***
IIT Bombay (F4)	1.2	0.17	0.32	30.11	*Ascend*	275	71.7	28.3	1.4	15.9	70.3	10.5	1.8	43.8	56.2	8.3	91.7	55.8	34.4	8.3	1.4
					Descend	126	77.0	23.0	1.6	10.3	69.8	14.3	4.0	43.7	56.3	12.7	87.3	73.0	22.2	4.8	0.0
Ultadanga (F5)	2.0	0.20	0.26	44.07	*Ascend*	255	73.3	26.7	0.8	2.7	60.4	29.4	6.7	54.4	48.6	9.8	90.2	71.4	17.6	8.2	2.7
					Descend	137	70.1	29.9	1.5	0.7	63.5	29.2	5.1	39.4	62.0	3.6	96.4	87.6	9.5	2.2	0.7
Lake Town (F6)	2.5	0.15	0.30	28.64	*Ascend*	202	47.0	53.0	1.0	19.8	37.6	27.2	14.4	38.1	61.9	10.9	89.1	62.4	25.7	6.9	5.0
					Descend	125	67.2	32.8	1.6	20.2	41.6	24.0	12.8	40.8	59.2	10.4	89.6	72.8	16.0	6.4	4.8
Sealdah (F7)	1.7	0.15	0.30	28.64	*Ascend*	163	77.9	22.1	1.2	21.5	23.9	44.2	9.2	38.0	62.0	3.1	96.9	83.4	15.3	1.2	0.0
					Descend	159	70.4	29.6	0.6	25.8	40.3	27.3	6.3	24.5	75.5	4.4	95.6	84.3	13.2	1.9	0.6
Anand Vihar (F8)	1.9	0.16	0.30	30.55	*Ascend*	217	77.0	23.0	7.8	9.7	56.7	20.3	5.5	60.8	39.2	5.1	94.9	60.8	23.0	10.1	6.0
					Descend	309	77.3	22.7	8.4	11.0	48.5	20.4	11.7	42.4	57.6	10.4	89.6	56.0	20.1	11.3	12.6
Akshardham (F9)	1.9	0.16	0.31	29.57	*Ascend*	306	78.4	21.6	0.0	1.3	91.8	5.6	1.3	71.6	28.4	12.7	87.3	97.7	1.3	0.7	0.3
					Descend	235	79.1	20.9	0.0	1.9	89.4	8.1	1.3	71.1	28.9	5.5	94.5	94.9	3.4	0.9	0.9
ITO (F10)	1.8	0.02	0.31	3.69	*Ascend*	118	82.2	17.8	0.0	6.8	50.8	34.7	7.6	50.8	49.2	15.3	84.7	78.0	16.9	2.5	2.5
					Descend	232	82.8	17.2	0.0	9.5	42.2	46.1	2.2	55.6	44.4	10.3	89.7	83.6	11.2	4.3	0.9
Maharani Bagh (F11)	2.4	0.02	0.30	3.82	*Ascend*	165	70.9	29.1	2.4	17.6	38.2	29.1	12.7	35.8	64.2	7.3	92.7	67.9	23.0	7.3	1.8
					Descend	120	65.8	34.2	1.7	11.7	55.0	18.3	13.3	33.3	66.7	5.8	94.2	76.7	17.5	4.2	1.7

Table 5.2. Details of FOB stairway locations with demographic characteristics *(continued)*

Location	**Geometry**				**Direction**	**Total Sample size**	**Sample size (in %)**														
							Gender		**Age**					**Luggage**		**Mobile Use**		**Group size**			
	Width (m)	**Riser (m)**	**Tread (m)**	**Slope (in °)**			***Male***	***Female***	***≤10***	***11-20***	***21-40***	***41-60***	***≥60***	***With***	***Without***	***With***	***Without***	***1***	***2***	***3***	***≥4***
Vaishali (F12)	3.3	0.14	0.30	26.73	*Ascend*	73	78.1	21.9	0.0	2.7	91.8	5.5	0.0	20.5	79.5	12.3	87.7	74.0	16.4	5.5	4.1
					Descend	337	65.9	34.1	0.9	2.4	88.1	8.0	0.6	53.1	46.9	7.4	92.6	54.6	25.5	12.8	7.1
Tin Factory (F13)	1.6	0.12	0.25	27.50	*Ascend*	253	64.8	35.2	1.2	8.3	58.9	22.9	8.7	34.5	65.5	11.1	88.9	88.5	9.1	1.2	1.2
					Descend	310	67.7	32.3	4.5	5.5	64.2	18.1	8.1	35.5	64.5	1.9	98.1	82.3	9.4	3.9	4.5
Yeshwantpur (F14)	0.9	0.09	0.26	19.83	*Ascend*	99	88.9	11.1	0.0	18.2	63.6	12.1	6.1	28.3	71.7	6.1	93.9	88.9	8.1	2.0	1.0
					Descend	264	87.9	12.1	0.8	13.3	67.8	16.7	1.5	37.9	62.1	5.7	94.3	93.6	3.8	1.5	1.1
Marathahalli (F15)	1.1	0.16	0.32	28.64	*Ascend*	231	75.3	24.7	0.4	16.5	60.6	16.5	6.1	28.1	71.9	16.9	83.1	73.2	19.5	5.2	2.2
					Descend	258	72.1	27.9	0.4	21.3	58.5	15.9	3.9	36.8	63.2	5.8	94.2	67.1	25.2	3.9	3.9
Christ University (F16)	1.2	0.14	0.29	27.65	*Ascend*	80	53.8	46.2	0.0	6.3	71.3	20.0	2.5	55.5	45.0	8.8	91.2	88.8	8.8	1.3	1.3
					Descend	305	31.8	68.2	0.0	31.8	56.4	9.8	2.0	80.0	20.0	20.0	80.0	55.4	29.2	12.8	2.6
Maligaon (F17)	1.1	0.13	0.26	28.64	*Ascend*	306	69.0	31.0	5.6	12.1	45.4	25.5	11.4	28.1	71.9	7.8	92.2	44.1	28.4	16.0	11.4
					Descend	220	65.0	35.0	7.3	12.7	53.6	19.5	6.8	23.2	76.8	3.2	96.8	46.8	24.5	16.8	11.8
Overall	***1.75***	***0.15***	***0.29***	***29.21***	***Ascend***	***196***	***72.0***	***28.0***	***1.6***	***11.4***	***58.7***	***21.7***	***6.7***	***41.8***	***58.2***	***9.7***	***90.3***	***73.9***	***17.7***	***5.5***	***2.9***
					Descend	***224***	***70.0***	***30.0***	***2.1***	***12.7***	***59.9***	***19.7***	***5.7***	***44.1***	***55.9***	***7.7***	***92.4***	***73.5***	***16.5***	***6.3***	***3.8***

5.3.1. Pedestrian speed data aggregated from all FOB stairway sections

In order to understand the speed variation over stairway sections of FOB facilities, probability density functions among pedestrians (based on gender, age, luggage condition, mobile use and group size) for all the locations combined together are shown in Figure 5.2. The x-axis represents the mean walking speed (in m/min) and the y-axis shows the relative frequency.

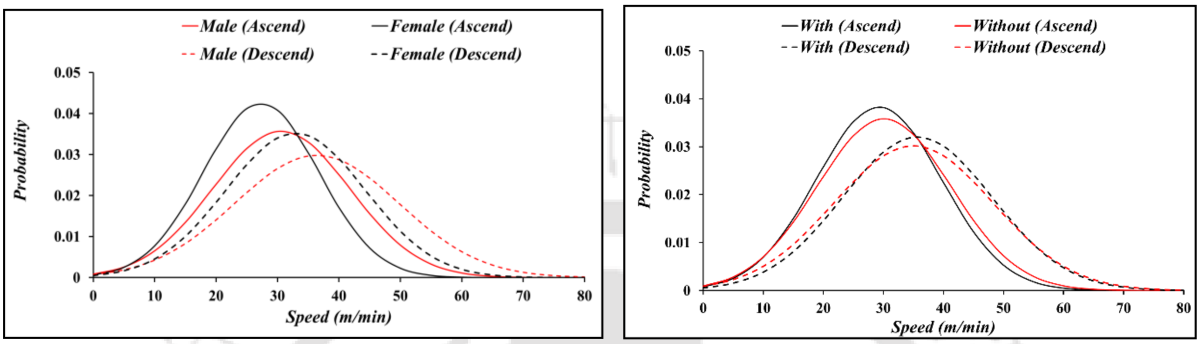


Fig. (a). Speed distribution based on gender

Fig. (b). Speed distribution based on luggage condition

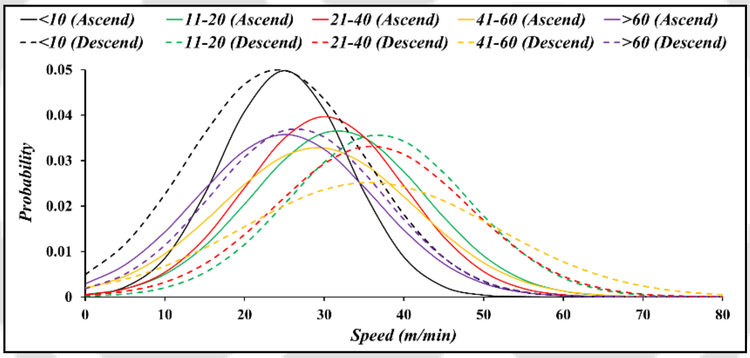


Fig. (c). Speed distribution based on age

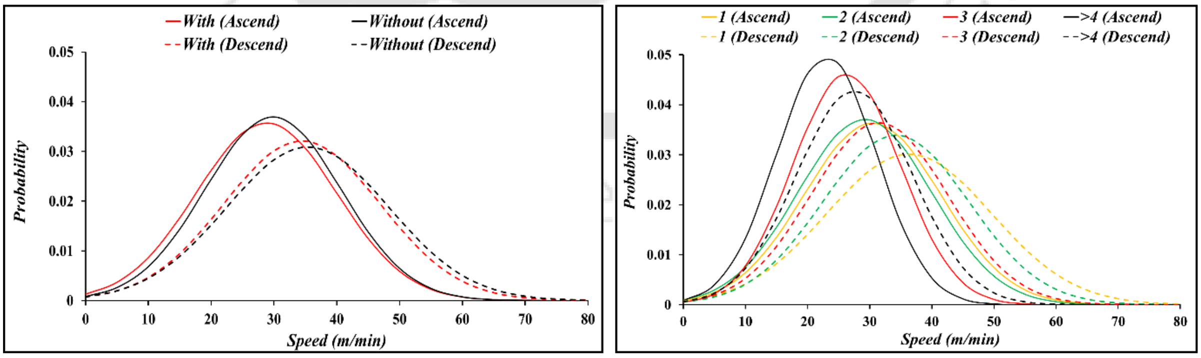


Fig. (d). Speed distribution based on mobile use

Fig. (e). Speed distribution based on group size

Figure 5.2. Speed distribution based on pedestrian gender, luggage condition, age, mobile use and group size

Figure 5.2(a) shows that the male pedestrians had a higher mean walking speed than female pedestrians while both ascending and descending stairways by approximately 3m/min. The speed distribution for pedestrians with and without luggage showed similar walking speeds for both ascending and descending pedestrians over FOB stairways sections. However, the difference between ascending and descending pedestrians with and without luggage was 5-6m/min.

The pedestrians in the age group of 11-20 years were found to have the highest average mean speed in comparison to other pedestrian age categories (refer Figure 5.2c), while moving in both the directions. Similarly, child (≤10 years) and elderly (≥60 years) pedestrians had similar speed distributions with an average speed of around 24m/min (ascending) and 27m/min (descending). Figure 5.2(d) showed that the pedestrians without mobile phone had higher walking speed in both ascending and descending directions than those without mobile by approximately 6m/min. Group size (refer Figure 5.2e) showed that the pedestrians walking in group size of 4 or more pedestrians had the lowest walking speeds in comparison to other group sizes while moving in both the directions.

5.3.2. Speed variation based on pedestrian characteristics for different FOB stairway sections

The box and whisker plots (refer Figure 5.3-Figure 5.12) are presented for the speed distribution of different pedestrians categories based on age, gender, luggage, mobile usage and group size for all the fourteen FOB stairway locations for ascending and descending directions. These plots help in identifying the lower (25th), median and upper (75th) quartile speeds along with skewness. The skewness defines how symmetric or asymmetric the distribution is, and positive skewness indicates larger accumulation of lower speeds.

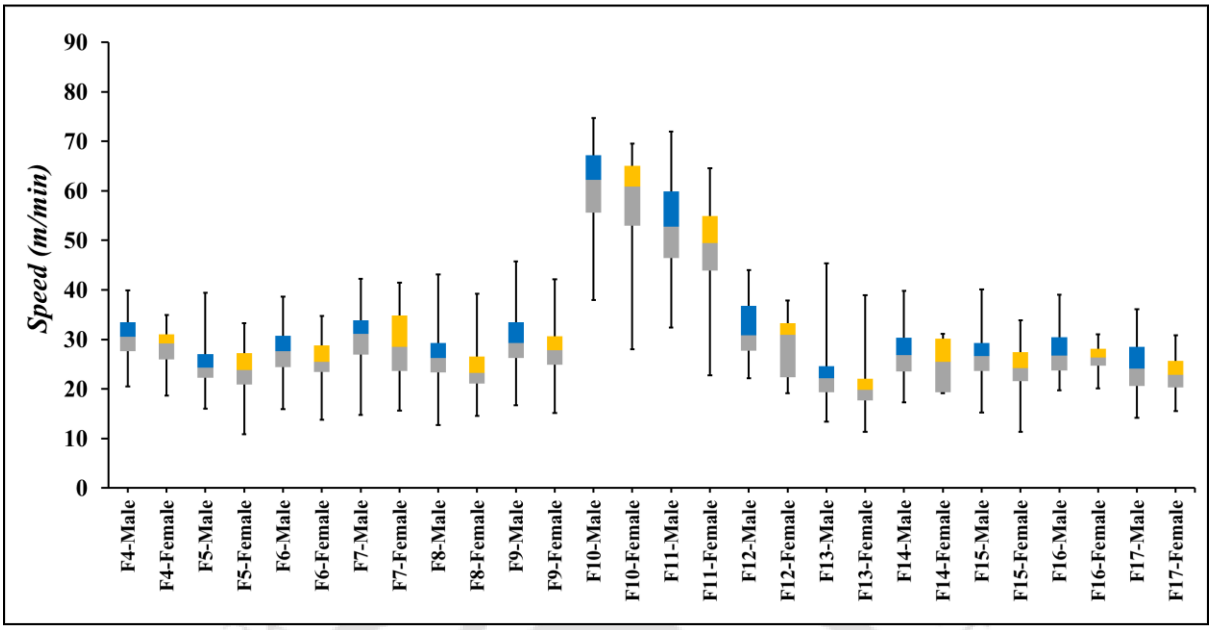


Figure 5.3. Gender wise speed variation for all FOB locations (ascending direction)

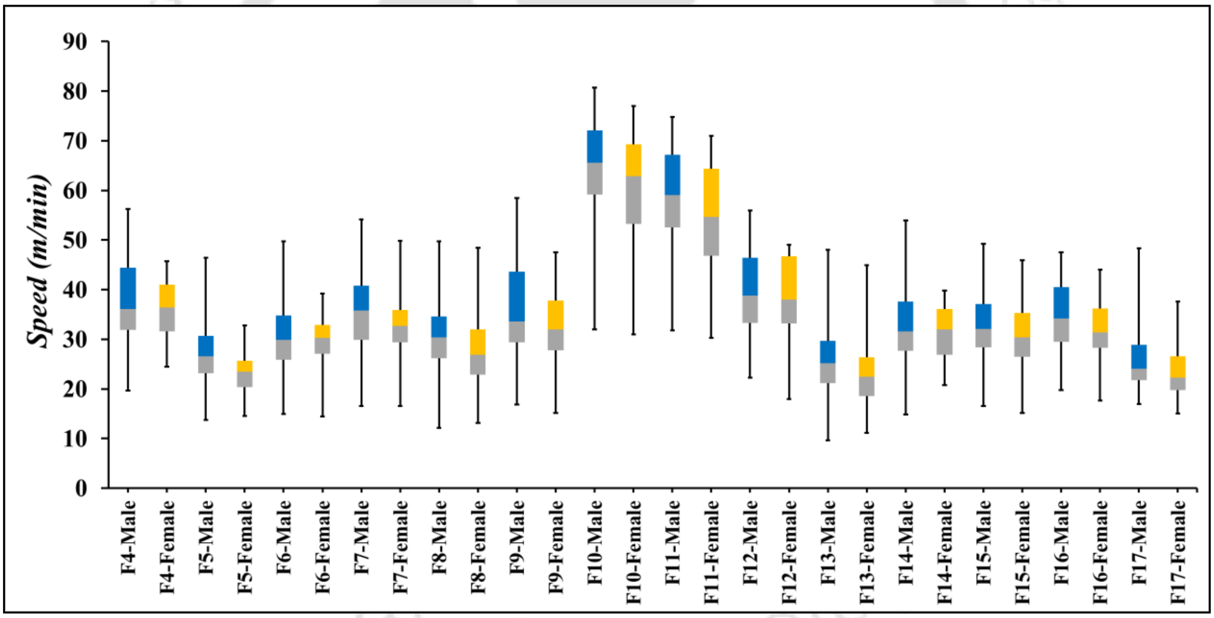


Figure 5.4. Gender wise speed variation for all FOB locations (descending direction)

As per Figure 5.3-Figure 5.4 it was observed that across all locations, male pedestrians had higher walking speeds in comparison to the female pedestrians in both ascending and descending directions. Previous studies by Fruin (1987), Fujiyama (1987), Zhang (2009), Patra (2017) and Shah (2017) also indicated that male pedestrians had higher walking speeds than

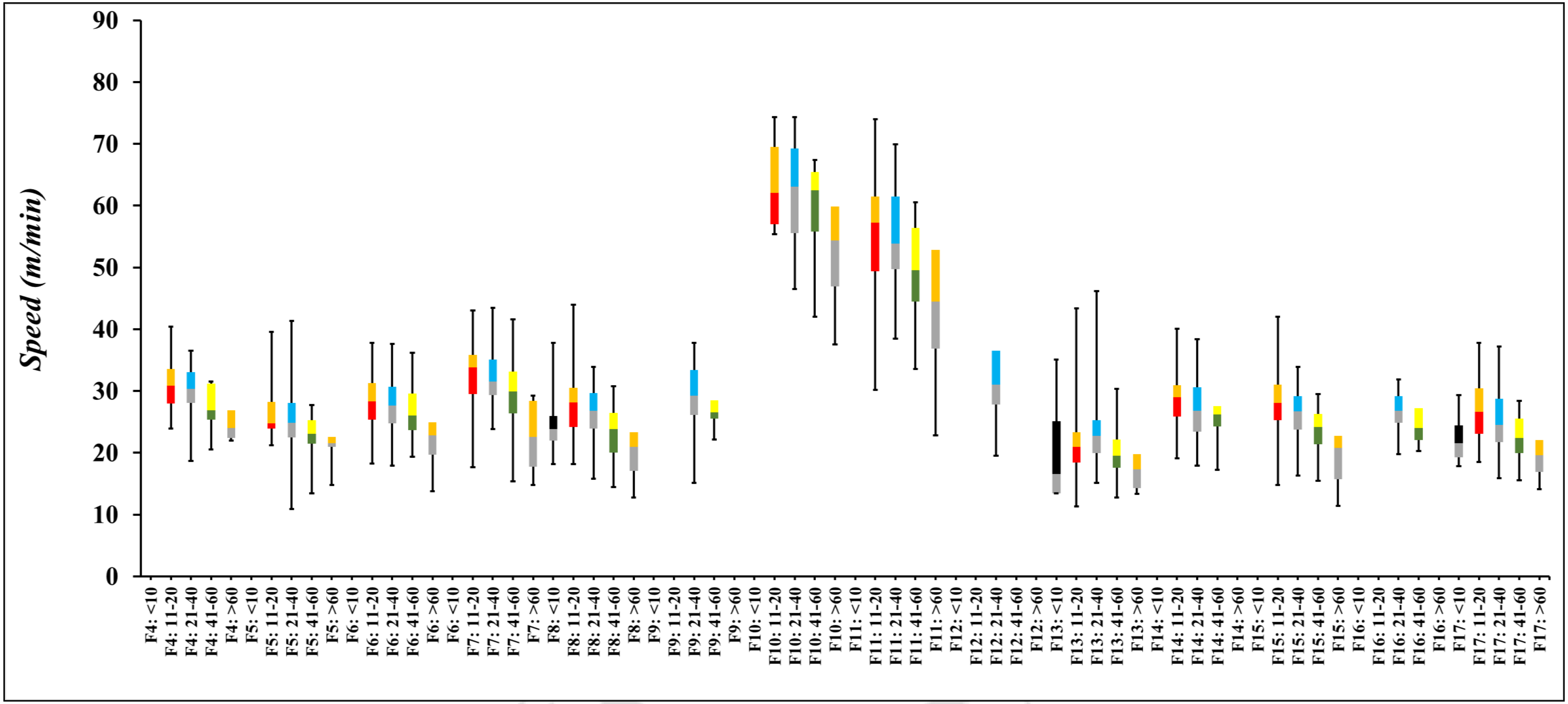


Figure 5.5. Age wise speed variation for all FOB locations (ascending direction)

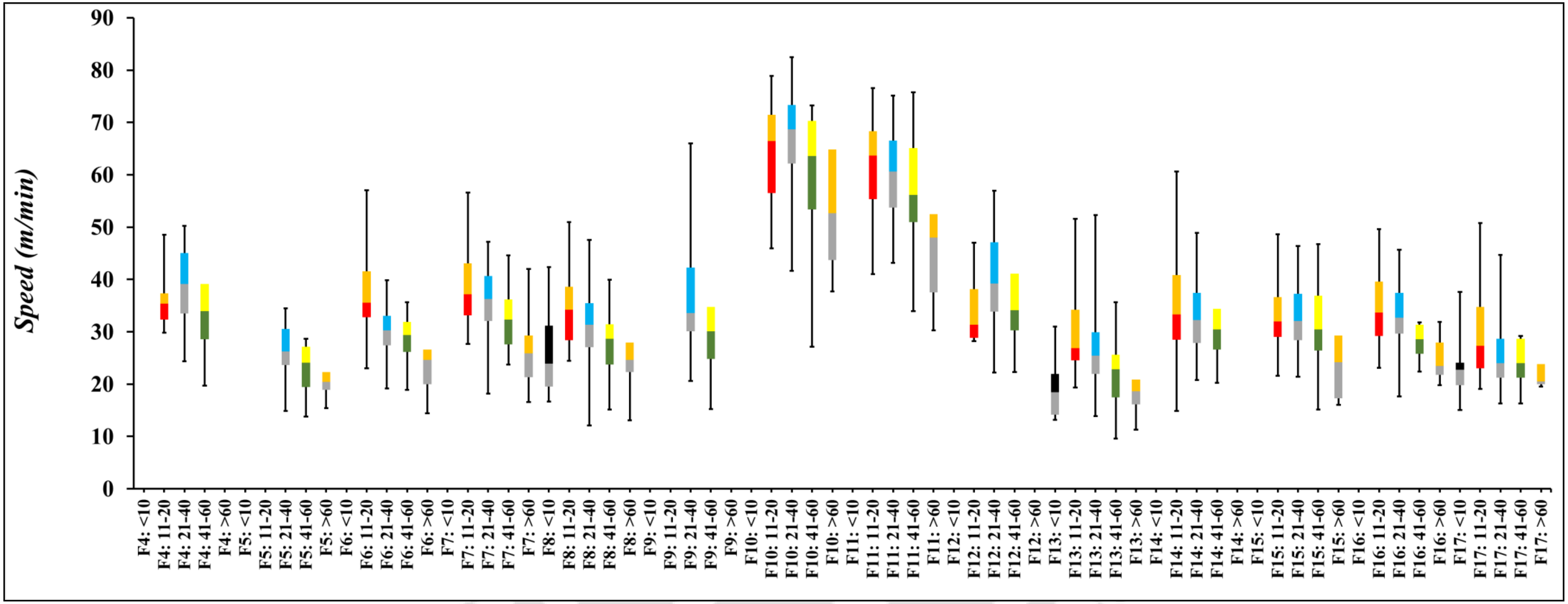


Figure 5.6. Age wise speed variation for all FOB locations (descending direction)

female pedestrians for both directions (ascending and descending). At locations F10 and F11 the male and female pedestrians had significantly higher median walking speeds in comparison to the other locations due to the lower riser height. At location F13 the lowest median speed was observed among all locations as there were many obstructions on the stairways in the form of beggars and vendors. In case of locations F10 and F11, negative skewness was observed which meant accumulation of higher walking speeds. For locations F13 and F17, positive skewness was observed and thus higher accumulation of lower speeds were found due to the obstruction in the form of vendors, beggars and width of the facility.

From Figure 5.5 it was observed that at all the sites, the pedestrians in the age category 11-20 years had the highest median speed, followed by the pedestrians in the age range of 21-40 years. The senior pedestrians (age ≥60 years) were observed to walk at lowest median speeds in comparison to other age groups across all the sites. The studies by Fruin (1987), Fujiyama (2004), Patra (2017) and Shah (2017) also observed that young pedestrians walked faster than the older pedestrians (both while ascending and descending stairways). Positive skewness, i.e., accumulation of lower speed was observed in the case of child pedestrians (≤10 years) for locations F1, F2, F4, and F7; and elderly pedestrians (≥60 years) for the locations F2, F3, F15 and F16. For all the other age categories, symmetric distributions were observed. The ascending and descending median speeds ranged between 16-63m/min and 18-68m/min respectively (refer Figure 5.5 and Figure 5.6). Due to the lower sample size of ascending pedestrians in the age group of ≤10 years (for locations F4-F7, F9, F11-F16), 11-20 years (for locations F9, F12) and ≥60 years (for locations F9, F12, F14, F16) box plots were not presented. Similarly in the case of descending direction, the box plots were not constructed for pedestrians in the age group of ≤10 years (for locations F4-F7, F9-F12, F14-F16), 11-20 years (for location F9) and ≥60 years (for locations F4, F9, F12 and F14) due to lower sample size.

Across all the locations, the variation of median walking speeds between the pedestrian with and without luggage in both directions was quite similar (refer Figure 5.7 and Figure 5.8). The average ascending mean speed across all locations for pedestrians with and without luggage were 29.98m/min and 32.48m/min respectively. Similarly, in the descending direction, the average pedestrian speed with and without luggage were observed to be 36.39m/min and 38.39m/min respectively. Shah (2013, 2019) found that while walking on stairways, the presence of luggage reduced the walking speed by 6m/min while ascending and descending. Figures 5.7 and 5.8 showed that the pedestrian speed was impacted (by 4-7m/min) due to luggage presence when a pedestrian was ascending, however the presence of luggage in the descending direction did not have much impact on the walking speed.

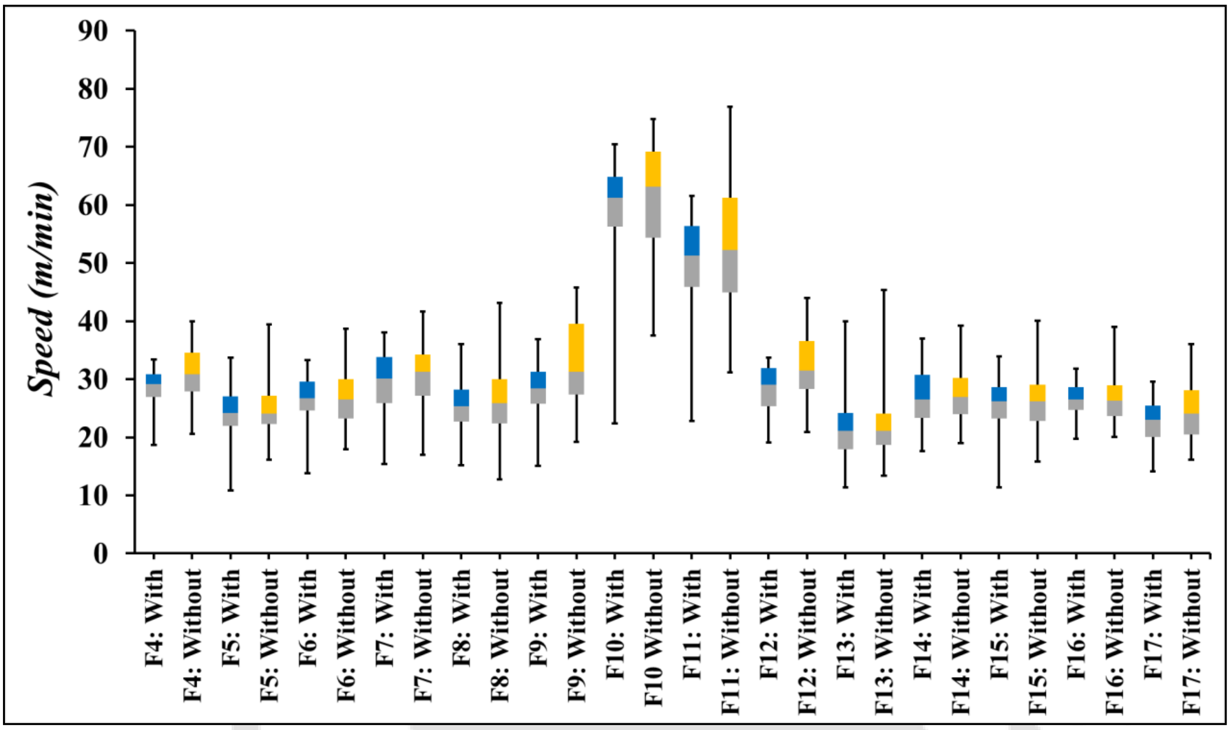


Figure 5.7. Luggage condition wise speed variation for all FOB locations (ascending direction)

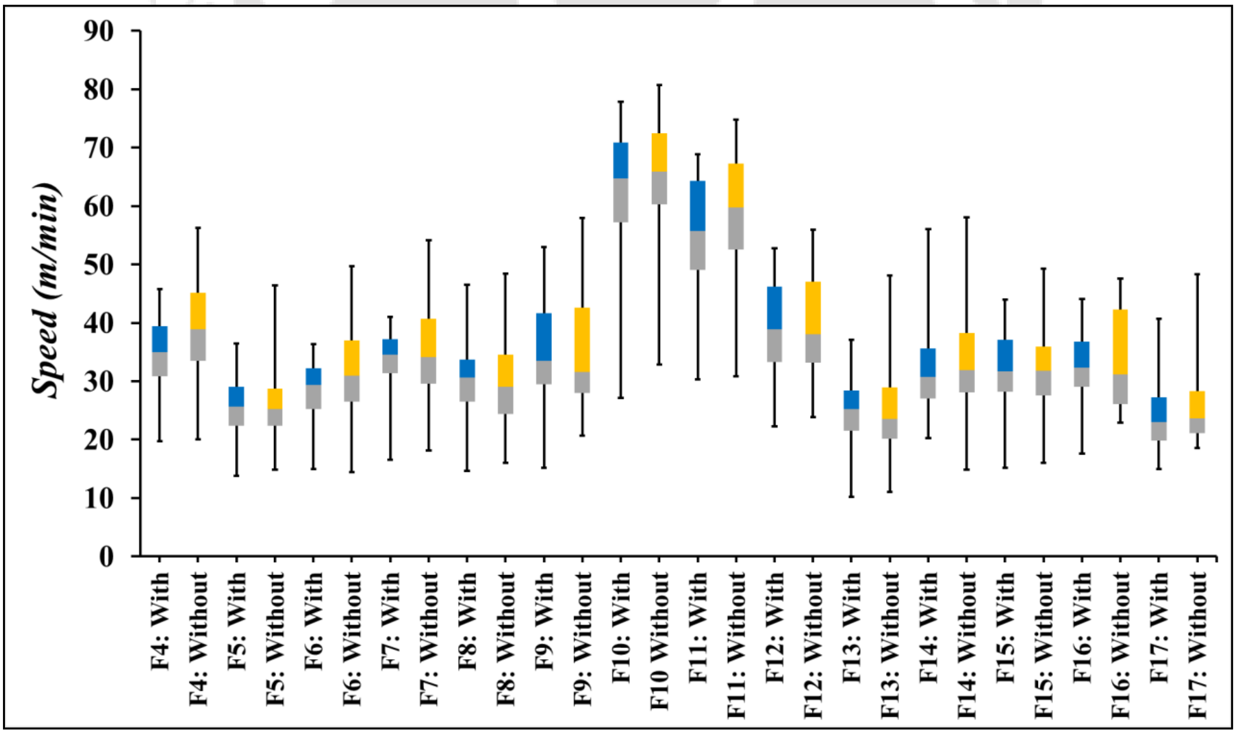


Figure 5.8. Luggage condition wise speed variation for all FOB locations (descending direction)

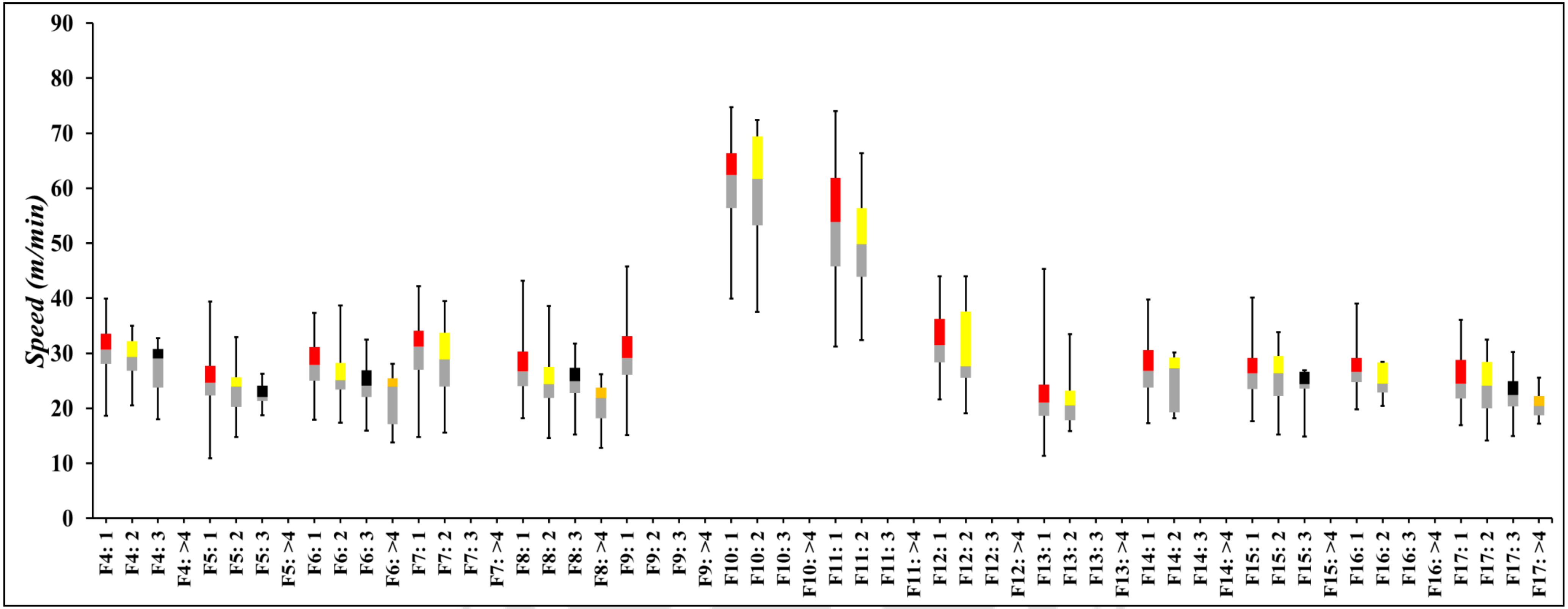


Figure 5.9. Group size wise speed variation for all the FOB locations (ascending direction)

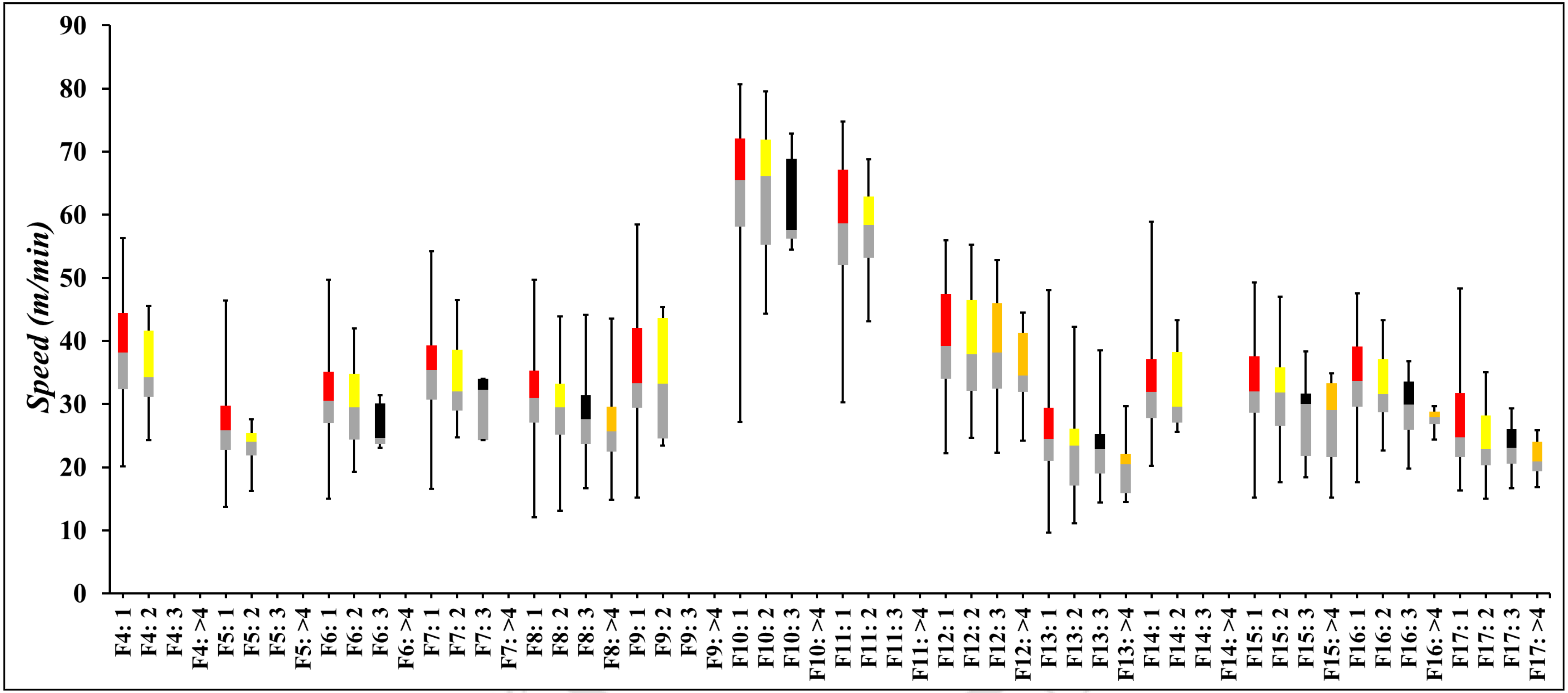


Figure 5.10. Group size wise speed variation for all the FOB locations (descending direction)

The results from Figure 5.9-Figure 5.10 showed that the pedestrians travelling alone had the highest median speed in comparison to all other group sizes across different locations. The group of size 3 or more pedestrians had the lowest median walking speed for all locations. Previous studies by Carey (2005) and Nakagawa et al. (2007) also showed that with increase in group size the walking speed kept on decreasing. For group size of two (for F9 location), three (for F7, F9-F14 and F16 locations) and group size of four (for F4, F5, F7, F9-F16 locations), box plots were not presented for ascending direction due to lower sample size. Similarly, in descending direction, due to lower sample size, pedestrian group size of three (for locations F4, F5, F7, F9, F11 and F14) and four or more (for locations F4-F7, F9-F11 and F14) were not presented.

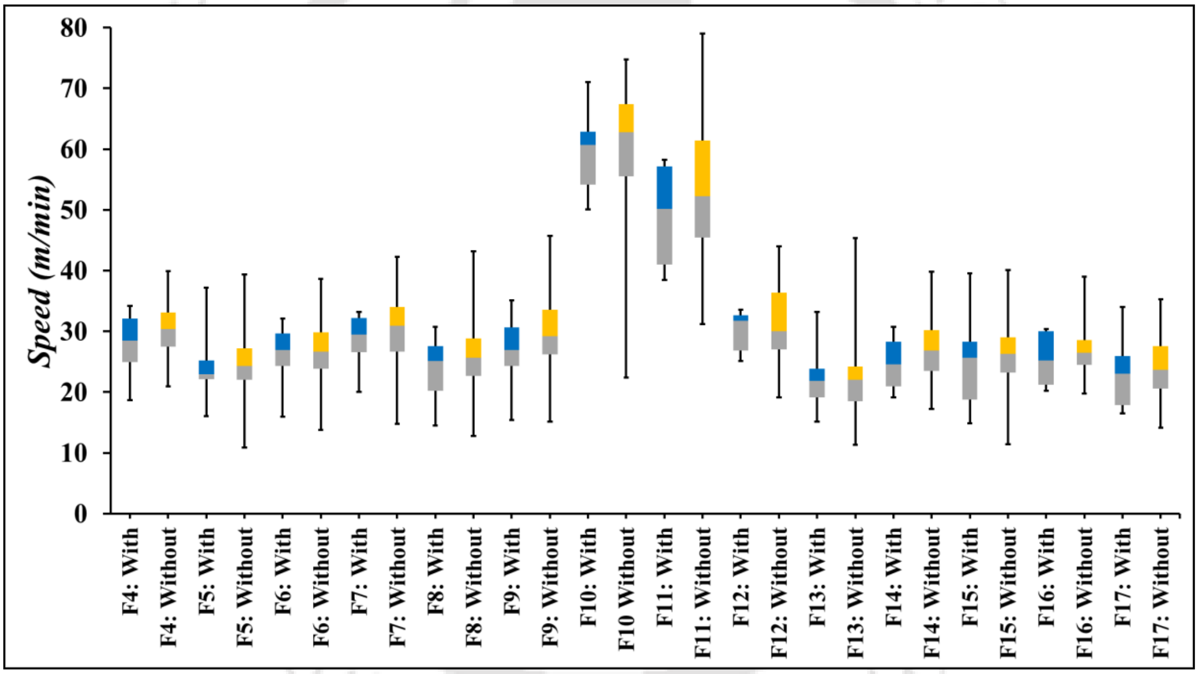


Figure 5.11. Mobile use speed variation for all FOB locations (ascending direction)

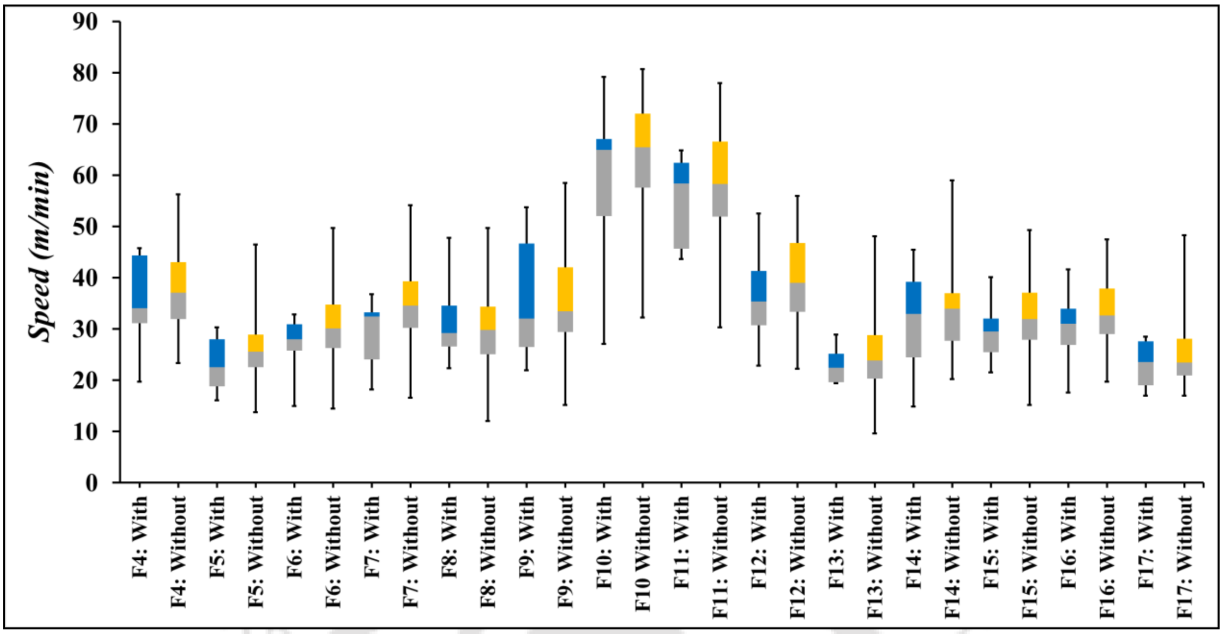


Figure 5.12. Mobile use speed variation for all FOB locations (descending direction)

For all the sites the pedestrians without mobile phones had significantly higher median speed than the ones with mobiles. The difference in walking speed between ascending and descending pedestrians with and without mobile was approximately 5-6m/min. The highest and lowest median ascending speeds were observed at locations F10 (without mobile) and F13 (with mobile), respectively. F10 being a predominantly commercial location with low riser height had pedestrians walking in ascending direction at much faster speed in comparison to F13 where pedestrians had to face many obstructions over the stairways.

5.3.3. Development of fundamental diagrams for FOB stairway sections

In order to observe the relationship between the different macroscopic parameters, Table 5.3 was presented which provides the mathematical flow models developed for the various FOB stairway study locations along with a general model (combining all data together). The table consists of the different speed-density, speed-flow rate, flow rate-density and flow rate-area module relationships along with the R^2 values. The R-squared (R^2) or coefficient of determination value represents the proportion of variance for a dependent variable which is explained by an independent variable in a regression model.

Table 5.3. Pedestrian flow models for FOB stairway locations

Study Location	**Speed-Density**		**Speed-Flow**		**Flow-Density**		**Flow-Area module**	
	Relationship	***R^2 value***	***Relationship***	***R^2 value***	***Relationship***	***R^2 value***	***Relationship***	***R^2 value***
IIT Bombay (F4)	$45.108 - 15.924*k$	0.478	$2.831*u - 0.062*u^2$	0.803	$45.108*k - 15.924*k^2$	0.767	$45.108/M - 15.924/M^2$	0.749
Ultadanga (F5)	$29.433 - 9.8997*k$	0.527	$2.973*u - 0.101*u^2$	0.822	$29.433*k - 9.8997*k^2$	0.803	$29.433/M - 9.8997/M^2$	0.771
Lake Town (F6)	$33.275 - 22.611*k$	0.629	$1.474*u - 0.044*u^2$	0.889	$33.275*k - 22.611*k^2$	0.871	$33.275/M - 22.611/M^2$	0.829
Sealdah (F7)	$36.924 - 29.861*k$	0.404	$1.244*u - 0.033*u^2$	0.757	$36.924*k - 29.861*k^2$	0.735	$36.924/M - 29.861/M^2$	0.728
Anand Vihar (F8)	$35.251 - 8.418*k$	0.546	$4.185*u - 0.118*u^2$	0.847	$35.251*k - 8.418*k^2$	0.805	$35.251/M - 8.418/M^2$	0.807
Akshardham (F9)	$36.891 - 15.314*k$	0.421	$2.412*u - 0.065*u^2$	0.772	$36.891*k - 15.314*k^2$	0.739	$36.891/M - 15.314/M^2$	0.732
Vaishali (F12)	$42.754 - 13.585*k$	0.572	$3.146*u - 0.073*u^2$	0.857	$42.754*k - 13.585*k^2$	0.858	$42.754/M - 13.585/M^2$	0.811
Tin Factory (F13)	$29.522 - 9.445*k$	0.532	$3.124*u - 0.106*u^2$	0.837	$29.522*k - 9.445*k^2$	0.815	$29.522/M - 9.445/M^2$	0.778
Yeshwantpur (F14)	$34.711 - 14.532*k$	0.489	$2.387*u - 0.068*u^2$	0.819	$34.711*k - 14.532*k^2$	0.792	$34.711/M - 14.532/M^2$	0.766
Marathahalli (F15)	$31.699 - 5.444*k$	0.545	$5.822*u - 0.183*u^2$	0.833	$31.699*k - 5.444*k^2$	0.827	$31.699/M - 5.444/M^2$	0.789
Christ University (F16)	$35.527 - 13.485*k$	0.564	$2.639*u - 0.074*u^2$	0.852	$35.527*k - 13.485*k^2$	0.839	$35.527/M - 13.485/M^2$	0.801
Maligaon (F17)	$37.034 - 13.358*k$	0.474	$2.775*u - 0.075*u^2$	0.799	$37.034*k - 13.358*k^2$	0.751	$37.034/M - 13.358/M^2$	0.741
Overall	***$34.239 - 9.639*k$***	***0.483***	***$3.558*u - 0.104*u^2$***	***0.811***	***$34.239*k - 9.639*k^2$***	***0.777***	***$34.239/M - 9.639/M^2$***	***0.752***

Figure 5.13 was plotted for speed-density, flow rate-density, speed-flow rate, and flow rate-area module relationships for the fourteen different FOB stairway sections combined. The diagrams give an overall view of the existing condition of the FOBs. Using these relationships, the planners and designers can either redesign the existing stairway facility or construct better facilities for the future. In the fundamental diagram development, locations F10 and F11 were not considered due to the geometric design consideration (i.e., low riser dimension) leading to higher walking speeds.

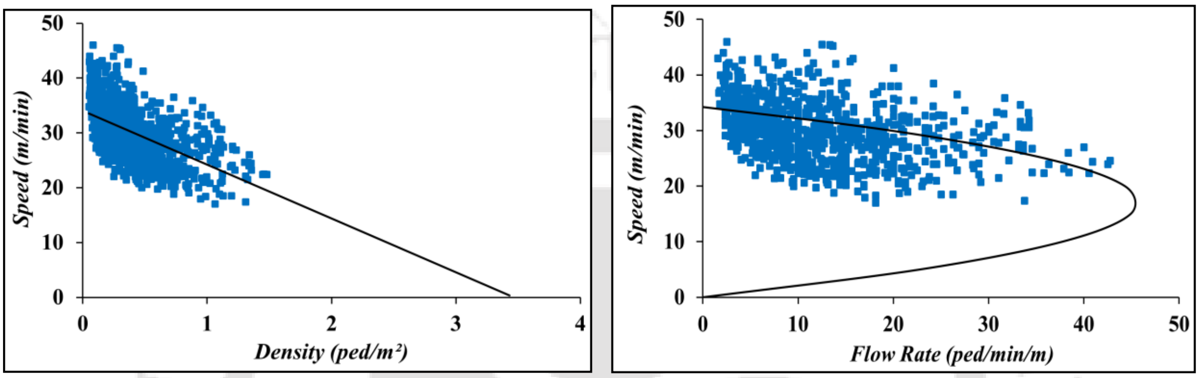


Fig. (a). Speed-Density relationship **Fig. (b).** Speed-Flow Rate relationship

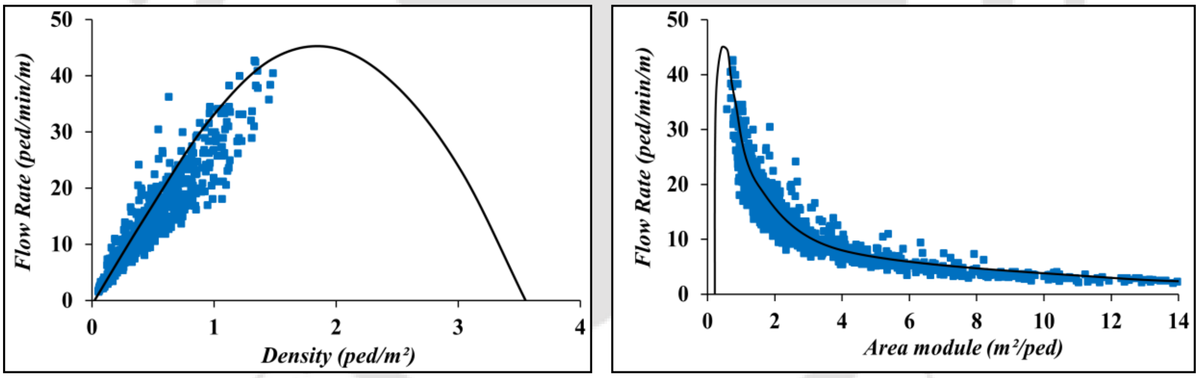


Fig. (c). Flow Rate-Density relationship **Fig. (d).** Flow Rate-Area Module relationship

Figure 5.13. Fundamental relationship diagrams of macroscopic parameters for combined data from all the sites

Figure 5.13(a) showed that the overall FFS for the different locations combined was 34.24m/min with the predicted jam density around 3.55ped/m^2. From Figure 5.13(c), the maximum flow rate predicted was 42.91ped/min/m occurring at an optimum density of 2.05ped/m^2. The optimum speed at the maximum flow rate was predicted to be 19.3m/min. Moreover, the area module predicted at maximum flow rate was 0.36m^2/ped.

Table 5.4 shows the pedestrian flow characteristics (i.e., FFS, q_{max}, area module at q_{max}, optimum speed and optimum density) for the different FOB stairway locations.

Table 5.4. Pedestrian flow characteristics for different FOB stairway sections

Location	Free Flow Speed (u_f), m/min	Maximum Flow Rate (q_{max}), ped/min/m	Area Module (M), at q_{max} (m^2/ped)	Optimum speed (m/min)	Optimum Density (ped/m^2)
IIT Bombay (F4)	45.11	31.54	0.79	21.40	1.35
Ultadanga (F5)	29.43	21.87	0.68	15.72	1.46
Lake Town (F6)	33.27	12.12	1.23	17.88	0.79
Sealdah (F7)	36.92	11.33	1.76	19.78	0.56
Anand Vihar (F8)	35.25	37.43	0.53	18.45	1.92
Akshardham (F9)	36.89	22.06	0.91	19.52	1.10
Vaishali (F12)	42.75	33.49	0.59	21.05	1.67
Tin Factory (F13)	29.52	23.02	0.65	15.52	1.53
Yeshwantpur (F14)	34.71	20.34	0.73	17.82	1.25
Marathahalli (F15)	31.69	43.01	0.33	15.25	2.91
Christ University (F16)	35.52	23.01	0.87	18.01	1.21
Maligaon (F17)	37.03	25.50	0.78	19.51	1.28

From Table 5.4, for location F15, at maximum predicted flow rate of 43.01ped/min/m, an area module of 0.33ped/m^2 was observed. The optimum speed across all stairway locations varied between 15-22m/min. The highest predicted optimum density was at F15, as it was a commercial cum shopping area with narrow stairway width. As the observed data were available mostly for only lower to moderate ranges of density, capacity values predicted by the fundamental relationships in Table 5.4 could have some variations.

5.4. Pedestrian characteristics on stairway sections of skywalks

The geometric and demographic characteristics of the individual locations covered are presented in Table 5.5. The mean effective width, riser and tread dimensions across different skywalk stairway sections were 1.48m, 0.16cm and 0.30cm respectively. The average number of samples collected per location in ascending and descending directions were 157 and 188 respectively. On an average across all locations, the male pedestrian proportion in comparison to female pedestrians was approximately 74% (ascending direction) and 67% (descending direction). The pedestrians in the age group of 21-40 years was the dominant pedestrian group in both the directions (~51-55%).

Table 5.5. Details of skywalk stairway locations with demographic characteristics

Location	**Geometry**				**Direction**	**Total Sample size**	**Sample size (in %)**														
							Gender		**Age**					**Luggage**		**Mobile Use**		**Group size**			
	Width (m)	**Riser (m)**	**Tread (m)**	**Slope (in °)**			***Male***	***Female***	***≤10***	***11-20***	***21-40***	***41-60***	***≥60***	***With***	***Without***	***With***	***Without***	***1***	***2***	***3***	***≥4***
Andheri (S1)	1.40	0.18	0.34	27.87	*Ascend*	57	71.9	28.1	0.0	14.0	57.9	22.8	5.3	64.9	35.1	0.11	99.9	93.0	5.3	1.8	0
					Descend	268	78.0	22.0	0.0	15.7	48.1	27.6	8.6	80.2	19.8	0.15	99.9	89.2	6.3	2.2	2.2
Goregaon (S2)	1.58	0.14	0.30	24.98	*Ascend*	75	78.7	21.3	0.0	6.7	60.0	26.7	6.7	56.0	44.0	0.11	99.9	78.7	14.7	6.7	0.0
					Descend	239	69.9	30.1	0.8	9.2	42.3	40.2	7.5	48.1	51.9	0.20	99.8	78.7	13.8	5.0	2.5
Ghatkopar (S3)	1.40	0.17	0.30	29.51	*Ascend*	217	73.7	26.3	0.00	30.9	51.2	13.4	4.6	53.9	46.1	0.10	99.9	83.9	12.4	1.8	1.8
					Descend	214	60.3	39.7	0.0	33.2	46.7	15.0	5.1	53.7	46.3	0.13	99.9	83.6	10.7	2.8	2.8
Bandra (S4)	1.46	0.14	0.28	26.56	*Ascend*	89	79.8	20.2	0.0	16.9	68.5	13.5	1.1	74.2	25.8	0.02	100.0	98.9	1.1	0.0	0.0
					Descend	153	68.0	32.0	0.0	3.3	63.4	30.1	3.3	79.7	20.3	0.11	99.9	90.2	7.8	1.3	0.7
Vile Parle (S5)	1.43	0.17	0.28	31.25	*Ascend*	147	68.0	32.0	1.4	44.2	29.9	22.4	2.0	53.1	46.9	0.12	99.9	85.0	13.6	1.4	0.0
					Descend	153	58.8	41.2	2.0	63.4	22.2	10.5	2.0	57.5	42.5	0.22	99.8	76.5	19.6	3.9	0.0
Santa Cruz (S6)	1.20	0.16	0.30	28.05	*Ascend*	369	81.6	18.4	0.0	1.4	75.6	21.1	1.9	67.2	32.8	0.14	99.9	94.9	4.6	0.5	0.0
					Descend	147	68.0	32.0	1.4	4.8	72.8	20.4	0.7	68.0	32.0	0.14	99.9	93.9	6.1	0.0	0.0
Kalyan (S7)	1.90	0.16	0.30	28.05	*Ascend*	147	64.6	35.4	1.4	25.2	37.4	31.3	4.8	47.6	52.4	0.10	99.9	81.0	15.0	2.7	1.4
					Descend	145	66.2	33.8	0.7	19.3	54.5	20.7	4.8	27.6	72.4	0.03	100.0	77.9	17.9	2.8	1.4
Overall	***1.48***	***0.16***	***0.30***	***28.03***	***Ascend***	***157***	***74.0***	***26.0***	***0.4***	***19.9***	***54.4***	***21.6***	***3.8***	***59.6***	***40.4***	***0.10***	***99.9***	***87.9***	***9.0***	***2.6***	***0.5***
					Descend	***188***	***67.0***	***33.0***	***0.7***	***21.3***	***50.5***	***23.5***	***4.6***	***59.3***	***40.7***	***0.12***	***99.9***	***84.3***	***11.8***	***2.6***	***1.4***

The proportion of pedestrians with luggage was around 60%, with highest percentage of pedestrians with luggage in both directions being at S1 and S4 (~80%), both locations having high flow of pedestrians moving to their workplace or educational institutes. Group size of single pedestrian was dominant across all locations in both the directions. Maximum composition of group size of 3 or more pedestrians was observed at location S2.

5.4.1. Pedestrian speed data aggregated from all skywalk stairway sections

In order to understand the speed variation over stairway section of skywalks, probability density functions among pedestrians (based on gender, age, luggage condition, mobile use and group size) for all the locations combined together were presented in Figure 5.14(a-e). The x-axis represents the mean walking speed (in m/min) and the y-axis shows the relative frequency.

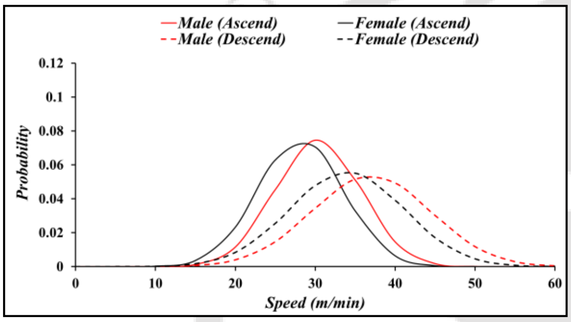


Fig. (a). Speed distribution based on gender

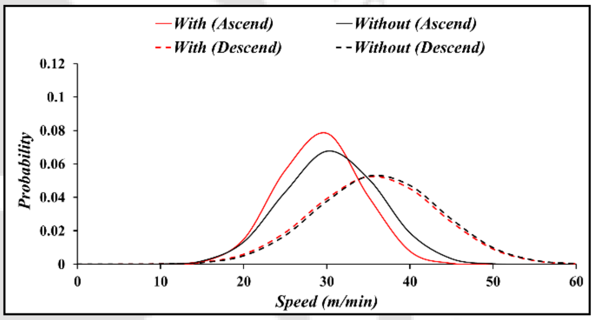


Fig. (b). Speed distribution based on luggage condition

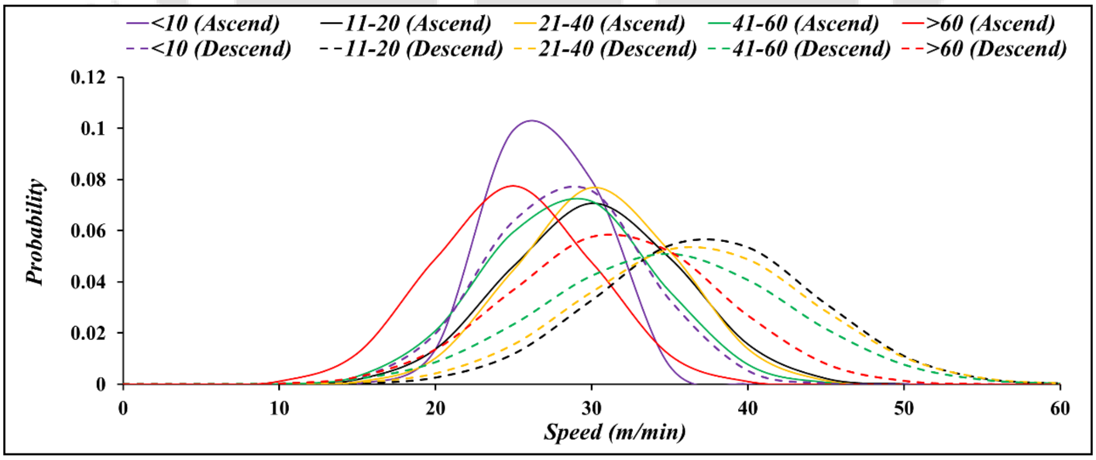


Fig. (c). Speed distribution based on age

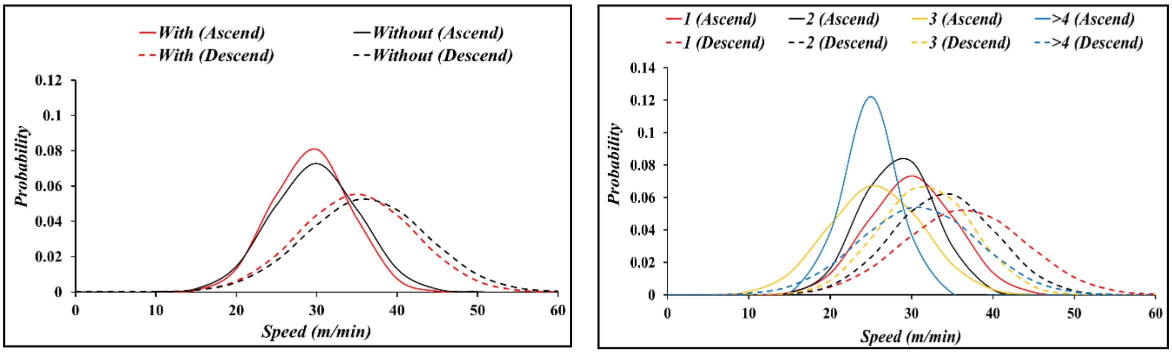


Fig. (d). Speed distribution based on mobile use

Fig. (e). Speed distribution based on group size

Figure 5.14. Speed distribution based on pedestrian gender, luggage condition, age, mobile use and group size

Figure 5.14(a) showed that the male pedestrians had higher mean walking speed in comparison to female pedestrians while both ascending (by 2-6m/min) and descending (by 2-4m/min). The male pedestrians while ascending and descending had mean walking speeds of 31.42m/min and 37.92m/min respectively. The distribution for luggage conditions showed that ascending pedestrians with luggage had slower median walking speeds by 3m/min in comparison to without luggage. Similarly, while descending the pedestrians with and without luggage had similar walking speeds. This showed that luggage condition affected the pedestrian speed more in ascending directions than descending direction on stairway across all stairway sections.

The pedestrians in the age group of 11-40 years were majorly found to have the highest average mean speed across all stairways in comparison to other pedestrian age categories (refer Figure 5.14c), while moving in both the directions. Group size showed that the group size of 4 or more pedestrians had the lowest walking speeds in comparison to other groups while moving in both the directions. The pedestrians moving alone had median walking speeds of 31.28m/min (ascending) and 37.58m/min (descending). While ascending the stairs, the pedestrians with mobile had a median speed of 27.66m/min and those without had a median speed of 31.92m/min.

5.4.2. Speed variation based on pedestrian characteristics for different skywalk stairway sections

The box and whisker plots (refer Figure 5.15-Figure 5.24) were presented for the speed distribution of different pedestrian categories (based on age, gender, luggage, mobile usage and group size) across all the seven skywalk stairway locations for both ascending and descending directions.

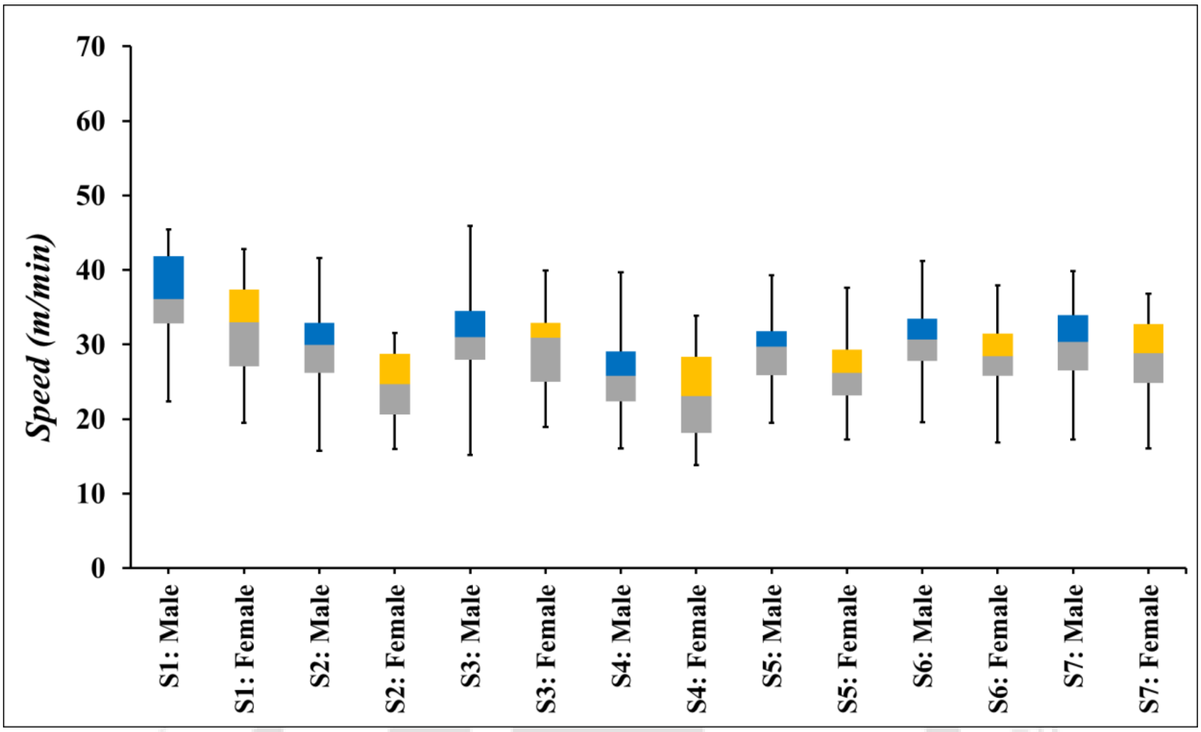


Figure 5.15. Gender wise speed variation for all skywalk locations (ascending direction)

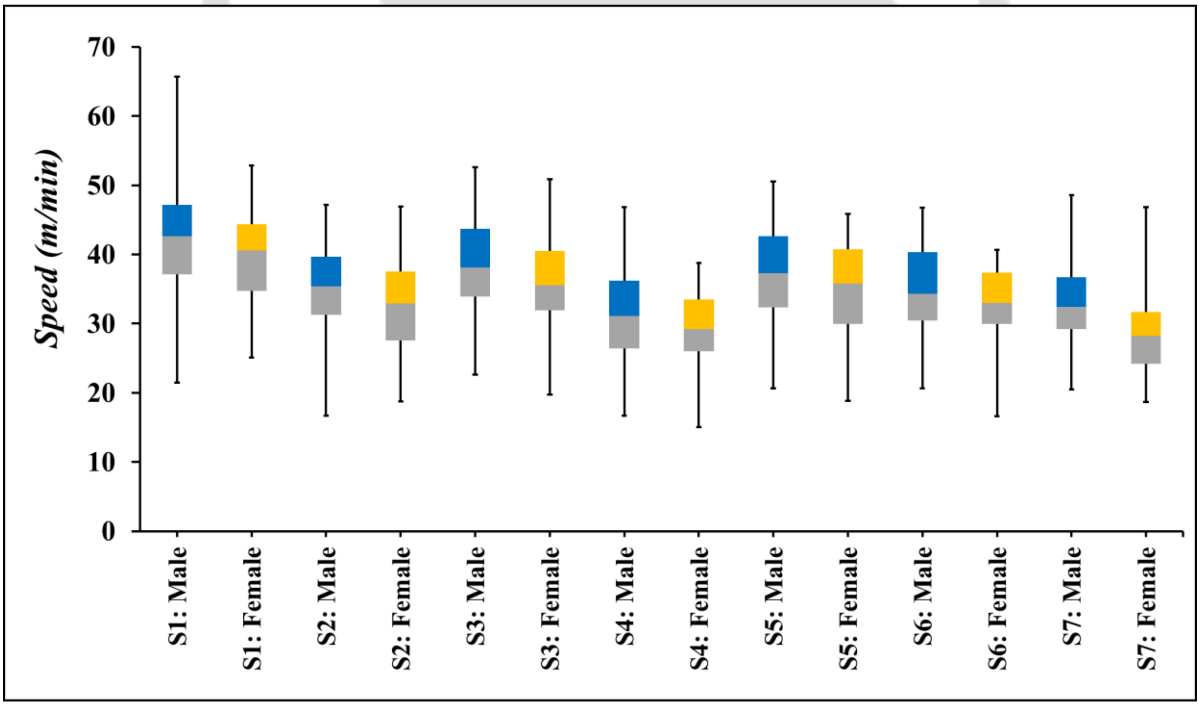


Figure 5.16. Gender wise speed variation for all skywalk locations (descending direction)

As per Figure 5.15 and Figure 5.16 it was observed that across all the locations, female pedestrians had lower median walking speeds for both ascending (by 2-5m/min) and descending (by 2-4m/min) directions. At location S4 the lowest median speed was observed as the flow was extremely high and pedestrians were forced to walk with the average speed of the queue. In case of female pedestrians (at locations F4 and F6) negative skewness was observed.

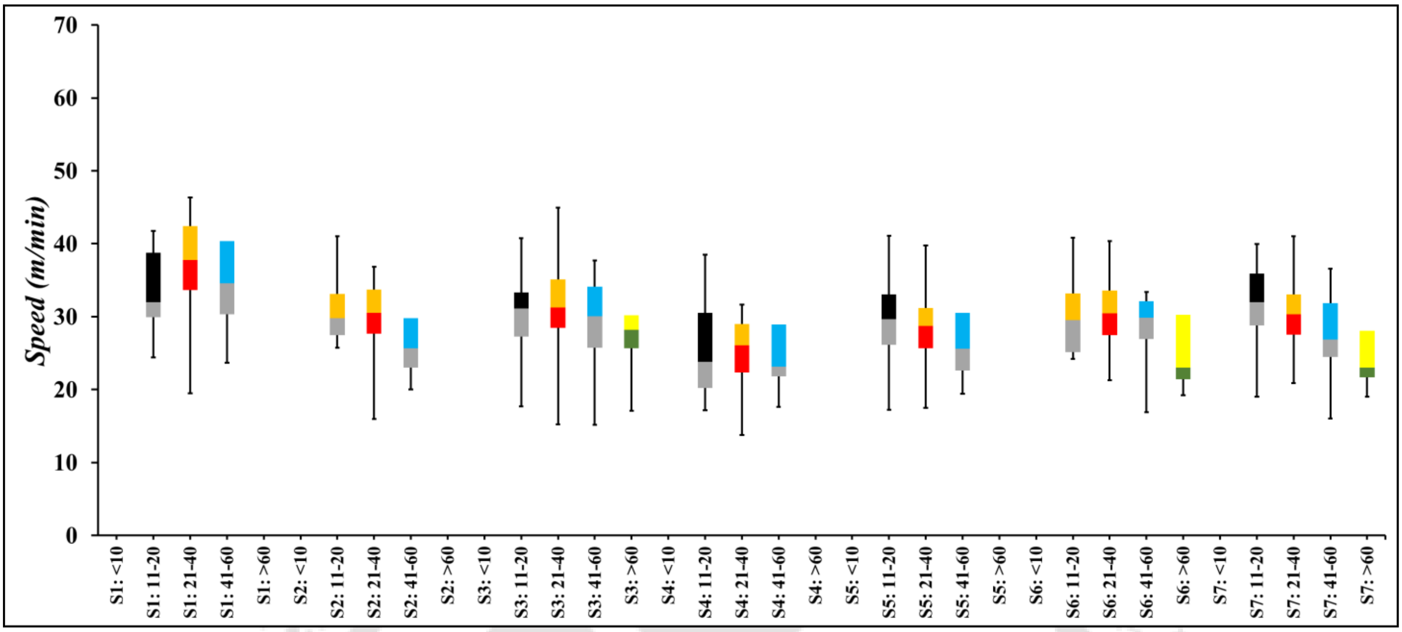


Figure 5.17. Age wise speed variation for all skywalk locations (ascending direction)

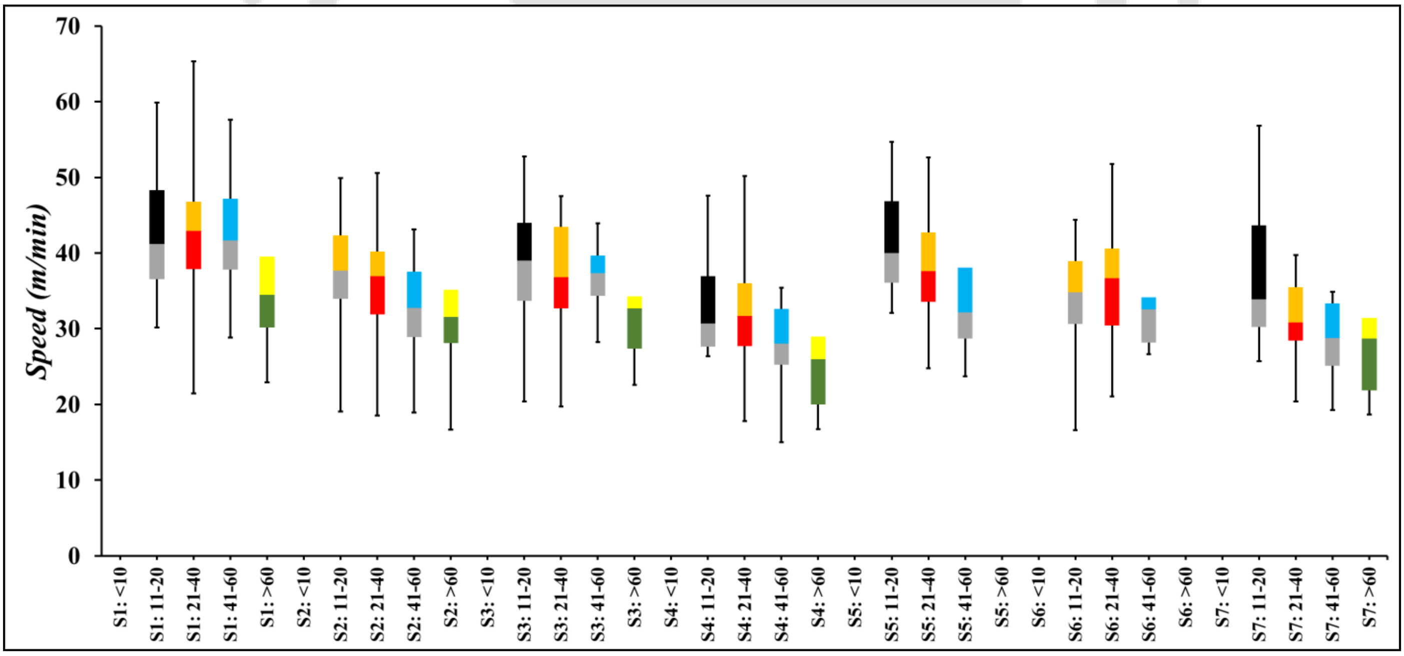


Figure 5.18. Age wise speed variation for all skywalk locations (descending direction)

From Figure 5.17-Figure 5.18 it was observed that while both ascending and descending stairways, pedestrians in the age group of 21-40 years had the highest median walking speed. At location S1, pedestrians had comparatively higher median speeds than the pedestrians in the other locations, as majority of the users were office goers or students travelling to and from adjoining railways station or metro station. Pedestrians in the age group of ≥60 years were the slowest travelers. Due to low sample size, pedestrian in the age category of ≤10 years was not presented.

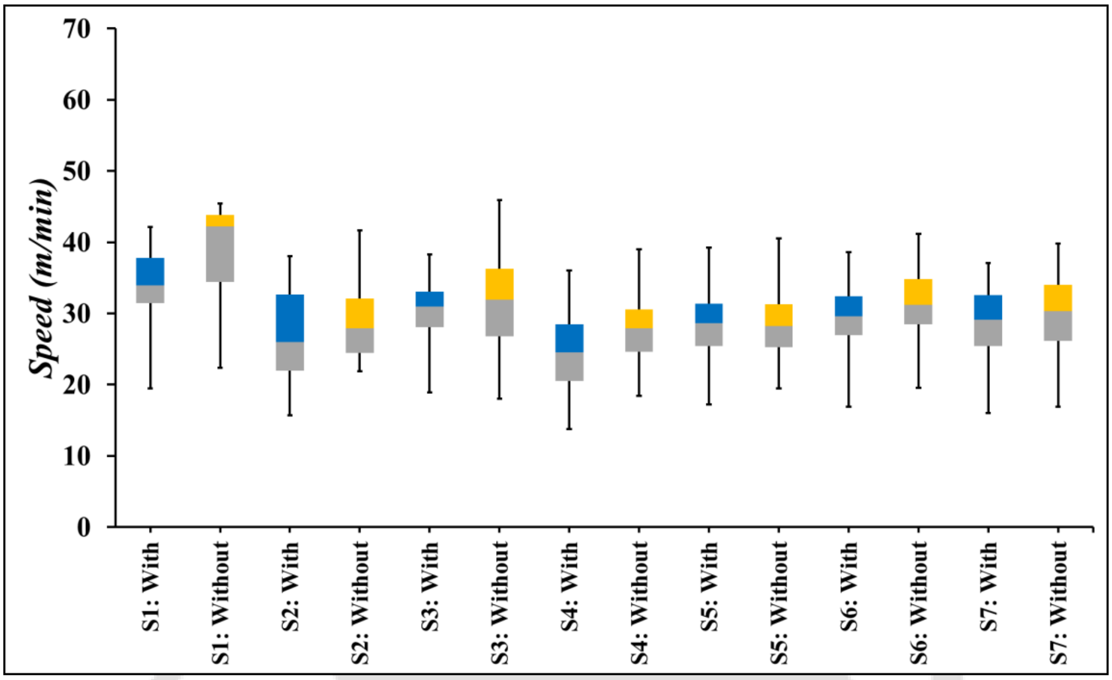


Figure 5.19. Luggage condition wise speed variation for all skywalk locations (ascending direction)

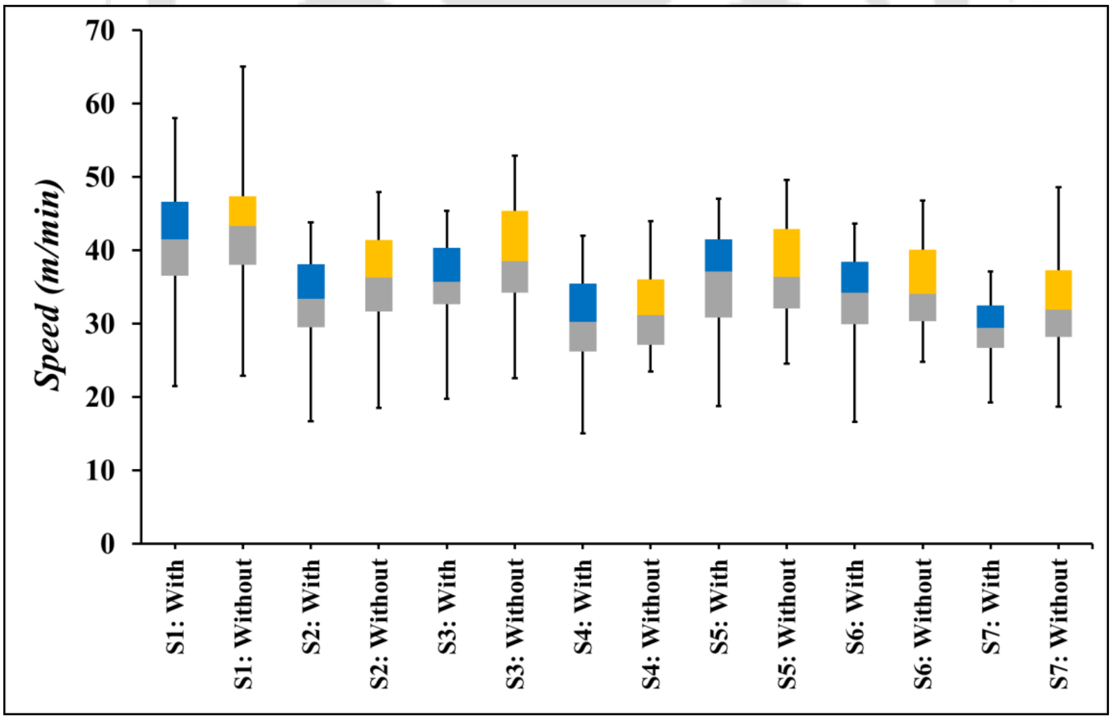


Figure 5.20. Luggage condition wise speed variation for all skywalk locations (descending direction)

Across all locations, the difference in median walking speed in ascending and descending directions were 1-2m/min (refer Figure 5.19-Figure 5.20). However in S1 location, the difference in ascending speeds between pedestrians with and without luggage was 9m/min, as majority of the pedestrians were moving in descending direction, which made movement difficult for the pedestrians with luggage. Thus directional split also had a major impact on the speed of the pedestrians, especially where the width of the facility was low and the stairway was located at commercial locations (were pedestrians are always in a rush).

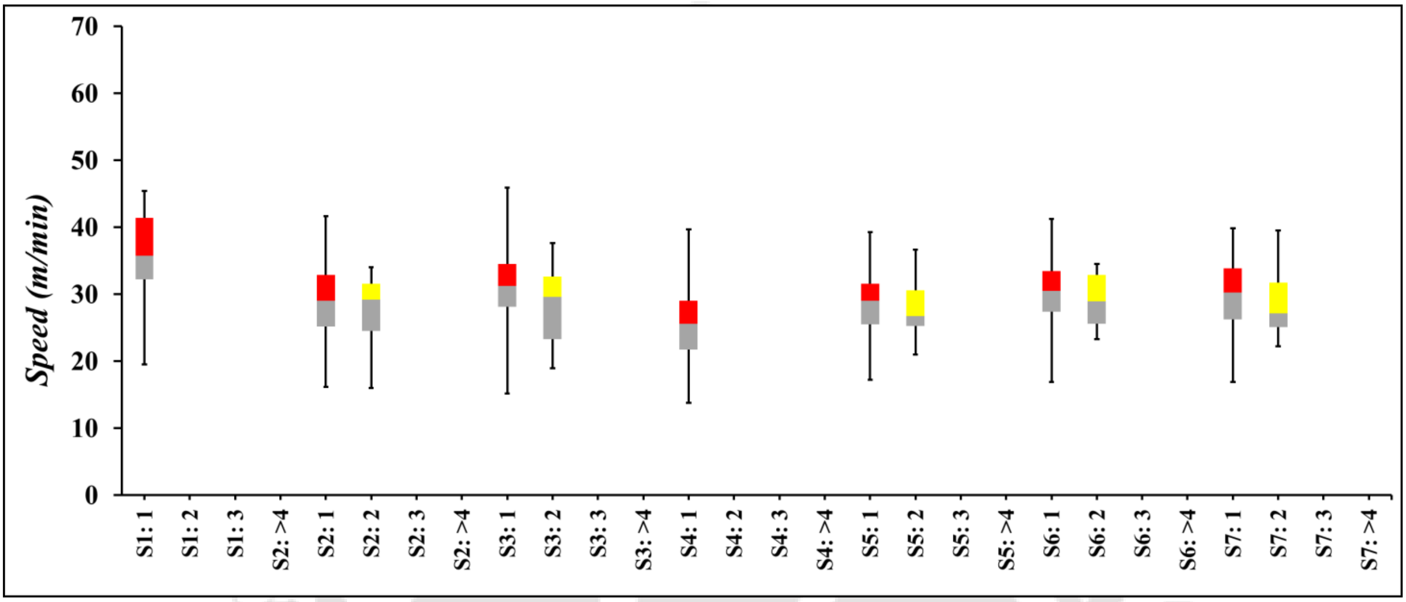


Figure 5.21. Group size wise speed variation for all skywalk locations (ascending direction)

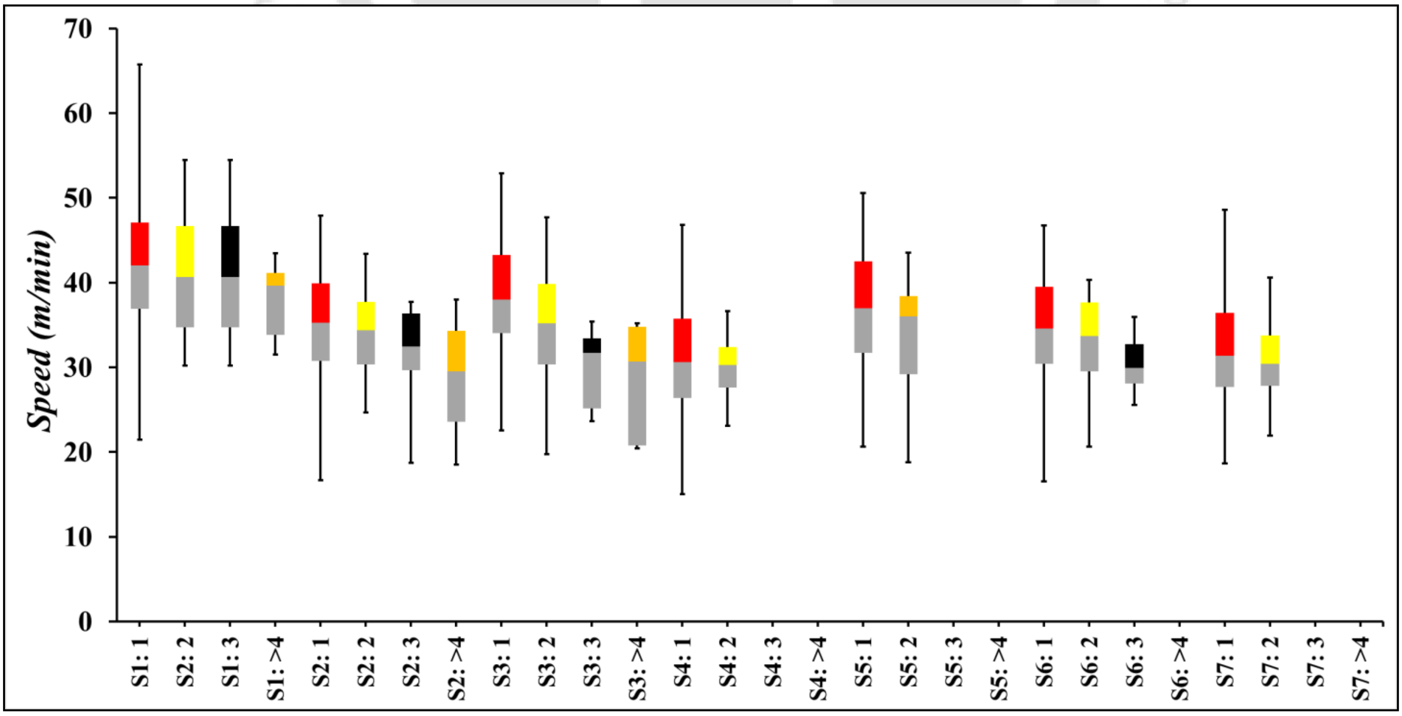


Figure 5.22. Group wise speed variation for all skywalk locations (descending direction)

In case of ascending direction pedestrians, the group formation of 3 or more pedestrians was quite a rare phenomenon and thus due to low samples size were not presented (refer Figure 5.21). The pedestrians moving in group size of 2 persons had lower median speeds (by 2-3m/min) than those moving alone. The highest median ascending speed as discussed earlier was observed at location S1. Similarly, while descending the group size of 4 or more pedestrians was observed to have lower median speeds than the pedestrians moving as single by 4-8m/min. Negative skewness, i.e., accumulation of higher median speeds was more common when a pedestrian was moving alone and not in a group.

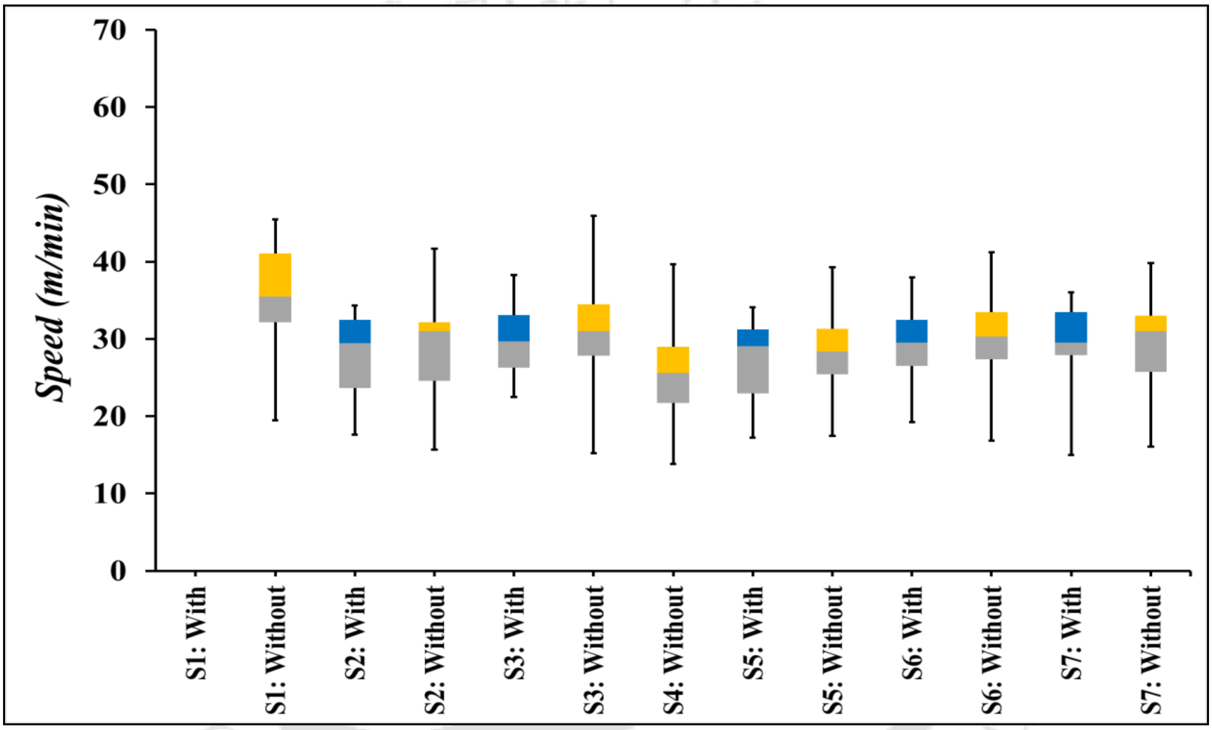


Figure 5.23. Mobile use speed variation for all skywalk locations (ascending direction)

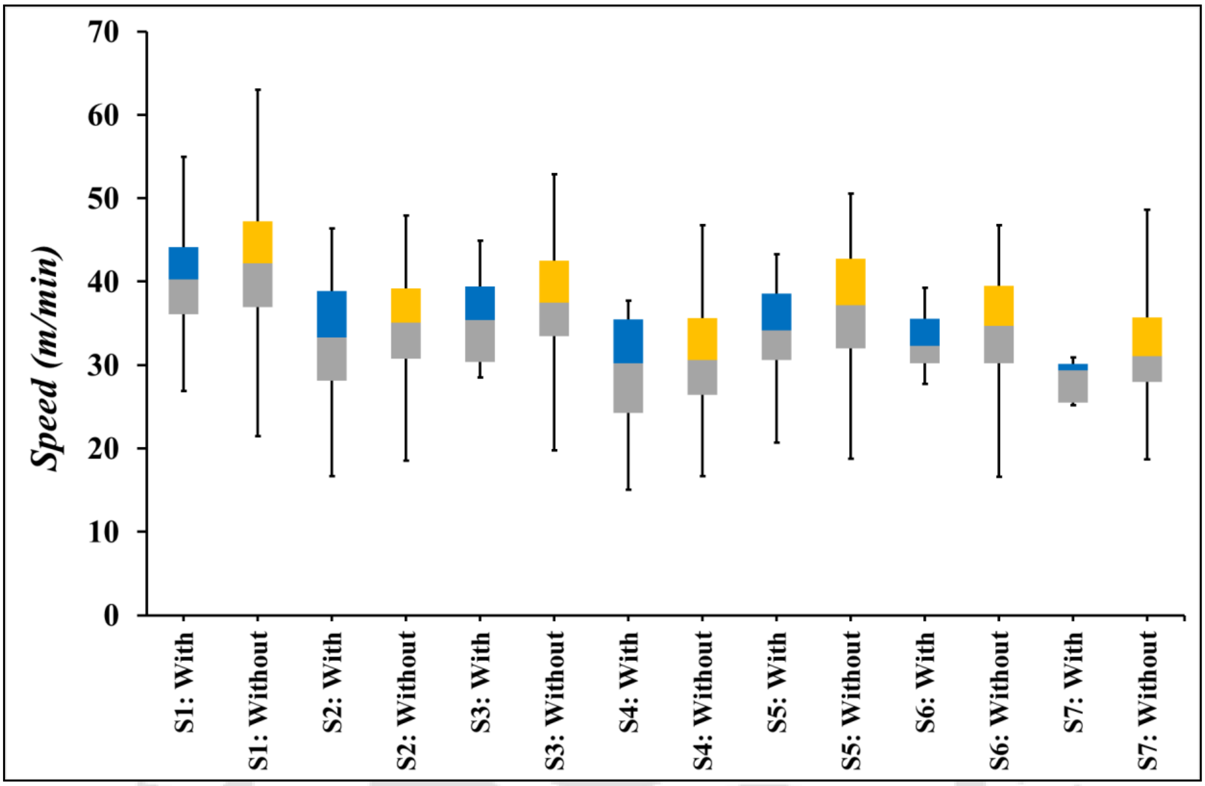


Figure 5.24. Mobile use speed variation for all skywalk locations (descending direction)

Figure 5.23-Figure 5.24 showed that for all the sites the pedestrians' not using mobile phones had significantly higher median speed than the ones using mobiles. The difference in walking speed between pedestrians with and without mobile was approximately 1-4m/min for both the directions. The highest and lowest median ascending speeds were observed at locations S1 (without mobile) and S4 (with mobile) respectively. Negative skewness was observed in case of pedestrians without luggage in both the directions. Due to low sample size, the pedestrians using mobile at S1 was not presented.

5.4.3. Development of fundamental diagrams for skywalk stairway sections

In order to establish the relationship between the different macroscopic parameters, Table 5.6 was presented which provides the mathematical flow models developed for the various skywalk stairway study locations considered and a general model (combining all data together). The table consists of the different speed-density, speed-flow, flow-density and flow-area module relationships along with the R^2 values for each location.

Table 5.6. Pedestrian flow models for skywalk stairway locations

Study Location	**Speed-Density**		**Speed-Flow**		**Flow-Density**		**Flow-Area module**	
	Relationship	***R^2 value***	***Relationship***	***R^2 value***	***Relationship***	***R^2 value***	***Relationship***	***R^2 value***
Andheri (S1)	46.746 – 22.181*k	0.596	2.107*u – 0.045*u^2	0.898	46.746*k – 22.181*k^2	0.892	46.746/M – 22.181/M^2	0.888
Goregaon (S2)	39.007 – 21.597*k	0.460	1.812*u – 0.046*u^2	0.789	39.007*k – 21.597*k^2	0.776	39.007/M – 21.597/M^2	0.762
Ghatkopar (S3)	41.368 – 13.084*k	0.449	3.163*u – 0.076*u^2	0.819	41.368*k – 13.084*k^2	0.803	41.368/M – 13.084/M^2	0.797
Bandra (S4)	40.006 – 14.791*k	0.552	2.714*u – 0.067*u^2	0.861	40.006*k – 14.791*k^2	0.847	40.006/M – 14.791/M^2	0.835
Vile Parle (S5)	37.522 – 6.618*k	0.532	5.661*u – 0.151*u^2	0.842	37.522*k – 6.618*k^2	0.822	37.522/M – 6.618/M^2	0.817
Santa Cruz (S6)	38.708 – 8.852*k	0.447	4.371*u – 0.113*u^2	0.801	38.708*k – 8.852*k^2	0.792	38.708/M – 8.852/M^2	0.788
Kalyan (S7)	38.123 – 18.574*k	0.530	2.052*u – 0.054*u^2	0.823	38.123*k – 18.574*k^2	0.811	38.123/M – 18.574/M^2	0.808
Overall	***38.617 – 6.443*k***	***0.561***	***5.996*u – 0.155*u^2***	0.877	***38.617*k – 6.443*k^2***	0.864	***38.617/M – 6.443/M^2***	0.858

Figure 5.25(a-d) were plotted for speed-density, flow rate-density, speed-flow rate, and flow rate-area module relationships for the seven different skywalk stairway sections combined. The diagrams give an overall view of the existing condition of the skywalks.

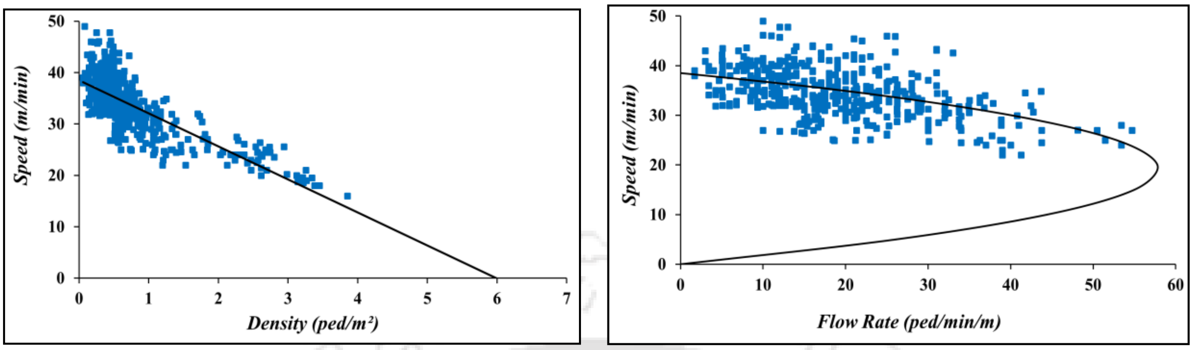


Fig. (a). Speed-Density relationship **Fig. (b).** Speed-Flow Rate relationship

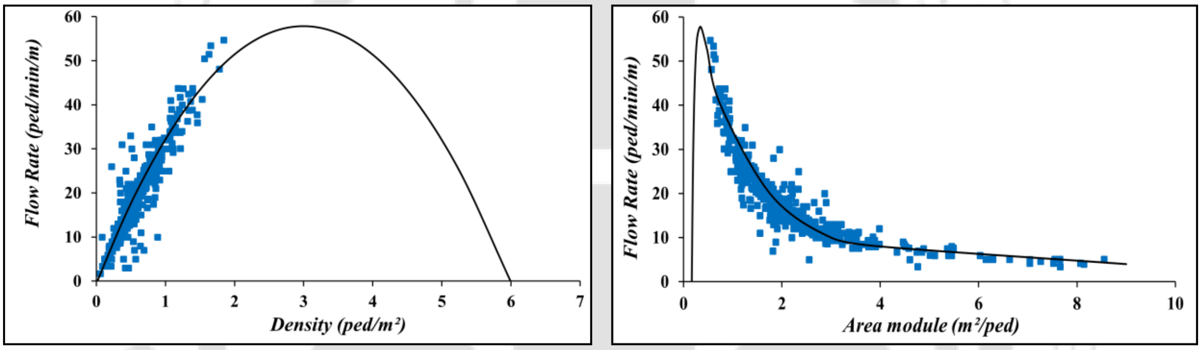


Fig. (c). Flow Rate-Density relationship **Fig. (d).** Flow Rate-Area Module relationship

Figure 5.25. Fundamental relationship diagrams of macroscopic parameters for combined data from all the sites

Figure 5.25(a) showed that the overall FFS for the different locations combined was 38.61m/min with the predicted jam density around 5.99ped/m^2. From Figure 5.25(c), the maximum predicted flow rate was 58ped/min/m occurring at an optimum density of 3.04ped/m^2. The optimum speed at the maximum flow rate was predicted to be 19.4m/min. Moreover, the area module observed predicted at maximum flow was 0.35m^2/ped.

Table 5.7 shows the pedestrian flow characteristics (i.e., FFS, q_{max}, area module at q_{max}, optimum speed and optimum density) for the different skywalk stairway locations. For location S5, at maximum predicted flow rate of 56.04ped/min/m, an area module of 0.37ped/m^2 was observed. The optimum speed across all stairway locations varied between 19-24m/min. The highest predicted optimum density was at S5, as it was an educational area with narrow stairway width.

Table 5.7. Pedestrian flow characteristics for different skywalk stairway sections

Location	Free Flow Speed (u_f), m/min	Maximum Flow Rate (q_{max}), ped/min/m	Area Module (M), at q_{max} (m^2/ped)	Optimum speed (m/min)	Optimum Density (ped/m^2)
Andheri (S1)	46.75	29.01	0.86	23.52	1.21
Goregaon (S2)	39.01	17.60	1.13	19.65	0.88
Ghatkopar (S3)	41.37	32.66	0.61	21.25	1.63
Bandra (S4)	40.01	27.05	0.74	20.32	1.35
Vile Parle (S5)	37.52	56.04	0.37	20.52	2.73
Santa Cruz (S6)	38.71	42.26	0.47	19.66	2.13
Kalyan (S7)	38.12	19.51	1.02	19.95	0.97

As the observed data for some locations were available mostly for lower to moderate ranges of density, capacity values predicted by the fundamental relationships in Table 5.7 could have some variations.

5.5. Development of speed models over stairway sections using microscopic pedestrian behaviour parameters

In the current section an attempt was made to understand the impact of different individual (age, Gen: gender, Lug: luggage carrying conditions, Mob: mobile use and Dis: disability) and group (GS: group size, LF: lane formation, LFR: leader-follower relationship, LS: lane shifting, Over: overtaking, SE: squeezing effect and FSE: faster-is-slower effect) behaviour characteristics on the walking speed of the pedestrians over stairway sections for both FOB and skywalk facilities. As discussed earlier in section 5.1, direction plays a crucial part in the walking speed determination. As per Table 5.1, for both the elevated walkways, significant difference existed between ascending and descending directions. However, no difference was observed between ascending direction for both facilities (FOBs and skywalks) and descending direction for both facilities (FOBs and skywalks). Thus for development of speed models using microscopic parameters, the ascending direction data for both the facilities and descending direction data for both facilities were combined.

5.5.1. Descriptive statistics of the field data

Table 5.7 shows the descriptive statistics of the fourteen FOB and seven skywalk stairway sections considered for the study. The gender, age, luggage conditions, mobile use and group

Table 5.8. Demographic characteristics of walking behaviour over stairway sections

Location ID	Direction	Sample size	Characteristics														Speed		
			Disability		LF		LFR		FSE		SE		Over		LS				
			W	*W/O*	*W*	*W/O*	*W*	*W/O*	*W*	*W/O*	*W*	*W/O*	*W*	*W/O*	*W*	*W/O*	*Mean*	*Median*	*S.D.*
F4	Ascend	276	0.00	100.0	22.83	77.17	8.70	91.30	0.00	100.0	0.00	100.00	1.09	98.91	9.42	90.58	29.94	30.25	4.04
	Descend	126	0.00	100.0	22.22	77.78	3.97	96.03	0.00	100.0	4.76	95.24	1.59	98.41	7.94	92.06	37.27	36.24	7.52
F5	Ascend	255	0.78	99.22	7.06	92.94	4.31	95.69	1.57	98.43	1.96	98.04	1.96	98.04	1.57	98.43	24.66	24.15	4.50
	Descend	137	1.46	98.54	18.25	81.75	15.33	84.67	0.00	100.0	28.47	71.53	0.00	100.0	2.19	97.81	25.90	25.41	6.04
F6	Ascend	202	1.49	98.51	13.37	86.63	8.91	91.09	0.99	99.01	1.98	98.02	2.97	97.03	2.97	97.03	26.69	26.64	4.60
	Descend	124	0.81	99.19	13.71	86.29	9.68	90.32	0.00	100.0	6.45	93.55	3.23	96.77	3.23	96.77	30.42	30.08	6.76
F7	Ascend	163	0.61	99.39	22.70	77.30	15.34	84.66	0.00	100.0	0.00	100.00	2.45	97.55	3.68	96.32	30.03	30.70	5.72
	Descend	159	0.00	100.0	22.64	77.36	11.32	88.68	0.00	100.0	0.00	100.00	1.26	98.74	4.40	95.60	34.61	34.23	6.76
F8	Ascend	217	2.30	97.70	35.94	64.06	29.03	70.97	0.00	100.0	15.21	84.79	2.30	97.70	4.61	95.39	25.95	25.38	5.17
	Descend	309	1.62	98.38	12.94	87.06	6.80	93.20	1.62	98.38	0.65	99.35	3.88	96.12	2.59	97.41	29.92	29.75	7.02
F9	Ascend	306	1.31	98.69	1.31	98.69	0.98	99.02	0.00	100.0	0.00	100.00	0.98	99.02	5.88	94.12	29.71	29.03	5.68
	Descend	235	0.43	99.57	2.98	97.02	1.70	98.30	0.00	100.0	0.00	100.00	0.43	99.57	4.68	95.32	35.28	33.35	8.77
F10	Ascend	118	0.85	99.15	4.24	95.76	2.54	97.46	0.00	100.0	0.85	99.15	0.00	100.0	0.00	100.0	60.79	62.00	8.41
	Descend	232	1.72	98.28	3.88	96.12	3.02	96.98	0.00	100.0	4.31	95.69	0.43	99.57	6.47	93.53	63.75	65.41	10.62
F11	Ascend	165	1.21	98.79	12.12	87.88	9.70	90.30	0.00	100.0	2.42	97.58	1.82	98.18	2.42	97.58	51.73	51.97	9.09
	Descend	120	2.50	97.50	11.67	88.33	9.17	90.83	0.00	100.0	3.33	96.67	2.50	97.50	5.00	95.00	57.62	58.28	10.34
F12	Ascend	73	0.00	100.0	8.22	91.78	8.22	91.78	0.00	100.0	5.48	94.52	0.00	100.0	2.74	97.26	31.52	30.82	6.18
	Descend	337	0.00	100.0	7.42	92.58	5.34	94.66	0.30	99.70	1.19	98.81	1.48	98.52	5.64	94.36	39.50	38.78	8.13
F13	Ascend	253	1.19	98.81	23.32	76.68	17.39	82.61	0.40	99.60	5.53	94.47	3.56	96.44	7.51	92.49	21.84	21.10	5.13
	Descend	310	2.90	97.10	19.35	80.65	15.48	84.52	0.65	99.35	1.61	98.39	1.94	98.06	7.74	92.26	25.03	23.82	7.09
F14	Ascend	99	0.00	100.0	9.09	90.91	0.00	100.0	0.00	100.0	0.00	100.0	0.00	100.0	0.00	100.0	26.78	26.76	5.15
	Descend	264	0.00	100.0	4.55	95.45	0.76	99.24	0.00	100.0	0.00	100.0	0.38	99.62	1.89	98.11	32.83	31.59	7.29

Table 5.8. Demographic characteristics of walking behaviour over stairway sections *(continued)*

Location ID	**Direction**	**Sample size**	**Characteristics**														**Speed**		
			Disability		**LF**		**LFR**		**FSE**		**SE**		**Over**		**LS**				
			W	***W/O***	***W***	***W/O***	***W***	***W/O***	***W***	***W/O***	***W***	***W/O***	***W***	***W/O***	***W***	***W/O***	***Mean***	***Median***	***S.D.***
F15	Ascend	231	1.73	98.27	19.91	80.09	13.42	86.58	0.00	100.0	4.33	95.67	1.30	98.70	1.30	98.70	25.87	26.22	4.53
	Descend	258	1.94	98.06	17.05	82.95	12.02	87.98	0.39	99.61	1.94	98.06	4.26	95.74	5.04	94.96	33.32	31.76	6.86
F16	Ascend	80	0.00	100.0	13.75	86.25	10.00	90.00	0.00	100.0	10.00	90.00	0.00	100.0	3.75	96.25	26.83	26.46	4.24
	Descend	305	0.00	100.0	30.16	69.84	25.25	74.75	0.00	100.0	0.00	100.0	0.98	99.02	0.66	99.34	33.74	33.19	6.31
F17	Ascend	306	0.98	99.02	26.14	73.86	23.53	76.47	0.00	100.0	1.31	98.69	0.00	100.0	0.65	99.35	24.05	23.60	4.81
	Descend	220	0.45	99.55	25.00	75.00	24.09	75.91	0.00	100.0	5.91	94.09	0.00	100.0	4.55	95.45	25.15	23.41	5.98
S1	Ascend	57	0.00	100.0	8.77	91.23	5.26	94.74	0.00	100.0	3.51	96.49	0.00	100.0	3.51	96.49	35.41	35.36	6.32
	Descend	268	0.37	99.63	12.69	87.31	5.22	94.78	0.37	99.63	1.12	98.88	1.49	98.51	1.49	98.51	41.81	41.70	7.18
S2	Ascend	75	0.00	100.0	33.33	66.67	32.00	68.00	0.00	100.0	2.67	97.33	2.67	97.33	4.00	96.00	28.42	29.02	5.63
	Descend	239	0.42	99.58	32.64	67.36	30.96	69.04	0.00	100.0	0.84	99.16	3.77	96.23	8.37	91.63	34.71	34.96	6.61
S3	Ascend	217	0.00	100.0	22.12	77.88	8.76	91.24	0.00	100.0	2.30	97.70	3.69	96.31	6.45	93.55	30.71	30.93	5.72
	Descend	214	0.47	99.53	15.89	84.11	7.48	92.52	0.00	100.0	0.93	99.07	7.94	92.06	9.35	90.65	37.48	37.03	6.62
S4	Ascend	89	0.00	100.0	41.57	58.43	35.96	64.04	0.00	100.0	7.87	92.13	0.00	100.0	0.00	100.0	25.50	25.60	5.45
	Descend	153	0.65	99.35	53.59	46.41	42.48	57.52	0.00	100.0	1.96	98.04	0.00	100.0	0.65	99.35	30.86	30.61	6.20
S5	Ascend	147	0.00	100.0	57.82	42.18	33.33	66.67	0.00	100.0	2.04	97.96	0.00	100.0	4.08	95.92	28.38	28.50	4.58
	Descend	153	0.00	100.0	46.41	53.59	34.64	65.36	0.00	100.0	1.96	98.04	1.96	98.04	3.92	96.08	34.47	34.19	5.89
S6	Ascend	369	0.27	99.73	43.63	56.37	18.97	81.03	1.36	98.64	0.81	99.19	1.36	98.64	8.40	91.60	30.39	30.24	4.32
	Descend	147	0.00	100.0	16.33	83.67	3.40	96.60	0.00	100.0	2.72	97.28	1.36	98.64	4.08	95.92	36.73	36.83	6.69
S7	Ascend	147	0.68	99.32	42.18	57.82	27.21	72.79	0.00	100.0	2.04	97.96	1.36	98.64	6.80	93.20	29.42	29.31	5.21
	Descend	145	0.69	99.31	38.62	61.38	26.21	73.79	0.00	100.0	2.76	97.24	2.07	97.93	10.34	89.66	31.66	30.83	6.47

size as discussed in Table 5.2 were used in the development of the model as well. From Table 5.8, the percentage of pedestrians without disability was quite high across all locations, while locations F8 (ascending), F11 (descending) and F13 (descending) had nearly 3% pedestrians with disability at each location. The lane formation phenomenon was frequently observed over skywalk stairways, with location S5 showing the maximum persons in lane formation phenomenon. Over FOB stairways, location F8 had many pedestrians in lane formation mode (ascending: 35.94% and descending: 12.94%). At skywalk locations S2 and S5, leader-follower relationship was highly predominant (~33% pedestrians). Faster-is-slower was the rarest phenomenon which was mainly observed at locations F5 and F8. The squeezing effect phenomenon was mostly observed at location F5 (descending) where major flow was in the ascending direction. Overtaking behaviour was predominantly observed at location S3 in both ascending (4%) and descending (8%) directions. The phenomenon of lane shifting was quite common among pedestrians across all locations.

5.5.2. Statistical test of walking behaviour over different stairway sections

Using SPSSv20, correlation analysis was carried out to understand the relationship between the different variables considered for ascending and descending directions. A value of *r* less than 0.3 indicates weak relationship. Table 5.9 and Table 5.10 show the results of the correlation analysis for ascending and descending directions.

In order to develop the walking behaviour model, different variables were coded as: age *(0: <10, 1:11-20, 2: 21-40, 3: 41-60, 4: >60)*, gender *(0: male, 1: female)*, luggage *(0: with, 1: without)*, group size *(0: Single pedestrian, 1: Two pedestrians, 2: Three pedestrians, 3: Four or more pedestrians together)*, mobile use *(0: with, 1: without)*, disability *(0: with, 1: without)*, lane formation *(0: with, 1: without)*, leader-follower relationship *(0: with, 1: without)*, faster-is-slower effect *(0: with, 1: without)*, squeezing effect *(0: with, 1: without)*, overtaking *(0: with, 1: without)*, and lane shifting *(0: with, 1: without)*.

As per Tables 5.9 and 5.10, positive or negative relationship indicates how speed (dependent variable) increases or decreases with the independent variables. For example, a negative gender-speed correlation coefficient indicates that when more female pedestrians are using the stairway facilities (while both ascending and descending), it leads to an overall decrease in the walking speed. A negative group size-speed correlation coefficient indicates that while ascending or descending, as the group size increases from a single pedestrian to four or more pedestrians, the overall walking speed is likely to decrease. Similarly, a positive disability-speed relationship indicates that when pedestrians are without disability their walking speed considerably increases. While ascending stairways, a positive value (0.04) between speed and luggage indicates that the walking speed increases when pedestrians are ascending stairways without luggage. In case of descending stairways no significant relationship (-0.04) was observed between luggage and speed. The difference between mean walking speed for pedestrians with/ without luggage while descending the stairways was also negligible (0.2m/min).

Moreover, as all the considered variables had a coefficient of less than 0.3, thus weak relationship exists between the different variable pairs for both ascending and descending directions. Considering pair-wise correlation of speed with the other independent variables, the results indicated uncorrelated relationship (≤0.30) between the dependent (speed) and the independent variables (variables other than speed). All these variables were therefore considered for the development of linear regression model for walking speeds prediction of pedestrians over stairway sections.

Table 5.9. Correlation analysis for all the variables considered for ascending stairways

	Age	**Gen**	**Lug**	**GS**	**Mob**	**Dis**	**LF**	**LFR**	**FS**	**SE**	**Over**	**LS**	**Speed**
Age	1												
Gen	-0.09	1											
Lug	0.12	-0.05	1										
GS	-0.06	0.09	0.01	1									
Mob	0.06	-0.03	0.08	0.06	1								
Dis	-0.11	0.01	-0.02	-0.07	0.02	1							
LF	-0.03	-0.04	-0.02	-0.25	-0.01	0.00	1						
LFR	-0.03	-0.04	-0.04	-0.28	-0.01	0.00	0.08	1					
FS	-0.04	-0.02	-0.02	-0.03	0.01	0.07	-0.02	-0.02	1				
SE	-0.03	0.01	-0.03	-0.03	-0.03	0.02	0.02	0.01	-0.01	1			
Over	0.04	0.03	-0.02	0.04	-0.02	0.01	-0.03	-0.03	-0.01	-0.02	1		
LS	0.03	0.03	-0.02	0.03	-0.01	0.03	-0.03	-0.04	0.02	-0.02	0.30	1	
Speed	-0.10	-0.14	0.04	-0.15	0.03	0.08	0.14	0.13	0.05	0.11	-0.04	-0.01	1

Note: *Gen-Gender, Lug-Luggage, GS-Group size, Mob-Mobile use, Dis-Disability, LF-Lane formation, LFR- Leader follower relationship, FS-Faster is slower effect, SE-Squeezing effect, Over-Overtaking, LS-Lane shifting*

Table 5.10. Correlation analysis for all the variables considered for descending stairways

	Age	Gen	Lug	GS	Mob	Dis	LF	LFR	FS	SE	Over	LS	Speed
Age	1												
Gen	-0.13	1											
Lug	0.09	-0.05	1										
GS	-0.10	0.11	0.02	1									
Mob	0.08	-0.05	0.09	0.02	1								
Dis	-0.09	-0.01	-0.02	0.00	-0.03	1							
LF	-0.04	-0.08	0.00	-0.21	0.00	-0.01	1						
LFR	-0.04	-0.10	-0.01	-0.25	-0.01	-0.01	0.18	1					
FS	-0.02	0.02	0.01	-0.05	0.02	-0.01	-0.01	0.00	1				
SE	-0.05	-0.01	-0.04	0.02	0.02	0.05	0.05	0.06	-0.01	1			
Over	0.05	0.03	-0.02	0.02	0.00	-0.01	0.00	-0.01	-0.01	-0.02	1		
LS	0.05	0.04	-0.01	0.02	0.00	-0.02	0.00	0.00	0.07	0.00	0.20	1	
Speed	-0.05	-0.13	-0.04	-0.17	0.02	0.09	0.14	0.14	0.02	0.11	-0.06	-0.05	1

Note: *Gen-Gender, Lug-Luggage, GS-Group size, Mob-Mobile use, Dis-Disability, LF-Lane formation, LFR- Leader follower relationship, FS-Faster is slower effect, SE-Squeezing effect, Over-Overtaking, LS-Lane shifting*

5.5.3. Development of microscopic speed prediction models

In an attempt to understand the impact of different pedestrian characteristics (individual and group) for ascending and descending directions, linear regression model (LRM) was used. In the walking behaviour modelling, multiple linear regression was used to obtain the relationship between the walking behaviour parameters and the walking speed over the stairway sections of FOBs and skywalks. In model development 80% data was used and remaining 20% data was segregated for model validation. Table 5.11 and Table 5.12 shows the most significant variables which impact the walking behaviour over ascending and descending stairway sections along with the coefficients.

As per Table 5.11, the most significant variables which impacted the walking behaviour of the pedestrians in ascending direction were age, gender, luggage, group size, mobile use, disability, lane formation, leader-follower relationship, and squeezing effect. The negative coefficient of female indicated that the walking speed of the female was lower than the male pedestrians. The pedestrians without luggage had a positive coefficient, indicating that they had more impact on the walking speed than the ones with luggage. Moreover, when the pedestrians were moving in lanes their speeds were observed to be higher than those without lane formation. The age coefficient showed that with the increase in age the walking speeds decreased. Factors such as age (41-60 years and ≥60 years), faster-is-slower effect, overtaking and lane shifting did not have significant impact on the overall walking behaviour.

Table 5.11. Coefficients for microscopic walking behaviour of ascending stairway walking behaviour

	Reference category	**Estimate**	**Std. Error**	**t value**	**Pr(≥|t|)**
(Intercept)		9.311	3.811	2.443	≤ 0.001 *
Age1 (11-20 years)	*Age (≤10 years)*	4.914	1.465	3.357	≤ 0.001 ***
Age2 (21-40 years)		3.072	1.426	2.155	≤ 0.001 *
Age3 (41-60 years)		1.886	1.446	1.304	0.192
Age4 (≥60 years)		-1.715	1.538	-1.115	0.264
Gender (Female)	*Gender (Male)*	-2.844	0.338	-8.409	≤ 0.001 ***
Luggage (Without)	*Luggage (With)*	1.257	0.302	4.227	≤ 0.001 ***
Group_size (GS: 2)	*Group_size (GS: 1)*	-0.887	0.418	-2.121	≤ 0.001 *
Group_size (GS: 3)		-2.801	0.669	-4.005	≤ 0.001 ***
Group_size (GS: ≥4)		-4.913	1.042	-4.716	≤ 0.001 ***
Mobile (Without)	*Mobile (With)*	1.305	0.498	2.618	≤ 0.001 **
Disability (Without)	*Disability (With)*	5.504	1.736	3.170	≤ 0.001 **
Lane_formation (Without)	*Lane_formation (With)*	1.573	0.538	2.934	≤ 0.001 **
Leader_follower (Without)	*Leader_follower (With)*	1.395	0.646	2.160	≤ 0.001 *
Faster.slower (Without)	*Faster_slower (With)*	4.775	0.653	1.801	0.071
Squeezing_effect (Without)	*Squeezing_effect (With)*	6.115	0.875	6.988	≤ 0.001 ***
Overtaking (Without)	*Overtaking (With)*	-1.915	1.271	-1.507	0.131
Lane_shift (Without)	*Lane_shift (With)*	0.316	0.746	0.424	0.671

Significance Codes: *'***'- 0; '**'- 0.001; '*'- 0.01; '.'- 0.05; ' '- 0.1*

Table 5.12 showed the most significant variables which impacted the walking behaviour of the pedestrians over the stairway sections in descending direction. As per Table 5.12 factors such as age, gender, group size, mobile use, disability, lane formation, squeezing effect and overtaking had significant effect on the walking speed behaviour over the stairway sections in descending direction. Factors such as age (≥60 years), luggage, leader follower, faster-is-slower effect, and lane shifting did not have significant impact on the overall walking behaviour of the pedestrians.

Table 5.12. Coefficients for microscopic walking behaviour of descending stairway walking behaviour

		Estimate	Std. Error	t value	Pr(≥|t|)
(Intercept)		6.419	4.496	1.428	0.153
Age1 (11-20 years)	*Age (≤10 years)*	11.911	1.374	8.666	≤ 0.001 ***
Age2 (21-40 years)		10.181	1.324	7.689	≤ 0.001 ***
Age3 (41-60 years)		9.395	1.357	6.920	≤ 0.001 ***
Age4 (≥60 years)		2.630	1.496	1.757	0.078
Gender (Female)	*Gender (Male)*	-3.187	0.336	-8.691	≤ 0.001 ***
Luggage (Without)	*Luggage (With)*	0.052	0.334	0.157	0.873
Group_size (GS: 2)	*Group_size (GS: 1)*	-1.131	0.473	-2.392	≤ 0.001 *
Group_size (GS: 3)		-3.005	0.736	-4.081	≤ 0.001 ***
Group_size (GS: ≥4)		-6.091	0.946	-6.435	≤ 0.001 ***
Mobile (Without)	*Mobile (With)*	1.481	0.573	2.583	≤ 0.001 **
Disabililty (Without)	*Disabililty (With)*	8.981	1.834	4.894	≤ 0.001 ***
Lane_formation (Without)	*Lane_formation (With)*	2.912	0.702	4.144	≤ 0.001 ***
Leader_follower (Without)	*Leader_follower (With)*	0.962	0.817	1.178	0.238
Faster_slower (Without)	*Faster_slower (With)*	5.084	3.463	1.468	0.142
Squeezing_effect (Without)	*Squeezing_effect (With)*	7.162	1.016	7.044	≤ 0.001 ***
Overtaking (Without)	*Overtaking (With)*	-3.125	1.238	-2.765	≤ 0.001 **
Lane_shift (Without)	*Lane_shift (With)*	-1.305	0.836	-1.560	0.118

Significance codes: *'***'- 0; '**'- 0.001; '*'- 0.01; '.'- 0.05; ' '- 0.1*

The microscopic speed prediction models for ascending and descending directions are given by Equations 5.1 and 5.2,

$$\textbf{Walking speed (Ascending)} = 9.311 + 4.914*Age(11\text{-}20years) + 3.072*Age(21\text{-}40years) - 2.844*Gen + 1.257*Lug - 0.887*GS2 - 2.801*GS3 - 4.913*GS4 + 1.305*Mob + 5.504*Dis + 1.573*LF + 1.395*LFR + 6.115*SE \quad \ldots\ldots \ \mathbf{5.1}$$

$$\textbf{Walking speed (Descending)} = 6.419 + 11.911*Age(11\text{-}20years) + 10.181*Age(21\text{-}40years) + 9.395*Age(41\text{-}60years) - 3.187*Gen - 1.131*GS2 - 3.005*GS3 - 6.091*GS4 + 1.481*Mob + 8.981*Dis + 2.912*LF + 1.395*LFR + 7.162*SE - 3.125*Over \quad \ldots\ldots \ \mathbf{5.2}$$

5.5.4. Validation of microscopic speed prediction models

The remaining 20% of the test data set was used to make a comparison between the predicted and actual speeds using MAPE (measure of prediction accuracy of a forecasting method). The

MAPE errors for ascending and descending directions were 17.41% and 16.45% respectively. As per Lewis scale of interpretation, a MAPE value of 10-20% specifies that the model forecasting was good.

5.6. Concluding remarks

In Chapter 5, an initial preliminary analysis (t-test) was conducted between the two facilities (FOB and skywalk) for ascending and descending directions using the dominant category data (*Gender: male, Age: 21-40 years and Luggage condition: without*). The results from t-test showed that significant difference existed between ascending and descending directions for both FOB and skywalk facilities. However, no significant difference was observed between ascending direction between the two facilities, as well as descending direction between the two facilities.

For both the stairway facilities, probability density functions were plotted for aggregated data across all locations, and box and whisker plots were plotted for individual locations. The fundamental diagrams were presented for different pedestrian flow relationships across all stairway locations. In order to the predict the speed of pedestrians using microscopic parameters (individual and group), the data was combined for both facilities in ascending (FOB and skywalk) and descending (FOB and skywalk) directions, due to insignificant difference in same direction movement between the two facilities. Thereafter, walking behaviour speed models were developed using linear regression model to understand the impact of the different behavioural factors on the pedestrian walking speed in both the directions.

CHAPTER 6

PEDESTRIANS' PERCEPTION TOWARDS USABILITY OF SKYWALK AND FOB

To develop pedestrian-friendly facilities, it is important to consider human perceptions along with engineering considerations. According to studies undertaken by Owen (2004) and Guo (2014), human perception is how well a pedestrian interprets the surrounding environment while passing through it. Perception is a key component of the relationship between the environment and the user. Studies by Lee (2009) and Wang (2012) showed that emotional satisfaction while using a pedestrian facility depends on perceptions and physical components. A study in India reported that socioeconomic status and characteristics of the surrounding locality majorly affected commuting pedestrians' perceptions (Rastogi, 2010).

Whereas the previous chapters discussed about the pedestrians' walking behaviour using videographic data collection technique, the present chapter tried to estimate the various factors that influence the pedestrians' perception towards using elevated walkway facilities through questionnaire survey technique. To understand the factors influencing the pedestrians' choice of using elevated walkways under the present scenario along with improvements which can be carried are further discussed in the chapter. Figure 6.1 shows the outline of the chapter in block diagram for the perception of pedestrians towards using elevated facilities.

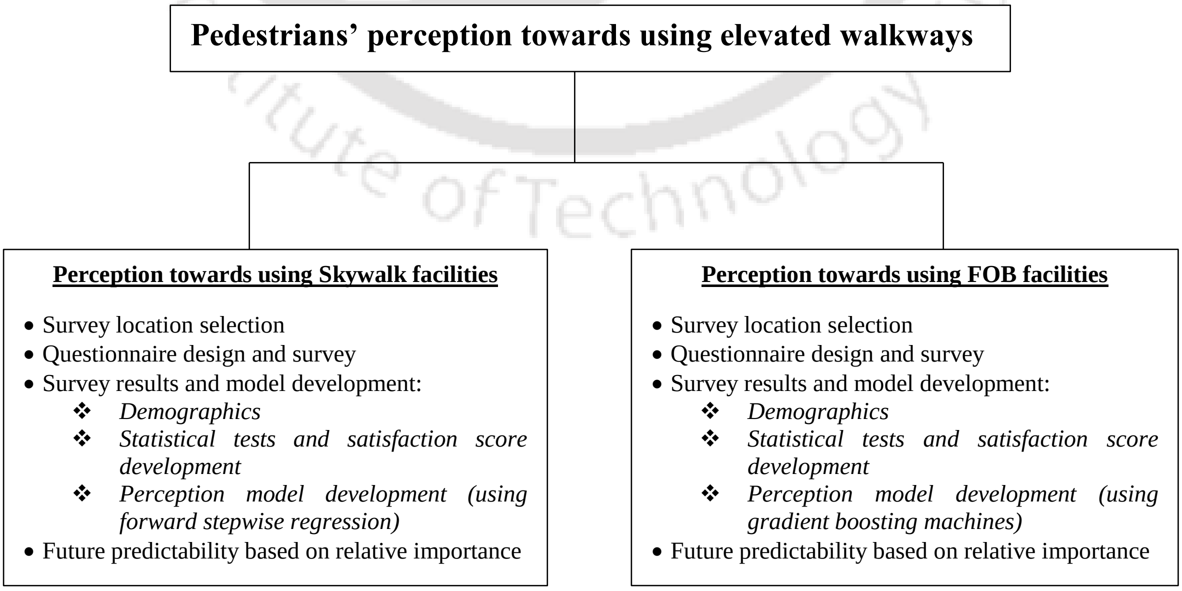


Figure 6.1. Block diagram for pedestrians' perception towards usability of elevated facilities

6.1. Determination of sample size requirement

In the present work, Krejcie and Morgan's (1970) sample size estimation technique was used to calculate the minimum number of samples. At a confidence level of 90%, margin of error of 5% and population proportion of 0.5, the estimated sample size was 273. In the present chapter, the total questionnaire sample collected over the skywalk locations and FOB locations were 350 and 552, respectively, which were above the minimum sample size requirement for perception modelling.

6.2. Perception modelling of factors impacting the usage of skywalk facilities

6.2.1. Survey location selection

After inspecting all the skywalk sections as discussed in chapter 3, only those skywalks were chosen for final questionnaire data collection, which had a reasonable flow of pedestrians throughout the day in order to get enough survey samples. A detailed summary of the selected field data collection locations is provided in Table 6.1.

Table 6.1. Site details of skywalk locations selected for survey data collection

Location	**Mid-block width (m)**	**Total length (m)**	**Vertical connectivity**	**No. of steps**	**Stairway width (m)**	**Tread (cm)**	**Riser (cm)**	**No. of entry exit points**	**Sample size**
S1: Andheri	3.94	581	Stairway	44	1.40	34	18	7	51
S2: Goregaon	4.40	625		49	1.58	30	17	5	49
S3: Ghatkopar	3.70	315		42	1.40	30	14	5	47
S4: Bandra	4.50	970		51	1.46	28	14	7	48
S5: Vile Parle	4.00	460		57	1.43	28	14	5	54
S6: Santa Cruz	3.60	685		42	1.00	32	14	5	46
S7: Kalyan	4.40	1287		54	1.90	32	17	8	55
Total									350

6.2.2. Questionnaire design and survey

The questionnaire prepared included five broad sections (A to E) representing demography, existing conditions, preference of use under existing conditions, future usability improvement and field observations (refer to Table 3.3 in Chapter 3). The factors chosen in Section D of Table 3.3 (i.e. predicting factors governing the use of skywalks in the future) were selected based on literature on pedestrian foot over bridges (FOBs) due to dearth of relevant research on skywalks and also based on the similarity (i.e. purpose of segregating pedestrian traffic from vehicular traffic and enhancing comfort and safety; geometric design standards, effect of vertical connectivity and the impact of lack of security on the pedestrian psychology) between the two types of elevated facilities (FOBs and skywalks). The final factors used for prediciting the improvement in future usability were obstruction removal (Saha, 2013, Pasha, 2015 and Malik, 2017), security improvement (Mutto, 2002; Gallegos, 2012; Saha, 2013; Pasha, 2015; Sinclair, 2016; Malik, 2017 and Oviedo-Trespalacios, 2017), elevator/escalator installation (Räsänen, 2007; Sabet, 2013, Demiroz, 2015; and Hasan, 2018), end connectivity improvement (Räsänen, 2007; Sangphong, 2014; Das, 2015; Demiroz, 2015 and Hasan, 2018), regular maintenance and cleanliness (Pasha, 2015; Saha, 2013; Hasan 2014) and redesigning (Rizati, 2013 and Das 2015). Lastly, the field observations were recorded in section E.

On all the selected skywalks, an interviewer-administered questionnaire survey was conducted at each location on weekdays either in morning (7.30-10.30am) or evening (4.30-7.30pm) peak hours, to obtain a representative sample of the commuters. All the respondents were selected and requested randomly by the interviewers to participate in the survey, and those willing to participate in the entire interview process were selected. As the survey was done during peak hours, the participation rate was low (i.e., 1 out of 20 pedestrians). In total, 386 pedestrians participated in the survey, and later, these samples were entered manually into excel sheets to be used for analysis. For the final analysis, only 350 adequately filled questionnaire sheets were used, which exemplified a representative sample size. A 5-point Likert scale was used to understand how much a pedestrian strongly agreed or disagreed with a particular statement.

6.2.3. Survey results and model development

6.2.3.1. Demographic characteristics

As described earlier in the introduction section, previous studies on elevated facilities observed that demographic factors such as gender, age, luggage, profession, trip purpose and frequency of daily use significantly affected the choice of pedestrians' using the elevated facilities. The demographic characteristics of all the respondents' who participated in the questionnaire survey from all the seven locations are shown in Table 6.2.

From Table 6.2, it could be observed that majority of the pedestrians using the skywalks were male pedestrians in the age group of 11-40 years (65.8%). At locations S3 and S5, the pedestrians carrying luggage were found to be highest (59-62%), and this was majorly because in both the locations the percentage of pedestrians in the age group 11-40 years was highest (75-85%). As reported by previous researchers (Mutto, 2002; Abojaradeh, 2013; Saha, 2013; Wu, 2014; Rankavat, 2016; Sinclair, 2016), this study also showed that gender and age played critical role in choosing the elevated facility by the pedestrians for their commute.

Table 6.2. Demographic characteristics of composition (in %) of respondents'

Characteristics	**Gender (%)**		**Age (%)**					**Luggage (%)**	
	Male	***Female***	***<10***	***11-20***	***21-40***	***41-60***	***≥60***	***With***	***Without***
Location ID									
S1: Andheri	70.5	29.5	4.00	35.3	31.4	23.5	5.80	45.1	54.9
S2: Goregaon	71.4	28.6	2.30	24.4	42.8	22.4	8.10	49.0	51.0
S3: Ghatkopar	68.1	31.9	8.60	38.3	27.6	14.9	10.6	61.7	38.3
S4: Bandra	58.3	41.7	2.10	18.7	39.6	33.3	6.30	48.0	52.0
S5: Vile Parle	64.8	35.2	3.70	48.1	33.3	11.1	3.80	59.4	40.6
S6: Santa Cruz	63.0	37.0	4.40	30.4	32.6	19.6	13.0	47.8	52.2
S7: Kalyan	72.7	27.3	3.70	20.0	38.2	32.7	5.40	45.5	54.5
Overall	***66.9***	***33.1***	***4.11***	***30.7***	***35.1***	***22.5***	***7.59***	***50.9***	***49.1***

Figure 6.2 shows the profession of pedestrians who responded to the questionnaire survey. The results showed that majority of the pedestrians using the skywalks were either servicemen (29.71%) or students (31.14%), which can also be corroborated by the fact presented in Table 6.2 that majority of the skywalk users were of young adults (11-40 years). Being young and commuters, they preferred to use shorter and safer travel through the skywalk. The percentage of homemakers and retired persons using the facility were meagre. The observations proved the fact that profession also does play an important part in deciding whether a pedestrian uses the elevated facilities or not (Saha, 2013 and Wu, 2014).

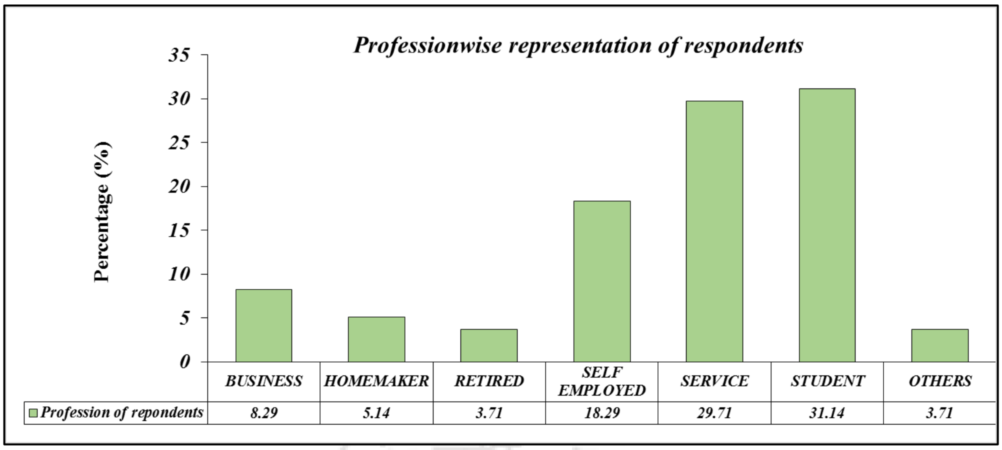


Figure 6.2. Profession wise classification of respondents *(Source: Banerjee and Maurya, 2020)*

Figure 6.3 represents the purpose of the trip of the respondents using the skywalks. The figure shows that most of the pedestrians using the skywalks either used it for work purpose (35.71%), change of mode (23.43%) or educational purpose (16.86%). This observation was also in line with Table 6.2 and Figure 6.2 that the majority of the pedestrians using the facility were servicemen or students in the age group of 11-40 years. A reasonable number of pedestrians also used such facilities for their shopping trips.

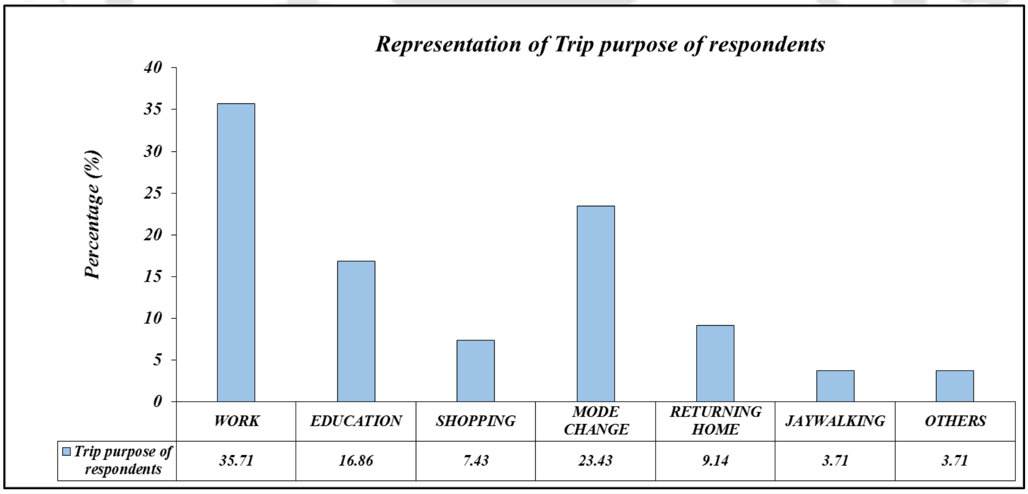


Figure 6.3. Trip purpose wise classification of respondents *(Source: Banerjee and Maurya, 2020)*

Daily frequency of using the skywalks was presented in Figure 6.4. It was observed that most of the pedestrians used the skywalks either twice (48%) or at least once (23%) in a day. The above statistics (Table 6.2, Figure 6.2 and Figure 6.3) also strengthens the fact that students or servicemen (of age group 11-40 years) were using the facility frequently for either work trips or educational trips. The lower percentage of first-timers indicated that the pedestrians who underwent the survey were mostly daily commuters who were well aware of the existing scenario of the facilities. Therefore, they were also expected to review the current conditions of the skywalk in a better way and suggest the required future improvements as well.

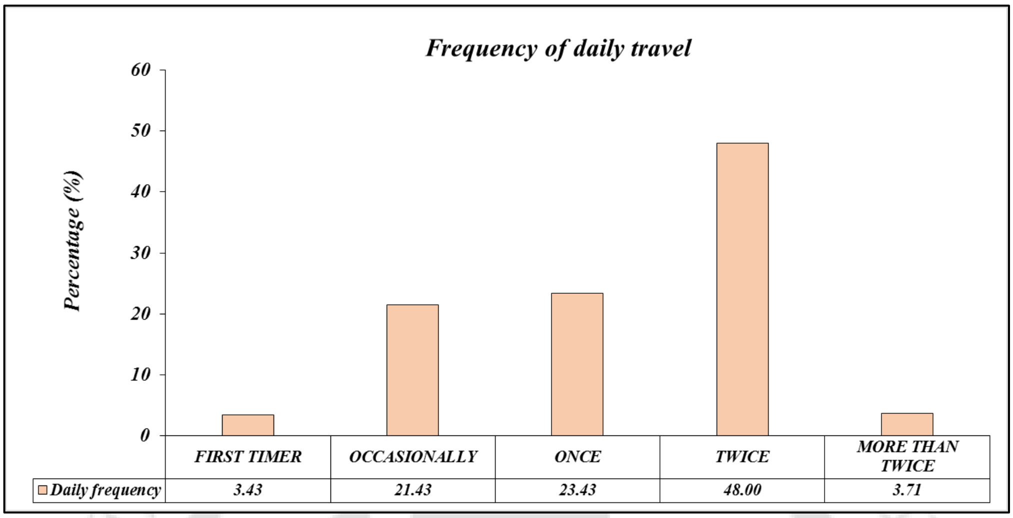


Figure 6.4. Frequency of daily use of skywalks by the respondents *(Source: Banerjee and Maurya, 2020)*

6.2.3.2. Statistical test and score development

The raw data from the questionnaire sheets were manually entered into excel sheets for the final analysis. The data were further analyzed using IBM Statistical Package for Social Sciences (SPSS) Statistics 20 software. To check the reliability or consistency of the Likert scale, Cronbach's alpha (α) test was conducted. The result of the reliability statistics showed a value of 0.815, which indicated a high level of internal consistency of the scale for the seven parameters used to define the current conditions (see section B, Table 3.3 for parameters used). Table 6.3 presents the item-total statistics, which shows that if any item (or factor) was removed, it would result in lower Cronbach's alpha value.

Table 6.3. Item-total statistics showing Cronbach's alpha if the item is deleted *(Source: Banerjee and Maurya, 2020)*

Factors	Scale mean if item deleted	Scale variance if item deleted	Corrected item-total correlation	Squared multiple correlation	Cronbach's alpha if item deleted
Width	15.04	12.778	0.609	0.495	**0.781**
Surface	15.27	13.170	0.600	0.470	**0.782**
Obstruction	15.87	14.808	0.507	0.282	**0.799**
Connectivity	14.65	14.561	0.457	0.238	**0.806**
Safety and security	15.70	13.129	0.578	0.373	**0.787**
Comfort	15.23	13.852	0.582	0.432	**0.786**
Walk environment	15.43	13.907	0.552	0.415	**0.791**

From Table 6.3, it was clear that removing any parameter resulted in a lower reliability of the model, and thus, all the parameters were important in the development of the final model.

Figure 6.5 shows the variable importance of each factor selected based on the perception of the pedestrians under the current conditions. All the six factors (width, surface, connectivity, safety and security, comfort and walking environment) were rated based on “1: Very Poor” to “5: Very Good”, while obstruction was rated from “1: Many” to “3: None”. The existing score was developed based on the responses received from the pedestrians for the seven factors related to the current condition of the skywalk systems.

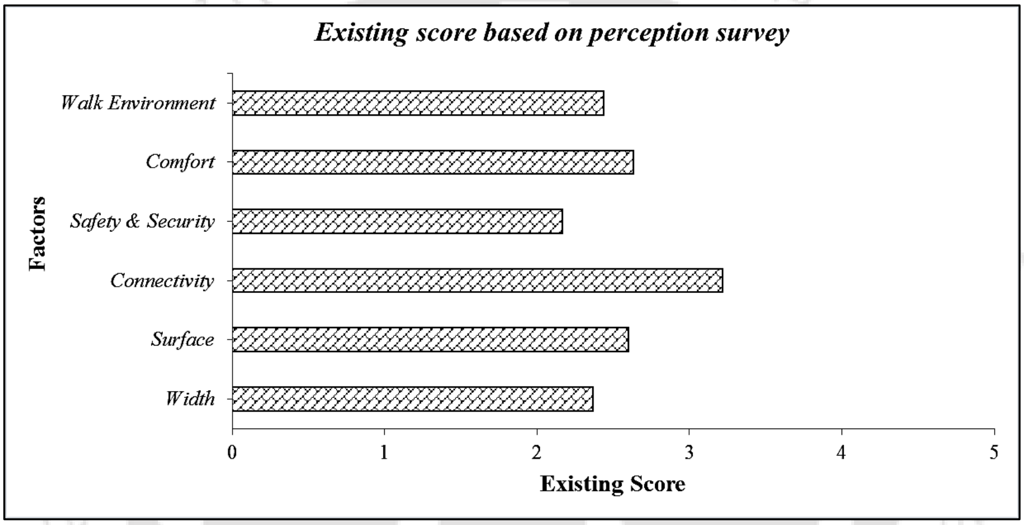


Figure 6.5. Variable importance plot of parameters based on scaled importance *(Source: Banerjee and Maurya, 2020)*

From Figure 6.5 it was evident that the respondents were highly dissatisfied with the existing safety and security (average score: 2.17 out of 5) provided over the skywalks, as CCTVs or security personnel were absent. Another critical factor which affected the pedestrians’ perception was the effective available width (score: 2.37 out of 5), and this was mainly due to the fact that the available walking width was too narrow or was occupied by vendors/ beggars/ standing pedestrians (which reduced the width even further). Similarly, obstruction was based on a rating of 1 to 3, and an average score of 1.99 was observed, which meant that pedestrians faced quite a few obstructions in the form of vendors, beggars or standing pedestrians over the skywalks.

6.2.3.3. Perception model development for skywalk facilities

The Statistical Package for Social Sciences (SPSSv20) was used to analyze and interpret the data. In SPSS, stepwise regression is a semi-automated process of building a model by successively either adding (forward regression) or removing (backward regression) variables solely based on estimated coefficients of certain statistics.

In comparison to the other regression models, the forward regression method is tractable, gives a good sequence of models and avoids overfitting. Also, the backward selection method is less successful than forward selection as the full model fit in the first step generally results in a complete or quasi-complete separation of response values. The following steps are usually followed in the forward method to get the best set of variables.

a) Initiating a null model, with no predictor and only one intercept.
b) Fitting *p* simple linear regression models, each with one of the variables in and the intercept.
c) Searching though *(p-1)* variables and finding out the variable which should be added to the current model to improve the residual sum of squares.
d) Continuing till the stopping criteria (for e.g., all remaining variables have p-value above some threshold) is satisfied.

As discussed above, in the forward stepwise method, a model is created at the first step without any independent variables (i.e. the beginning block), and after that, independent variables are added one after the other in the subsequent steps based on the highest impact. Equation 6.1 shows the regression model predicting the logit, i.e., natural log of the odds of having made one or the other decision.

$$ln(ODDS) = \beta + \beta_1 X_1 + \beta_2 X_2 + \ldots.. \beta_n X_n \qquad \text{........... } \mathbf{Eq.\ 6.1}$$

where β represents the coefficients, X_1 to X_n represents the parameters influencing the model.

In the current study, the "stepwise forward binary logistic regression" method (with Wald statistic at $p < 0.05$ significance level) was used to relate the dependent variable, i.e., preference of pedestrians in using the skywalk (Y_i) based on the existing conditions to the independent variables (X_i).

Table 6.4 shows the dependent and independent variables used for the model (also refer to Table 3.3 for the sub-groupings).

Table 6.4. Model parameters for preference of pedestrians' in using skywalk under existing conditions

Dependent variable (Y_i)	**Independent/ predictor variables (X_i)**
Preference of using skywalk	Gender (Gen), Age (A), Luggage (Lug), Profession (Prof), Trip purpose (TP), Frequency of daily use (FD), Width (Wid), Surface (Surf), Obstruction (Obs), Connectivity (Conn), Safety and Security (SS), Comfort (Comf), Walk environment (WE)

The similarity between the pedestrian foot over bridges (FOBs) and skywalk characteristics and the lack of literature related to skywalk systems, encouraged the selection of the independent variables for predicting the outcome (i.e. factors governing usability of skywalks in future) based on the factors chosen by previous researchers for predicting the usability of FOBs (refer to Chapter 2, Section 2.5.1.1). As described earlier by the researchers predicting usability of foot over bridges, demographic factors (*such as Gen: gender, A: age, Lug: luggage, Prof: profession, TP: trip purpose and FD: frequency of daily use*) along with existing physical and user characteristics (*Wid: width, Surf: surface, Obs: obstruction, Conn: connectivity, SS: safety and security, Comf: comfort, and WE: walk environment*) were used in the present study to predict the preference of using skywalks under current conditions.

A multivariate correlation analysis was conducted (using the Pearson correlation coefficient) on different variables (refer Table 6.5), to predict the usability of skywalks. It was observed that at 5% significance level, gender had a negative correlation with safety-security, comfort and walk environment. This implied that female pedestrians felt insecured and uncomfortable (especially at night) in absence of proper safety and security measures. Similarly, age was found to have negative correlation with luggage and daily frequency at 1% significance level, which showed that an aged pedestrian preferred to use the skywalk more frequently if luggage was absent. Profession was also observed to have a positive correlation with trip purpose and frequency of daily use. This was understandable as majority of the regular commuters were servicemen or students who used the facilities twice or more daily for commuting to their workplace or educational institutes.

Table 6.5. Multivariate correlation analysis for demography and using Pearson correlation coefficient

		GEN	AGE	LUG	PROF	TP	FD	WID	SURF	OBS	CONN	SS	COMF	WE
GEN	***PC***	1	-0.017	0.038	-0.066	0.023	-0.021	-.119*	-.108*	-.323**	0.039	-.257**	-.217**	-.287**
	Sig.		0.758	0.476	0.22	0.667	0.702	0.026	0.043	0	0.464	0	0	0
AGE	***PC***	-0.017	1	-.183**	-.586**	-0.023	-.167**	-0.076	-0.045	-0.093	-0.045	-0.053	-0.04	0.005
	Sig.	0.758		0.001	0.000	0.661	0.002	0.157	0.406	0.084	0.404	0.32	0.459	0.927
LUG	***PC***	0.038	-.183**	1	0.094	0.000	0.077	-0.028	-0.046	-0.008	0.025	-0.019	-0.016	-0.076
	Sig.	0.476	0.001		0.079	0.999	0.149	0.603	0.393	0.879	0.646	0.728	0.764	0.156
PROF	***PC***	-0.066	-.586**	0.094	1	.117*	.119*	0.051	0.058	0.074	0.041	0.026	0.05	0.042
	Sig.	0.22	0	0.079		0.029	0.026	0.344	0.282	0.167	0.441	0.631	0.347	0.433
TP	***PC***	0.023	-0.023	0	.117*	1	-.187**	.137*	.201**	0.078	0.048	0.077	0.03	0.054
	Sig.	0.667	0.661	0.999	0.029		0	0.01	0.000	0.145	0.372	0.151	0.572	0.31
FD	***PC***	-0.021	-.167**	0.077	.119*	-.187**	1	-.237**	-.201**	-.198**	-0.07	-.117*	-0.043	-0.023
	Sig.	0.702	0.002	0.149	0.026	0		0	0	0	0.191	0.029	0.419	0.668
WID	***PC***	-.119*	-0.076	-0.028	0.051	.137*	-.237**	1	.651**	.458**	.369**	.347**	.354**	.345**
	Sig.	0.026	0.157	0.603	0.344	0.01	0		0	0	0	0	0	0
SURF	***PC***	-.108*	-0.045	-0.046	0.058	.201**	-.201**	.651**	1	.364**	.386**	.368**	.334**	.360**
	Sig.	0.043	0.406	0.393	0.282	0	0	0		0	0	0	0	0
OBS	***PC***	-.323**	-0.093	-0.008	0.074	0.078	-.198**	.458**	.364**	1	.265**	.393**	.326**	.325**
	Sig.	0	0.084	0.879	0.167	0.145	0	0	0		0	0	0	0
CONN	***PC***	0.039	-0.045	0.025	0.041	0.048	-0.07	.369**	.386**	.265**	1	.356**	.338**	.223**
	Sig.	0.464	0.404	0.646	0.441	0.372	0.191	0	0	0		0	0	0
SS	***PC***	-.257**	-0.053	-0.019	0.026	0.077	-.117*	.347**	.368**	.393**	.356**	1	.493**	.478**
	Sig.	0	0.32	0.728	0.631	0.151	0.029	0	0	0	0		0	0
COMF	***PC***	-.217**	-0.04	-0.016	0.05	0.03	-0.043	.354**	.334**	.326**	.338**	.493**	1	.587**
	Sig.	0	0.459	0.764	0.347	0.572	0.419	0	0	0	0	0		0
WE	***PC***	-.287**	0.005	-0.076	0.042	0.054	-0.023	.345**	.360**	.325**	.223**	.478**	.587**	1
	Sig.	0	0.927	0.156	0.433	0.31	0.668	0	0	0	0	0	0	

Note: *2-tailed correlation significance level: '*'- 5%;’**’- 1%; GEN- Gender, LUG- Luggage, PROF- Profession, TP-Trip purpose, FD- Frequency daily, WID- Width, SURF- Surface, Obs- Obstruction, Conn- Connectivity, SS- Safety & Security, COMF- Comfort, WE- Walk environment, PC- Pearson correlation, Sig.- Significance (2-tailed) value*

The Omnibus tests of model coefficients (refer to Table 6.6) was also performed to check whether the new model (with explanatory variables included) had any improvement over the baseline model. The test uses the chi-square tests to check if there is a significant difference between the Log-likelihoods (-2 Log Likelihood) of the baseline model and the new model. A reduction in the -2 Log-likelihood (-2LL) compared to baseline suggests that the new model is explaining more variation and is an improvement over the baseline model.

Table 6.6. Omnibus tests of model coefficients *(Source: Banerjee and Maurya, 2020)*

Step no.	Version	Chi-square	df	Sig.
Step 1	Step	25.661	1	0.000
	Block	25.661	1	0.000
	Model	25.661	1	0.000
Step 2	Step	5.611	1	0.018
	Block	31.273	2	0.000
	Model	31.273	2	0.000
Step 3	Step	4.794	1	0.029
	Block	36.067	3	0.000
	Model	36.067	3	0.000
Step 4	Step	4.447	1	0.035
	Block	40.514	4	0.000
	Model	40.514	4	0.000
Step 5	**Step**	**5.548**	**1**	**0.019**
	Block	**46.062**	**5**	**0.000**
	Model	**46.062**	**5**	**0.000**

It was observed from Table 6.6 that in the 5th step, a chi-square value (of 46.062) with degree of freedom (5) and p-value (0), performed best in comparison to previous models.

Further, in order to measure the variability in the dependent variable, a model fit summary table (refer to Table 6.7) with the -2LL (i.e., used to compare nested/ reduced models) and Pseudo R square statistics (i.e., the Cox & Snell R square and the Nagelkerke R square) were obtained using SPSS.

Table 6.7. Model fit summary *(Source: Banerjee and Maurya, 2020)*

Step	-2 Log likelihood	Cox & Snell R square	Nagelkerke R square
1	257.813	0.071	0.127
2	252.202	0.085	0.154
3	247.408	0.098	0.176
4	242.961	0.109	0.197
5	**237.413**	**0.123**	**0.222**

It was evident from the result obtained in step 5 of model fit summary (Table 6.7) that the variation in dependent variable ranged between 12.3% (Cox & Snell R square) to 22% (Nagelkerke R square) depending on the reference chosen. The higher variation in outcome explained by the Nagelkerke R square (22%) along with a higher -2LL value (237.413) showed that there was better variation in the model. In Step 6, the parameter estimates did not change significantly (<0.001), so the model estimation was terminated at the 5th iteration.

The Hosmer and Lemenshow test (HL test), a goodness of fit test for logistic regression, was also performed (refer to Table 6.8). The HL calculates if the observed event rates match the expected event rates in population subgroups. The null hypothesis assumed for the test was that the model adequately fits the data; and if the significance level is less than 0.05, then we reject the hypothesis. The test returns chi-square and p-values. Higher chi-square values and higher p-values (≥ 0.05), indicate that the model fits well.

Table 6.8. Hosmer and Lemeshow test *(Source: Banerjee and Maurya, 2020)*

Step	Chi-square	df	Significance
1	4.267	2	0.118
2	7.351	6	0.290
3	5.650	8	0.686
4	6.337	8	0.610
5	**11.182**	**8**	**0.192**

The results of the HL test showed that in step 5, the highest chi-square value was obtained (11.182) with a p-value higher than 0.05, which indicated that the model had a good fit.

Classification table statistics (refer to Table 6.9) which shows the observed (i.e., number of 0's and 1's observed) and predicted (i.e. how many cases are correctly predicted) values of the dependent variable, percentage accuracy in classification (PAC), sensitivity (i.e. true positive or cases that had the observed characteristic which were correctly predicted by the model) and specificity (i.e. true negative or percentage of cases that did not have the observed characteristics, yet were correctly predicted as not having the observed characteristics) information was also obtained.

Table 6.9. Classification table *(Source: Banerjee and Maurya, 2020)*

Step	Observed		Predicted		
			Facility preferable for using		Percentage correct
			No	***Yes***	
Step 1	Facility preferable for using	***No***	0	49	00.0
		Yes	0	301	100.0
	Overall Percentage				86.0
Step 2	Facility preferable for using	***No***	5	44	10.2
		Yes	3	298	99.0
	Overall Percentage				86.6
Step 3	Facility preferable for using	***No***	5	44	10.2
		Yes	2	299	99.3
	Overall Percentage				86.9
Step 4	Facility preferable for using	***No***	7	42	14.3
		Yes	3	298	99.0
	Overall Percentage				87.1
Step 5	**Facility preferable for using**	***No***	**9**	**40**	**18.4**
		Yes	**3**	**298**	**99.0**
	Overall Percentage				**87.7**

The cut value is 0.500

The final model in step 5 could correctly classify the outcome for 87.7% of the cases in comparison to 66% in the null model. Hence there was a significant improvement observed in the final step (5th step) of the model.

The variables considered in the final model are shown in Table 6.10. The table presents the results of ‘B’ (estimated coefficient), Wald statistics, odds ratio [(Exp B)], p values and 95% confidence interval of odds ratio. The estimated binary logistic regression coefficients for the constant (also called intercept) are represented by the ‘B’ values. The ‘S.E.’ represents the standard error around the coefficient for the constant. The ‘Wald’ and ‘Sig’ defines the Wald chi-square test which assesses the null hypothesis that the constant equals to zero. Also, the odds ratio of the predictors is represented by the ‘Exp(B)’. The risk of the outcome falling in the comparison group relative to the risk of the outcome falling in the reference group is represented by odds ratio greater than 1, and it increases as the variable increases.

Table 6.10. Variables in the equation *(Source: Banerjee and Maurya, 2020)*

Step no.	**Variable**	**B**	**S.E.**	**Wald**	**df**	**Sig.**	**Exp(B)**	**95% C.I. for Exp(B)**	
								Lower	**Upper**
Step 1[a]	*Safety_security (SS)*	0.986	0.206	22.996	1	0.000	2.681	1.792	4.013
	Constant	-0.553	0.479	1.329	1	0.249	0.575		
Step 2[b]	*Safety_security (SS)*	0.969	0.207	21.974	1	0.000	2.635	1.757	3.951
	Age (A)	0.229	0.095	5.788	1	0.016	1.257	1.043	1.515
	Constant	-1.298	0.579	5.033	1	0.025	0.273		
Step 3[c]	*Safety_security (SS)*	0.670	0.243	7.589	1	0.006	1.954	1.213	3.146
	Walk_environment (WE)	0.534	0.245	4.724	1	0.030	1.705	1.054	2.758
	Age (A)	0.230	0.095	5.840	1	0.016	1.259	1.045	1.518
	Constant	-1.765	0.627	7.934	1	0.005	0.171		
Step 4[d]	*Obstruction (Obs)*	-0.527	0.254	4.320	1	0.038	0.590	0.359	0.970
	Safety_security (SS)	0.783	0.251	9.703	1	0.002	2.188	1.337	3.582
	Walk_environment (WE)	0.645	0.252	6.572	1	0.010	1.906	1.164	3.121
	Age (A)	0.244	0.097	6.389	1	0.011	1.277	1.056	1.544
	Constant	-1.288	0.669	3.705	1	0.054	0.276		
Step 5[e]	***Width (Wid)***	**0.483**	**0.210**	**5.305**	**1**	**0.021**	**1.621**	**1.075**	**2.446**
	Obstruction (Obs)	**-0.765**	**0.276**	**7.682**	**1**	**0.006**	**0.465**	**0.271**	**0.799**
	Safety_security (SS)	**0.716**	**0.261**	**7.535**	**1**	**0.006**	**2.047**	**1.227**	**3.413**
	Walk_environment (WE)	**0.557**	**0.256**	**4.730**	**1**	**0.030**	**1.745**	**1.057**	**2.882**
	Age (A)	**0.254**	**0.099**	**6.533**	**1**	**0.011**	**1.289**	**1.061**	**1.567**
	Constant	**-1.764**	**0.715**	**6.094**	**1**	**0.014**	**0.171**		

a. Variable(s) entered on step 1. Safety_security (SS)
b. Variable(s) entered on step 2. Age (A)
c. Variable(s) entered on step 3. Walk_environment (WE)
d. Variable(s) entered on step 4. Obstruction (Obs)
e. Variable(s) entered on step 5. Width (Wid)

The results from Table 6.10 showed that in the 5th step, the most significant variables were considered which profoundly affected the perception of the pedestrians towards using the skywalks under the current scenario. It could be seen that the Wald chi-square test rejected the null hypothesis as p-value was smaller than the critical p-value (i.e., 0.05), and hence, the constant was not zero. The final form of the parsimonious model as obtained from Table 6.10 is represented by Equation 6.2.

$$\ln(ODDS) = -1.764 + 0.483*Wid - 0.765*Obs + 0.716*SS + 0.557*WE + 0.254*A \quad \text{….. } \textbf{Eq. 6.2}$$

The result from the forward stepwise model (as per Table 6.10) showed that factors such as width (*W*), safety and security (*SS*), walk environment (*WE*) and age (*A*) had positive coefficient values which meant that improving these factors would enhance the probability of pedestrians using the skywalks. Among all positive coefficients, safety and security was observed to have the highest coefficient value (0.716), which indicated that this was a factor which was strongly affecting the pedestrians' perception and thus improving the safety and security (in the form of CCTV camera installation and/ or security personnel deployment) would highly motivate the pedestrians and encourage them to use the skywalks in the future. Similarly, age had a much lower positive coefficient (0.254) in comparison to the other positive coefficients, which meant that age was an important parameter which influenced the usability of skywalks, but it was not a highly influencing parameter when pedestrians had to travel longer distances using the skywalks. Also, a negative coefficient value of obstruction, *Obs* (-0.765) indicated that removing obstructions (in the form of vendors, beggars and standing pedestrians) would have a positive impact on the preference of using the facilities. Again, the other variables (such as gender, luggage, profession, trip purpose, the frequency of daily use, surface, connectivity and comfort) had very scarce or no impact on the choice of pedestrians using the skywalk facilities.

To predict the odds that a respondent would prefer to use the skywalk based on width was ODDS = e^{a+bX}. If the preference was no (value = 0), the ODDS = $e^{-1.764+0.483(0)}$ = 0.171. This indicated that pedestrians were 0.171 times more likely to avoid using the skywalks based on the width. Similarly, for the other factors, the odds ratio could be calculated to understand the impact on pedestrians' preference to either choose or not choose a skywalk facility.

6.2.4. Future use predictability based on the relative importance

Apart from current preference, a further set of questions were put up before the respondents (which were predefined based on the existing literature). The pedestrians were questioned whether any improvement (no/ yes) in existing connectivity, installation of elevators/ escalators/ ramps, improvement in maintenance, installation/ improvement of security, removal of an obstruction or redesigning would govern their future usability. Figure 6.6 shows the relative importance of these different factors intervening the users' prioritization, and whose improvement could impact the future usage of skywalks among pedestrians.

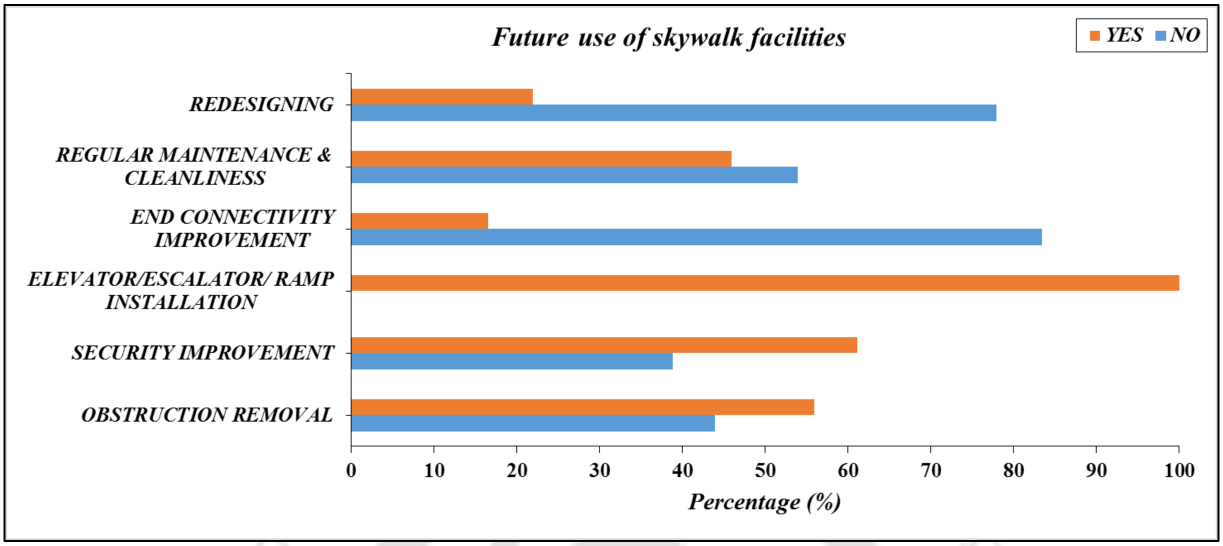


Figure 6.6. Choice of improvement required to enhance facility for future use *(Source: Banerjee and Maurya, 2020)*

The result from Figure 6.6 showed that all the pedestrians (100%) felt that the installation of elevator/ escalator/ ramp was of utmost importance and would profoundly impact their choice of using the skywalks in the future. Also, the improvement of security, removal of obstructions and regular maintenance would enhance their chances of using the facility as well. The respondents also felt that improving end connectivity and redesigning were of least importance and would not govern their choice of using the skywalk systems.

6.2.5. Important conclusions related to skywalk perception modelling

The study aimed to find the primary factors affecting the pedestrian choice of using the skywalk facilities under the current existing conditions through forward stepwise binary logistic regression method using IBM SPSS 20 software. Using the interviewer-administered questionnaire survey, the pedestrians' perception towards the use of skywalks under current as well as future use were obtained. Some of the significant findings of this study were:

i. Majority of pedestrians using the skywalks were male pedestrians (67%), in the age group of 11-40 years (66%).

ii. Students or servicemen (61%) mostly used the skywalk facilities for their work trips (36%), education trips (17%) or mode change (23%).

iii. Majority of the pedestrians were using the skywalk facilities more than once daily (~52%), and were thus aware of the existing conditions.

iv. The existing score based on perception survey revealed that respondents were dissatisfied with the prevailing safety and security along with available walkable width of the skywalk, due to the presence of obstructions in the form of vendors or standing pedestrians (refer to Figure 6.5).

v. Based on the results of the forward stepwise binary logistic regression method, it could be observed that width, obstruction, safety and security, walk environment along with age of the pedestrians affected the usability of the skywalks.

vi. The future response from the pedestrians also revealed that the installation of elevator/ escalator/ ramp, improvement of security, removal of obstructions and regular maintenance could strongly govern their future usability of elevated skywalk facilities (refer to Figure 6.6).

6.3. Perception modelling of factors impacting the usage of FOB facilities

6.3.1. Survey location selection

Major cities covering the different regions of India were visited, and all possible survey locations were observed prior to final data collection. Only those locations were selected where the FOBs had an adequate flow of pedestrians throughout the day and were connecting from one side of the road to the other side through a single entry and exit. In total fourteen locations were covered and 552 completed questionnaire samples were collected. A detailed summary of the different foot over bridges selected for this study is illustrated in Table 6.11. All the foot over bridge locations considered for the study had different flow levels during peak and off-peak hours. The foot over bridges were provided with either stairway alone, or along with escalators, lifts, and ramps. The questionnaire data were not collected for locations F1-F3.

Table 6.11. Site details of FOB locations selected for survey data collection

City	Location	*Length (m)*	*Mid-block width (m)*	*Number of steps*	*Stair width (m)*	*Tread (cm)*	*Riser (cm)*	*Vertical movement*	*Sample size*
Mumbai	*IIT Bombay (F4)*	46.5	3.6	52	1.60	32	17	S	31
Kolkata	*Ultadanga (F5)*	42.4	3.1	41	2.40	26	20	S	122
	Lake Town (F6)	42.2	2.9	19	2.90	30	15	S, R	
	Sealdah (F7)	36.9	2.4	53	2.10	30	15	S	
NCR	*Anand Vihar (F8)*	61.5	5.7	48	2.30	30	16	S, E	163
	Akshardham (F9)	66.5	2.2	48	2.30	31	16	S, E	
	ITO (F10)	39.2	2.6	117	2.20	31	2	R*, E	
	Maharani Bagh (F11)	41.3	2.6	115	2.80	30	2	R*, E	
	Vaishali (F12)	88.1	3.5	50	3.70	30	14	S, L	53
Bengaluru	*Tin factory (F13)*	49.8	2.6	50	2.09	25	12	S	141
	Yeshwantpur (F15)	31.1	3.1	54	1.10	26	9	S, L	
	Marathahalli (F16)	32.1	3.4	44	1.50	32	16	S, L	
	Christ University (F17)	21.2	2.8	39	3.10	29	14	S, L	
Guwahati	*Maligaon (F17)*	33.8	2.1	55	1.22	28	8	S	42

Note: *S-Stairways, L-Lift/ Elevator, E-Escalator, R-Ramp, R*-Ramp like stairways*

6.3.2. Questionnaire design and survey

The questionnaire was prepared including five broad sections (A to E) representing demography, the current condition of FOBs, preference of use under existing conditions, future usability dependents and field observation (refer to Table 3.3).

After finalizing the survey locations, the field observers (two in number for each location) gathered necessary details of the FOBs including GPS coordinates and dimensions of the facilities. An interviewer-administered questionnaire survey (by two interviewers) of the pedestrians in the neighbourhood of the facility was conducted at each survey location for weekdays in morning (7.30-10.30am) or evening (4.30-7.30pm) peak hours, respectively, to obtain a representative sample. During the survey, both set of participants (including users and non-users of FOBs) were randomly selected (using random sampling technique) and requested for the survey participation; and those willing to undergo the entire interview process were finally interviewed. Due to the massive rush in morning and evening peak hours, the participation rate was low (i.e., out of approximately twenty random pedestrians, only one participated when requested). Among all participants, 552 respondents answered all the questions, thoroughly. Later, in the lab, these 552 questionnaire samples were manually entered into an excel sheet for the final data analysis and modelling.

6.3.3. Survey results and model development

6.3.3.1. Demographic characteristics

The demographic parameters including gender, age, profession, and frequency of daily use are essential in understanding the existing usage pattern of pedestrians. Table 6.12 shows the aggregated demographic characteristics of the respondents across different cities.

Table 6.12. Demographic characteristics of composition (in %) of respondents'

Demographic characteristics		**Percentage (%)**
Gender (%)	*Male*	71.4
	Female	28.6
Age (%)	*≤ 10*	2.4
	11-20	27.6
	21-40	36.3
	41-60	25.5
	≥ 60	8.3
Daily frequency (%)	*First time user*	3.7
	Occasional user	14.7
	Daily once	14.2
	Daily twice	39.3
	More than twice	28.1
Profession (%)	*Business*	10.2
	Home maker	5.1
	Retired	3.6
	Self employed	*13.0*
	Service	*32.0*
	Student	*32.0*
	Others	*4.2*

From Table 6.12 it was observed that majority of the participants were male pedestrians (~72%) across all the locations combined. Most of the users (~64%) were in the age group of 11-40 years, which is consistent with the report of Ministry of Statistics and Programme Implementation (2018) which states that India holds the highest proportion of the young population (i.e., around 242 million). It was further noticeable that the usage rate decreased with the increase in age, which was in accordance with the findings reported by Räsänen (2007). The population of pedestrians below

10 years of age was low (2.4%), as parents tend to drop them using private vehicles or they travel by buses to school, instead of walking to their destinations using FOBs.

The statistics shown in Table 6.12 revealed that majority of the respondents (~68%) were regular users, as they were using the FOBs daily twice or more than twice. The frequency of users using the facility occasionally or daily once was low (~14%), as people using the FOBs generally used the facility for both ways of their trips (for example, from residence to workplace and back). There were very few first-timers (~4%) who used the facility for commuting.

Based on Table 6.12, it was also observed that majority of the regular users consisted of predominantly students and servicemen (64%), while the proportion of businessmen and self-employed personnel ranged between 10-13% across different locations. The results were similar to the previous findings reported by Saha (2011) and Wu (2014) that the tendency of using FOBs increased with higher education and better employment. The percentage of retired persons (age ≥60 years) and homemaker were significantly low across all the locations with 4% and 5% respectively.

6.3.3.2. Satisfaction of existing FOBs

For understanding how much pedestrians were satisfied/dissatisfied with the available features in existing FOBs, seven quality assessment parameters were asked to the participants across all FOBs. These parameters were comfort, connectivity, safety and security, surface condition, walk environment, width, and obstruction. The factors were selected from a list of physical and user characteristics provided by IRC: 103 (2012) for pedestrian facilities. The rating of six parameters were obtained from very poor (1) to very good (5) categories, while obstruction was rated between many (1) to none (3). The participants' responses from all FOBs were combined and analyzed together as shown in Figure 6.7.

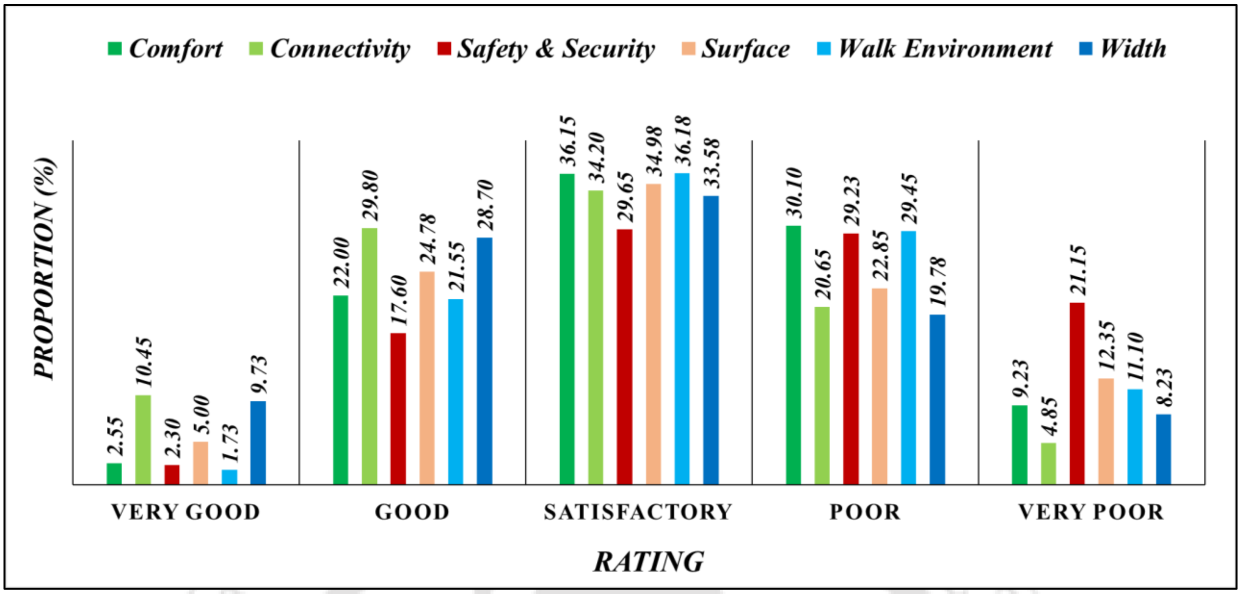


Figure 6.7. Perceived satisfaction/dissatisfaction on existing features of FOBs

The response statistics from Figure 6.7 revealed that safety and security was the most critical parameter, which the pedestrians perceived from 'poor' (29%) to very poor (21%) across majority of the FOB locations is India. The users also expressed dissatisfaction (poor to very poor) related to walk environment (~41%), comfort (~40%), and surface (~35%). Respondents' satisfaction regarding connectivity between FOBs with their desired destination was perceived to be between 'good' to 'satisfactory' (54%), however 20% users also expressed 'poor' satisfaction with the existing connectivity.

Further respondents' felt that the walkable width (poor to very poor: 28%) and perceived obstructions (some to many: 50%) were not satisfactory for comfortable movement across all locations (refer Figure 6.7 and Figure 6.8). The dissatisfaction was mainly because during peak hours; these locations were crowded by standing pedestrians/ vendors/ beggars, reducing the effective walkway width and resulting in increased mobility friction.

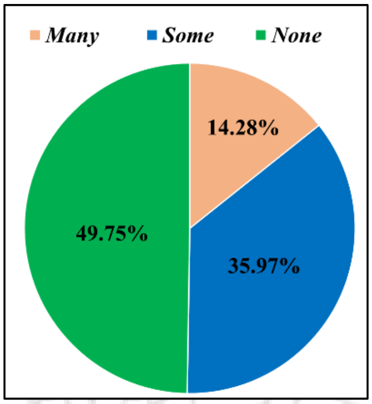


Figure 6.8. Perceived obstruction across different FOBs

6.3.3.3. Future usability model development

To obtain the essential parameters that determine the use of FOBs, in the current study three different modeling approaches (Generalized linear model: GLM, Random forest: RF, and Gradient boosting machine: GBM) were explored to predict the future usability determinants of FOBs (binary outcomes: yes/ no) using open-source statistical programming language R (version 3.4.3), under four different contexts. The four contexts included obstruction removal and relocation (Model 1), CCTV installation and security personnel deployment (Model 2), vertical end connectivity improvement in terms of lift/ escalator/ ramp installation and maintenance (Model 3) and horizontal end connectivity improvement (Model 4) corresponding to their selected predictors, presented in Table 6.13.

Table 6.13. Model parameters for modeling the usability of FOBs

Model No.	Context	Future Usability	Predictors	Sample Split
Model 1	Obstruction (mobility friction)	*0: No/* *1: Yes*	Gender, age, daily frequency, safety and security, comfort, walk environment, location type, effective width, effective width value, stair width	***Training*** = 80% *(n = 443)* and ***Testing*** 20% *(n = 109)*
Model 2	Safety and security	*0: No/* *1: Yes*	Gender, age, daily frequency, obstruction, walk environment, location type	
Model 3	Vertical end connectivity (lift/escalator/ ramp)	*0: No/* *1: Yes*	Gender, age, presence or absence of luggage, daily frequency, connectivity, comfort, location type, number of steps, stair width, tread dimension, riser dimension	
Model 4	Horizontal end connectivity	*0: No/* *1: Yes*	Gender, age, luggage, daily frequency, comfort, location type, length of FOB	

Note: *n- number of samples*

The samples split used was 80:20, and thus 443 samples were used for training the models and 109 for testing them (as per Table 6.13).

Model configuration and hyper parameters

In order to train the models and to use early stopping criteria, an open-source R package named "H2O" was used. For training and performance testing of the models, a total of 552 samples were randomly split into 80% *(n = 443)* train and 20% *(n = 109)* test dataset. To identify the best set of model parameters and to avoid unnecessary search, a randomized grid search approach (randomDiscrete) was used in the case of RF and GBM methods, as this helps in minimizing the computational time (Bergstra, 2012). The grid search parameters are illustrated in Table 6.14.

Table 6.14. Grid search parameters and early stopping criteria *(Source: Banerjee et al., 2020)*

		Random forest		**Gradient Boosting Machine**	
Hyper-Parameter Search Criteria	***ntrees***	100, 200, 300, 400, 500		100, 200, 300, 400, 500	
	mtries	Model1 = 4, 6, 8, 10	Model2 = 4, 6	-	
		Model3 = 4, 6, 8, 10	Model4 = 3, 5, 7		
	Max Tree Depth	40		2, 4, 6, 8, 10	
	Sample rate	0.5, 0.7, 0.9		0.5, 0.7, 0.9	
	Column sample rate per tree	0.5, 0.8, 1.0		0.5, 0.8, 1.0	
	Learning rate	-		0.01	
Early Stopping Criteria		**Random forest**		**Gradient Boosting Machine**	
		On the Grid	***On the Models***	***On the Grid***	***On the Models***
	Stopping metric	AUC	AUC	AUC	AUC
	Stopping tolerance	0.001	0	0.001	0
	Stopping round	10	10	10	10
	Score tree interval	-	5	-	5

A random grid search was performed to get the best set of parameter combinations that would provide better prediction accuracy. In the random grid search, a number of trees were tried ranging from 100 to 500 for both RF and GBM. Instead of default mtries (H2O default, square root of the number of variables for classification), a range of mtries for each of the four models were used in RF, reported in Table 6.14. Further, the column sample rate at tree level and the sampling rate was varied from 0.5 to 1.0. The maximum tree depth was fixed at 40 for RF; while it was varied between 2 and 10 at an interval of 2 for GBM. In the case of GBM, a learning rate of 0.01 was used.

For minimizing the training time and to avoid model overfitting, among all available early stopping criteria offered by H2O package (such as misclassification, logloss, MSE, and AUC), the

AUC based early stopping criterion was selected. The AUC based early stopping criteria was applied with the condition that if in ten successive models, the AUROC (Area Under Receiver Operating Curve) does not improve by 0.1%, then H2O stops further grid search. Simultaneously, per-model level early stopping criteria was applied with the condition that if training goes for ten scoring rounds without any improvement at all (stopping tolerance = 0) in the AUC, then it stops. Due to smaller sample size (n= 552), instead of creating a separate validation data set, 10-fold cross-validation criteria with a random fold assignment was used to get a better and reliable estimate of the trained models.

Model training and performance testing

The models were trained in R environment with the training samples (n = 443) using H2O package. In total 180 models were generated for Model 1 (predicting FOBs use in the context of future improvement in mobility friction) using RF and 225 models using GBM. Consecutively, for Model 2 (predicting FOBs use in the context of enhancement in safety and security), Model 3 (predicting usability in the context of future improvement in lift/escalator/ramp) and Model 4 (predicting usability in the context of future horizontal end connectivity improvement), RF generated 90, 47 and 135 models; while GBM generated 225, 225 and 450 models respectively. Next, all the generated models were sorted in decreasing order according to the AUC values, and the models with the highest AUC value were selected as the final optimized model. The final model summary is illustrated in Table 6.15.

Table 6.15. Summary of the best model hyper-parameters *(Source: Banerjee et al., 2020)*

Optimized parameters	**Random Forest Models**				**Gradient Boosting Machine Models**			
	Model 1	***Model 2***	***Model 3***	***Model 4***	***Model 1***	***Model 2***	***Model 3***	***Model 4***
ntrees	100	151	147	167	217	205	131	138
mtries	4	6	10	3	-	-	-	-
max depth	16	10	13	14	6	10	6	4
Column sample rate per tree	0.5	0.5	0.8	0.5	1.0	0.8	0.5	0.5
Sample rate	0.7	0.5	0.7	0.5	0.5	0.5	0.9	0.7
Learning rate	-	-	-	-	0.01	0.01	0.01	0.01

The optimized model results (from Table 6.15) revealed that both RF and GBM identified the accurate solution using less than 220 trees. RF models used max depth ranging from 10 to 16, while GBM achieved the best optimized model within maximum depth of 4 to 10. Additionally, the model trained on different contexts utilized the whole range of column sample rate per tree and sample rate, thus no distinct pattern was observed.

The various statistical measures used to measure the statistical significance of the models were Accuracy, LogLoss, AUC (Area Under Curve), MSE (Mean Squared Error) and F_{beta} measure (good performance measure used for unbalanced classes; in this study only estimated during model performance on test data set). Further, model prediction accuracy was separately estimated and reported. The model performance on the training data is shown in Table 6.16.

Table 6.16. Summary of model performance on training data *(Source: Banerjee et al., 2020)*

Modeling technique	Evaluation parameters	Accuracy	LogLoss	AUC	MSE
GLM	*Model 1*	0.7156	0.5528	0.7771	0.1865
	Model 2	0.7720	0.4994	0.8388	0.1629
	Model 3	0.9278	0.2454	0.9604	0.0742
	Model 4	0.7743	0.4087	0.7896	0.1304
RF	*Model 1*	0.7043	0.5248	0.7883	0.1769
	Model 2	0.7404	0.5500	0.8174	0.1831
	Model 3	0.9594	0.1217	0.9847	0.0356
	Model 4	0.7156	0.4424	0.7328	0.1416
GBM	*Model 1*	0.8804	0.3858	0.9475	0.1154
	Model 2	0.7968	0.4555	0.8934	0.1431
	Model 3	0.9774	0.1670	0.9927	0.0420
	Model 4	0.7743	0.4271	0.8451	0.1355

The results from Table 6.16 showed that in case of all the four models, GBM performed best in comparison to GLM and RF. The cross-validation estimates for each final model (illustrated in Table 6.17) for RF and GBM showed that AUC ranged between 0.72 to 0.98 (in case of RF) and between 0.72-0.97 (in case of GBM), which indicated an overall good model prediction in case of both the approaches.

Table 6.17. Summary of 10-fold cross-validation mean estimates of final models *(Source: Banerjee et al., 2020)*

Modeling approach	Evaluation parameters	Accuracy	LogLoss	Precision	Recall	AUC	MSE
RF	*Model 1*	0.7708	0.5145	0.6395	0.8623	0.8088	0.1636
	Model 2	0.7894	0.5482	0.7722	0.8901	0.8286	0.1819
	Model 3	0.9745	0.1213	0.9864	0.9832	0.9842	0.0362
	Model 4	0.7346	0.4433	0.4259	0.7431	0.7298	0.1407
GBM	*Model 1*	0.7835	0.5343	0.6587	0.8381	0.7943	0.1794
	Model 2	0.7930	0.5234	0.7767	0.9014	0.8246	0.1723
	Model 3	0.9631	0.2042	0.9627	0.9955	0.9759	0.0572
	Model 4	0.7454	0.4704	0.4572	0.7218	0.7258	0.1512

Further, for obtaining model performance on unseen test dataset, the final models were tested on the remaining 20% *(n = 109)* test dataset. Table 6.18 shows the model performance summary on the test data set.

Table 6.18. Summary of model performance estimated on the test dataset *(Source: Banerjee et al., 2020)*

Modeling technique	Evaluation Parameters	Accuracy	AUC	MSE	Precision	Recall	F-measure
GLM	*Model 1*	0.8073	0.8344	0.1704	0.7750	0.7209	0.7470
	Model 2	0.7982	0.8101	0.1801	0.7273	0.8511	0.7843
	Model 3	0.8991	0.9325	0.0839	0.9011	0.9762	0.9371
	Model 4	0.7523	0.6942	0.1477	0.6667	0.4118	0.5091
RF	*Model 1*	0.7982	0.8300	0.1587	0.6750	0.7500	0.7105
	Model 2	0.7431	0.8000	0.1879	0.8909	0.6901	0.7749
	Model 3	0.9633	0.9700	0.0415	0.9780	0.9780	0.9780
	Model 4	0.8165	0.7300	0.1422	0.5714	0.5217	0.5455
GBM	*Model 1*	0.8349	0.8800	0.1424	0.7750	0.7750	0.7750
	Model 2	0.7431	0.8200	0.1775	0.8727	0.6957	0.7742
	Model 3	0.9633	0.9800	0.0499	0.9780	0.9780	0.9780
	Model 4	0.8349	0.8500	0.1246	0.6667	0.5600	0.6087

The performance summary revealed that the overall optimized models using GBM *(based on F_{beta} measure: 0.61-0.97)* performed best in comparison to GLM (F_{beta} *measure: 0.51-0.93)* and RF *(F_{beta} measure: 0.54-0.97)* methods on the same test data as illustrated in Table 6.18.

6.3.4. Future predictability based on variable importance analysis

In the modeling process, variable importance was further estimated for each optimized model using the GBM method. The importance was estimated by calculating the relative influence of each variable: whether the variable was selected during the splitting in the tree building process and how much the squared error decreased. The variable importance obtained from each final selected model was illustrated in Figure 6.9. All scaled importance ranging from low (0) to high (1) for each selected factors were arranged in descending order to get the most important factors influencing the FOBs use, as illustrated in Figure 6.9.

6.3.4.1. Future use concerning mobility friction improvement

In the future usability model corresponding to mobility friction (*model 1: obstruction*), the importance plot revealed that stair width and daily frequency of use were the most crucial factors which influenced the use of FOBs (illustrated in Figure 6.9, Plot A). Usually, narrow stair width and high pedestrian flow increased the mobility friction. Even the presence of vendors/ beggars/ standing pedestrians reduced the effective walkway width, which was further responsible for the reduction in the use of the FOBs, and this was in accordance with the findings reported by Pasha (2015). A study by Saha (2011), confirmed that in heavy crowded locations (such as central business district or public transport terminals), unwanted people's presence discouraged the use of FOBs. It was further noticed that the type of location (whether commercial, educational, public transport or residential type of land use), age, existing walk environment, and security further also played a vital role in usability choice. Though the presence of people (vendors, standing pedestrians, and beggars) usually gave a sense of safety and security, yet this might not be true under all scenarios. During night time, the presence of vendors and beggars might discourage pedestrians from using FOBs due to the prevalence of illegal activities and fear of victimization. The study of Malik (2017) also highlighted a similar concern, which made people feel insecure in the presence of many beggars and shops.

6.3.4.2. Usability concerning safety and security

Perceived safety and security is the most prominent factor related to use of elevated facilities (Räsänen, 2007). The future usability prediction model (*Model 2*) concerning perceived safety and security (i.e., CCTV installation and security personnel deployment) revealed walk environment (i.e., the facility surroundings and whether they are pleasant or not) and gender as the most crucial predictors that influenced the use of FOBs across Indian cities (see Figure 6.9, plot B). The significant determinants of safety and security differed based on the time when pedestrians used the facility. At daytime, safety and security-related concerns arose among people in highly crowded areas (such as PTT), where the pickpocket and theft-related issues were frequently noticeable. At night time, the security-related issues (such as walk environment being uncomfortable due to illegal activities) were primarily gender-specific (related to female pedestrians), which debarred them from using the FOBs (Malik, 2017; Pasha, 2015).

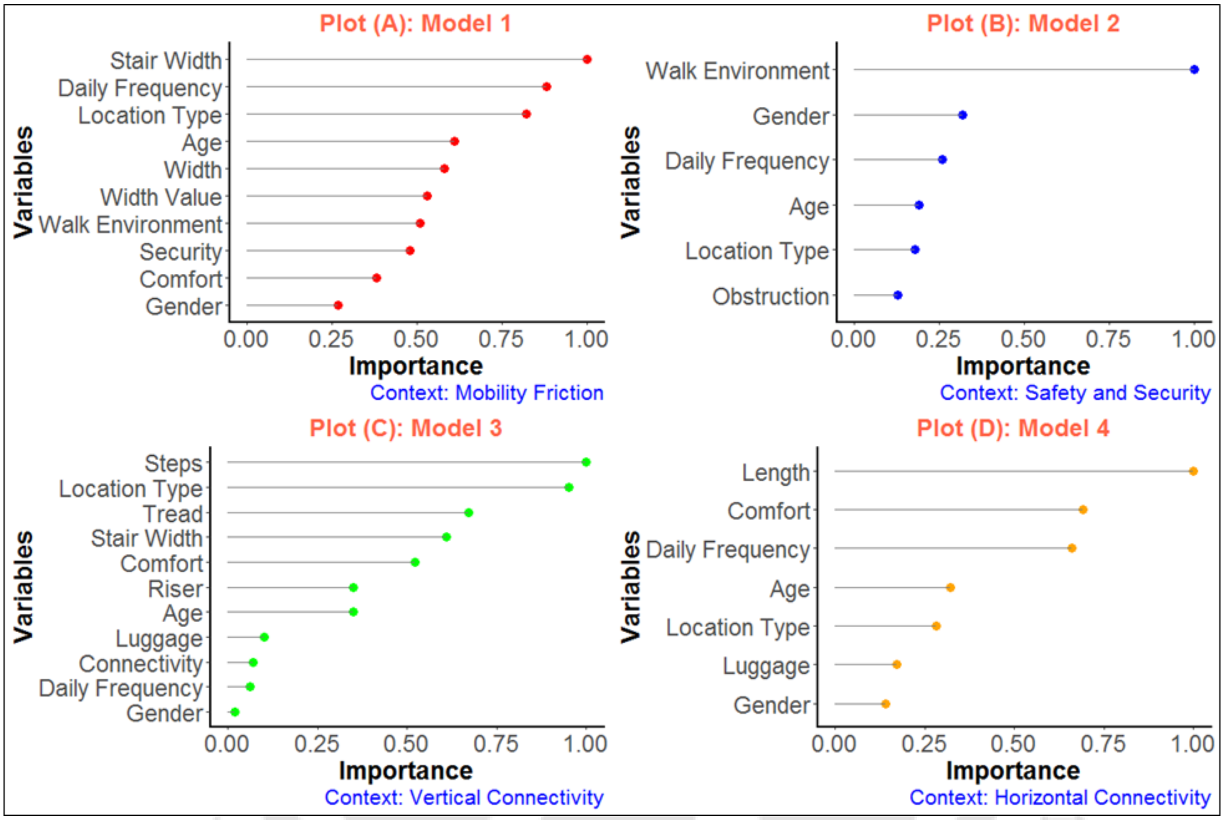


Figure 6.9. Variable importance plot *(Source: Banerjee et al., 2020)*

Moreover, the absence of CCTV and security personnel at PTT and commercial locations demotivated users and increased the perceived fear of victimization. Insufficient security regarding the absence of lighting (Malik, 2017; Pasha, 2015), perceived insecurity of getting robbed (Hasan, 2014; Malik, 2017; Villaveces, 2012) and criminal activities (Villaveces, 2012, Saha, 2011) were previously found to deter the use of FOBs amongst pedestrians. Past studies, as well as current respondents' expressed concerns also supported the fact that to enhance safety and security, most common measures were the provision of proper lighting (Hasan, 2014; Malik, 2017; Villaveces, 2012; Pasha, 2015) and removal of advertisement banners (Koepsell, 2002; Malik, 2017; Oviedo-Trespalacios, 2017). Moreover, the provision of surveillance systems such as CCTV cameras along with proper placement of security personnel (Gallegos, 2012) and stricter laws (Hidalgo-

Solórzano, 2010; Sabet, 2013) would also strengthen the safety perception among pedestrians and motivate them to use the facility frequently.

6.3.4.3. Usability concerning vertical end connectivity

The variable importance obtained from *Model 3* (predicting usability concerning vertical end connectivity: lift/ escalator/ ramp) illustrated future usability was highly related to the design-related parameters such as steepness of stairs (Mutto, 2002; Sabet, 2013; Saha, 2011), narrow width of stairs (Hasan, 2014) and absence of escalators/ramps (Desriani, 2008; Hasan, 2014; Räsänen, 2007; Rizati, 2013) which caused discomfort to the users (Sharples, 2011; Hasan, 2014; Hasan, 2018; Saha, 2011). These reported facts also supported the findings obtained from Model 3 (refer Figure 6.9, Plot C), where the dimension of the stairway (i.e., number of steps, tread dimension, width, and riser dimension) and comfort played significant role in deciding the future use of the FOBs. Further, location type, i.e., where the facility was situated also played a pivotal role in the choice of use. Further, the age of the respondent was found out to be a prevalent determinant, as with the increase in age pedestrians felt uncomfortable in putting extra effort to climb stairs (Rankavat, 2016). Provision of short stairs, ramps (Desriani, 2008) and lift/escalator (Demiroz, 2015; Hasan, 2018; Räsänen, 2007), while designing new elevated facilities and reconstructing existing FOBs would reduce extra effort and enhance comfort, leading to an increase in the use of FOBs.

6.3.4.4. Usability concerning horizontal end connectivity

The future usability concerning the horizontal end connectivity (*Model 4*) was majorly influenced by the length of travel, comfort, daily frequency of use and age of the pedestrian (see Figure 6.9, Plot D). The travelled length was found out to be a highly influencing factor in deciding the use of the FOBs. Mutto (2002) in their study highlighted the fact that extra traveled distance negatively influenced pedestrian behaviour while choosing a crossing facility. Other studies also used similar predictors, but instead of travelled distance, travelled time was used as a function of covered distance, which was also directly related to the perceived comfort. Past studies identified that when the travelled length increased significantly as compared to at-grade facilities and the time needed to cover the distance was more than 50% (Anciaes, 2018; Hasan, 2014; Malik, 2017; Rankavat, 2016; Wu, 2014) people tried to avoid FOBs and used nearest illegal exits available by attempting to cross through median openings or jumping over fences (Demiroz, 2015; Desriani, 2008). This indicated that providing additional length and detour distances would discourage pedestrians from FOB use. The current model findings also revealed that pedestrians' perceived comfort was another important factor. The comfort was derived based on whether proper horizontal end connectivity gave the pedestrians easy and direct access towards their destination or not. In this regard, proper signboards mentioning the connecting locations (i.e., entry and exit location name) would likely give initial information to pedestrians about their destination and provide comfort to existing as well as new users (Desriani, 2008).

6.3.5. Important conclusions related to FOB perception modelling

In the current study, information was obtained through interviewer-administered questionnaire survey and field measurement sessions near fourteen FOB locations across five different regions of India. In total, 552 valid survey samples were collected from the respondents. Analysis results revealed that majority of the pedestrians who were using the FOBs were young (11-40years), regular users (used twice or more than twice daily) and mostly comprised of male (~72%) pedestrians. The career of the users' further influenced the preference of use. The students and working professionals were more likely to use the FOBs than other profession types.

In the present study, machine learning techniques such as generalized linear model (GLM), random forest (RF) and gradient boosting machine (GBM) learning algorithms were compared to find the optimal solution that could accurately predict primary factors affecting the use of FOBs. Among different machine learning techniques, GBM outperformed the other two in terms of prediction performance on unknown (test) data set for identifying the essential parameters affecting pedestrians' choice of using the elevated facility under four different contexts (i.e., mobility friction, safety and security, vertical end connectivity and horizontal end connectivity). The major conclusions drawn from this study are described as follows:

i. One of the most crucial factors that decided the usability was safety and security, which was gender-specific and depended on the existing walk environment. The feedback provided by the respondents revealed that the unavailability of CCTV cameras and security personnel, along with the prevalence of antisocial activities were significant concerns that influenced the usability choice.

ii. The age of the pedestrian played a crucial role in the choice of FOBs when the decision was derived regarding ease in vertical movement (climbing stairs) and when longer travelled distance (length) was a matter of concern.

iii. The gender acted as a significant influencer when the usability choice was solely dependent on perceived safety & security.

iv. The stairway width above 1.5m increased the usability preference of pedestrians.

v. As the number of steps to climb increased, the usability preference decreased amongst aged pedestrians.

vi. The design parameters of FOB such as the number of stairs to climb, stair width, width of the walkway and length of the facility were associated with the perceived comfort and also determined whether a pedestrian would choose the facility. The provision of stairs with short risers and escalator/ lift/ ramp would enhance the comfort of pedestrians and motivate them to use FOBs more frequently.

6.4. Concluding remarks

In the present chapter, an estimate was made in order to understand the influence of various factors on pedestrian perception towards using elevated walkways. Using questionnaire survey data, the perception based models for usability of elevated walkways (for skywalk and FOB) were developed separately. In case of skywalk, the forward stepwise regression model was used and the factors such as safety-security, age, walk-environment, obstruction and width were the most significant factors affecting the pedestrian perception towards using the facility. In case of FOBs, Gradient boosting machine (GBM) predicted that stair width, frequency of use, walk environment, number of steps and length of facility highly affect the pedestrian choice towards using the elevated facility. In order to increase of the use of elevated walkways, suggestions and recommendations were also put forward. The next chapter discusses about the level of service of the different elevated walkways based on qualitative and quantitative measures.

CHAPTER 7

DEVELOPMENT OF PEDESTRIAN LEVEL OF SERVICE (PLOS) FOR FOB AND SKYWALK

Pedestrian Level of Service (PLOS) is a quality measure describing operational conditions within a traffic stream, generally in terms of service measures such as speed and travel time, freedom to maneuver, traffic interruptions, comfort and convenience. Six LOS ranges are generally defined for each type of facility. LOS A represents the best operating condition and LOS F the worst. As per previous literature and manuals (Indo-HCM 2018, US-HCM 2010, and IRC: 103-2012), the LOS was defined based on quantitative data as well as qualitative data. The different levels of service for pedestrian flow (from LOS A to F) are shown below in Figure 7.1 .

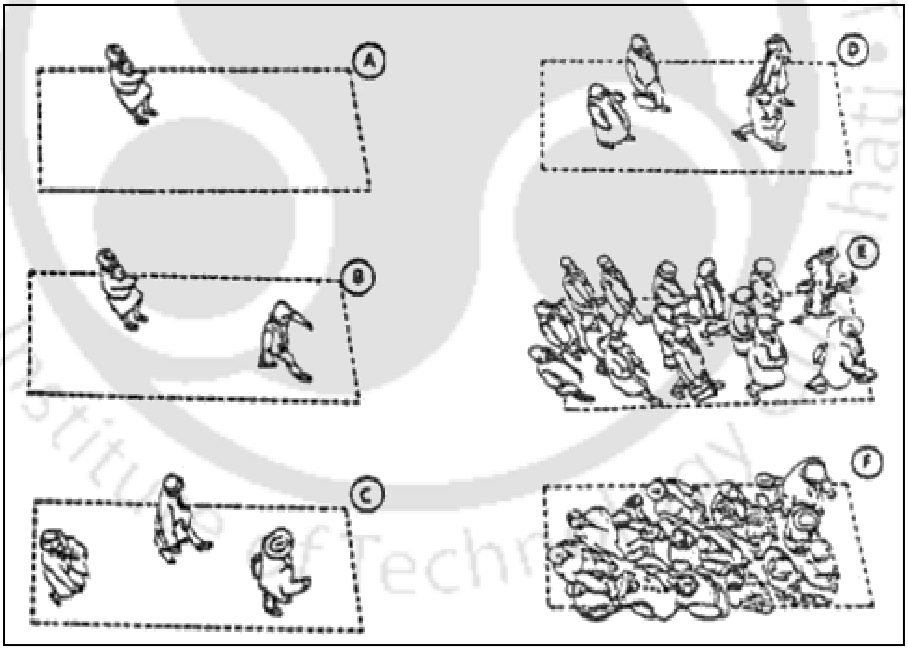


Figure 7.1. Pedestrian LOS *(Source: Table 1.1, IRC: 103-2012)*

As per Indo-HCM (2018), PLOS is defined as “a measure for assessing the operating condition of facilities in a quantitative manner. It denotes the level of comfort provided by the facility to pedestrians while using the facility”. Moreover, qualitative LOS determination in Indo-HCM uses the perception of the pedestrians based on the environmental qualities of the facility. Similarly, IRC: 103 (2012), defines PLOS as factors that "indicates the environmental qualities of a pedestrian space and serves as a guide for development of standards for pedestrian facilities. Environmental factors that contribute to the walking experience and therefore to the perceived PLOS, such as comfort, convenience, safety, security and attractiveness should also be considered". Also, as per US-HCM (2010), PLOS is defined as "a quantitative stratification of a performance measure or measures that represents quality of service, measured on an A-F scale, with LOS A representing the best operating conditions, from the traveler's perspective and LOS F the worst".

Previous literatures and manuals (US-HCM 2010 and IRC: 103-2012) show that majority of the quantitative PLOS were developed for sidewalks or crosswalks. However, for elevated walkways (especially FOBs and skywalks) which are important infrastructures for the urban setting, very few PLOS guidelines are available. Recently, Indo-HCM 2018 defined quantitative LOS for five FOBs (across three cities) based on flow, speed and space. Similarly, Indo-HCM (2018) has also developed qualitative PLOS for FOBs using importance and satisfaction ratings from users on certain physical and user-based characteristics. Thus, PLOS definitions for elevated walkway is considerably low in the current literature and those that are developed are either context specific or developed over a handful of specific environmental factors. Therefore there is an urgent need to develop LOS guidelines for FOB and skywalk facilities considering both qualitative and quantitative approaches, which can cover different regions of India and can be used an update to the existing LOS guidelines provided by the Indo-HCM (2018). Table 7.1 shows the different factors considered by the different manuals along with the ranges of the LOS.

As per Table 7.1, Indo-HCM (2018), US-HCM (2010) and IRC: 103 (2012) were developed based on quantitative and qualitative measures. Quantitative models have always been based on different measures such as flow rate, speed and delay for sidewalks, walkways, and stairways. In case of quantitative LOS development, the width of the facility is measured, then the pedestrian flow (ped/min) is observed, maximum or peak flow rate is estimated and thereafter the LOS is defined based on the tables which are generated from the field data. In the case of qualitative LOS development, Indo-HCM (2018) developed a walkability index based on importance weight and satisfaction rating for physical and user characteristics for five LOS ranges.

Table 7.1. LOS criteria for different guidelines

Manual	Facility	Measure	PLOS ranges					
			A	B	C	D	E	F
Indo-HCM (2018)	***Sidewalk***	*Flow Rate*	≤12	>12-20	>20-32	>32-54	>54-91	Variable
	Crosswalk	*Delay*	≤5	5-10	11-25	25-45	46-80	>80
	Stairway	*Flow Rate*	≤10	>10-22	>22-46	>46-55	>55-70	Variable
		Speed	≥42.6	>37.2-42.6	>31.2-37.2	>28.2-31.2	>24.2-28.2	-
	FOB	*Flow Rate*	≤12	>12-17	>17-27	>27-38	>38-52	Variable
		Speed	≥56.8	>55.1-56.8	>51.7-55.7	>45.6-51.7	>30.9-45.6	<30.9
IRC: 103-(2012)	***Sidewalk***	*Flow Rate*	≤12	>12-15	>15-21	>21-27	>27-45	Variable
US-HCM (2010)	***Walkway***	*Flow Rate*	≤16.4	>16.4-22.9	>22.9-32.8	>32.8-49.2	>49.2-75.4	Variable
		Speed	>77.69	>76.2-77.7	>73.1-76.2	>68.5-73.1	>45.7-68.5	≤45.7
	Stairways	*Flow Rate*	≤16.4	>15.6-19.7	>19.7-26.2	>26.2-36.1	>36.1-49.2	Variable

Note: *Flow rate (ped/min/m), Speed (m/min), Delay (secs)*

In the current study, an attempt was made to define the LOS for elevated walkways considering fourteen FOB locations and seven skywalk locations across six different cities (with varied geographical locations and land uses) based on quantitative measures (speed and flow rate) as well as qualitative measures (walkability score). The speed-flow rate macroscopic relationship (as shown in Figure 7.2), provides a rough estimation on the existing LOS over the elevated walkways.

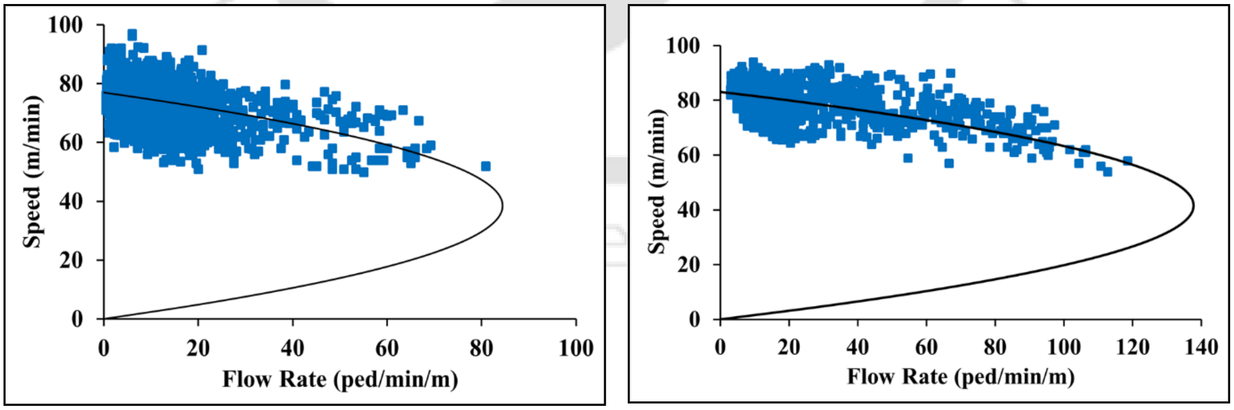


Fig. (a). FOB facility

Fig. (b). Skywalk facility

Figure 7.2. Speed-flow rate relationship

From Figure 7.2, it is difficult to predict the actual LOS ranges, thus using different flow parameters (speed and flow rate) for the all FOB and skywalk locations, the actual ranges were developed, as discussed below.

The quantitative measures such as speed and flow rate were considered as the measures of effectiveness (MOEs) for defining the PLOS. The qualitative PLOS was developed for pedestrians using these facilities for seven design factors chosen based on physical characteristics (surface, width, obstructions, and continuity) and user characteristics (security, comfort, and walk environment). In case of both quantitative and qualitative LOS, six different ranges were defined. Finally for estimating the existing condition of an elevated walkway (FOB or skywalk), a single score based on the ranges provided were used to reach at the current working LOS for each facility. Statistical tests (such as t-test and Mann Whitney U-test) were also conducted to check whether the mean speed data for the skywalk and FOB were statistically different for different facilities/users characteristics or not.

7.1. Quantitative LOS (QN-LOS) development for FOB and skywalk facilities

A t-test (at 5% alpha value) was conducted for the similar pedestrian category (*gender: male/ female, age group: 20-40 years and luggage: without*) to check whether significant difference existed between the mean speed for the two elevated walkway facilities (FOBs and skywalks), as shown in Table 7.2.

Table 7.2. t-test statistics between the mean speed for the FOB and skywalk facilities

Facility	Measure	Mean	t-Stat	t-Critical	Difference
FOB	*M:40-60:W/O*	76.33	18.69	1.96	Significant
Skywalk	*M:40-60:W/O*	81.14			
FOB	*F:40-60:W/O*	68.53	18.85	1.96	Significant
Skywalk	*F:40-60:W/O*	75.39			

Note: *M- male, F- female, 40-60- age category, W/O- without luggage*

Based on Table 7.2 it was observed that significant difference existed between pedestrians in the same gender, age and luggage carrying conditions for FOB and skywalk facilities. Therefore, it was decided to segregate the data for development of two separate quantitative PLOS tables for FOB and skywalk facilities.

Thereafter, minute wise analysis was done for the two quantitative measures (flow rate and speed) for the FOB and skywalk locations. Approximately 42 hours of FOB videographic data and 20 hours of skywalk videographic data was used for developing the LOS ranges. Table 7.3 provides an information on the variation in two measures (flow rate and speed) for both the elevated walkways considered.

Table 7.3. Variation in measures amongst two different elevated facilities

Measure	Facility	Mean	Minimum	Maximum	Standard Deviation	15th percentile
Speed (m/min)	*FOB*	72.04	50.14	97.52	6.84	63.75
	Skywalk	78.65	54.15	94.15	5.85	73.00
Flow rate (ped/min/m)	*FOB*	12.22	0.48	80.83	9.83	-
	Skywalk	25.31	2.96	118.51	22.28	-

Table 7.3 shows the variation in the two elevated walkways based on mean, minimum, maximum and 15th percentile speeds. It was observed from the table that difference in mean speed and flow rate between FOB and skywalk facilities were approximately 6m/min and 13ped/min/m respectively.

As per previous literature (Nag, 2020), majority of the existing studies used equal data binning technique to cluster the data and thereafter adjusted the LOS ranges as per field conditions. Similar methodology was also adopted in this work for the development of quantitative LOS ranges. Initially, equal data binning or equal width discretization method was applied for obtaining the bin ranges for the six LOS levels. After getting the ranges, the definition of the ranges were applied to the dataset and the classified service levels were obtained for different facilities. However, it was observed that the classified service levels sometimes did not represent the actual ground condition, and thus the bin widths were adjusted accordingly. Say for example, after applying equal binning, FOB 1 was observed to fall within service level B, whereas ground condition (i.e., visual observation as an expert) indicated a worse service level (C) for the same location. Therefore, the bins were adjusted such that the ground condition was taken into consideration as well for all the facilities. Finally, the data collected over fourteen FOB and seven skywalk facilities were assigned into different bins as presented in Table 7.4 and Table 7.5 respectively.

Table 7.4. Quantitative-LOS (QN-LOS) table for FOB

LOS	Flow rate (ped/min/m)	Speed (m/min)
A	≤16	≥64.1
B	>16-29	>58.5-64.1
C	>29-47	>52.8-58.5
D	>47-63	>49.9-52.8
E	>63-78	>41.6-49.9
F	Variable	≤41.6

Table 7.5. Quantitative-LOS (QL-LOS) table for skywalk

LOS	Flow rate (ped/min/m)	Speed (m/min)
A	≤23	≥73.4
B	>23-43	>65.6-73.4
C	>43-68	>59.5-65.6
D	>68-92	>53.5-59.5
E	>92-118	>47.4-53.5
F	Variable	≤47.4

7.2. Qualitative LOS (QL-LOS) development for FOB and skywalk facilities

For defining qualitative LOS of elevated walkways (FOBs and skywalks), the satisfaction ratings (based on Likert scale) for seven factors (width, surface, connectivity, obstruction, safety-security, comfort and walk environment) as based on IRC: 103 (2012) and Indo-HCM (2018) were obtained from questionnaire survey. The respondents were asked to rate (on a scale of five: *Very Poor* to *Very Good*) the existing conditions of the width, surface, connectivity, safety and security, comfort and walk environment. Similarly, obstruction was rated on a scale of 3 (*many, some, and none*). To check the reliability or consistency of the Likert scale, Cronbach’s alpha (α) test was used. The result of the reliability statistics showed a value of 0.815, which indicated a high level of internal consistency of the scale, for the seven parameters used. Moreover, the test also showed that removing any factor would result is lower reliability. In total 902 respondent samples (552: FOB and 350: Skywalk) were used for developing the qualitative LOS score.

Mann-Whitney U test was conducted using SPSS (version 20) for the two data sets of FOB and skywalk questionnaire data to check the descriptive statistics along with the significance between the seven factors used. It is assumed that if the asymptotic significance (2-tailed) is less than 0.01 significance level or 99% confidence interval, then significant difference exists between the two group of pedestrians using the two elevated walkways (refer to Table 7.6).

Table 7.6. Mann Whitney U-test for checking test significance level

	Test statistics						
	Width	**Surface**	**Obstruction**	**Connectivity**	**Safety & Security**	**Comfort**	**Walk Environment**
Asymp. Sig. (2-tailed)	.028	.008	.000	.029	.002	.861	.009

Note: *Asymp. Sig.- Asymptotic significance level*

Mann Whitney U-test statistics from Table 7.6 showed that at 0.01 significance level: surface, obstruction, safety-security and walk environment were significantly different in case of FOB and skywalk respondent perceptions. At 0.03 significance level, width and connectivity were found to be significant. This meant that significant difference existed between the perceptions of respondents related for FOB and skywalks for the above mentioned six factors at 1% and 3% significance levels. However, no statistically significant difference existed in perception of pedestrians of FOB and skywalk facilities related to comfort.

Based on the following method (as per Indo-HCM 2018), the qualitative LOS was defined,

$$\textbf{\textit{Qualitative LOS (QL-LOS)}} = \sum_{i=1}^{7} A_i * B_i \qquad \text{.......... } \textbf{Eq. 7.1}$$

Where, A_i refers to the importance rating and B_i refers to the weightage factor.

The importance ratings were obtained from the satisfaction score provided by the respondents' for the seven physical and user characteristics. Weightage for each factor was obtained from previous literature (refer to Table 7.7).

Table 7.7. Previous literature for weightage factor calculation

Author	Facility	Factors (number of times used)
Sarkar (1994), Mitra-Sarkar (1994), Khisty (1994), Dixon (1996), Jaskiewicz (2000), Landis (2001), Gallin (2001), Sisiopiku (2002), Muraleetharan (2003), Sarkar (2003), Lee (2003), Rahaman (2006), Lopez (2006), Parida (2007), Bian (2007), Ferreira (2007), Jensen (2007), Parida (2008), Dowling (2008), Hidayat (2011), Bahari (2012), Christopoulou (2012), Televska (2012), Kang (2013), Gokhale (2013), Martokusumo (2013), Asadi-Shekari (2013), Rastogi (2014), Kim (2014), Zakaria (2015), Daniel (2015), Talavera-Garcia (2015), Hasan (2015), Babu (2016), Marisamynathan (2016), Zhao (2016), Karatas (2018), Parvathi (2018), Zannat (2019), Sangeeth (2019), Bivina (2019), Jahan (2020), Vallejo-Borda (2020)	***Sidewalk, Walkway & Stairway***	Width (26), Surface (18), Obstruction (20), End connectivity (18), Safety and security (22), Comfort (17), Walk environment (24)
Pai (2007), Räsänen (2007), Soltani (2013), Saha (2013), Wu (2014), Pasha (2015), Das (2015), Rankavat (2016), Sinclair (2016), Hasan (2017), Malik (2017), Nejad (2017), Oviedo-Trespalacios (2017), Mulyadi (2018), Rana (2018), Umar (2019), Ngoc (2019), Sundararajan (2020), Landa-Blanco (2020), Banerjee (2020)	***FOB & Skywalk***	Width (3), Surface (2), Obstruction (8), End connectivity (10), Safety and security 19), Comfort (11), Walk environment (11)

Table 7.7 showed that safety-security was the most important parameter which was considered by majority of the researchers for the different pedestrian facilities. Thereafter, walk environment was found to be quite important. Similarly, surface was the least important factor. Based on Table 7.7, the weightages to be assigned to each factor was calculated and are shown in Table 7.8.

Table 7.8. Weightages applied for QL-LOS calculation

Width	Surface	Obstruction	Connectivity	Safety & security	Comfort	Walk Environment
0.45	0.31	0.44	0.44	0.64	0.44	0.55

Using the satisfaction score (*Min: 1 and Max: 5*), weightage obtained from Table 7.8, the minimum and maximum scores were obtained. Thereafter, equal width discretization method was applied to develop the six LOS ranges as shown in Table 7.9.

Table 7.9. Qualitative-LOS (QL-LOS) table for elevated walkways

LOS	QL-Score
A	≥13.00
B	>10.57-13.00
C	>8.14-10.57
D	>5.71-8.14
E	>3.26-5.71
F	≤3.26

7.3. Final Pedestrian Level of Service (PLOS) determination

Even though for each location one can have separate LOS based on quantitative and qualitative data, however comparing between quantitative and qualitative factors gives a better understanding of the existing LOS over each facility. Table 7.10 shows the QN-PLOS or QL-PLOS assigned to different facilities/ sites across different cities.

Based on engineering observation and perception point of view, the quantitative and qualitative LOS are expected to mismatch by at least 1 level. However, in our case (as shown in Table 7.10), the mismatch of 2 levels were for four locations only, suggesting that the QN-LOS and QL-LOS tables developed could be used by designers and practitioners. Moreover in order to calculate the final PLOS, the following equation can be used.

Final PLOS= *Worst (QN-PLOS, QL-PLOS) --> i.e. worst value between QN and QL PLOS*

…… **Eq. 7.2**

Table 7.10. Quantitative and qualitative LOS assignment

Facility	Location	City	QN-LOS	QL-LOS
Skywalk	Ghatkopar	*Mumbai*	B	D
Skywalk	Santa Cruz		B	C
Skywalk	Andheri		D	D
Skywalk	Goregaon		B	C
Skywalk	Bandra		C	C
Skywalk	Kalyan		D	D
Skywalk	Vile Parle		B	C
FOB	Tin Factory	*Bengaluru*	C	D
FOB	Yeshwantpur		A	C
FOB	Marathahalli		B	C
FOB	Christ University		A	B
FOB	IITB	*Mumbai*	B	C
FOB	Ultadanga	*Kolkata*	C	C
FOB	Lake Town		B	C
FOB	Sealdah		B	C
FOB	Anand Vihar	*NCR*	C	C
FOB	Akshardham		D	D
FOB	ITO		B	C
FOB	Maharani Bagh		B	D
FOB	Vaishali		B	C
FOB	Maligaon	*Guwahati*	C	D

In order to compare between the quantitative LOS developed for FOB based on Indo-HCM (2018) and the current study, Table 7.11 was developed.

Table 7.11. QN-LOS comparison for FOB facilities

	Measure	**PLOS ranges**					
		A	**B**	**C**	**D**	**E**	**F**
Indo-HCM (2018)	***Flow Rate***	≤12	>12-17	>17-27	>27-38	>38-52	Variable
	Speed	≥56.8	>55.1-56.8	>51.7-55.7	>45.6-51.7	>30.9-45.6	<30.9
Present study	***Flow Rate***	≤16	>16-29	>29-47	>47-63	>63-78	Variable
	Speed	≥64.1	>58.5-64.1	>52.8-58.5	>49.9-52.8	>41.6-49.9	≤41.6

The speed variability captured in the present study for different LOS ranges were quite different in comparison to the Indo-HCM study (refer Table 7.11).

In order to calculate the QN-LOS, the following flow chart (Figure 7.3) can be used.

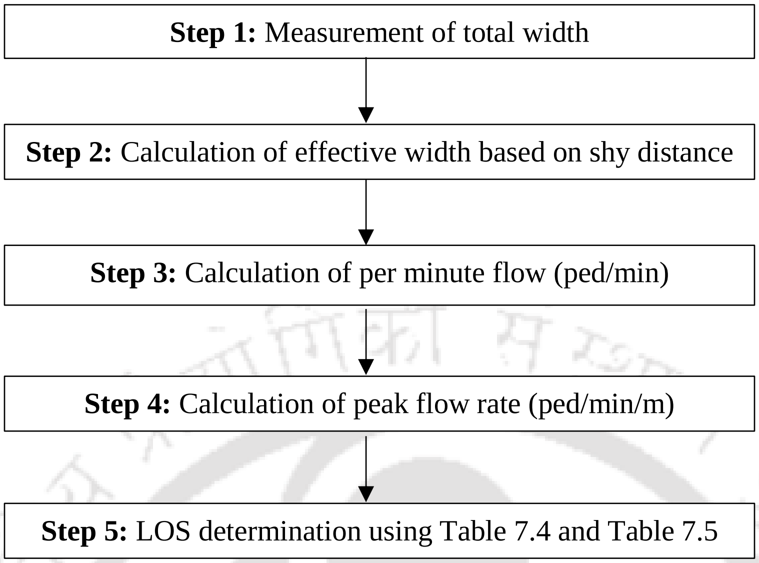


Figure 7.3. Flow chart for quantitative LOS calculation

7.4. Concluding remarks

In this chapter, the quantitative LOS (QN-LOS) and qualitative LOS (QL-LOS) were developed for elevated walkways (fourteen FOB locations and seven skywalk locations) across five different cities. The statistical tests (t-test and Mann Whitney U-test) were used to compare significance between the skywalk and FOB users based on videographic as well as questionnaire data. Separate quantitative LOS tables were generated for FOB and skywalk facilities using flow rate and speed data. A common qualitative LOS table was generated for FOB and skywalk based on score developed for seven qualitative factors (width, surface, connectivity, safety and security, comfort, walk environment, and obstruction). Finally a comparative table (QN-LOS and QL-LOS) was developed which could compare between the levels of service for each location. The next and final chapter discusses about the major findings and conclusions of the present study.

CHAPTER 8

CONCLUSIONS

8.1. General

In a developing country like India, where pedestrian facilities are highly neglected, the research conducted in the present study tried to identify the pedestrian behaviour over mid-block and vertical connectivity (stairway) sections for elevated walkways (FOB and skywalks). In this work, videographic and questionnaire survey data from 17 Foot Over Bridge (FOB) and 7 skywalk locations were collected, extracted, analyzed and modelled. The review of literature suggested that different factors (microscopic, macroscopic and geometric) influenced the walking behaviour (i.e., walking speed) of pedestrians. The microscopic factors such as individual behaviour characteristics (age, gender, luggage condition, use of mobiles, direction of movement and disability) and group behaviour characteristics (groups size, lane formation, leader-follower relationship, squeezing effect, faster-is-slower effect, overtaking, and lane shifting) influenced the walking speed. Similarly, different macroscopic factors (such average flow and average density) and geometric factors (such as obstruction, land use type, time of data collection, length of facility, connectivity, and effective width) also highly influenced the pedestrian walking behaviour over mid-block and stairways sections of elevated walkways.

In the present study initial statistical tests revealed that significant difference existed between pedestrian behaviour (i.e. free flow speed) on mid-block section as well as stairway sections of both FOB and skywalk facilities. Therefore, data analysis for both the elevated facilities were conducted separately. In order to achieve the objective of the present study (i.e., study of pedestrian movement behaviour over elevated walkways), the following analysis were carried out over mid-block and stairway sections of FOBs and skywalks:

- Study of behavioural characteristics of pedestrians over mid-block sections through perception survey, empirical data analysis and modelling.
- Study of behavioural characteristics over vertical connectivity (stairways) sections through empirical data analysis and modelling.
- Study of perception of pedestrians' towards the usability of elevated facilities.

- Development of level of service (LOS) standards for elevated facilities.

This chapter presents the major findings, research contributions, applications of this study, recommendations for improving future usability of elevated walkways and limitations of the study along with the scope for further research work.

8.2. Major research findings

This section presents the major research findings of this study as per Figure 8.1.

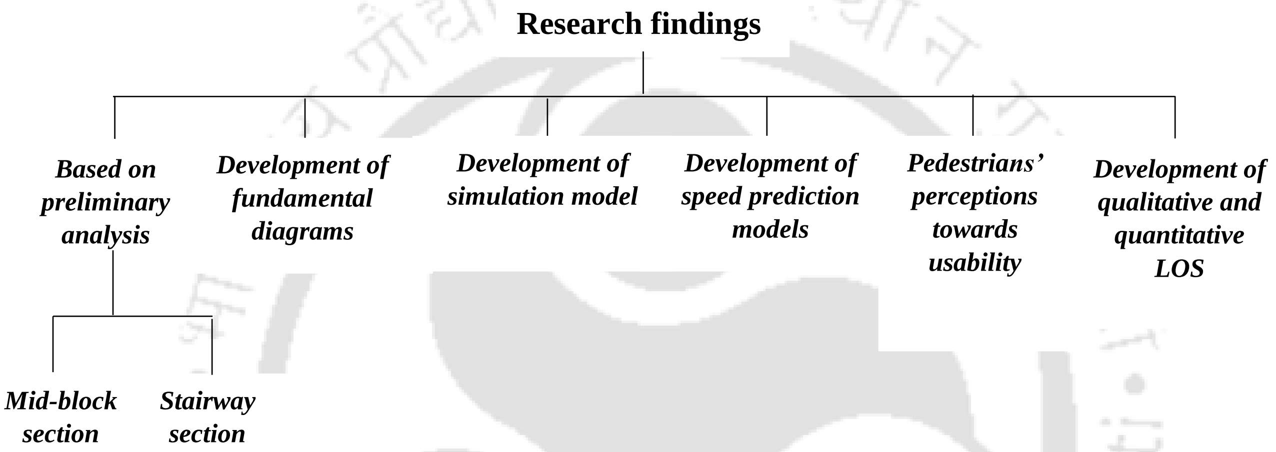


Figure 8.1. Major research findings

8.2.1. Based on preliminary data analysis

8.2.1.1. Mid-block sections of FOB

- The mean effective width and length across all FOB locations were 2m and 41.7m respectively.
- Mean speed over all FOBs were observed as 71.31m/min, with standard deviation as 13.17 and speed range between 24.59 - 116.52 m/min.
- Except two FOBs (F1 & F16), use of these facilities were dominated by male pedestrians (~70%). Female pedestrian speeds were lower than the male pedestrians by ~7m/min.
- Approximately equal proportion (48:52) of pedestrians with and without luggage were observed across all locations except locations F9 and F16, where ~75% of pedestrians were carrying luggage. No significant difference were observed between the speed of pedestrians with and without luggage.

- Maximum utilization (63%) of FOB facilities were done by young adult pedestrians (age 21-40 years) followed by pedestrian in the age group of 41-60 years (22%). The average walking speed of young adult pedestrians (age: 11-40 years) were observed to be ~74m/min, while the mean walking speed of child pedestrians (age ≤10 years) and elderly pedestrians (age ≥60 years) was 62m/min across all locations.
- On an average 8% pedestrians were using their mobile phones while walking across different locations (except F16 where mobile user proportion was 14%). The mean walking speed of the mobile phone users was 68m/min in comparison to non-mobile users' speed of 71m/min.
- Across different sections, the composition of group size of single, two and three pedestrian walking together were 80%, 15.5% and 4% respectively. In the case of F4 location (with majority proportion being students), the group size of two (~32%) or three (~13%) pedestrians was quite high. The reduction in average walking speed for pedestrians walking alone in comparison to walking in pair was significant (~6m/min).

8.2.1.2. Mid-block sections of skywalk

- The average width and length of mid-block sections across all the skywalks were observed as 2.7m and 600m respectively.
- The mean pedestrian speed over skywalks was 78.95m/min, with standard deviation of speeds as 13.00 and range as 25.64 - 114.90m/min.
- Male pedestrians (~77%) dominated the female proportion in skywalk use, and were walking with 6m/min higher speed in comparison to females.
- Similar to FOB users, the young adults (of age group of 21-40 years) were the major users (65%) of skywalk followed by the pedestrian with age group 41-60 years (18.7%) and 11-20 years (11.0%). As expected, the highest walking speed (80.65m/min) was observed for young-adult pedestrians of age group 21-40 years.
- Higher proportion of pedestrians (66.4%) were carrying luggage. This proportion was very high (>85%) for locations S1 and S3. Significant speed reduction of 4m/min was observed in case of pedestrians with luggage.
- The average proportion of mobile users were ~15% on skywalks, which was higher than FOBs. Mobile users were relatively higher (>21%) at locations S2 and S5. Similar to FOB,

an average speed reduction of 3m/min was observed due to mobile phone use while walking on skywalks.

- Across all the skywalks, it was observed that majority of the pedestrians were walking alone, except at skywalk S7 where 39% pedestrians were observed to walk in groups of 2 or 3 pedestrians. Higher percentage of pedestrians walking in groups of 4 or more was observed at locations S4 (5.9%) and S5 (4.4%). The speed of pedestrians walking in the group (size ≥3) reduced up to 13m/min in comparison to a pedestrian walking alone.

8.2.1.3. Stairway sections of FOB

- The mean effective width, riser and tread dimensions across different stairway sections were 1.75m, 0.13cm and 0.29cm respectively.
- The proportion of male pedestrians (70%) were significantly higher than female pedestrians in both (ascending and descending) directions of the stairways. Speed difference between male and female pedestrians was ~3m/min in both the directions.
- Across all locations, ~60% pedestrians were in the young-adult age group (21-40 years). Highest average mean speed (33.7m/min ascending and 37.7m/min descending) were observed for pedestrians with age 11-20 years among all age categories moving in both the directions. The child (≤10 years) and elderly (≥60 years) pedestrians had similar speed distributions with average speed ~24 m/min (ascending) and ~27m/min (descending).
- The proportion of pedestrians with luggage was 42-44% (both in ascending and descending direction). The speed difference between ascending and descending pedestrians with and without luggage was 5-6m/min.
- The pedestrians without mobile phones had higher walking speed of 6m/min in both directions (ascending and descending) than pedestrians using mobile phones.
- A pedestrian moving alone had a mean walking speed of 30.5m/min (ascending) and 36.5m/min (descending) on stairways of FOBs. Walking speed reduced to 26.6m/min (ascending) and 30.9m/min (descending) if the group size became ≥3.

8.2.1.4. Stairway sections of skywalk

- The mean effective width, riser and tread dimensions across different stairway sections of skywalks were 1.48m, 0.16cm and 0.30cm respectively.

- The male pedestrians had a higher mean walking speed than female pedestrians while both ascending (by 2-6m/min) and descending (by 2-4m/min). The walking speeds of male pedestrians in ascending and descending directions of stairways were 31.42m/min and 37.92m/min respectively. Young adult pedestrian group (21-40 years) were in majority and had the highest speed among all other age groups (30.3m/min ascending and 36.8m/min descending).
- The proportion of pedestrians with luggage was ~60% in both the directions. These luggage laden pedestrians' walking speed reduced by 3m/min.
- On ascending stairs, the pedestrians using mobiles had a median speed of 27.66m/min in comparison to the median speed of 31.92m/min for pedestrian without mobile use.
- Pedestrian moving alone was dominant across all locations and had a median walking speeds of 31.28m/min (ascending) and 37.58m/min (descending).

8.2.2. Development of fundamental diagrams (FDs)

The fundamental diagrams for the mid-block sections and stairways sections of FOBs and skywalks were plotted to have an overall estimate about the FFS, predicted jam density, maximum flow rate, optimum density and speed at maximum flow rate, and area module. Table 8.1 shows the different macroscopic parameters for the overall facilities combined.

Table 8.1. Pedestrian flow characteristics for different FOB and skywalk sections

Section	Facility	FFS (m/min)	Jam density (ped/m^2)	Max. flow rate (ped/min/m)	Optimum density (ped/m^2)	Optimum speed (m/min)	Area module (m^2/ped)
Mid-block	*FOB*	76.96	4.38	84	2.11	41.2	0.48
	Skywalk	83.13	6.62	138	3.35	42.1	0.29
Stairway	*FOB*	34.24	3.55	43	2.05	19.3	0.36
	Skywalk	38.61	5.99	58	3.04	19.4	0.35

In case of mid-block sections, the maximum flow rate (138ped/min/m) was observed to be higher for skywalk facilities at an optimum density of 3.35ped/m^2 and optimum speed of 42.1m/min. Among stairway sections, higher maximum flow rate (58ped/min/m) was observed in skywalk stairways in comparison to FOB stairways at optimum speed and density of 3.04ped/m^2 and 19.4m/min.

8.2.3. Development of simulation model for elevated walkways

The visible similarities (i.e. purpose of segregating pedestrian traffic from vehicular traffic, enhancing comfort and safety; geometric design standards, effect of vertical connectivity and lack of security on the pedestrian psychology) between the two types of elevated facilities (FOBs and skywalks) encouraged in developing a common global simulation model which could represent the walking behaviour of pedestrians over any elevated walkway. The global model was developed which included creation of a simulation model using the geometry of the elevated walkway, feeding the pedestrian types as per extracted data, carrying out sensitive analysis of the different parameters, calibrating the model using genetic algorithm through COM interface in MATLAB, and validating with the new data set. The parameters Tau, ASocIso, BSocIso, ASocMean and VD were found to be the most sensitive parameters and the calibrated values of the parameters are given in Table 8.2.

Table 8.2. Calibrated global parameters for elevated walkways

ASocIsoTropic	BSocIsoTropic	ASocMean	Tau	VD
0.4833	0.12264	0.1043	0.3	0.6427

Using the calibrated parameters, validation was conducted for different locations and the MAPE was found to be less than 20% across all locations, and as per Lewis scale of interpretation the global model performed well.

8.2.4. Development of speed prediction models using microscopic pedestrian behaviour parameters

An attempt was made to understand the impact of different individual (age, gender, luggage carrying conditions, mobile use and disability) and group (group size, lane formation, leader-follower relationship, lane shifting, overtaking, squeezing effect and faster-is-slower effect) behavioural characteristics on the walking speed of the pedestrians over mid-block and stairway sections of elevated facilities. Based on statistical tests, significant difference was observed for mid-block sections of FOB and skywalk facilities, and thus two separate models were created. On the other hand, as insignificant difference was observed between ascending direction (FOB and skywalk) and descending direction (FOB and skywalk), thus two separate models were constructed for ascending and descending directions of FOBs and skywalks combined. The final models were validated and the obtained MAPE and RMSE showed that all the models performed well.

8.2.5. Development of speed prediction models using macroscopic pedestrian behaviour parameters

In order to predict the walking speed of pedestrians over elevated walkways, different tree-based machine learning algorithms (Gradient boosting regressor, Light gradient boosting machine regressor, Extreme gradient boost, Adaboost regressor, Random forest, Extra trees regressor and Decision tree) were used based on different pedestrian flow characteristics (microscopic and macroscopic) along with geometric parameters. Two separate models were created with 80% training data for FOB and skywalk each. 10-fold cross validation was conducted and Light GBM algorithm (for FOB) and Gradient boosting regressor algorithm (for skywalk) performed best with MAE of 9.52 and 9.23 respectively. Table 8.3 shows the optimized model parameters.

Table 8.3. Optimized model parameters

Facility	**Modelling approach**	**Model hyper parameter**
FOB	Light GBM Regressor	num_leaves: 20, max_depth: 20, learning_rate: 0.1, n_estimators: 90, min_split_gain: 0.2, reg_alpha: 0.1, reg_lambda: 0.1
Skywalk	Gradient Boosting Regressor	loss: huber, n_estimators: 175, learning_rate: 0.01, subsample: 0.3, criterion: friedman_mse, min_samples_split: 10, min_samples_leaf: 1, max_depth: 10, max_features: auto

The model performance for FOBs and skywalks were tested separately on 20% unseen data sets. The performance summary revealed that the overall optimized LGBM speed prediction model (*based on MAE: 9.96*) for FOB and GBM speed prediction model (*based on MAE: 9.27*) for skywalk performed well on the unseen data sets.

Variable importance plots were made based on LGBM (for FOB) and GBM (for skywalk) to identify the top variables which were important for speed prediction using macroscopic parameters over elevated walkways. Table 8.4 shows the most significant factors in descending order of relative importance.

Table 8.4. Feature importance for elevated walkway speed prediction

Facility	Feature importance
FOB	Total length of facility, average density, average flow rate, facility height and mid-block width
Skywalk	Average flow rate, average density, gender, total length of facility, and age

8.2.6. Pedestrians' perception towards usability of elevated walkways of FOBs and skywalks

In order to identify the significant factors impacting the pedestrians' perception towards choosing the elevated walkways, perception models were developed for skywalk usage and FOB usage.

8.2.6.1. Factors impacting skywalk usage

A forward stepwise binary logistic regression model was developed to identify the most significant factors which impacted the usability of skywalk facilities based on the perception of pedestrians. A total of 350 respondent samples from seven skywalk locations were used. The result from the forward stepwise model showed that factors such as width, safety and security, walk environment and age had positive coefficient values which meant that improving these factors would enhance the probability of pedestrians using the skywalk facilities. The future response from the pedestrians also revealed that the installation of elevator/ escalator/ ramp, improvement of security, removal of obstructions and regular maintenance could strongly govern the future usability of elevated skywalk facilities.

8.2.6.2. Factors impacting FOB usage

Whereas previous studies focused on a single context (for example, safety and security), in the study related to FOB facilities, an attempt was made to estimate the relative importance of different parameters from four different users' perspectives (such as mobility friction, safety and security, vertical end connectivity and horizontal end connectivity) together using advanced machine learning tools (GLM: Generalized linear model, RF: Random forest and GBM: Gradient boosting machines). In total 552 respondent samples were used for 14 different FOB locations. Results showed that GBM outperformed the other models (on the basis of f_{beta} measure: 0.61-0.97). Moreover, on the basis of variable importance it was observed that the top factors (based on relative importance) which influenced the pedestrians' perception towards using FOB facilities were:

- ***Mobility friction:*** stair width and daily frequency.
- ***Safety & security:*** walk environment and gender.
- ***Vertical connectivity:*** number of steps and location type.
- ***Horizontal connectivity:*** length and comfort.

8.2.7. Development of Quantitative (QN) and Qualitative (QL) LOS

8.2.7.1. Quantitative LOS for FOB and Skywalk (QN-LOS)

To define the QN-LOS for elevated walkways, an initial t-test was conducted for the similar pedestrian category (male, age group 20-40 years and without luggage) and results revealed that significant difference existed between the two elevated walkway facilities (FOB and skywalk). Thereafter, based on the observed field data, two separate quantitative LOS tables (Table 8.5 and Table 8.6 for FOB and skywalk facilities respectively) were developed based on flow rate and speed. It was observed that for majority of the elevated walkways, the quantitative LOS ranged between B and C LOS categories.

Table 8.5. Quantitative-LOS (QN-LOS) table for FOB

LOS	**Flow rate (ped/min/m)**	**Speed (m/min)**
A	≤16	≥64.1
B	>16-29	>58.5-64.1
C	>29-47	>52.8-58.5
D	>47-63	>49.9-52.8
E	>63-78	>41.6-49.9
F	Variable	≤41.6

Table 8.6. Quantitative-LOS (QL-LOS) table for skywalk

LOS	**Flow rate (ped/min/m)**	**Speed (m/min)**
A	≤23	≥73.4
B	>23-43	>65.6-73.4
C	>43-68	>59.5-65.6
D	>68-92	>53.5-59.5
E	>92-118	>47.4-53.5
F	Variable	≤47.4

8.2.7.2. Qualitative LOS for FOB and Skywalk (QL-LOS)

For defining QL-LOS for FOB and skywalk facilities, the satisfaction ratings (based on Likert scale) for seven factors (width, surface, connectivity, obstruction, safety-security, comfort and walk environment) were obtained from the questionnaire survey while the weightage for each factor was obtained from previous literature. Mann-Whitney U test was conducted for the two data sets of FOB and skywalk questionnaire data to check the descriptive statistics along with the significance between the seven factors used. Based on the final minimum and maximum score which could be obtained, six level of service ranges were defined (as shown in Table 8.7). It was observed that the qualitative LOS for majority of the elevated walkways lied between LOS B and C categories.

Table 8.7. Qualitative-LOS (QL-LOS) table for elevated walkways

LOS	QL-Score
A	≥13.00
B	>10.57-13.00
C	>8.14-10.57
D	>5.71-8.14
E	>3.26-5.71
F	≤3.26

A final pedestrian PLOS equation was also developed for calculating the worse of the two LOS (quantitative and qualitative) conditions and thus redesigning the existing elevated walkways. A comparison based on PLOS ranges was also made with the existing quantitative LOS defined by Indo-HCM 2018.

8.2.8. Development of semi-manual technique for data extraction technique for studying gap maintaining behaviour of pedestrians

A novel method of semi-manual data extraction technique was developed for pedestrian position (subsequently speed and trajectory) data using front inclined camera angle as many times top-down angle is unavailable due to height restrictions. Vanishing point method was used to extract data for pedestrian body dimensions across vertical and pedestrian-specific trajectory planes.

Using the trajectory and body dimension information, the spacing maintained between the pedestrians were estimated. Subsequently, JUPedSim software was used for extracting the fundamental macroscopic properties (speed, flow and density) from the pedestrian position data, and the results were compared using classical and voronoi approaches.

The developed technique was able to extract the pedestrian trajectories with an error (standard deviation) of 0.039m at the exit section and 0.11m at the entry section. The average lateral, longitudinal and diagonal clearances maintained by a pedestrian to walk comfortably were observed as 0.25m, 0.90m and 1.07m respectively. The comparison study for voronoi vs classical approach showed that voronoi approach had lower fluctuations in estimation of macroscopic parameters.

8.3. Research contributions of this study

The major contributions of the present study over elevated walkway facilities are follows:

- The present study provided a detailed understanding about the existing walking speed over mid-block and vertical connectivity (stairway) sections on elevated walkways (FOBs and skywalks) across six different cities.
- Development of fundamental diagrams for mid-block and stairway sections of elevated walkways.
- Development of a global simulation model using Viswalk for better understanding of the walking behaviour of pedestrians over elevated walkways.
- Identification of individual behaviour characteristics (such as age, gender, luggage, mobile use, disability) and group behaviour characteristics (such as group size, lane formation, leader-follower relationship, lane shifting, overtaking, squeezing effect and faster-is-slower effect) and studying their impact on the walking speed of pedestrians for mid-block sections and vertical connectivity sections of elevated walkways.
- Development of walking speed prediction model of pedestrians over elevated walkways using microscopic and macroscopic pedestrian behaviour parameters along with geometric dimensions using linear regression model and tree based modelling approaches.

- Development of perception based usability models based on regression analysis as well as advanced machine learning tools to predict the preference of users in choosing the elevated walkways.
- Development of quantitative and qualitative LOS for elevated walkways.
- Development and implementation of a semi-manual data extraction technique for elevated walkways using frontal camera angle and thus identifying the different clearances (lateral, longitudinal and diagonal) maintained by the pedestrians.

8.4. Applications of the study

The outcomes of this research could be used to improve the existing users' experience (by improving the existing facilities or constructing better elevated facilities in the future), that could encourage them to use the facility more often as well as attract new pedestrians to use elevated walkways. To achieve these goals, it is also essential to make the facilities more attractive and friendly to the users, which provides them a safe and comfortable travelling experience. By attracting new pedestrians and enabling existing users to use the facility continuously, might indirectly reduce at-grade road crossing risk. Some major applications of the current research work are:

- Developed fundamental diagrams would provide guidelines for predicted capacity estimation over elevated walkways (both for mid-block sections as well as stairway sections).
- Identifying individual and group behaviour characteristics would be beneficial in understanding the movement of pedestrians over elevated walkways as well as incorporating such behaviour into microscopic simulation models.
- The prediction of walking speeds would help designers and planners understand the primary factors affecting the walking speed and thus constructing better elevated walkways.
- Perception usability models would help in understanding the qualitative factors impacting the pedestrians' choice in using the elevated walkways.
- Quantitative (QN) and qualitative (QL) LOS development would provide proper guidelines for estimation of LOS over elevated facilities.

- Global simulated model and the estimated calibrated parameters could be useful to researchers who plan to study microscopic behaviour over elevated walkways using Viswalk software.
- The development of semi-manual technique could be helpful in studying pedestrian gap maintaining behaviour and also establishment of different threshold levels for the crowd management where data collection using top down video is not possible, and only frontal camera angle view is available. Such approach can directly be applied to CCTV footage (which mostly gives front inclined views of camera) to ensure the physical distancing in the current ongoing pandemic COVID-19. Further, the proposed approach can made automated using the image processing tools for different applications like determination of pedestrian stream characteristics, level of services, safety evaluation and ensuring physical distancing.

8.5. Recommendations for better planning, designing and operation of elevated walkway facilities

Based on the geometric considerations and field survey, the current study proposes the following recommendations for better usability of elevated walkways across different Indian cities:

- Provision of ramp-like stairways (with minimum width of 2m and riser height of 2cm) instead of stairways (if the space permits), with prohibition of motorized two wheelers and cycles on the ramps.
- In case of normal stairways, a rise ≤ 0.15m and tread ≥ 0.29m, with inclination angle $\leq 26°$ is suitable for comfortable walking.
- Provision of escalator or elevator for elderly, differently abled, and child pedestrians.
- Provision of proper safety and security measures in the form of CCTV cameras and security personnel or both.
- Regular maintenance (of lighting and surface), and cleaning.
- Provision of shade and proper guardrails.
- Prohibition of vendors and standing pedestrians on the elevated facilities.
- Prohibition of advertisement boards (which blocks the pedestrian view) on the sides of the mid-block sections of elevated walkways to improve safety.

8.6. Limitations of the study

While the results of the present study are promising, yet the research work has its own limitations. The major limitations of the research work are:

- The response rate and language diversity (in case of questionnaire survey)
- The duration of data collection (i.e., restricted to a single day for approximately 3 hours per location).
- The collected field data from different FOBs and skywalks are mostly limited to LOS B and C which impact the accuracy of the developed speed-flow relationship.

8.7. Scope for further research work

Some of the related research works which can be attempted in the future are:

- Considering the broader population and covering more types of locations (e.g., institutional and recreational areas) across other Indian cities under different climatic conditions.
- Studies can be carried out by comparing both at-grade and grade-separated pedestrian facilities (FOBs or subways), considering both questionnaire and videographic surveying techniques.
- Comparative study between vertical connectivity (stairways) of mechanized and non-mechanized elevated walkways.
- Development of LOS standards for vertical connectivity (stairways) for FOB and skywalk facilities.
- More in-depth analysis into the group behaviour characteristics can be done which can be used for microscopic model development.

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Annexure I

INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI

CIVIL ENGINEERING DEPARTMENT

Interviewer-Administered Pedestrian Questionnaire Survey

The survey is being conducted in order to understand the perception of pedestrians towards using the **ELEVATED PEDESTRIAN FACILITY (FOOT OVER BRIDGE/ SKYWALK)** and thus estimate the Qualitative Level of Service of the facility.

Part A: Demographic characteristics

1. **Gender:** *0: Female/ 1: Male*
2. **Age:** *0: ≤10/ 1: 11-20/ 2: 21-40/ 3: 41-60/ 4: ≥60*
3. **Luggage:** *0: With/ 1: Without*
4. **Person with disability:** *0: With/ 1: Without*
5. **Profession:** *0: Businessman/ 1: Homemaker/ 2. Retired/ 3: Self-employed/ 4: Service/ 5: Student: 6: Others*
6. **Purpose of trip:** *0: Work/ 1: Education/ 2: Shopping/ 3: Change of mode/ 4. Returning home/ 5. Jaywalking/ 6. Others:*
7. **Frequency of daily use:** *0: First time/ 1: Occasionally/ 2: Once/ 3: Twice/ 4: More than twice*

Part B: Current existing conditions

Parameter	**Perception rating**				
		Evaluation of Physical factors			
Width	*1: Very Poor*	*2: Poor*	*3: Satisfactory*	*4: Good*	*5: Very Good*
Surface	*1: Very Poor*	*2: Poor*	*3: Satisfactory*	*4: Good*	*5: Very Good*
Obstruction	*1: Many*	*2: Some*	*3: None*	*Type:*	
		Evaluation of User factors			
Connectivity	*1: Very Poor*	*2: Poor*	*3: Satisfactory*	*4: Good*	*5: Very Good*
Safety and security	*1: Very Poor*	*2: Poor*	*3: Satisfactory*	*4: Good*	*5: Very Good*
Comfort	*1: Very Poor*	*2: Poor*	*3: Satisfactory*	*4: Good*	*5: Very Good*
Walk environment	*1: Very Poor*	*2: Poor*	*3: Satisfactory*	*4: Good*	*5: Very Good*

Part C: Preference of use

Preference of using elevated walkway under existing conditions *(0: Do not prefer, 1: Prefer)*

Part D: Future usability dependents

Sl. No.	Factor	Improvement required	
1.	**Obstruction removal or relocation**	*0: No*	*1: Yes*
2.	**CCTV installation and security personnel deployment**	*0: No*	*1: Yes*
3.	**Vertical end connectivity** *(lift/ escalator/ ramp)* **installation and maintenance**	*0: No*	*1: Yes*
4.	**Horizontal end connectivity improvement**	*0: No*	*1: Yes*
5.	**Regular maintenance and cleanliness**	*0: No*	*1: Yes*
6.	**Redesigning of facility**	*0: No*	*1: Yes*

Part E: Field observations

1. **Length of the elevated walkway** (*in meter*):
2. **Walkable width of the walkway** (*in meter*):
3. **Number of steps**:
4. **Stairway width** (*in meter*):
5. **Tread dimension** (*in centimeter*):
6. **Riser dimension** (*in centimeter*):
7. **Land use type** (*0: Commercial, 1: Residential, 2: Public Transport Terminal, 3: Educational, 4: Shopping*):
8. **Type of facility for vertical movement** (*0:Stairway, 1: Escalator, 2: Lift, 3: Ramp*):
9. **Number of entry-exit points**:

End Note:

- **Width** (available effective walkable width over the midblock and stairway sections)
- **Surface** (in terms of broken/ slippery tiles or well-maintained surface)
- **Connectivity** (in form of entry/ exits along with type of vertical connectivity available)
- **Safety and security** (in terms of CCTV cameras and security personnel)
- **Comfort** (in form of lighting, shade, proper guard rails, sitting benches and drinking water availability)
- **Walk environment** (surrounding existing conditions in form of maintenance and cleanliness)
- **Obstruction** (in form of hawkers, beggars and standing pedestrians)

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Journal Publications

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