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Analysis and Modeling of Pedestrian Walking Behaviors Involving Individuals with Disabilities

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ANALYSIS AND MODELING OF PEDESTRIAN WALKING BEHAVIORS

INVOLVING INDIVIDUALS WITH DISABILITIES

by

Mohammad Sadra Sharifi

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ABSTRACT

Analysis and Modeling of Pedestrian Walking Behaviors Involving Individuals with Disabilities

by

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Utah State University, 2016

Major Professor: Dr. Anthony Chen
Department: Civil and Environmental Engineering

The objective of this dissertation was to study walking behaviors of pedestrian groups involving individuals with disabilities. To this end, large scale controlled walking experiments were conducted at Utah State University (USU) to examine walking behaviors in various walking facility types, such as passageway, right angle, oblique angle, queuing area, bottleneck, and stairs. Walking experiments were conducted over four days involving participants with and without disabilities. Automated video identification and semi-structured questionnaires were used to collect revealed and stated walking data. This study provided statistical analysis and models to study three different aspects of operational walking behaviors.

Firstly, walking speed was examined as one of the most important behavioral variables. The differences in crowd walking speeds were carefully noted in analyzing the effects of adding individuals with disabilities and the impacts of different indoor walking facilities. Results showed that the presence of individuals with disabilities in a crowd significantly reduces the overall crowd speed. Statistical analysis also provided to compare walking speeds of pedestrian groups involving individuals with disabilities in different walking environments.

Secondly, the dissertation proposed a framework to study the interactions of different pedestrian groups. Specifically, a mixed time headway distribution model was used to examine the time headway between followers and different leader types. In addition, the implications of interaction behaviors were studied based on the capacity of the queuing area behind the doorway. Results revealed that: (1) individuals with disabilities had significant effects on capacity reduction; (2) individuals with visual impairments and non-motorized ambulatory devices had the minimum capacity reduction effects in queuing area; and (2) individuals with motorized wheelchairs and individuals with mobility canes had the maximum capacity reduction effects in queuing area.

Lastly, this study explored how a heterogeneous mix of pedestrians (including individuals with disabilities) perceive and evaluate operational performance of walking facilities. Both trajectory and survey data sources were used, and an ordered statistical approach was applied to analyze pedestrian perceptions. Results indicated that individuals with disabilities were less tolerant of extreme congested environments. Furthermore, analysis showed that the Level of Service (LOS) criteria provided in HCM does not follow the actual perceptions.

(175 pages)

PUBLIC ABSTRACT

Analysis and Modeling of Pedestrian Walking Behaviors Involving Individuals with Disabilities

Mohammad Sadra Sharifi

Walking facilities like walkways and stairs are important infrastructures which must be designed to effectively accommodate the behavior of pedestrians. Heterogeneity in pedestrian composition is one important factor generally overlooked in walking facility design guidelines and handbooks. While individuals with disabilities constitute a significant portion of the population in the United States, they are often overlooked due to lack of available data. To remedy this, large scale controlled walking experiments were performed at Utah State University (USU) to study the walking behavior of various types of individuals with disabilities (including vision and mobility impairments) in different walking environments. These environments included passageways with different types of angles (right and oblique) and bottlenecks. 202 participants (180 without disabilities and 42 with disabilities) were recruited for the circuit experiments and 100 participants (80 without disabilities and 20 with disabilities) were recruited for the stair experiments. Automated video identification, tracking technology, and survey methods were used to record reveled and stated data. The objective of this dissertation is to use the collected data to:

(1) Analyze the walking speeds of different individuals with various disability types in a variety of walking environments,

(2) Explore behavioral interactions of heterogeneous pedestrian streams in the queuing area behind a doorway,

(3) Develop a framework to analyze the capacity of a queuing area involving individuals with disabilities,

(4) Propose a framework to describe pedestrian group perceptions on walkway quality of service, and

(5) Assess proposed Level of Service (LOS) thresholds provided in HCM guidelines.

The findings will contribute to the improved design of built environments by measuring and disseminating empirical data concerning the pedestrian behavior of individuals with mobility related conditions and disabilities. By improving society's understanding of the behavior of vulnerable populations, this research can help public policy professionals develop sound public policy concerning the built environment for the elderly and individuals with mobility related conditions and disabilities. Public policy professionals can make better informed decisions based on more effective, evidence-based planning and environmental design methods.

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Mohammad Sadra Sharifi

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CHAPTER 1

INTRODUCTION

1.1 General background

For most individuals, walking is a primary mode of transportation used for many purposes (e.g., going to work, going to school, recreation, etc.). In smaller scale settings such as building interiors, public transit transfer stations, or shopping malls, walking is the sole means of conveyance. Moreover, people tend to use this mode of transport for their short trips. In the United States, 50% of trips are less than three miles and about 24% of U.S. travelers reported taking at least one walking trip per day (National Household Travel Survey, 2009). A travel survey report for the city of Chicago indicates that the walking mode share was about 15% and 26% of total trips, respectively, for North Chicago and Central Chicago in 2008 (Chicago Regional Household Travel Inventory, 2010). As a result, walking demand becomes significant, especially in populated communities.

Improperly designed walking facilities may fail to operate at satisfactory levels when pedestrian demand exceeds the walkway capacity. In this situation, available space for pedestrian movement can drop drastically and there is possibility of crowd-related disasters (e.g., stampede at the Love Parade dance music festival in 2010 and stampede during the 2013 new year's firework show in Ivory Coast) (Zhang, 2012). Therefore, it is imperative that walking facilities are designed effectively to provide a safe environment with preferred level-of-service for future pedestrian demand. To design and assess walking systems, planners and design engineers need to have a good understanding of crowd behavior. Crowd walking behavior is complicated by the multi-dimensional nature of pedestrian decisions, the interactions with the built environment and other pedestrians, movements in continuous spaces, and heterogeneity in pedestrian characteristics. Given this complexity, reliable empirical studies, models, and tools are needed to effectively design and evaluate walking facility systems.

A great deal of research has been conducted to describe observed pedestrian behaviors. Based on the hierarchical nature of pedestrian decisions, pedestrian studies can be classified into three levels: strategic, tactical, and operational (Hoogendoorn et al., 2001; Daamen, 2004). At the strategic level, pedestrian decisions on activity planning (e.g., activity choice, departure time choice, etc.) are studied (Timmermans et al., 1992; Arentze and Timmermans, 2004). The tactical level includes short-term decisions of pedestrians (e.g., activity scheduling, activity location choice, route choice, etc.) (Borgers and Timmermans, 1986; Timmermans et al., 1992; Kretz et al., 2011). At the operational level, pedestrian movements and their interactions with the built environment and other pedestrians are examined (Tecknomo, 2002; Hoogendoorn et al., 2003; Daamen and Hoogendoorn, 2003; Daamen, 2004; Moussaid et al., 2009; Moussaid et al., 2010; Daamen and Hoogendoorn, 2012; Hediyeh 2012; Versluis, 2010; Duives, 2012; Gorrini et al., 2014; Dias et al., 2014). Although numerous studies have focused on pedestrian behavior, but they overlooked heterogeneity in pedestrian compositions. Specifically, individuals with disabilities are often overlooked due to a lack of available data on their pedestrian behaviors.

1.2 Research needs

To accommodate the needs of all types of pedestrians, planners and design engineers must include pedestrians as part of their analysis of the environment. The characteristics of pedestrians who use walking facilities are diverse. Therefore, walking facilities should be designed to accommodate the whole range of pedestrian types, including vulnerable pedestrian groups. Individuals affected by a disability may have different walking behavior specifications due to their walking ability constraints. Individuals with different types of disabilities represent a significant portion of the population (i.e., 16.6% of the working age population and 18.7% of the total population of the United States (U.S. Census Bureau, 2010). The Americans with Disabilities Act (ADA) (Americans with Disabilities Act, 1990) requires that all pedestrian facilities in the public right-of-way should provide equal rights for people with disabilities. Thus, it is imperative to explore walking characteristics of individuals with disabilities and consider them as a part of walking designs and assessments.

Furthermore, most existing public building design guidelines, such as those found in the Highway Capacity Manual (HCM) (Highway Capacity Manual, 2010) and the International Building Code (IBC) (International Building Code, 2012), fail to offer adequate consideration for individuals with disabilities. To account for the needs of individuals with disabilities, the Americans with Disabilities Act Accessibility Guidelines (ADAAG) (ADA accessibility guidelines for buildings and facilities, 2002) provide guidelines for the design of pedestrian facilities. This code is based only on physical properties; it does not consider the interactions between people with and without disabilities. Ultimately, conducting empirical research on the relationship between the design of the built environment and the needs of individuals with disabilities is necessary.

1.3 Research objectives and outcomes

The purpose of this study is to address the identified knowledge gap by collecting and statistically analyzing pedestrian operational walking behaviors (including individuals with different types of disabilities (e.g., sensory, physical disabilities)) through a series of large scale controlled walking experiments. Individual characteristics (e.g., age, gender, health, disability, etc.), stated behavior (e.g., walking habits, targeted behaviors, etc.), and revealed walking behavior (e.g., operational behavior, interactions with the built environment and other pedestrians, etc.) data are collected in a controlled environment using survey instruments and automated video tracking technology. The goals of this research effort are to observe and identify various exogenous factors affecting pedestrian behaviors, explore the characteristics of walking behaviors of different pedestrian groups, examine the performance of various walking environments (including level passageway, right angle, oblique angle, queuing area, bottleneck, and stairway), and assess walking design guidelines. The objectives of this study specifically include:

- Objective 1: Collecting and analyzing operational pedestrian walking behaviors with an emphasis on individuals with various types of disabilities using state-of-the-art technologies.
- Objective 2: Providing an exploratory statistical analysis to compare walking speeds of individuals with disabilities in different walking environments.

- Objective 3: Modeling time headway between different individual types in the queuing area behind a door.
- Objective 4: Analyzing pedestrian group interactions involving individuals with disabilities and identifying implications for walkway capacity estimations.
- Objective 5: Establishing a quantitative framework to describe pedestrian group perceptions on walkway quality of service and assessing proposed Level of Service (LOS) thresholds provided in HCM guidelines.

This dissertation will contribute to the design of built environments by measuring and disseminating empirical data concerning the pedestrian behavior of individuals with mobility and visual-related disabilities. The research findings will be used to assess existing pedestrian walking facility design guidelines and refine them to accommodate the pedestrian needs of a heterogeneous population, which includes individuals with disabilities. Furthermore, the data, tools, and analyses provided in this research study are expected to be helpful for the development of robust and well-characterized individual-based theories and models, which reflect the observed patterns of pedestrian behaviors of a diverse population.

1.4 Organization

This dissertation consists of seven chapters as illustrated in Fig. 1.1. Chapter 1 presents the research background, research motivation, and objectives of the study. In Chapter 2, relevant literature is reviewed. The review includes prior efforts on pedestrian walking behavior data collection, walking speed analysis, walking facility capacity analysis, and pedestrian perception level of service analysis. Chapter 3 provides a description on walking experiment setup and data collection procedures. The remainder of this dissertation constitutes the main contributions of this research. Chapter 4 presents an exploratory statistical analysis on the walking speed of pedestrians to explore similarities and differences between walking speeds of various pedestrian groups. Impacts of different walking facilities on walking speeds are also examined. In Chapter 5, a statistical model is proposed to investigate interactions between different pedestrian types in a queuing are behind a doorway. Specifically, a mixed distribution model is used to study on time headway between different pedestrian groups. The model then can be used to estimate the capacity of different walking facilities and identify the impacts of involving individuals with disabilities on capacity estimations. Chapter 6 provides a statistical model to identify and quantify the effects of individual pedestrian characteristics and their walking behaviors on walkway level of service (LOS) evaluations. Then, LOS thresholds, provided by the Highway Capacity Manual (HCM), are assessed by comparing pedestrian group perceptions. Chapter 7 summarizes the findings and provides directions for future research.

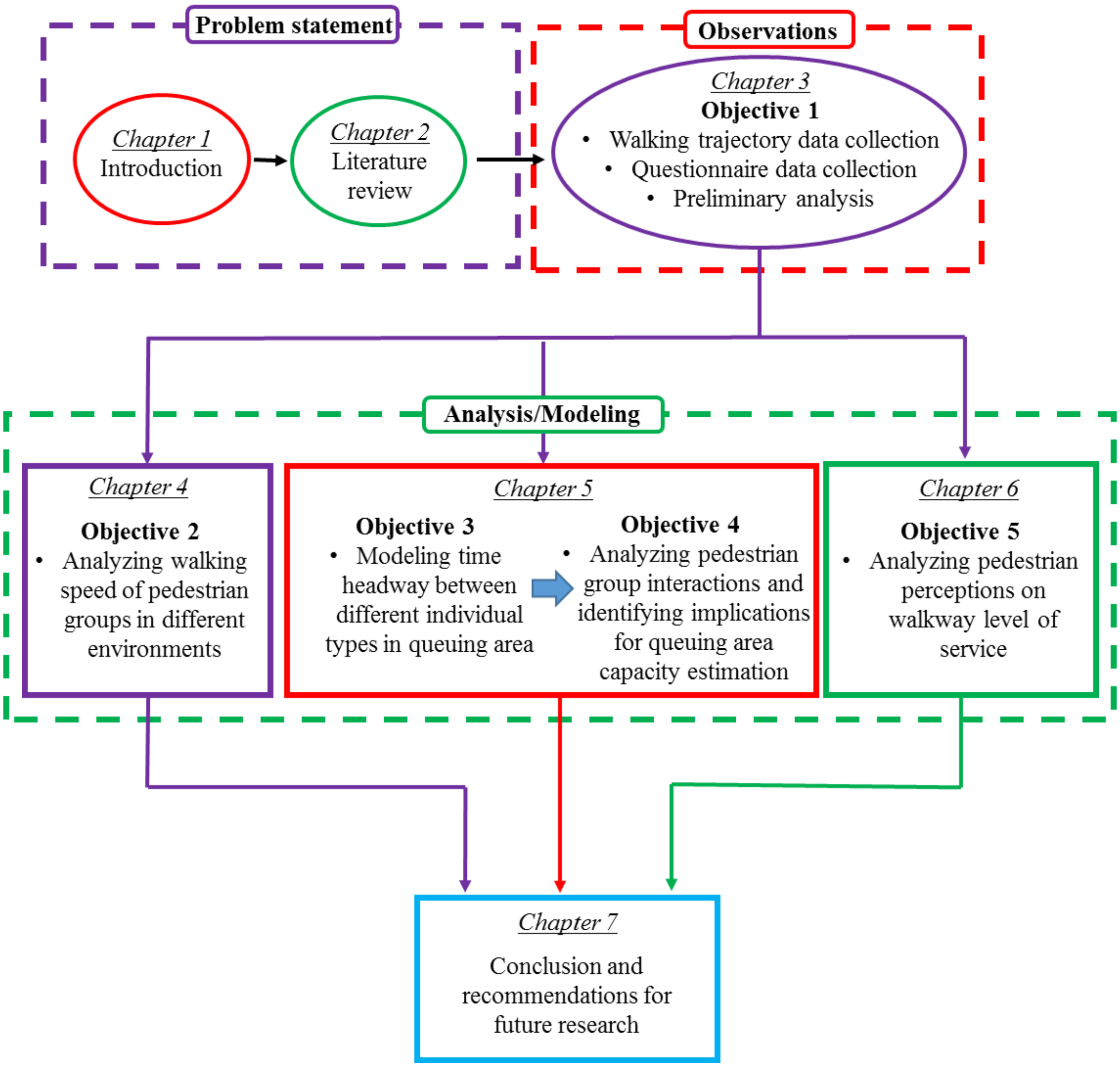

Fig. 1.1. Organization of the dissertation.

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CHAPTER 2

LITERATURE REVIEW

A great deal of research has been conducted to collect and analyze pedestrian walking behaviors. This chapter reviews relevant literature including walking trajectory data collection, walking speed analysis, and walking infrastructure capacity estimation methods.

2.1 Data collection

Initial attempts to collect walking behavior data started in 1963 through uncontrolled (e.g., on-site) observations in Germany. Oeding (1963) recorded pedestrian movement data in a commercial retail street using photographs taken from an elevated position. Five years later, Older (1968) studied bidirectional pedestrian flow characteristics by observing behavior in a commercial street in London, United Kingdom. He recorded the data using a cine camera placed on a roof top. Mori and Tsukaguchi (1987) studied unidirectional pedestrian flow in downtown Osaka City, Japan. They used a bird's eye view camera to take time-lapse photographs of commuters. Predtechenskii and Milinskii (1978) collected pedestrian data in a street in Russia using observer and photography methods simultaneously. Polous et al. (1983) collected pedestrian walking data in the central business district of Haifa, Israel, using a videotape recorder and a digital clock. Most of these studies collected walking behavior data at the macroscopic level (e.g., flow, density, platoon formation).

In recent years, advances in technologies have assisted researchers to collect more accurate data in different fields (for example see Khalilikhah et al., 2015; Khalilikhah et al., 2016, Zolghadri et al., 2013; Zolghadri et al., 2016). In pedestrian studies, Lam et al. (2002) studied pedestrian behaviors in indoor walkways in Hong Kong. They collected the data for two commercial and shopping areas during peak hours. A time-lapse photography technique was used to record walking speed and pedestrian flow data. Al-Azzawi and Reaside (2007) collected the walking data of 7,535 pedestrians in several urban business and shopping areas using video recording technology in the United Kingdom. They designed a procedure to manually extract the pedestrian movement data. Some studies made use of pedestrian traffic surveillance systems to monitor walking behaviors in dense environments such as public areas for long time periods. Ye et al. (2008) studied pedestrian flow characteristics in a metro station in Shanghai, China and obtained data for different walking facilities such as passageways and stairways (ascending and descending). They recorded pedestrian flow on weekdays during the morning and evening peak hours and manually extracted pedestrian traffic flow parameters. While these studies provided great insight on pedestrian behavior modeling, the manual data extraction approach is very labor intensive, time consuming, and not sufficiently accurate (Tecknomo, 2002; Diogenese et al., 2007; Schneider et al., 2005).

To date, only a few researchers have applied their own designed system for pedestrian data collection and walking trajectory extraction. Helbing et al. (2007) evaluated a crowd disaster in Mecca, Saudi Arabia during the Hajj pilgrimage using video recordings data. They designed a computer algorithm using digital transformation, contrast enhancement, motion prediction, and pattern recognition techniques to extract pedestrian macroscopic characteristics in a panic situation. Tecknomo (2002) developed manual, semi-manual, and automatic image processing data extraction systems and used them to study microscopic pedestrian flow characteristics. Duives et al. (2013) recorded pedestrian movements in a music festival in the Netherlands by using an octocopter equipped with a lightweight high-speed camera. Hediyeh (2010) used computer vision techniques to track pedestrian behaviors at selected intersection crossings.

The possibility of observing extremely congested situations is very low in practice. In response, some studies have conducted controllable experiments to examine pedestrian behaviors in desired environments and desired conditions. The advantage of laboratory experiments is the possibility of controlling exogenous variables (e.g., built environment configuration, flow directions) and context variables (e.g., pedestrian characteristics). While experimental approaches can provide great sources of walking data, they are generally very expensive and pedestrians' natural behaviors may be influenced by controlled conditions. Many researchers have conducted small scale walking experiments to derive pedestrian behaviors in various environments and conditions. For example, Seyfried et al. (2005) studied pedestrian movements in a wide corridor through controlled walking experiments. To set up the experiments, they built a circular corridor using chairs and ropes. 34 participants were involved in the experiments and they were required to walk along the circuit. To enable measurements at different density levels, they conducted various scenarios using different numbers of participants. A combination of manual and automatic procedures were used to collect walking data. Kretz et al. (2006) examined pedestrian counter flow characteristics in a corridor using 67 participants. They divided the participants into two groups and conducted different scenarios by varying the size of the counter group. Three cameras were used to record passing time and walking speed of participants. Wong et al. (2010) designed controlled walking experiments to study bi-directional pedestrian flows in different interacting angles including head-on (180^o), perpendicular (90^0), and oblique (45^0 and 135^0) crossings. The pedestrians were assigned into two streams (i.e., major and minor streams) and a total of 89 scenarios were conducted. Two cameras were set with an oblique angle view, and the coordinate transformation method was used to convert image coordinates to real world coordinates. Dias et al. (2014) used an experimental approach to study characteristics of walking behaviors through angled corridors. Sixteen pedestrians, including 11 males and 5 females between 26 to 33 years of age, participated in the experiments, where they were instructed to walk through the corridor at normal, high, and slow running speeds. The experiments were recorded using a digital video camera installed in an elevated location and the image sequence was obtained from the recordings. A projective transformation method was applied to convert image coordinates to ground coordinates and walking trajectories were extracted.

Only a few large scale walking experiments have been conducted to examine pedestrian behaviors in various walking facilities. For example, Daamen and Hoogendoorn (2003) conducted walking experiments at Delft University of Technology in the Netherlands to derive walking behaviors in passageways and bottlenecks under different pedestrian flow scenarios such as un-directional, bi-directional, and cross pedestrian flows. 80 participants were invited to serve as a sample for the Dutch population and ten experiments were performed to observe pedestrian walking behavior in standard, station, and shopping conditions. The experimental process was recorded using a wide lens digital camera with a resolution of 720 x 576 pixels mounted to a digital video recorder. Video data was converted to image sequences and an algorithmic approach was designed to extract walking trajectories (Hoogendoorn et al., 2003). They conducted another research experiment to investigate the capacity of doorways with explicit consideration for children, the elderly, and disabled people in the Netherlands (Daamen and Hoogendoorn, 2011). A total of 75 children (all of whom were 11years of age), 90 adults, and 50 elderly individuals participated in the experiments. Colored hats were used for different participant groups, enabling researchers to distinguish the behaviors. The experiments were recorded using digital video and infrared cameras, and the capacity of the doors was estimated manually from the video images.

Another series of large scale walking experiments were conducted in Germany to observe pedestrian behaviors in various walking environments, including corridors (Zhang, 2012; Zhang et al., 2012), bottlenecks (Seyfried et al., 2009; Seyfried et al., 2008), T-junctions (Zhang et al., 2011a; Boltes et al., 2011; Zhang et al., 2011b), and slope-inclined environments such as stairs (Burghardt et al., 2013). While these empirical studies do provide great resources for pedestrian behavior modeling, the literature review demonstrates that vulnerable groups of people, including individuals with disabilities, are generally overlooked in pedestrian-related research. The exclusion of individuals with disabilities may be partially explained by the unavailability of pedestrian trajectory data due to the difficulty of data collection. Expensive tracking technologies are required to collect sufficiently accurate walking trajectory data. Unfortunately, most of the existing studies used video recordings for their analysis, making it impossible to obtain reliable walking trajectories. Moreover, none of the studies were conducted in the United States, so it is difficult to determine how U.S. built environment regulatory standards are affecting the behavior of individuals with disabilities.

2.2 Walking speed analysis

In recent years, many researchers have extensively studied pedestrian walking behavior through controlled and uncontrolled data collection. But, a limited number of studies considered people with low mobility, including individuals with disabilities. Christensen et al. (2006) reviewed the literature on the behavior of individuals with disabilities in navigating the built environment. The review found only a few studies in this area of research. For example, Boyce et al. (1999a) determined movement capabilities of 155 individuals in different walking facilities (level surfaces, ramps, and stairs) in an emergency situation. Results were reported in four categories of disabilities: unassisted ambulant, unassisted wheelchair users, assisted ambulant and assisted wheelchair users. They also conducted two other studies to measure the ability of people with disabilities to negotiate the environment in emergency conditions (Boyce et al., 1999b; Boyce et al., 1999c). Clark-Carter et al. (1986) measured the walking speed of people with visual impairments in environments of varying complexity. Results showed that the walking speed of individuals with visual impairments is negatively affected by the increasing complexity of the travel environment. Yet, individuals with visual impairments who use guide dogs are not as affected by complex built environments as those who use long canes. Furthermore, Miyazaki et al. (2003) evaluated the behavior of 30 pedestrians and a wheelchair user. The authors found that the behavior of the pedestrians influenced the behavior of the wheelchair user and vice-versa. Moreover, pedestrian speed changed depending on the psychological condition (e.g., competitive, noncompetitive). The researchers developed a model demonstrating psychological phenomena (e.g., "group psychology") and pedestrian behavior (e.g., speed) in relation to the distance from an individual using a wheelchair. Rubadiri et al. (1997) did an experiment to estimate speed of individuals with mobility impairments in an obstacle-free route and two evacuation routes. Wright et al. (1999) examined the speed of individuals with visual impairments and compared their speed with the walking speed of individuals without disabilities. Passini et al. (1998) evaluated navigation ability of individuals with cognitive impairments. They concluded that complexity of the built environment can decrease the ability of participants to navigate the environment. Table 2.1 summarizes the studies of the behavior of vulnerable populations in the built environment.

Three conclusions can be drawn from the preceding review of the literature. First, it is unfortunate that individuals with disabilities have received so little scholarly attention. Second, the majority of the existing studies used speed of egress almost exclusively to describe the behavior of an individual with a disability in response to the built environment. This indicates a significant lack of understanding on the normal behavior of vulnerable pedestrians. This also indicates that there are few studies on the interactions of people with disabilities in crowd conditions including people without disabilities in a built environment. Thus, the question remains as to whether the individual with a disability is a constraint in the built environment or the built environment is a constraint on the individual with a disability. Third, almost none of the studies were conducted in the United States.

Generalizing the findings of existing research to apply to the United States, or any other nation for that matter, is problematic given different built environment standards and practices. Therefore, the question remains as to what extent the behavior of individuals with disabilities is affected by U.S. built environment regulatory standards.

Table 2.1
Studies of the behavior of vulnerable populations in the built environment.

Reference	Locale	Limitation condition	Par num	Dep var	Reported Results
Boyce et al. (1999a)	UK	Mobility/ Elderly	155	Speed	Various travel speeds on horizontal, ramps, corner, and stairs.
Boyce et al. (1999b)	UK	Various	113	Time to negotiate	Door closing forces negotiable by participants, and time to negotiate.
Clark-Carter et al. (1986)	UK	Visual	4	Speed	The walking speed of participants is negatively affected by the complexity of the built environment.
Miyazaki et al. (2003)	Japan	Mobility	30	Speed	The behavior of the pedestrians influence the behavior of the wheelchair user and vice-versa.
Rubadiri et al. (1997)	UK	Mobility	6	Speed	Speed of movement in an obstacle-free route and 2 evacuation routes.
Wright et al. (1999)	UK	Visual	30	Speed	Participants walk at 43-69% of typical walking speed on level routes, 70-87% on stairs
Passini et al. (1998)	Canada	Cognitive	28	Ability to negotiate	Complexity of the built environment decreases the ability of participants to navigate the environment.

Par num: Number of participants; Dep var: Dependent variable

2.3 Confirmatory review on existing regulations and guidelines

Planners generally use existing regulations and guidelines for designing and assessing public pedestrian facilities. The Highway Capacity Manual (HCM) (HCM, 2010), the International Building Code (IBC) (ICC, 2012), and the Americans with Disabilities Act Accessibility Guidelines (ADAAG, 2002) are three reference manuals generally used in the United States to design and evaluate capacities of different outdoor walking facilities (i.e. sidewalks with different geometrics) and indoor walking facilities (i.e. sizing building components). This section provides a review on these design guidelines to identify the properties of different references.

2.3.1 Highway capacity manual

The Highway Capacity Manual (HCM), published by Transportation Research Board (TRB), is extensively used for designing and assessing transportation facilities in the United States. While HCM has been viewed as a reference document in engineering analysis processes, it doesn’t constitute a legal standard for transportation facility design. Originally published in 1950, this guideline was the first manual to define and quantify the concept of capacity for different transportation facilities. (HCM, 2010). This measure assists planners, designers, and operators in evaluating the adequacy of a transportation facility's ability to meet the predicted demand. In early versions, only methodologies to evaluate capacity of roadway elements (i.e. freeway, highway, streets, etc.) were provided. However, the fourth edition was extended to enable the evaluation of different pedestrian facilities including walkways, pedestrian queuing areas (i.e. elevators, transit platforms), shared off-street paths, pedestrian crosswalks, and pedestrian facilities along urban streets.

The following macroscopic traffic flow definitions were used in the HCM for pedestrian capacity analysis (HCM, 2010):

- **Pedestrian flow rate**: Pedestrian flow rate is the number of pedestrians passing a line across the width of a walkway perpendicular to the pedestrian path per unit of time. Pedestrian flow rate can be determined for unit of effective width expressed as pedestrian per minute per meter (P/min/m).
- **Pedestrian density**: Pedestrian density is defined as the average number of pedestrians per unit of area within a walkway expressed as pedestrians per square meter (P/m^2).
- **Pedestrian space**: Pedestrian space is the inverse of density and it determines the average area provided for each pedestrian in a walkway. Space unit is expressed as square meters per pedestrians (m^2/P).

The proposed capacity analysis methods in HCM guidelines are mainly based on the relationships among macroscopic traffic flow variables (i.e. flow, density, space). These relationships can be presented using fundamental traffic flow diagrams. HCM adopts several basic research efforts on these diagrams for capacity analysis purposes. Fundamental diagrams presented in the manual are generally obtained from basic empirical studies by Fruin (1987), Older (1968), Oeding (1963), Navin and Wheeler (1969), and Pushkarev and Zupan (1975). Fig. 2.1 shows relationships between pedestrian flow and space for different populations, extracted from different empirical studies.

Generally, pedestrian flow increases with increasing pedestrian space up to a certain range of space. Then, flow rates decline because of excess space between pedestrians. HCM determines the capacity of walking facilities by specifying maximum observed pedestrian flow. Fig. 2.1 indicates that the maximum pedestrian flow (i.e. capacity) varies between 65 p/min/m to 110 p/min/m and it lies within a certain range of space from 0.4 m^2/p to 0.9 m^2/p. Although the HCM guideline provides a systematic way for capacity analysis, there is a limitation in the proposed method. HCM analyzes the capacity of walkways using macroscopic properties of pedestrian flow. It does not consider microscopic behavior of pedestrians. Therefore, it is not possible to study on the impact of heterogeneity in pedestrian compositions and behaviors on the capacity of walking facilities. Also, the fundamental diagrams provided in the guidelines are limited for straight walkways and different walking geometrics were not studied.

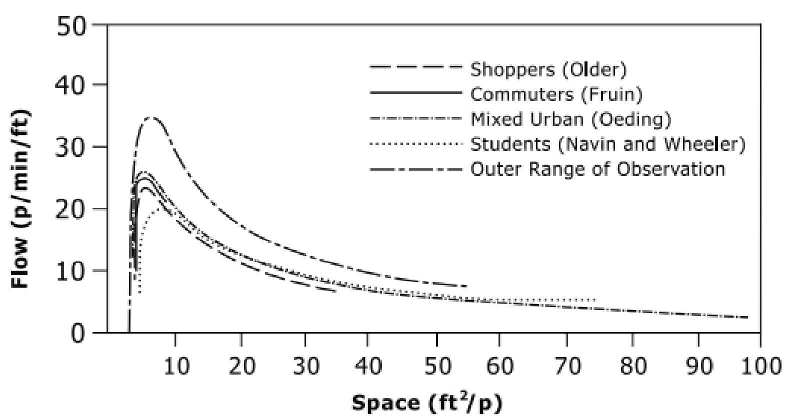

Fig. 2.1. Relationship between pedestrian flow and space for different populations (HCM, 2010).

2.3.2 International building code

The International Building Code (IBC), which is published by the International Code Council (ICC), is a standard reference addressing design and building systems requirements. This manual establishes the minimum requirements to guarantee the performance of buildings during emergency situations. The sizing requirements are mainly based on past experiences in consequence of some hazardous situations. The manual contains 35 chapters defining regulations for different building components. Chapter 10, "Means of egress," mainly focuses on designing indoor walking facilities in buildings including corridors, ramps, and stairways. This chapter defines minimum sizing for different building elements in order to provide an effective means of egress (i.e. unobstructed egress path from occupied portion of a building to a public way). The code classifies the buildings into different types, including residential buildings, business buildings, and high rise buildings, and establishes the minimum sizing with respect to building categories. For example, it requires that corridor widths should be at least 36 inches for buildings with occupant loads lower than 50. This code also determines the capacity (i.e. maximum occupant loads) for different built environments with respect to building category. For instance, it considers requirements of 100 gross floor area (GFA) for each occupant in business area. Thus, a 120,000 sq. ft. building used for business occupancy can accommodate a maximum of 1200 people. It can be found that pedestrian flow characteristics and occupant specifications were not investigated and requirements were established only based on safety considerations. Therefore, this code may either overestimate or underestimate the capacity of built environments.

2.3.3 Americans with disabilities act accessibility guidelines

While vulnerable groups of people (including individuals with disabilities) are a significant portion of the population of United States, most walking facility and building design guidelines overlook them in their design considerations. To account for the needs of individuals with disabilities in society, U.S. Congress established a federal act called "Americans with Disabilities Act (ADA)" in 1990 (ADA, 1990). This law prohibits discrimination based on disability in the United States. The Americans with Disabilities Act Accessibility Guidelines (ADAAG) is a manual containing requirements for building and walking facility designs to accommodate the needs of individuals with disabilities. This guideline includes 15 chapters containing regulations for different public environments. Chapter 4, "Accessible elements and spaces: scope and technical requirements," mainly describes sizing requirements for different building components such as corridors, ramps, stairs, etc. Fig. 2.2 presents the required sizing for a corridor to consider people with wheelchair specifications.

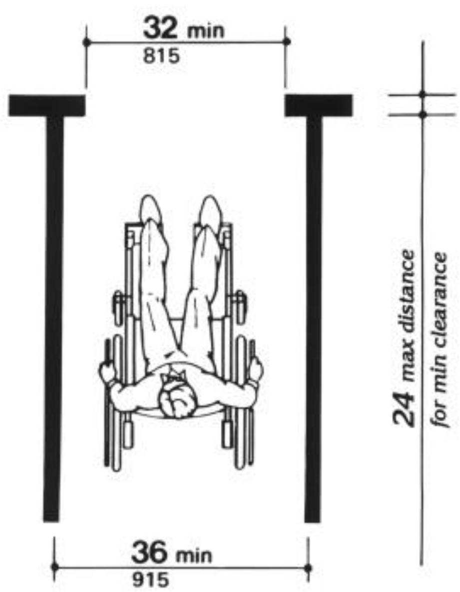

Fig. 2.2. Required sizing for a corridor considering wheelchair dimensions (ADAAG, 2002).

Although ADAAG considers vulnerable pedestrian groups in indoor walking facility design, the regulations are not able to account for interactions between people with and without disabilities. On the other hand, this guideline does not provide any systematic way to determine the capacity of different walking environments considering individuals with disabilities. Therefore, whether this regulatory standard can accommodate all walking needs of individuals with disabilities is questionable.

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CHAPTER 3

DATA COLLECTION

Abstract

It is imperative to design walking facility infrastructures to accommodate the needs of all pedestrian, including individuals with disabilities. Unfortunately, individuals with disabilities are often overlooked due to the lack of available data. The purpose of this chapter was to measure the individual pedestrian walking behaviors of individuals with disabilities through controlled video tracking experiments of heterogeneous crowds in various walking facilities; including passageways, right and oblique corners, doorways, bottlenecks, and stairs. The goal of this chapter is to provide an overview of conducting experimental research on pedestrian walking behavior involving individuals with and without disabilities, including automated video tracking methods, data collection, logistical issues, processing methods, and lessons learned from conducting a large-scale study. The findings support future large-scale experiments related to the pedestrian walking behavior of individuals with disabilities. The results can be used to calibrate and validate pedestrian traffic flow models capturing the behaviors and interactions of crowds which include different types of individuals with disabilities.

3.1 Introduction

Walking facilities are important infrastructures which must be designed to accommodate the behavior of pedestrians to be effective. Heterogeneity in pedestrian composition is one important factor generally overlooked in walking facility design guidelines. Particularly, individuals with disabilities are often overlooked due to a lack of available data on their pedestrian behaviors. Yet individuals with disabilities represent a significant portion of the population, accounting for 12.6% of the working age population (i.e., about 30.2 million) and 16.7% of the total population (i.e., about 51.5 million) of the United States (U.S. Census Bureau, 2010).

In the United States, the International Building Code (IBC) comprises the relevant health, safety, and welfare codes for the design and construction of walking facilities. However, the guidelines overlook heterogeneity in pedestrian composition. To account for the needs of individuals with disabilities, the Americans with Disabilities Act Accessibility Guidelines guide the design and construction of accessible walking facilities for individuals with disabilities. These codes grew out of civil rights policy, the ADA, and are not necessarily evidence-based practices, but were developed through a public consensus process. Whether these regulatory standards, particularly those for pedestrian environments, effectively protect the health, safety, and welfare of individuals with disabilities is not well understood and little empirical research has been conducted to evaluate the standards for individuals with disabilities' needs.

Shi et al. (2015) completed a comprehensive review of the literature and found a great deal of research has been done to collect and observe pedestrian walking behavior. Some studies involved walking experiments to examine pedestrian behaviors in specific built environments and controlled conditions such as crowd environments. For example, Daamen and Hoogendoorn (2003) conducted walking experiments in the Netherlands to derive walking behaviors in passageways and bottlenecks under different pedestrian flow scenarios such as un-directional, bi-directional, and cross pedestrian flows. Another series of large-scale walking experiments were conducted in Germany to observe pedestrian behaviors in corridors (Zhang, 2012; Zhang et al., 2012) and bottlenecks (Seyfried et al., 2008; Seyfried et al., 2009; Kretz et al., (2006)). Turning movements of pedestrians were studied in complex geometrics such as T-junctions (Zhang et al., 2011a; Boltes et al., 2011; Zhang et al., 2011; Shiwakoti et al., (2015); Shi et al., (2015)), and angled corridors (Dias et al., (2013); Dias et al., (2014); Gorrini et al., (2013); Aghabayk et al., (2015)). Moreover, crowd movements on slope-inclined environments such as stairs were examined in a study by Burghardt et al. (2013). While these empirical studies provide valuable knowledge on pedestrian needs, none of these studies addressed vulnerable pedestrians such as individuals with disabilities. The lack of research on the walking behavior of individuals with disabilities is in part due to the difficulty of data collection.

Notwithstanding, there are limited number of studies on walking behaviors of individuals with disabilities. For instance, Boyce et al. (1999a) measured egress speed of 155 individuals involving unassisted ambulant, unassisted wheelchair users, assisted ambulant and assisted wheelchair users on level surfaces, ramps, corners, and stairs. They also conducted another study to measure the ability of 113 individuals with disabilities to negotiate doors (Boyce et al., 1999 b). Kuligowski et al. (2013) conducted an experiment in a six-story building and studied the stair evacuation speed of older adults and people with mobility impairments. Wright et al. (1999) evaluated walking speed of 30 individuals with visual impairments through an egress route. Miyazaki et al. (2003) carried out a series of experiments using 30 participants and one participant with a wheelchair to describe the behavior of individuals encountering an individual using a wheelchair in a corridor with variable widths. Daamen and Hoogendoorn (2011) conducted an experiment to investigate the capacity of doorways with consideration of the elderly and people with disabilities in the Netherlands. In their experiments 75 children, 90 adults, 50 elderly individuals, 3 individuals using wheelchairs, and 3 individuals with visual impairments took part. The researchers tried to simulate different stress levels and collected behavior data using digital video and an infrared video cameras. Review of past studies demonstrates that most of studies focused on egress behavior of individuals with disabilities and few articles addressed the ability of individuals with disabilities to negotiate built environments in crowded situations. Therefore, large-scale empirical research is needed to examine to what extent the behavior of individuals with disabilities is affected by U.S. built environment regulatory standards.

To address this lack, in 2012 a series of large-scale controlled pedestrian behavior experiments which included individuals with disabilities were carried out at Utah State University (USU). The purpose of the study was to measure the stated and revealed pedestrian walking behaviors of individuals with disabilities in different walking facilities, including a level passageway, right angle, oblique angle, doorway, bottleneck, and stairway. The goal of this paper is to provide an overview of the experimental research on individuals with disabilities' pedestrian walking behaviors, including automated video tracking methods, data collection, logistical issues, processing methods, and lessons learned from conducting a large-scale study. The findings support future large-scale experiments related to pedestrians with disabilities' walking behavior. The collected microscopic and macroscopic behavior datasets advance our empirical understanding of the pedestrian behaviors of individuals with disabilities.

3.2 Participant recruitment

Study participants were a mixture of people without disabilities and people with mobility-related physical, sensory, or other types of disabilities, including hearing and intellectual impairments. The criteria for a mobility-related disability were based on the definition from the U.S. Census Bureau's American Community Survey (ACS) (U.S. Census Bureau, 2010) as: (Sensory Disability) blindness, deafness, or a severe vision or hearing impairment; (Physical Disability) a condition which substantially limits basic activities such as walking, climbing stairs, etc.; or (Go-Outside-Home Disability) a condition which creates difficulty in going outside the home to shop or visit a doctor's office. Participants with disabilities were recruited in collaboration with the Center for Persons with Disabilities (CPD) at USU. Study participants without a mobility related disability were selected from USU students. Participants were partially compensated for their time with a $50 stipend for each day of experiments.

Two hundred and thirty one participants (189 without disabilities and 42 with disabilities) were recruited for the circuit experiments and 80 participants (60 without disabilities and 20 with disabilities) were recruited for the stair experiments. The number of participants allowed intentionally congested conditions during the experiments. In total, 311 individuals between 17 and 80 years old participated. For the circuit experiments about 26% of the participants with disabilities had a visual impairment, 38% had a physical impairment, and 36% had other types of disabilities. For the stair experiments, 35% of the participants with disabilities had a visual impairment, 25% had a physical impairment and 40% had other disability types. Some participants had more than one disability. Fig. 3.1 shows the distribution of disabled participants in both the circuit and stair experiments. For detailed information about participant recruitment process, readers are referred to Sharifi et al. (2014), Sharifi et al. (2015a), Sharifi et al. (2015b), Sharifi et al. (2015c), Sharifi et al. (2015d), , Sharifi et al. (2016), and Stuart et al. (2015).

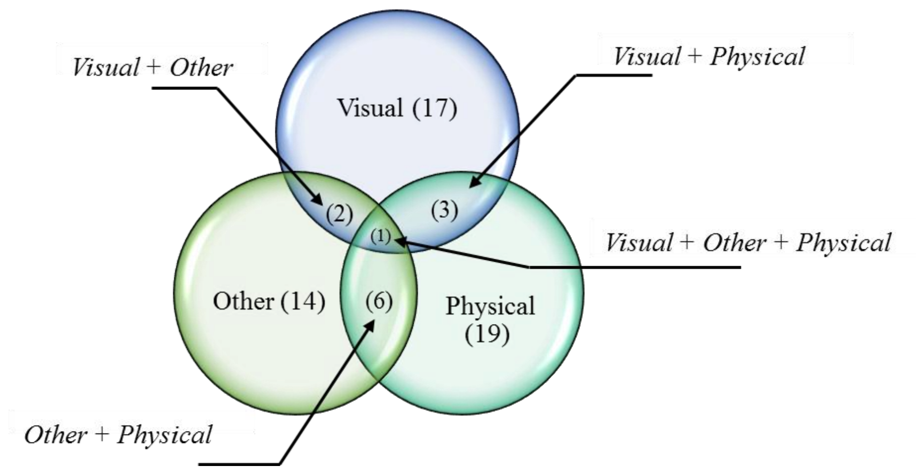

Fig. 3.1. Distribution of disabled participants.

3.3 Setting

For the crowd experiments, the Motion Analysis Lab of USU's department of Health, Physical Education and Recreation was selected. The 3,000 square foot laboratory with 8-meter high ceilings was conducive to video tracking technology and camera suspension. A circuit was temporarily constructed within the Motion Analysis Lab to allow participants to pass through various walking facilities in an efficient loop. Eight foot tall panels formed the desired walking facilities designed to comply with Americans with Disabilities Act Accessibility guidelines (ADAAG, 2002) and the International Building

Code (IBC, 2012). For the stairwell experiments, two standard stairwells in the HPER were chosen. Fig. 3.2 presents the layout of the study areas.

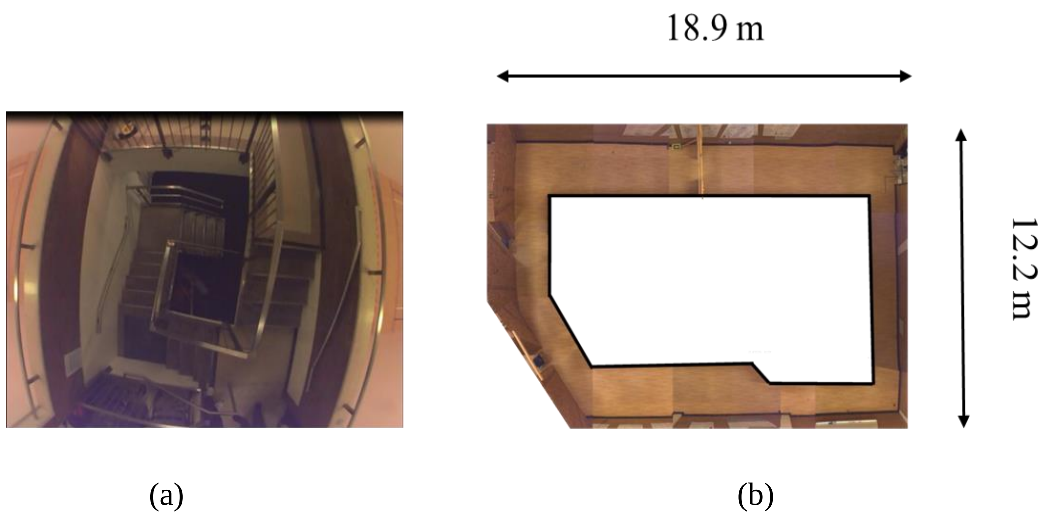

Fig. 3.2. Experimental areas a) stair and b) circuit.

3.4 Experimental measures

Many factors affect pedestrian behavior, including an individual's characteristics (age, gender, health, disabilities, etc.), characteristics of the environment (type, dimensions, attractiveness, etc.), and ambient conditions (temperature, visibility, etc.). To make the experiment manageable, only the most significant independent variables were included. These variables were divided into two categories: experimental variables related to the built environment and context variables related to the characteristics of the individuals. Primary microscopic dependent variables were identified from previous studies (Daamen and Hoogendoorn, 2003; Helbing et al., 2005) including, (1) the speed of the participants in meters per second, (2) the latitudinal and longitudinal distances maintained between the participants, other participants, and components of the environment, and (3) the walking trajectory. Macroscopic dependent variables like traffic flow diagrams were also included as a basic measure for evaluating the walking facilities. Table 3.1 presents experimental variables.

Table 3.1
Experimental variables.

Independent variables	Experimental variables	Walkways • Level passageway • Right angle • Oblique angle • Bottleneck • Doorway Stairway Direction • Uni/bidirectional • Flow compositions • Density level
	Context variables	Physical disabilities Sensory disabilities Go-Outside-Home disabilities Individuals without disabilities Age Gender
Dependent variables	Microscopic	Walking speed Walking trajectory Longitudinal spacing Lateral spacing
	Macroscopic	Speed-Density relationship Flow-Density relationship Speed-Flow relationship

3.5 Video tracking

To collect walking trajectories, a tracking system was developed using ARToolKitPlus (ARTKP) (Wagner and Schmalstieg, 2007). ARTKP includes a series of libraries and functions that allow the tracking of up to 512 identifiable fiducially markers of known shape and pattern at one time. Power-over-Ethernet (POE) cameras were used to record the unique patterns mounted on graduation hats worn by participants. These cameras are compact but have a high resolution of 1280x1024 pixels at a maximum frame rate of 50 fps. For full camera coverage, a c-mount 3.5 mm focal length lens that gives a large area of coverage per camera were selected. Table 3.2 presents performance specifications video tracking and camera hardware.

Table 3.2
Required specifications for video tracking and camera hardware.

System	Item	Specification
Video Tracking	2-D Accuracy	0.3 meter or within foot path
	Tracking	Individually identifiable over multiple cameras
	Capacity	60-150 participants possible, 30-60 in a frame.
	Vertical Height	1.2, and 4.5 meters in height for the circuit, and stair
	Reliability	Minimized error in accuracy and loss of tracking
Camera Hardware	Weight	Light enough to be suspended above the participants
	Coverage	Cover as much of an area as possible
	Speed	50 fps to reduce actions interfering with tracking

Twelve cameras were suspended from steel building girders to provide full coverage of the study area with enough overlap. To suspend the cameras, a cord system was used to hoist each camera and supported Ethernet cable into position. To account for inaccuracies in suspending the cameras and to allow for adjustments, each camera was mounted on a gimbal which used the weight of the camera to keep the lenses parallel to the ground. A sample camera, encoded tracking pattern and the camera gimbal can be found in Fig. 3.3.

(a) (b) (c)

Fig. 3.3. Tracking hardware a) power-over-erhernet (POE) b) encoded tracking c) camera gimbal.

A 50 fps recording frame rate was selected to mitigate participants looking down or engaging in any other behavior which would hide the pattern from tracking. However, this high frame rate led to increased data volume. To manage the data, Ethernet cables lead back to three 8-core 32 gb RAM computers with solid state drives to decrease data storage write time, each handling the data from 4 cameras. Power to each camera, as well as communication, was handled using Adlink GIE64+ POE PCIe cards. For detailed information about the tracking system and technical setup, readers are referred to Stuart et al. (2013). Fig. 3.4 presents the steps of tracking system procedure. The process includes camera calibration, edge detection, and pose detection.

3.5.1 Camera calibration

To optimize tracking accuracy and reduce errors the cameras were calibrated prior to data collection. Camera calibration is a process to determine camera’s extrinsic parameters (i.e., position, orientation) and intrinsic parameters (i.e., focal length, lens distortion, skew) to map three-dimensional world to a two-dimensional image. The traditional calibration sequence used for ARTKP is the Matlab Camera Calibration Toolbox. The results of this step are a perspective projection matrix and image distortion parameters of cameras (Wagner and Schmalstieg, 2007). Preliminary tests revealed that distortion existed due to the wide angle lenses chosen for coverage. To overcome the problem, Omni Camera Calibration (OCC) Toolbox for Matlab, which allows for greater distortion and aberration correction, was used. OCC uses a standard calibration planar checkboard and applies multipoint reference checking for camera calibration. Several attempts were made to obtain good calibration data using this platform and results showed errors in acceptable ranges.

3.5.2 Edge detection

After sending the captured video to the computer, ARTKP searches through each video frame to detect markers. As shown in Fig. 3.3 (b), each marker is composed of a black border and a pattern. The first step in the tracking process is finding a marker's edges. To this end, ARTKP first thresholds each frame using an adjustable value (i.e., the median of all extracted marker pixels) to produce a black and white binary image. It then searches for quadrangles while removing too large/small areas to finally detect the marker's pattern (Wagner and Schmalstieg, 2007).

3.5.3 Pose detection

In this step, ARTKP uses the marker's edges to detect pose and orientation of each frame. It first estimates the marker's pose matrix using the matrix fitting. ARTKP then determines the transformation matrix from the camera plane to a local coordinate system in the center of the marker. The local coordinates are further used to determine the location of each marker in the video frame (i.e., the Cartesian coordinates of the center pixel of the marker). The resulting coordinates are then written to a text file annotated by marker identifier.

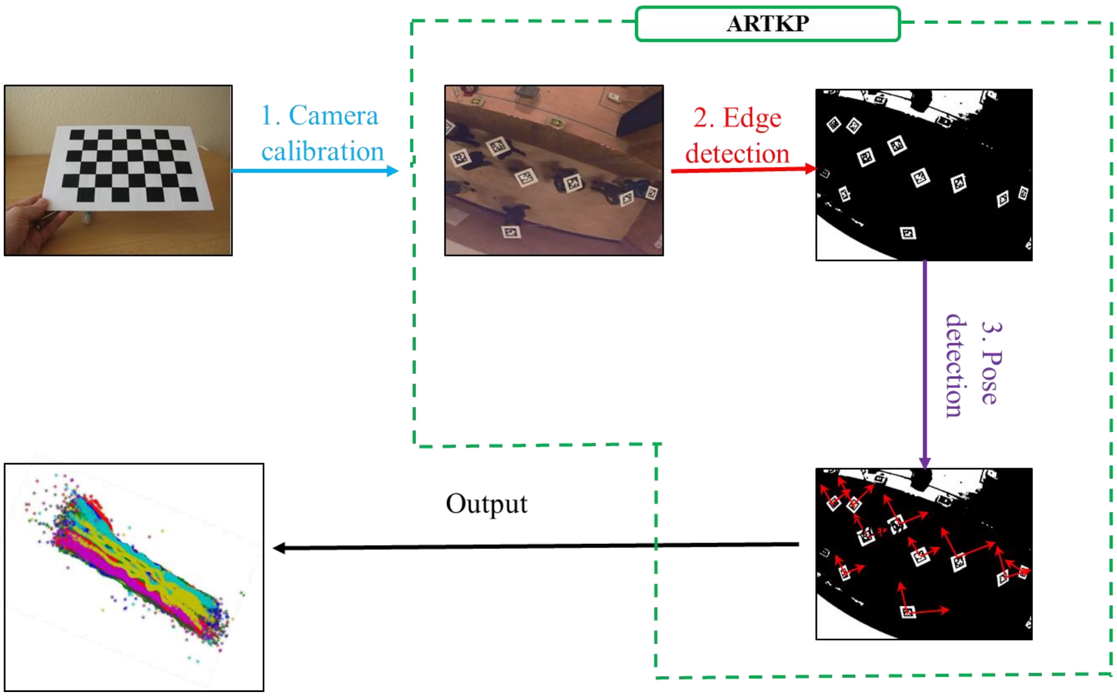

Fig. 3.4. Steps of tracking system.

3.6 Survey design

A survey questionnaire was employed to examine stated walking behavior. Both pre-surveys and post-surveys were used. The pre-survey instrument included 22 questions (5 short answers and 17 ordered multiple choice questions): Four questions covered personal demographic data (e.g., age, gender, and type of disability); three questions related to walking habits (average distance a person walks each day, number of days per week a person walks for at least 10 minutes continuously, and purposes for walking [going to work or school, shopping, exercise]); The remaining questions assessed the participant's tactical motivators for walking behavior and interactions with other participants. For example: in a walking facility how likely would you be to (a) follow another individual(s), (b) pass another individual(s), (c) change walking behavior toward another pedestrian with disabilities, (d) be impacted by encountering an individual with disabilities. Following the experiments, the post-survey instrument included six ordered multiple choice questions used to assess conditions during the experiments and another question to determine the role of perception in the observed pedestrian behaviors. The latter question used six images from the Highway Capacity Manual (HCM) (HCM, 2010) representing different level of service (LOS) conditions. Each of the photos represented different pedestrian occupancy loads, spacing, and flow volume. The participants were asked to select the image that best represented their walking condition. Using revealed behavior and responses to this question we were able to analyze participant perceptions regarding their ability to maneuver and or negotiate the environment. Participant responses were coded according to common terms (short answer) and ordinal values (Likert-scaled responses) in relation to the spatial location referenced in the participant's response. In this way, participants stated data were compared to the revealed behaviors observed in the spatial location. Survey data were stored in a database in addition to the measured data to allow for more informed analyses of the relationship between components and observed behaviors.

3.7 Pilot test

Prior to beginning the experiments, pilot tests were conducted with people without disabilities to ensure that the tracking system, including camera settings, tracking hardware, and tracking software, worked at an acceptable level. Using a large number of people for the pilot tests was helpful in anticipating possible problems in conditions such as congestion. In addition, both pre and post-surveys were reviewed by experts for readability, length, and ability to collect required feedback within the time available.

Despite detailed planning and assessment of pilot tests, some organizational or technical aspects could not be predicted. Managing an experiment involving a large number of people without and with disabilities requires a high degree of coordination within the research team. This section narrates the experimental procedures used in circuit and stairway experiments.

3.8 Principal experiments

The walking behavior or circuit study was conducted over two days (November 9th, and 15th, 2012). The stair experiments were conducted in one day (November 22th). Before conducting the experiments, administrators were delegated specific duties to allow them to manage and direct large numbers of people including individuals with disabilities. For example, someone was responsible for administering surveys and assisting people with disabilities. Another researcher was to control the participant entering and exiting process. This researcher acted like a ramp meter, allowing participants to enter the circuit according to a predefined plan and controlling the number of participants in the circuit.

To minimize the risk of accidental injury or fatigue during the experiments, every participant received safety instructions before the experiments. Researchers then familiarized participants with the environment, explained procedures for entering and exiting the circuit, and instructed them to walk naturally. As the tracking patterns can be hidden if participants remove their hats or tilt their hats and/or heads to far, pictures guides (see Fig. 3.5 below) were hung on the walls of the study area to remind participants to keep their hats in an upright, readable positon.

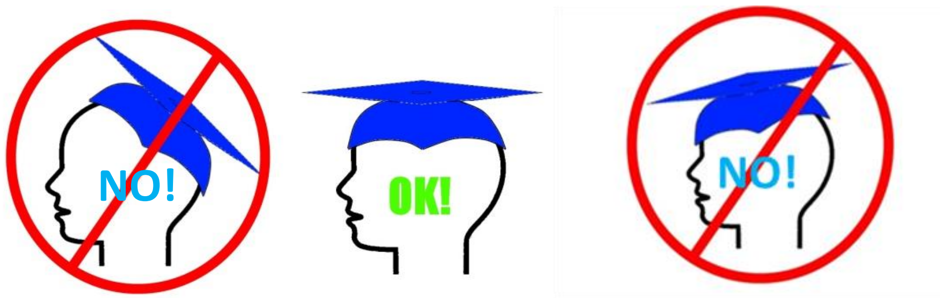

Fig. 3.5. Guiding pictures.

To examine different scenarios of flow compositions, the experiments were categorized into two major groups:

1. One-way experiment (i.e., one-directional flow experiments with different congestion levels)

2. Two-way experiments with different flow compositions (90% major stream 10% minor stream, 80 major 20% minor, 70% major 30% minor, 60% major 40% minor, and 50% major 50% minor).

Each experiment day was divided into ten-minute recording sessions of a single scenario. The circuit experiments required participants to move at their maximum comfortable speed through circuit. During the experiments, some of participants were randomly selected by the ramp meter person after their lap completion to answer post-survey questions. After running 10-minute movement period, all participants were asked to exit the circuit and rest prior to the start of another scenario. For the stairwell experiments, two stairways connected by a hallway were used. This made it possible for participants to circulate between the two sets of stairs. The experiment process and surveys used for the stairway experiments were exactly the same as the circuit experiments except for the necessary exclusion of wheelchair users. Fig. 3.6 presents a snapshot of circuit experiments.

3.9 Data processing

To control the large amount of collected trajectory data, a tool with database management and visualization capability was developed using MATLAB software. This user-friendly GUI is able to manage, process, and visualize the video data collected from the walking experiments. The developed GUI consists of three main components: visualization, processing, and behavioral data extraction. To visualize the experimental process, a simple CAD drawing of the study area was incorporated into the GUI. This map replicates pedestrian movements using their identification IDs during the experiments. The processing component makes it possible to extract the raw trajectory data for a selective area or selected time duration for all pedestrians or for a selective group of pedestrians (e.g. pedestrians with disabilities). In addition, microscopic behavioral variables (e.g., instantaneous speed and acceleration longitudinal and lateral spacing, time headway, orientation, local speed, flow and density) can be extracted using the GUI. The software is able to pull out the behavioral data for all pedestrians or for a particular target pedestrian. Fig. 3.7 presents the GUI structure and components.

Fig. 3.8 shows a snapshot of the developed GUI. Detailed applications of the developed components including preview circuit map, toolbar, and analysis functions of the GUI are illustrated as follows.

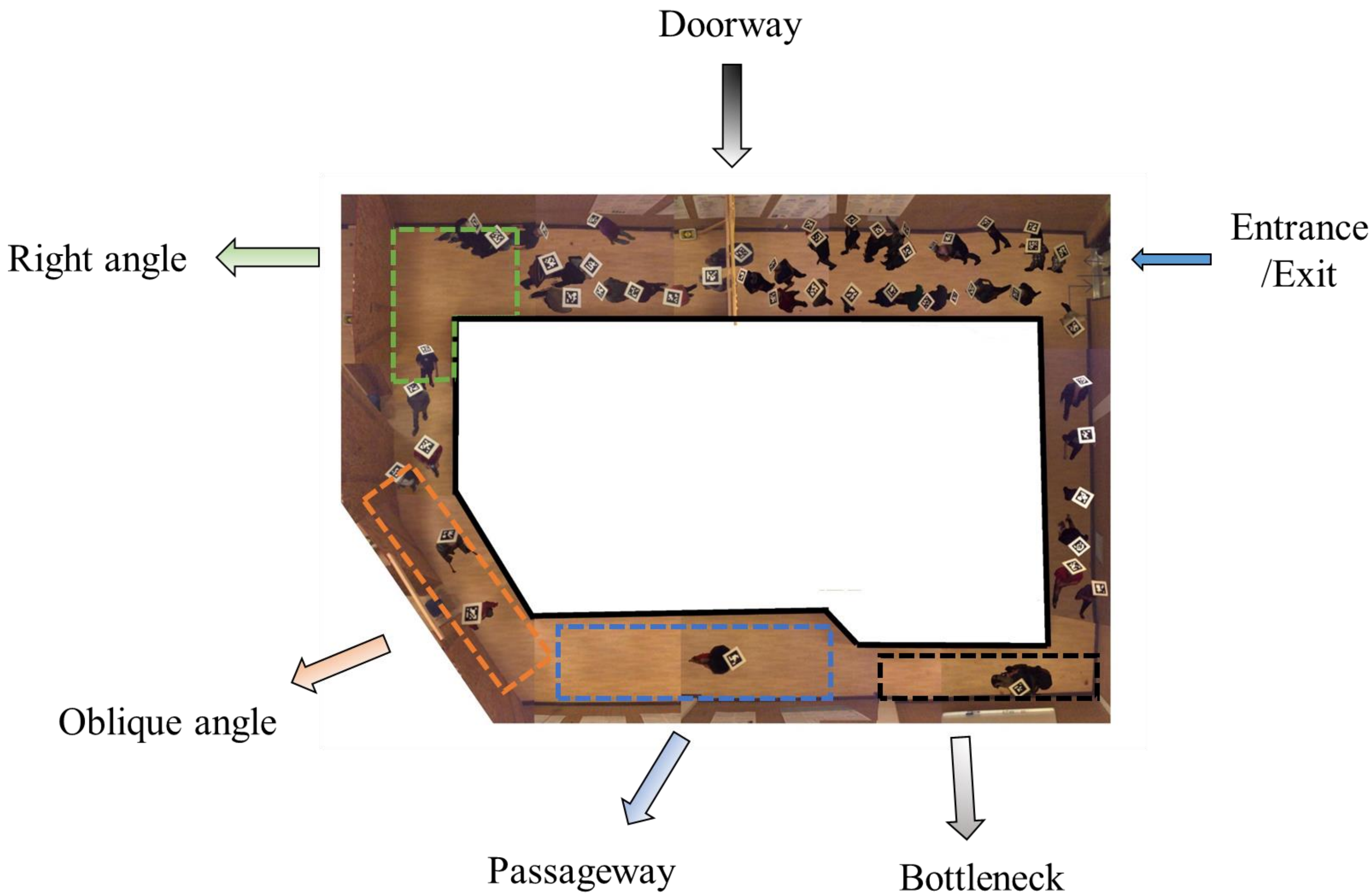

Fig. 3.6. Snapshot of circuit experiment.

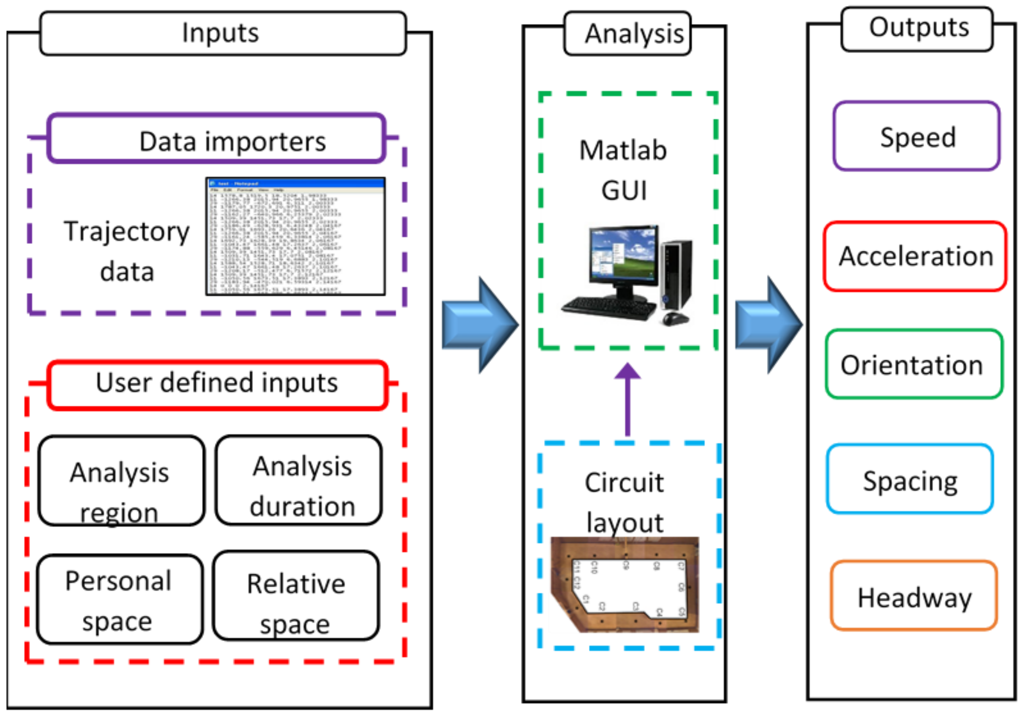

Fig. 3.7. GUI structure.

3.9.1 Loading experimental data

After each experimental session, each of the 14 cameras was processed and 14 text files of the raw trajectory data were generated. These text files include IDs of each tracked participant and the positions (x, y, z) of tracked patterns in relation to the camera's center. Each file was named using the session time and camera number. To further process these raw data, the data needed to be loaded in the GUI. Data loading can be done by entering the session time and camera number into "Session time" and "Cam Num" fields respectively.

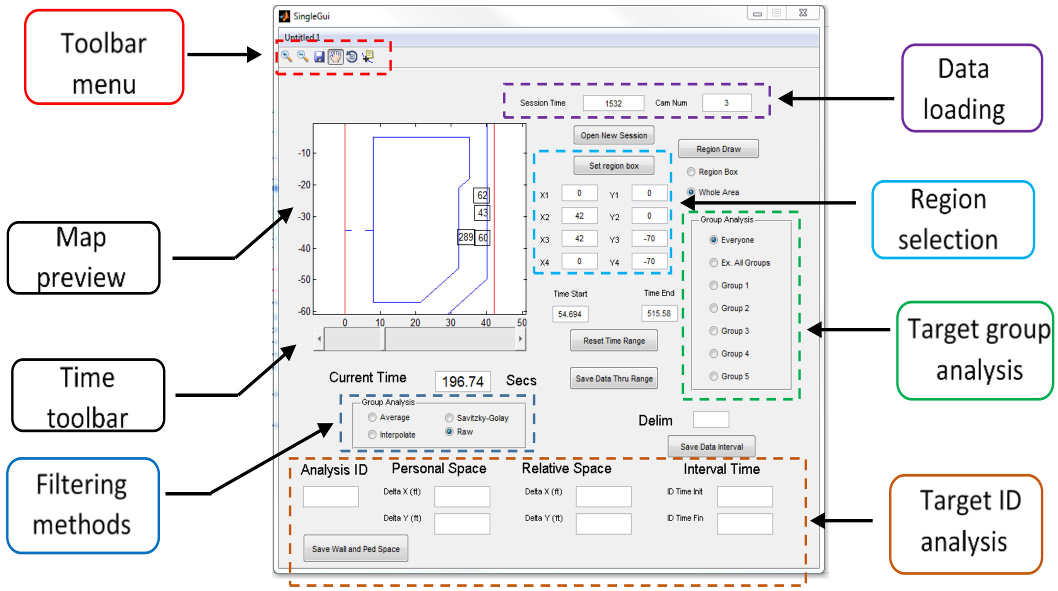

Fig. 3.8. Snapshot of the GUI.

3.9.2 Visualization

A preview of the circuit map was incorporated into the GUI to graphically observe pedestrian interactions during the experiments. The map shows positions of observed pedestrian IDs for selected time frames (current time field). Pedestrian movements and their interactions can be tracked by gradually increasing the time using the time bar.

3.9.3 Time toolbar

The toolbar provides functions to adjust the circuit map. It allows users to view the circuit map closer or view more of the map by using the zoom in and zoom out buttons. In addition, the current view can be moved to any desired direction by using the pan button. The desired view can be saved using save button.

3.9.4 Study area and time duration selection

Defining proper spatial scales (i.e., area unit for computing density, speed and flow) is crucial in the processing procedures for obtaining reasonable results. The GUI makes it possible to process the raw trajectory data for a selective area and time duration. The desired area can be specified either by drawing the region on the map using the “Region draw” button or by inserting coordinates of the corners of selective area in the “Set region box”. The selective time duration of data process can be determined by defining “Time Start” and “Time End”.

3.9.5 Target group analysis

Sometimes it may be important to study on the behavior of a particular group (i.e. pedestrian with motorized wheelchair). Users can create up to five groups of pedestrians using their IDs. The GUI can pull out and analyze the trajectory data for the target group for specified region and time duration. In addition, it is possible to smooth the walking trajectory data for each group by removing errors from the data set. The GUI provides different filtering procedures including average, interpolation, and Savitzky-Golay filtering method to smooth the data. Users can insert the desired time step into the “Delim” field and select the filtering method to obtain the trajectory data with less noise.

3.9.6 Target ID analysis

In addition to group analysis, the GUI is able to extract microscopic behavioral data for a particular pedestrian in a pre-defined time duration. This can be done by inserting the pedestrian ID and defining personal space, relative space, and interval time. The GUI reports the mean value of behavioral variables for the selected interval time.

3.10 Summary and conclusion

This chapter presented an overview of a controlled large-scale study on walking behavior considering individuals with different types of disabilities. Experimental design and processes were explained. The data analysis results can be used to calibrate and validate pedestrian traffic flow models capturing the behaviors and interactions of crowds considering different types of individuals with disabilities.

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CHAPTER 4

ANALYSIS OF WALKING SPEEDS INVOLVING INDIVIDUALS WITH DISABILITIES IN DIFFERENT INDOOR WALKING ENVIRONMENTS

Abstract

Walking facilities are important infrastructures in communities. These facilities should be designed to accommodate the needs of all types of pedestrians. Unfortunately, existing design guidelines fail to offer adequate consideration for individuals with disabilities owing to a lack of empirical data. To address this knowledge gap, a controlled large-scale research project was conducted at Utah State University (USU) to study the walking behavior of people with various types of disabilities in various indoor walking facilities. These facilities included a passageway, different types of angles (right and oblique), bottleneck, and stairwells. The purpose of this chapter is twofold: to examine the impacts of individuals with disabilities on crowd walking speed, and to study the impacts of different indoor walking facilities on the movements of various pedestrian groups. Results show that the presence of individuals with disabilities in a crowd significantly reduces the overall crowd speed. Statistical analysis also reveals similarities and differences between the walking speeds of various pedestrian groups. The findings of this chapter may help urban planners and walking facility designers consider the needs of people with disabilities.

4.1 Introduction

Walking facilities like walkways and stairs are important infrastructures in buildings and urban areas (e.g., transit transfer stations, shopping malls, urban plazas, etc.). Individuals frequently use these facilities for traveling short distances; while some also use them for recreation. To provide safe and comfortable walking environments for all types of pedestrians, evidence-based research is a necessary building block. In the literature, researchers have used pedestrian traffic flow relationships and characteristics (Chen et al., 2010) to assess different types of walking facilities. While individuals with disabilities represent a significant portion of the population (i.e., 16.6% of the working age population and 18.7% of the total population of the United States (U.S. Census Bureau, 2010), most existing designs and assessments overlook heterogeneity in crowd composition. Little is understood concerning the effect of the built environment on individuals with disabilities or their interactions with people without disabilities in a congested environment. Failing to address people with disabilities is possibly related to the significant lack of empirical studies on the pedestrian behavior of individuals with disabilities (Christensen et al., 2013).

The Highway Capacity Manual (HCM) (HCM, 2010) is generally consulted for the design of walking facilities in the United States. The HCM documents some regulations for designing public pedestrian facilities but lacks specifications for individuals with disabilities. To account for the needs of individuals with disabilities, the Americans with Disabilities Act Accessibility Guidelines (ADAAG) (ADAAG, 2002) provides guidelines for the design of pedestrian facilities. However, this code is based largely on physical properties and does not consider the interactions between people with and without disabilities. To consider interactions among heterogeneous populations and between people and environments, a set of large-scale controlled experiments was carried out by a multi-disciplinary research team at Utah State University (USU). The team included individuals from the following disciplines: disability studies, landscape architecture and environmental planning, transportation engineering, electrical engineering and information management. The goal of the experiments was to study the walking behavior of different types of pedestrians in various indoor walking facilities: passageways, angles (right and oblique), bottlenecks, and stairwells.

This chapter presents the statistical analysis of the impacts of individuals with disabilities on crowd walking speed and the impacts of different indoor walking facilities on the movement of various types of pedestrians. The first objective was to determine whether there is a significant difference, in terms of mean walking speed, between a homogeneous crowd (a crowd excluding individuals with disabilities) and a heterogeneous crowd (a crowd including individuals with disabilities). The second objective was to collect and analyze the walking speed of different types of pedestrians. The results will allow planners to improve built environment design policies to better accommodate the needs of diverse individuals with disabilities.

4.2 Background

Many researchers have extensively studied pedestrian walking behavior. In early efforts, pedestrian studies were conducted in many cities through manual data collections (Polus et al., 1983; Tanaboriboon et al., 1986; Koushki, 1988). In recent years, more advanced technology is used in pedestrian studies. Laxman et al. (2010) conducted research to examine relationships between pedestrian speed, volume, and density in India using video graphic techniques. Al-azzawi and Raeside (2007) collected pedestrian movement data through video recordings to estimate pedestrian speed and flow on sidewalks. Rastogi et al. (2011) presented pedestrian crossing speeds at midblock sections for three cities in India. They determined walking speed of different types of pedestrians categorized by gender and age groups. In some cases, it is difficult to observe pedestrian behavior in desired conditions (i.e., behaviors in congested situations). Hence, many controllable walking experiments have also been conducted to draw inference for urban facilities such as sidewalks with different geometric configurations. For example, Daamen and Hoogendoorn (2003) conducted walking experiments to collect pedestrian behaviors in passageway and bottleneck walking environments. A series of controlled walking experiments were conducted in Germany to derive walking behaviors in a circular passageway (Seyfried et al., 2005), bottleneck (Seyfried et al., 2009), T-junction (Zhang et al., 2011), and stair (Burghardt et al., 2013).

Most mentioned studies overlooked the heterogeneity of physical ability in pedestrian compositions. Only a limited number of studies considered people with low mobility, including individuals with disabilities. Christensen et al. (2014) conducted a review literature with emphasis on the behavioral measurements of individuals with disabilities in navigating the built environment. The review found only a few studies in this research area. For example, Boyce et al. (1999 a, c) determined movement capabilities of 155 individuals in different walking facilities (level surfaces, ramps, and stairs) in an emergency situation. Results were reported in four categories of disabilities: unassisted ambulant, unassisted wheelchair users, assisted ambulant and assisted wheelchair users. They also conducted another study to measure the ability of people with disabilities to negotiate the environment in emergency conditions (Boyce et al., 1999 b). Clark-Carter et al. (1986) measured the walking speed of people with visual impairments in environments of varying complexity. Results showed that the walking speed of individuals with visual impairments is negatively affected by the increasing complexity of the travel environment. Yet, individuals with visual impairments who use guide dogs are not as affected by complex built environments as those who use long canes. Furthermore, Miyazaki et al. (2003) evaluated the behavior of 30 pedestrians and a wheelchair user. The authors found that the behavior of the pedestrians influenced the behavior of the wheelchair user and vice-versa. Moreover, pedestrian speed changed depending on the psychological condition (e.g., competitive or noncompetitive). The researchers developed a model demonstrating psychological phenomena (e.g., group psychology) and pedestrian behavior (e.g., speed) in relation to the distance from an individual using a wheelchair. Rubadiri et al. (1997) conducted an experiment to estimate speed of individuals with mobility impairments in an obstacle-free route and two evacuation routes. They provided a quantitative attribute called the Evacuation Performance Index (EPI) for measuring and predicting the evacuation performance of individuals with mobility impairment. Their proposed index measures the relative ease of evacuating people with impaired movements using different factors such as evacuation speed and escape route layout. Wright et al. (1999) examined speed of individuals with visual impairments through an evacuation route. They found that visually impaired individuals walk at 43%-69% of typical walking speed on level routes and 70%-

80% on stairs. Passini et al. (1998) evaluated the ability of individuals with cognitive impairments to navigate various built environments, and concluded that complexity of the built environment could decrease the ability of participants to navigate the environment. Arango and Montufar (2008) investigated the walking speed of older pedestrians who use walkers or canes in Winnipeg, Canada. They concluded that crossing walking speed is significantly higher than normal walking speed for older pedestrians with or without walkers/canes. Recently, Kuligowski et al. (2013) studied the stair evacuation speed of older adults and people with mobility impairments of 45 residents with various mobility impairments evacuating a six-story building.

Three conclusions can be drawn from the preceding literature review. First, it is unfortunate that individuals with disabilities have received less scholarly attention. Second, the majority of the existing studies used egress speed to describe the behavior of an individual with a disability in response to the built environment. This indicates a lack of understanding of the walking behavior of individuals with disabilities. Thus, the question remains as to whether the build environment imposes constraints on individuals with disabilities. Third, almost none of the past studies examined the walking speed of individuals with disabilities in crowd conditions. Therefore, the question remains as to what extent the walking speed of individuals with disabilities is affected by interactions of people with disabilities in crowd conditions.

4.3 Methodology

The objectives of this research were to study the impacts of individuals with different types of disabilities on crowd speed, and the impacts of different walking facilities on the movement of various pedestrian groups. These objectives can be expressed by hypotheses. The first objective was to examine the effect of pedestrian characteristics on crowd moving speed in different walking facilities. The null hypothesis can be expressed as follows:

Hypothesis 1. There is no significant difference in the mean walking speed (μ) between homogeneous (populations excluding individuals with disabilities) and heterogeneous populations (populations including individuals with disabilities) in various walking facilities. For this hypothesis five different walking facilities were considered: a level passageway, oblique angle, right angle, bottleneck and stairs.

H^1_n: $\mu_{\text{homogenous population}} = \mu_{\text{heterogeneous population}}$

H^1_a: $\mu_{\text{homogenous population}} < \mu_{\text{heterogeneous population}}$

The second objective was to study the walking speed of different types of pedestrians in different walking facilities. Specifically, the impact of different walking facilities on the mean speed of people with and without disabilities was examined:

Hypothesis 2. Mean walking speed of people with different types of disabilities is not affected by walking facility configuration.

H^2_n: $\mu_{\text{facility type A}} = \mu_{\text{facility type B}}$ for different types of pedestrians

H^2_a: $\mu_{\text{facility type A}} \neq \mu_{\text{facility type B}}$ for different types of pedestrians

Four classifications of individuals were used in this research: individuals without disabilities, individuals with visual impairments, individuals with physical impairments who use non-motorized ambulatory devices (e.g., wheelchair/cane/roller) or individuals who have physical constraints (non-motorized group), and individuals using motorized wheelchairs. While there are many different types and degrees of disability, these three types were identified as those most likely to be impacted by conditions in the built environment.

4.3.1 Experimental area

The research goal was to examine the behavior of different types of pedestrians, including people with disabilities, in a variety of walking facilities at varying congestion levels. In order to accomplish this research goal, a controlled environment was adopted to conduct different walking experiments. To this end, large-scale walking experiments were conducted at Utah State University's (USU) Motion Analysis Lab. The 3,000 square foot laboratory, similar to a gymnasium, is conducive to the instrumentation necessary for data collection. A temporary circuit with the necessary walking facilities (level passageway, right angle, oblique angle, and bottleneck) was constructed using eight foot self-standing walls. The circuit was designed to include various walking facilities based on the Americans with Disabilities Act Accessibility guidelines (ADAAG, 2002) and the International Building Codes (IBC, 2012). In addition, a standard stairwell near the motion lab was used for the stair experiments. The stairwell had 18 steps with each step measured at 0.9 m wide with a 0.18 m rise and 0.25 m deep tread.

4.3.2 Participants

To recruit a representative sample of individuals, an electronic advertisement was distributed among respective populations to select the participants without disabilities. The recruiting advertisement offered $50 stipend for each day of experiments. The recruitment process considered only working age individuals without disabilities who are between 18 to 64 years of age (U.S. Census Bureau, 2010). Except age constraint, the recruitment process did not require any conditions for applicants to participate in walking experiments, and all participants were randomly selected among the received applications for both sexes. The number of invited participants was determined to observe a congested condition during the experiments. Participants with disabilities were recruited through the Center for Persons with Disabilities (CPD) at USU. They possessed a mobility-related physical, sensory, or 'Go-Outside-Home' disability. The criteria for a mobility-related disability were based on the U.S. Census Bureau's American Community Survey (ACS) definition (U.S. Census Bureau, 2010). Individuals over 80 years of age were not included in the study due to health protection concerns.

The walking experiments were conducted over four days (November 2nd, 9th, 15th, and 22th of 2012). In total, 302 individuals between 18 and 80 years old participated in the experiments. Specifically, 202 individuals (180 without disabilities and 42 with disabilities) participated in the circuit experiments and 100 participants (80 without disabilities and 20 with disabilities) participated in the stair experiments. Individuals using wheelchairs were excluded in the stair experiments. For the circuit experiments, about 5% of the participants had a visual impairment, 9% had a physical impairment, and 6% had other impairments.

Similarly, for the stair experiments, 10% of the participants had a visual impairment, 6% had a physical impairment and 6% had other impairments. According to the 2010 disability status report (Erickson et al., 2012), the prevalence of visual and ambulatory disability among persons of all ages in the U.S. was 2.1% and 6.8% respectively. Therefore, the number of disabled participants was considered representative of their respective populations.

4.3.3 Data collection

Two types of experiments were conducted for the circuit experiments: unidirectional and bi-directional. In the unidirectional experiments, all participants walked in the same direction. Bi-directional experiments were conducted with different scenarios of flow compositions (90% major stream 10% minor stream, 80% major 20% minor, 70% major 30% minor, 60% major 40% minor, and 50% major 50% minor). For each experiment, participants moved at their maximum (or comfortable) speed, without endangering their safety. Each scenario was split into 10-minute recording sessions with about two hours of data collection. To control and manage the experimental process, one researcher acted as a ramp meter to distribute participants and generate a wide range of crowd density levels. In this way, data at various congestion levels was collected.

Automated video identification and tracking technology was used for data collection to track participant positions within an average of 0.3 meter or one footstep, which enables tracking and collection of each individual participant's walking trajectory. Derived from augmented reality, ARToolKitPlus (ARTKP) is a software library that allows the tracking of up to 512 identifiable markers in a camera field at once (Wagner and

Schmalstieg, 2007). A system was designed using this technology to track and uniquely identify the participants. To utilize this system, markers were attached to participants using graduation caps, and read by cameras suspended above the experimental area. Power-over-Ethernet (POE) cameras, which only need one cable for power and communication, were used. The chosen POE camera is compact at 29 x 29 x 41 mm, but still affords a high resolution of 1280x1024 pixels at a maximum frame rate of 50 frames per second. Twelve cameras provided a full coverage with overlap for the circuit experiments and one camera was sufficient per stairwell. For detailed information about the tracking system and technical setup, readers are referred to Stuart et al. (2013).

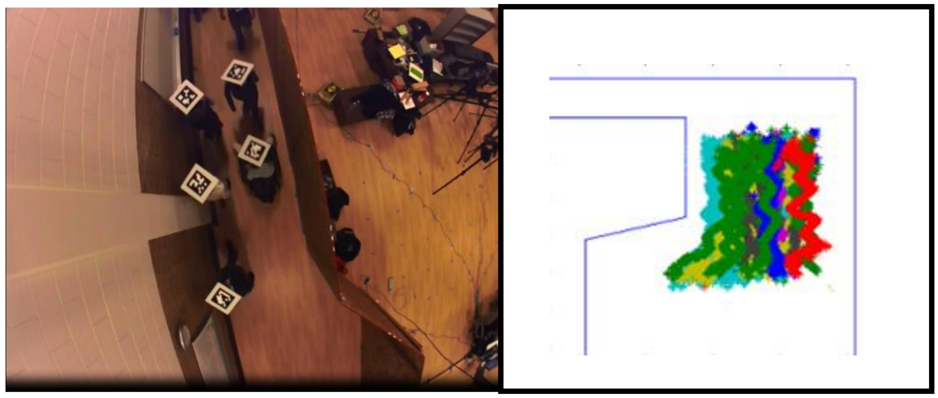
4.4 Analysis and results

The collected trajectory data was organized according to the different days, scenarios, and facilities and diagramed for validation and quality checking as shown in Fig. 4.1. This figure shows a sample of visualized trajectory data for ten participants in the circuit experiment, and the 3D trajectories of four participants in the stairwell experiment. Data visualization shows formation consistent with the built environment and validates the quality of the trajectory data. Time-space trajectories of pedestrian crowd dynamics are depicted in Fig. 4.2. These time-space diagrams were created by plotting the position of each participant, given at a distance from a reference point (e.g., entrance of the circuit) against time. The vertical distance between two consecutive lines indicates the spacing between the pedestrians, while the horizontal distance between two consecutive lines indicates the time headway between pedestrians. The time-space trajectories are especially useful in identifying patterns of walking behavior. For example, it can be observed that individuals without disabilities maintain a more conservative spacing from individuals with disabilities, and the time headway between individuals without disabilities is lower compared to the time headway between individuals without and with disabilities. In addition, the slope of the trajectories represents the speed of participants with the curved portions indicating speed changes. To show these changes more clearly, a segment of the time-space diagram is enlarged and labeled with the location within the circuit. The expanded diagram indicates that the speed of participants reduces in the bottleneck area more than other segments, especially under crowd conditions where the concentration of lines is high.

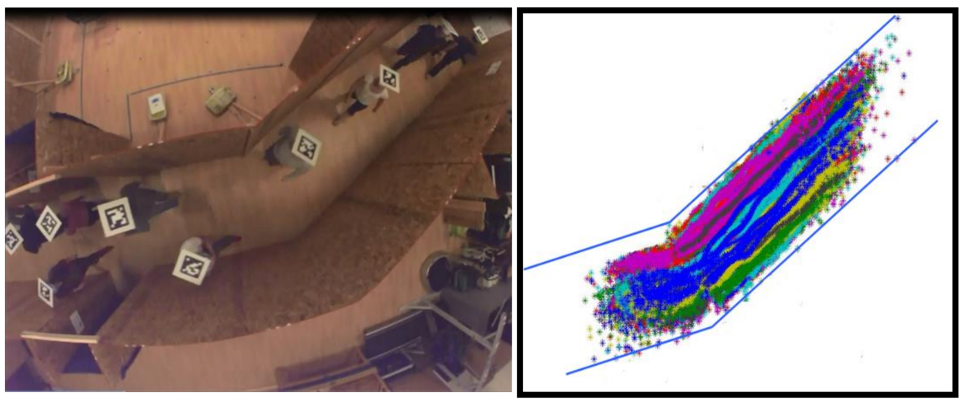
4.4.1 Hypothesis 1

The purpose of the first hypothesis was to examine the effect of involving individuals with disabilities on crowd walking speed. The first day of experiments involved only individuals without disabilities and subsequent days used the same procedure and equivalent number of participants, but included both individuals with and without disabilities. Thus, it was possible to compare the effect of individuals with disabilities in crowd speed. To test the hypothesis, it was necessary to determine the speed of participants and density caused by the volume of pedestrians using the trajectory data. A straightforward procedure was used to extract the population speed and density as follows:

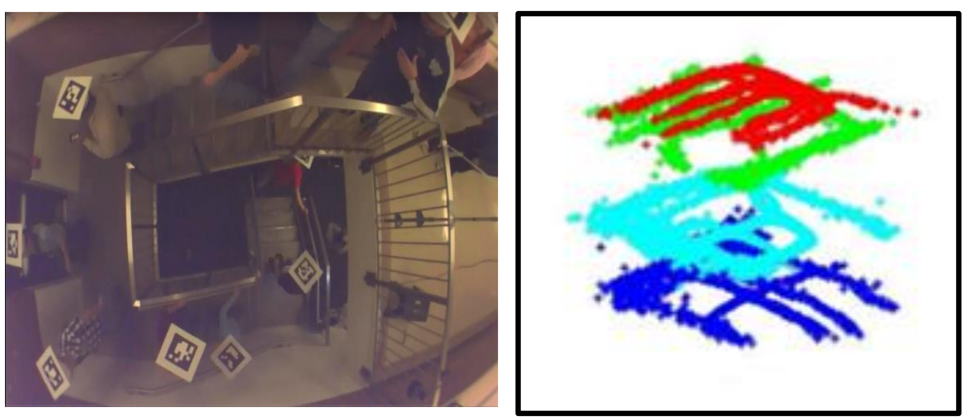
1. A time interval was selected to extract the speed data. Walking distance is determined during the time interval used to compute the walking speed. A 30-second interval was considered appropriate for data extraction.



(a)



(b)



(c)

Fig. 4.1. Trajectories at different facilities a) bottleneck b) oblique angle c) stairwell.

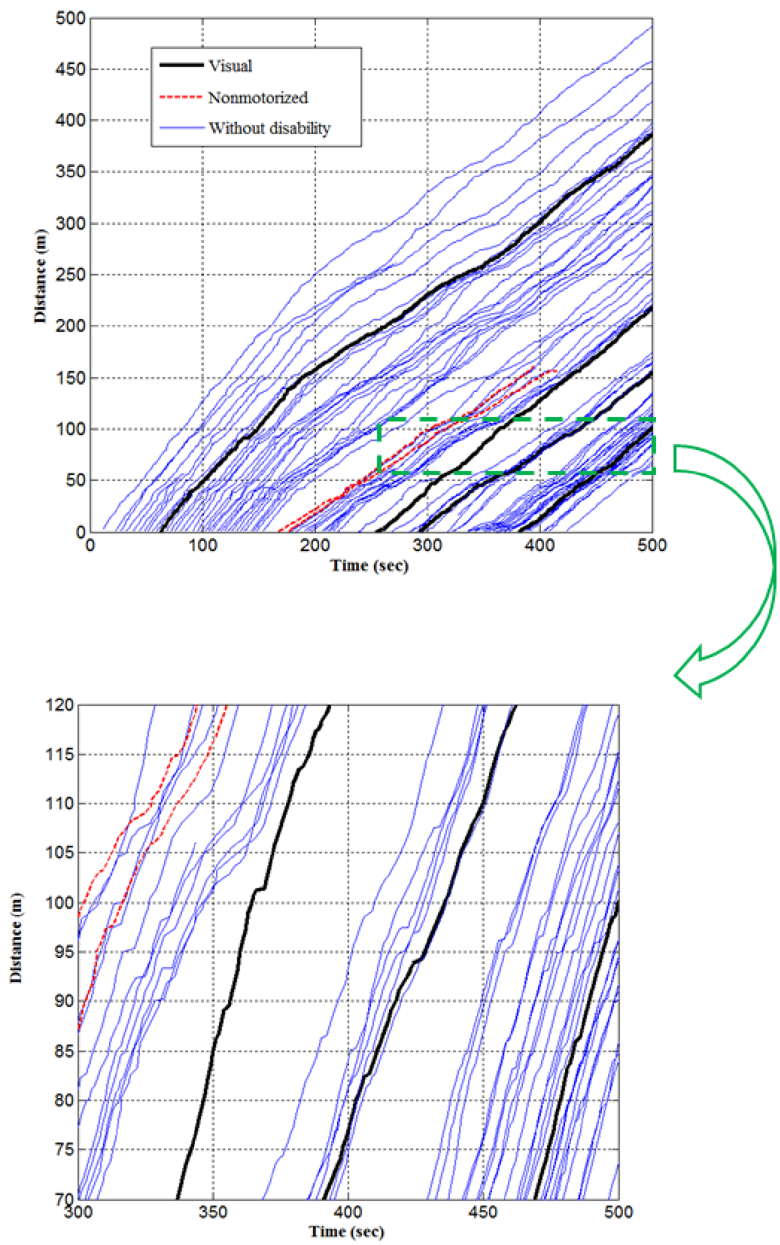


Fig. 4.2. Time-space diagram.

2. Position of each participant was recorded every second using the trajectory data. For the stair experiments, only horizontal movement was used to calculate the walking speed.

3. Walking distance of each participant during the time interval was determined using the recorded positions.

4. Walking speed of each participant during the time interval was computed by dividing the walking distance by the time interval.

5. Population mean speed was obtained by averaging the speeds of all participants.

6. To obtain the corresponding density for the time interval of interest, the number of participants was recorded in each second and the arithmetic mean of the number of participants was divided by the observation area.

Crowd mean speeds were computed for both homogeneous and heterogeneous population scenarios. Fig. 4.3 compares and illustrates the impact of individuals with disabilities on crowd speed reduction in various walking facilities. In Fig. 4.3, the two lines compare the walking speeds of homogeneous and heterogeneous populations in different walking facilities, while the bar graphs show the speed reduction percentage for each facility. These reductions were most evident for the stair, right angle, and passageway facilities. For instance, results showed that the mean speed of the heterogeneous population was about 14% lower than the mean speed of the homogenous population in the stair facility. Table 4.1 presents the quantitative comparison of mean walking speed for the two population scenarios. In the table, the number of observations (N) represents the number of extracted speed data obtained from step 4 of the data extraction procedure. Analysis indicated that populations reached their maximum and minimum speeds in the passageway and stair facilities respectively. Mean walking speeds of the homogeneous and heterogeneous populations in the passageway were 0.93 m/s (3.05 ft/s) and 0.82 m/s (2.69

ft/s), respectively, while their respective mean walking speeds were 0.51 m/s (1.67 ft/s) and 0.44 m/s (1.44 ft/s) in the stair.

Mean speed of each scenario was statistically compared using analysis of variance (ANOVA) as presented in Table 4.1 For all facilities, the *p*-value was lower than 0.01, indicating a significant difference between the mean walking speed of a homogenous and a heterogeneous population. Therefore, the first null hypothesis was not supported as the walking speed of individuals with disabilities was much lower than that of the general pedestrian population, resulting in clogging and congestion within different walking facilities. As expected, this phenomenon was more critical for complex geometries like stairs. The findings suggested that individuals with disabilities, albeit the minority in the pedestrian stream, had a major impact on crowd speed.

4.4.2 Hypothesis 2

To test the second hypothesis, walking speed data of participant groups was extracted separately for different walking environments as presented in Fig. 4.4. The minimum, maximum, median, quartiles of speed data, and speed ranges can be inferred from this figure. The purpose of this hypothesis was to examine the effect of different walking facilities on the mean walking speed of different individual types. In general, walking speed is dependent on the density level (i.e., number of pedestrians divided by the observation area) in addition to the physical ability and type of walking environments.

To compare walking speed of individuals, speed and density were computed for each time interval. Then, speed data were categorized based on the density levels obtained from the HCM Level of Service (LOS) definitions (HCM, 2010). This guideline classifies

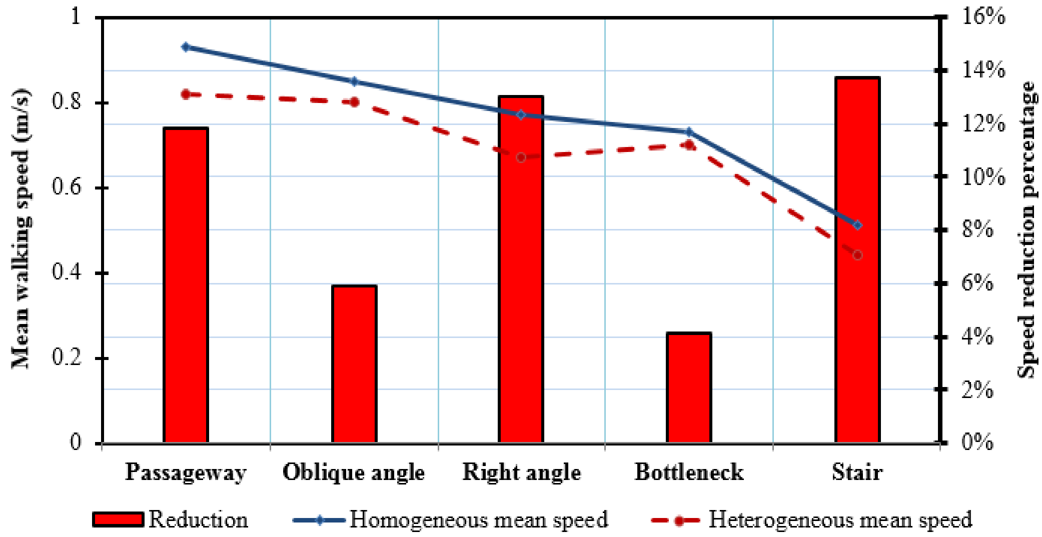


Fig. 4.3. Mean walking speeds of homogeneous and heterogeneous population in different walking environments.

Table 4.1
Statistical analysis of mean walking speeds of homogeneous and heterogeneous populations in different walking environments.

Facility	Population	Mean speed (m/s)	SD	N	*p*-value	H^1_n
Passageway	HM	0.93	0.22	577	< 0.01	Reject
	HT	0.82	0.22	3057		
Oblique angle	HM	0.85	0.21	578	< 0.01	Reject
	HT	0.8	0.22	3078		
Right angle	HM	0.77	0.19	573	< 0.01	Reject
	HT	0.67	0.21	3203		
Bottleneck	HM	0.73	0.19	398	< 0.01	Reject
	HT	0.7	0.21	2785		
Stair	HM	0.51	0.16	836	< 0.01	Reject
	HT	0.44	0.18	1161		

Note: SD = standard deviation; N = number of observations; HM: homogeneous; HT: heterogeneous

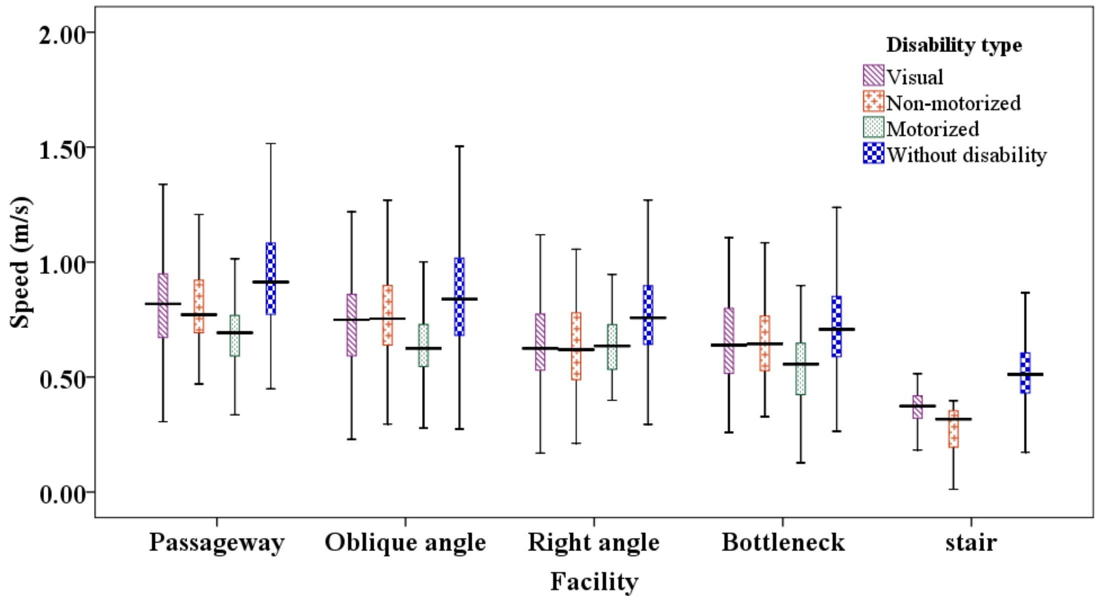


Fig. 4.4. Walking speed statistic for different pedestrian groups and environments.

the LOS performance of walkways and stairs using different measures such as density level. HCM uses letters A through F to denote the level of service: LOS A stands for the best and LOS F represents the worst quality of service. To assess the impact of walking configurations, walking speeds in the middle density ranges (i.e., LOS C and LOS D) with majority of the data were used for comparing individual walking speeds. Therefore, only the mean speed values for LOS C and LOS D corresponding to the density values from 0.27 p/m^2 to 0.71 p/m^2 and from 0.63 p/m^2 to 1.35 p/m^2 were computed for the circuit and stair experiments respectively. Speed analysis for different groups is summarized in Table 4.2 and indicates that all groups had the highest walking speed in the passageway facility and people with motorized wheelchairs had the lowest mean speed in all facilities except in the right angle and stair facilities, where they were not observed. All types of individuals with disabilities had their minimum speed in the bottleneck and right angle facilities, suggesting that turning movements and space unavailability could make it difficult for these individuals to maneuver. For the stair experiment, the obtained values were comparable to the findings in Boyce et al. (1999a). The study indicates that the walking speed for individuals with disabilities is considerably lower than individuals without disabilities.

Table 4.2 also shows the level of significance for a pairwise ANOVA comparison of mean walking speed. For example, the statistical test for mean walking speed in the passageway facility compared with all other facilities indicates that the speed reduction was statistically significant (p-value < 0.05) across all pedestrian groups except for people with motorized wheelchair. It indicates that the physical configurations of the walking environment had a significant impact on walking speed for all pedestrian groups. These findings are consistent with the study by Clark-Carter et al. (1986) who found that the walking speed of participants was significantly reduced by the complexity of the built environment.

Table 4.2 could also be used to compare different conditions. For instance, switching from an oblique angle to a right angle leads to a considerable speed reduction from 0.76 m/s (2.49 ft/s) to 0.67 m/s (2.20 ft/s) for individuals with a visual impairment (a 12% reduction) and from 0.76 m/s (2.49 ft/s) to 0.64 m/s (2.10 ft/s) for non-motorized ambulatory device users (a 16 % reduction). This change is marginal for individuals using motorized wheelchair. This finding may be due to the lower speed of motorized wheelchair users which enables them to control and maintain their speeds in more complex walking environments. An interesting similarity between all groups of people with disabilities was the insignificance of the difference between their mean walking speeds in the right angle facility versus their speed at the bottleneck. Although both turning movement and space unavailability significantly reduced the speed of individuals with disabilities, the magnitude of their impacts is not statistically different. However, this result is true only for individuals with disabilities. Individuals without disabilities walked slower in a narrow area (bottleneck) than a facility required a turning maneuver (right angle). This is likely the result of individuals with disabilities' increased need for advanced movement planning in a complex environment.

Table 4.3 presents the results of statistical tests for comparing walking speeds of different pedestrian groups. Similar to the previous hypothesis, ANOVA was used to identify differences in walking speed among different groups. The results indicate that the mean walking speed of people without disabilities was higher than all types of people with disabilities in all facilities except the bottleneck facility. There was no statistical difference between the walking speed of people with a visual impairment and people who used non-motorized ambulatory devices for walking in normal walking environments. People who used motorized wheelchairs, however, were slower than both people with visual impairments and people with non-motorized ambulatory devices, with the exception at the right angle facility. This finding might be attributed to the speed constraints of the motorized wheelchair itself. Video records showed that these people were more conservative in keeping a safe distance from other participants especially in situations with limited space. This might have also affected their speed. The comparisons also show that speeds of people with non-motorized devices are lower than visual impaired people in stair

Table 4.2
Hypothesis test of walking speeds for different pedestrian groups.

Type	Facility	Mean speed(m/s)	SD	N	*p*-value				
					Passageway	Oblique	Right	Bottleneck	Stair
Visual	Passageway	0.83	0.20	110	-	< 0.01	< 0.01	< 0.01	< 0.01
	Oblique	0.76	0.20	81	< 0.01	-	< 0.01	0.03	< 0.01
	Right angle	0.67	0.20	67	< 0.01	< 0.01	-	0.3	< 0.01
	Bottleneck	0.69	0.21	46	< 0.01	0.03	0.3	-	< 0.01
	Stair	0.38	0.12	45	< 0.01	< 0.01	< 0.01	< 0.01	-
Non-motorized	Passageway	0.83	0.19	51	-	0.04	< 0.01	< 0.01	< 0.01
	Oblique	0.76	0.22	49	0.04	-	< 0.01	0.11	< 0.01
	Right angle	0.64	0.18	38	< 0.01	< 0.01	-	0.1	< 0.01
	Bottleneck	0.7	0.21	31	< 0.01	0.11	0.1	-	< 0.01
	Stair	0.21	0.15	17	< 0.01	< 0.01	< 0.01	< 0.01	-
Motorized wheelchair	Passageway	0.69	0.21	32	-	0.34	0.18	0.02	-
	Oblique	0.67	0.18	34	0.34	-	0.3	0.03	-
	Right angle	0.65	0.14	30	0.18	0.3	-	0.053	-
	Bottleneck	0.56	0.31	39	0.02	0.03	0.053	-	-
Individuals without disabilities	Passageway	0.94	0.21	467	-	< 0.01	< 0.01	< 0.01	< 0.01
	Oblique	0.86	0.21	478	< 0.01	-	< 0.01	< 0.01	< 0.01
	Right angle	0.77	0.19	541	< 0.01	< 0.01	-	< 0.01	< 0.01
	Bottleneck	0.71	0.17	81	< 0.01	< 0.01	< 0.01	-	< 0.01
	Stair	0.54	0.15	511	< 0.01	< 0.01	< 0.01	< 0.01	-

experiments. This fact implies that mobility constraints are more restrictive on walking speed than visual impairments.

Table 4.3
Hypothesis testing for comparing walking speeds of different pedestrian groups.

Comparison groups		H_n^1 (5% significance level)				
		Passageway	Oblique	Right angle	Bottleneck	Stair
Visual	Non-motorized	No reject	No reject	No reject	No reject	Reject
	Motorized wheelchair	Reject	Reject	No reject	Reject	-
	Without disabilities	Reject	Reject	Reject	No reject	Reject
Non-motorized	Visual	No reject	No reject	No reject	No reject	Reject
	Motorized wheelchair	Reject	Reject	No reject	Reject	-
	Without disabilities	Reject	Reject	Reject	No reject	Reject
Motorized wheelchair	Visual	Reject	Reject	No reject	Reject	-
	Non-motorized	Reject	Reject	No reject	Reject	-
	Without disabilities	Reject	Reject	Reject	Reject	-
Without disabilities	Visual	Reject	Reject	Reject	No reject	Reject
	Non-motorized	Reject	Reject	Reject	No reject	Reject
	Motorized wheelchair	Reject	Reject	Reject	No reject	-

4.5 Summary and conclusions

Pedestrian walking behaviors have been extensively explored for planning and designing more effective transport infrastructures (Ma and Yarlagadda, 2014). However, majority of the past studies only considered homogeneous pedestrian stream and overlooked the heterogeneity in pedestrian population. There is limited research on walking speed of individuals with different type of disabilities and almost none examined the speed in crowd conditions. The purpose of this research was to explore the effect individuals with disabilities on crowd walking speed in different walking environments and compare and analyze walking speed of different individual types in various walking facilities. To this end, the walking speed of different type of pedestrians was studied through controlled experiments. More than 300 people including individuals without disabilities and individuals with mobility and visual impairments took part in the experiments conducted in a constructed circuit with different walking facilities (passageway, oblique angle, right angle, and bottleneck), as well as on a stairway. Participants were tracked using an advanced tracking system and their individual speeds were calculated using the resulting trajectory data. Statistical analysis of this data suggested the following key findings:

- The inclusion of individuals with disabilities had a considerable reduction of the mean speed of a heterogeneous population in all types of walking facilities. This effect was more pronounced for the stair facility.
- All pedestrian groups reached their maximum speed in the passageway. Considering this speed as their typical walking speed, all other facilities had a slowing effect. Facilities with more complex configurations (e.g., stair, bottleneck, and right angle) had the greatest slowing effect.
- Individuals without disabilities had a considerably higher speed than individuals with disabilities in all studied facilities except right angle. People who use motorized

wheelchairs had the lowest mean speed among all groups in all facilities. This finding might be attributed to the speed constraints of the motorized wheelchair itself.

- No statistical difference in the mean speed of people with visual impairments and people with non-motorized ambulatory devices was found in plain walking facilities.
- People with non-motorized ambulatory devices had a considerably lower speed than individuals with visual impairment in stair facility. This finding indicates that mobility constraints are more restrictive than visual impairments in this facility.
- Although both the right angle and bottleneck had a significant negative impact on the speed of individuals with disabilities, the magnitude of their impacts was not statistically different.
- Unlike individuals with disabilities, the walking speed of individuals without disabilities was considerably higher in the right angle compared to the bottleneck.
- Mean walking speed of visually impaired people, individuals with non-motorized ambulatory devices, and people who use motorized wheelchairs were 12%, 12%, and 26% lower than the people without disabilities in a passageway.

This study suggested many possibilities for future research. One possible extension would be to study other properties of crowd dynamics such as the capacity of facilities with the inclusion of individuals with disabilities. The majority of existing studies explored properties of a homogeneous pedestrian stream in different walking environments (Lam et al., 2002; Lam et al., 2003; Wong et al., 2010; Xie et al., 2013). These studies could be reexamined using heterogeneous pedestrian stream data. Examining the relationships between the basic traffic flow variables while considering individuals with disabilities could also be meaningful. Finally, developing fundamental diagrams for heterogeneous populations and comparing those with homogenous populations would provide valuable information to improve the planning and design of walking facilities.

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CHAPTER 5

CAPACITY ANALYSIS OF PEDESTRIAN QUEUING FACILITIES INVOLVING INDIVIDUALS WITH DISABILITIES

Abstract

To plan and design livable urban environments, it is imperative that walking facilities be designed to meet the needs of all pedestrians, including the elderly and individuals with disabilities. The design of pedestrian infrastructure is an important process usually achieved by means of supply/demand analysis. Critical to this process is correctly estimating infrastructure supply levels or capacities. While individuals with disabilities constitute a significant portion of the population in the United States, little is understood concerning the effect of including such individuals (the heterogeneous crowd) in the capacity of different build environments due to lack of available data. A controlled large-scaled walking experiment involving individuals with disabilities was conducted at Utah State University to observe individual pedestrian walking behaviors in various walking facilities including a queuing area. This chapter presents a framework to analyze time headways between different pedestrian groups in one directional pedestrian streams and identify the implications for capacity analysis of a queuing area. Results showed that including individuals with disabilities can significantly reduce the capacity of a queuing area. Specifically, individuals with visual impairments and non-motorized ambulatory devices had the minimum and individuals with motorized wheelchairs and individuals with mobility canes had the maximum capacity reduction effects. The outcomes are expected to

enhance current practice by considering vulnerable pedestrian groups as a part of capacity estimation process.

5.1 Introduction

Walking facilities are important infrastructure in a community's transportation systems. The pedestrians who use these facilities are diverse. Therefore, it is imperative to design and evaluate the effectiveness of these facilities to meet the walking needs of diverse pedestrian groups, including individuals with disabilities who represent a significant population in the United States (12.1% of the total U.S. population) (U.S. Census, 2010). Improperly designed walking systems may fail to operate at satisfactory levels when pedestrian demand exceeds the capacity. In practice, facility designers use Highway Capacity Manual (HCM) (HCM, 2010) guideline to estimate the walkway capacities. However, the guideline assumes typical homogenous population characteristics. The presence of different components in the pedestrian flow stream, such as individuals with mobility and visual constraints, may have a substantial impact on walkway capacities. In this case, walking design manuals need to be modified accordingly to consider walking needs of all types of pedestrians.

In the literature, macroscopic approaches have been applied to estimate the capacity of different walking facilities such as corridors (Lam and Cheung, 2000; Ye et al., 2008) and bottlenecks (Seyfried et al., 2009). In this approach, it is necessary to collect macroscopic pedestrian flow in saturation density levels to obtain reliable capacity estimations. However, the approach is not able to account for impacts of different pedestrian groups such as individuals with disabilities on walkway capacities. Only few studies investigated microscopic behavior of pedestrians in crowd environment (Hoogendoorn and Daamen, 2005; Duives et al., 2015; Johonson, 2009). But, they also overlooked heterogeneity in pedestrian composition due to data collection constraints. To overcome this limitation, a controlled large-scaled walking experiment involving individuals with disabilities was conducted at Utah State University (USU) to explore the impacts of involving individuals with disabilities on the capacity of various walking facilities such as queuing area behind a doorway. Queuing areas can be observed in many real situations where people queue for services such as public transfer stations. Ignoring diverse pedestrian groups as a part of capacity analysis may lead to improperly designed environments and the consequence is unsatisfactory performance particularly in emergency situations. There are limited studies investigated impacts of involving diverse groups on the capacity of a doorway. For example, Daamen and Hoogendoorn (2012) conducted a research experiment in the Netherlands to investigate the capacity of doorways with consideration of elderly and disabled people. They analyzed the relation between doorway capacities, population compositions, and stress level during emergency situations. However, their provided method was applicable only for a cross section (e.g., a doorway) and couldn't be used to estimate the capacity of the areas adjacent to the doorway.

This Chapter presents a microscopic approach to estimate capacity of a queuing area for a uni-directional pedestrian flow. Specifically, time headway between different pedestrian groups is examined and a mixed time headway distribution is used to estimate the capacity. Moreover, the effects of involving different individuals with disabilities are investigated. Fig. 5.1 shows a snapshot of the experimental area.

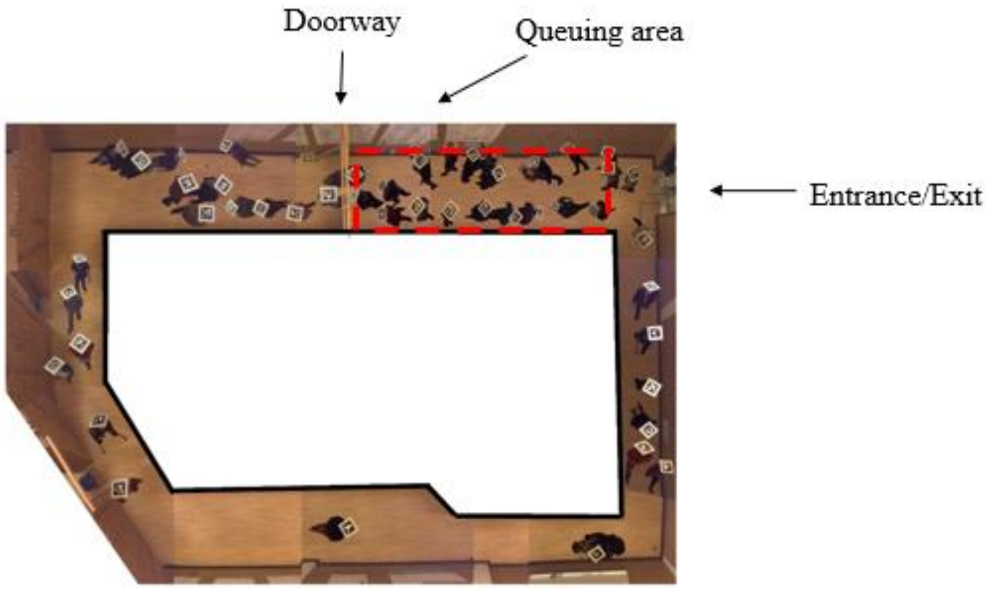


Fig. 5.1. A snapshot of the queuing area.

5.2 Background

In order to provide effective walking infrastructure, designers should have insight into the capacity of walking facilities to meet the preferred level of service for planned walking demands. In the pedestrian literature, many researchers have extensively explored macroscopic pedestrian traffic flow characteristics to study walkway capacities and operational performance of walking facilities. These studies began in 1963 with an attempt to study on pedestrian flow characteristics in Germany. Oeding (1963) collected pedestrian volumes, densities and speeds in a shopping street and examined relationships between them. Five years later, he collected and analyzed macroscopic characteristics of pedestrian flow in a shopping street in London, United Kingdom (Older 1968). He then developed a fundamental diagram to specify the performance of walkways. Navin and Wheeler (1969) recorded pedestrian flow variables on walkways at three locations on the University of

Missouri campus in Columbia. They provided fundamental relationships between pedestrian speed, density, and flow. Polous et al. (1983) collected pedestrian data in the central business district of Haifa, Israel, using a videotape recorder and a digital clock. They analyzed properties of pedestrian flow on sidewalks and calibrated pedestrian traffic flow models. Tanariboon et al. (1991) conducted research on several sidewalks in Singapore and recorded pedestrian movements using a video recorder. They extracted macroscopic pedestrian flow variables using photographic techniques and proposed mathematical models for fundamental flow relationships (i.e. speed-density, speed-flow, and flow, density). Calibrated models revealed that the optimal pedestrian space and maximum observed flow (i.e. capacity) were about 0.7 m^2/p and 90 p/min/min, respectively. Other primary efforts on pedestrian flow modeling can be found in studies by Pushkarev and Zupan (1975), Khisty (1985), Tanaboriboon and Guyano (1991), Daly et al. (1991), Ando et al. (1988), and Virkler and Elayadath (1994).

Later, more advanced technologies were used to collect pedestrian stream characteristics. Lam and Cheung (2000) empirically investigated the effects of bi-directional pedestrian flows on free-flow walking speed, at-capacity walking speed, and effective capacity for a selected indoor walkway in Hong Kong. Helbing et al. (2007) analyzed a crowd disaster in Makkah, Saudi Arabia during the Hajj pilgrimage using video recording data. They explored relationships between macroscopic fundamental variables and analyzed various self-organization phenomena during the disaster. Ye et al. (2008) collected data for longitudinal pedestrian flows (i.e. unidirectional and multidirectional flows) in a metro station in Shanghai, China using video recordings. They calibrated pedestrian fundamental traffic flow diagrams for different indoor walking facilities including level passageway and stairs (ascending, descending and two-way). Based on calibration results, they concluded that the capacity of ascending stairways are slightly higher than descending stairways and two-way stairs have considerable lower capacities than one-way stairs. Most of the mentioned studies have been conducted in in urban areas. Pedestrian traffic density on sidewalks does not regularly reach to high extreme levels. Therefore, there is a significant lack of observations in density ranges in which the walking facility is operating at its capacity level. In response, controllable walking experiments have been conducted by many researches to collect pedestrian data for extreme conditions such as highly congested situations.

Daamen and Hoogendoorn (2003) conducted walking experiments at Delft University of Technology in Netherlands to derive walking behavior in passageways and bottlenecks under different pedestrian flow scenarios such as un-directional, bi-directional, and cross pedestrian flows. A sample representative for the Dutch population with 80 participants was invited and ten experiments were performed to observe pedestrian walking behavior in standard, station, and shopping conditions. They observed and analyzed pedestrian stream characteristics for a wide range of density levels, from free-flow conditions to extremely congested situations. A fundamental diagram was developed to analyze operation performance of the walking facilities. Specifically, they found that the capacity of the bottleneck facility was approximately 90 p/min/m for uni-directional pedestrian flow. Another set of controlled walking experiments was administered in Germany to analyze and evaluate performance of various walking facilities such as circular passageway (Seyfried et al., 2005), a corridor (Kretz et al., 2006 (a)), a bottleneck (Kretz et al., 2006 (b)), a T-junction (Zhang et al., 2011), and a set of stairs (Burghardt et al., 2013). Seyfried et al. (2009) examined the capacity of bottlenecks with different widths under uni-directional pedestrian stream. 18 runs of experiments were conducted using 20, 40 and 60 pedestrians. Data analysis revealed that the bottleneck capacity grew linearly with increasing width. Wong et al. (2010) developed and calibrated a bidirectional pedestrian model with an oblique intersecting angle through controlled walking experiments. They used the calibrated model to explore pedestrian flow characteristics in oblique angle environment.

5.2.1 Criticism on existing capacity analysis approaches

As summarized above, a great deal of study has been conducted on pedestrian stream characteristics and capacity of different walking environments. However, there are two limitations embedded in the existing regulations and pedestrian studies: (1) these studies did not address the pedestrian flow characteristics involving people with mobility and visual constraints, and (2) the proposed capacity estimation methods were not able to account for pedestrian microscopic behaviors.

While individuals with disabilities constitute a significant proportion of the population of United States, little is understood concerning the effect of involving such individuals (the heterogeneous crowd) on the capacity and flow conductibility of different build environments. Most of existing walking facility guidelines and regulations such as the HCM and the IBC code overlook individuals with disabilities as part of pedestrian stream and they do not account for the impact of individuals with disabilities on walkway capacity evaluations. Only the ADAAG manual proposes building facility design considering individuals with disability needs. However, this code establishes the sizing of the walking facilities based only on dimensions and space needs of individuals with disabilities; it does not account for interactions between individuals and built environments. In addition, the guideline does not provide a systematic way to evaluate the capacity of walking environments in presence of individuals with disabilities. There is a limited number of studies considering people with low mobility, including individuals with disabilities in capacity analysis process. Daamen and Hoogendoorn (2011) conducted a research experiment in the Netherlands to investigate the capacity of doorways with consideration of elderly and disabled people. They analyzed the relation between doorway capacities, population compositions, and stress level during emergency situations.

Generally, proposed capacity estimation approaches use macroscopic fundamental diagrams to estimate the capacities. These diagrams are developed based on macroscopic flow characteristics. Therefore, these approaches are incapable of capturing the impacts of any one individual's behavior on the capacity of walking facilities. The presence of special components in the pedestrian flow stream, such as individuals with mobility and visual constraints, may have a substantial impact on design guidelines (Hoogendoorn, 2004). In this case, walking design requirements need to be modified accordingly to consider walking needs of all types of pedestrians. Table 5.1 summarizes some existing walking facility guidelines and pedestrian studies and their approaches in walking capacity analysis.

Table 5.1
Summary of capacity analysis specifications in manuals and pedestrian studies.

Reference	Approach		Considering Individuals with disabilities	Facility types
	Macroscopic	Microscopic		
HCM	•		No	Crosswalk
IBC	•		No	Building components
ADAAG	•		Yes	Building components, crosswalk
Oeding (1963)	•		No	Crosswalk
Older (1968)	•		No	Crosswalk
Navin and Wheeler (1969)	•		No	Crosswalk
Polous et al. (1983)	•		No	Crosswalk
Tanariboon et al. (1991)	•		No	Crosswalk
Lam and Cheung (2000)	•		No	Indoor walkways
Helbing et al. (2007)	•		No	Circular passageway
Ye et al. (2008)	•		No	Level passageway, stairs
Daamen and Hoogendoorn (2003)	•		No	Passageway, bottleneck
kretz et al. (2006)	•		No	Corridor
Zhang et al. (2011)	•			T-junction
Burghardt et al. (2013)	•			Stair
Seyfried et al. (2009)	•		No	Bottleneck
Wong et al. (2010)	•			Oblique angle
Daamen and Hoogendoorn (2011)	•		Yes	Doorway

5.3 Methodology

In vehicular traffic flow analysis, the time headway is defined as the time that elapses between the arrival of the leading vehicle and following vehicle at a designated cross section. This concept can be slightly modified and extended for modeling pedestrian flow. The first step is to define a personal space for each individual. This space determines a region surrounding each individual for specifying pedestrian groups which potentially can have substantial influence on their walking behaviors. The personal space can be considered as a rectangular space defining the lateral and longitudinal boundaries. Considering the shoulder width, body sway, and avoidance of contact with others, Fruin suggested a minimum lateral space of 0.71 m (28 inches) to 0.76 m (30 inches), and 2.5 m (8 ft) to 3 m (10 ft) for lateral and longitudinal space, respectively (Fruin, 1971). In this study, the latitude personal space is assumed to be 0.71 m and the longitudinal personal space is considered to be 2.5 m. Two groups of pedestrians can have influence on a particular pedestrian's walking behavior; 1. Leader group 2. Collider group. Leader group is defined as a set of pedestrians which are effectively being followed by other individuals. On the other hand, collider group is a set of pedestrians walking toward individuals and influence on walking behaviors. Fig. 5.2 depicts the concept of personal space and leader/collider definition.

In this study, instantaneous time headway is proposed as a temporal distance measure between followers and leaders. Trajectory data makes it possible to differentiate leader and collider groups and compute the instantaneous time headway for each individual using the following basic relationship:

$$TH_f(t) = \frac{\left\| \overrightarrow{r_f(t)} - \overrightarrow{r_l(t)} \right\|}{\overrightarrow{v_f(t)}} \qquad \overrightarrow{v_f(t)} > 0 \tag{5.1}$$

where $\overrightarrow{r_f(t)}$, $\overrightarrow{r_l(t)}$, and $\overrightarrow{v_f(t)}$ stand for follower position in time t in meter unit, leader position in time t in meter unit, and instantaneous follower speed in time t in meter per second unit, respectively.

The relationship implies that the instantaneous time headway for each time frame can be obtained by spacing between follower and leaders divided by the follower walking speed. Note that the definition is slightly different than the time headway concept used in highway traffic. While, time headway is directly measured in highway traffic at a specific location, the proposed method computes instantaneous time headway (temporal distances) by keeping track of follower and leader trajectories in each time frame.

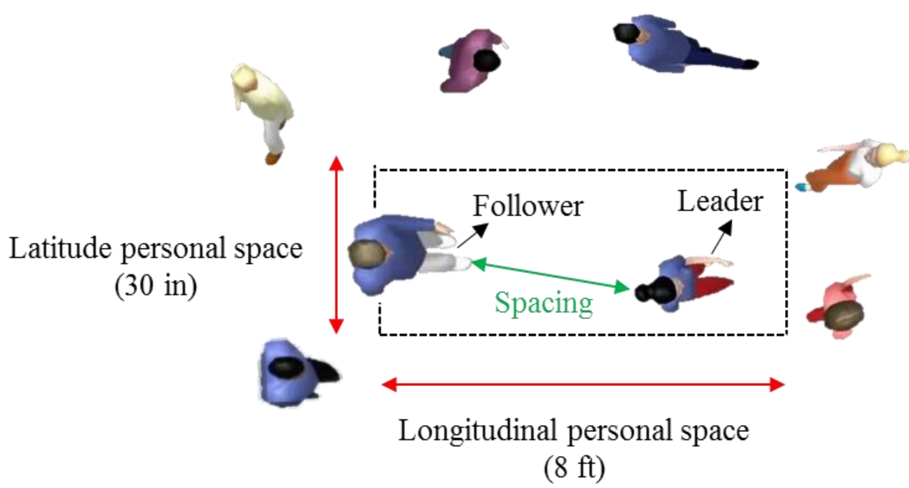


Fig. 5.2. Personal space definition.

5.3.1 Time headway modeling methodology

A large number of simple headway distribution models have been proposed in traffic flow studies. However, the main problem of the simple distributions is their inability to identify minimum or adequate time headway for capacity estimation purpose. Therefore, a mixed headway distribution model, distinguishing between unconstrained (or freely moving) and constrained (or following) time headway was applied in this study. The Generalized Queuing Model (GQM), proposed by Cowan (Cowan, 1975) and Branston (Branston, 1976), is a mixed probabilistic distribution model handling time headway as the sum of two mutually independent variables: constrained and free flowing headway. Constrained time headways are always less than free flow time headways and there is a probabilistic threshold to classify time headways into unconstrained and constrained time headways. The general form of GQM can be defined as follows:

$$f_{\pi}(t) = \theta_{\pi} \times g_{\pi}(t) + (1-\theta_{\pi}) \times h_{\pi}(t) \tag{5.2}$$

where $f_{\pi}(t)$ = time headway probability density function for leader type π

θ_{π}= fraction of constrained time headways by leader type π

$g_{\pi}(t)$ = probability density function of the constrained headway (empty zone distribution) for leader type π

$h_{\pi}(t)$ = probability density function of the free flowing headway for leader type π

Cowan derived the model, assuming that the empty zone distribution (constrained time headways) could be represented by Gamma distribution while free flowing time headways can be represented by mixed exponential-gamma distribution consequent to the convolution theorem (Cowan, 1975). The model is called Gamma-GQM. Note that the model is applied to investigate time headways between pedestrians and different leader types and it doesn't account for the percentage of specific leader types in traffic stream. In this study, time headways between followers (individuals without disabilities) and six leader classes were studied: 1. individuals without disabilities leaders (homogeneous experiments), 2. Mixture of individuals without and with disabilities (heterogeneous experiments) 3. individuals with visual impairments, 4. individuals who use mobility canes, 5. individuals who use non-motorized devices for walking (e.g., wheelchair/roller walker), and 6. individuals using motorized wheelchairs. The Gamma-GQM model can be presented as follow:

$$f(t) = \theta \frac{\beta^{\alpha} t^{\alpha-1}}{\Gamma(\alpha)} e^{-\beta t} + (1-\theta) \frac{\beta^{\alpha}}{\Gamma(\alpha)} \lambda e^{-\lambda t} \int_0^t x^{\alpha-1} e^{-x(\beta-\lambda)} dx \tag{5.3}$$

where α, β, denote shape and scale parameters of Gamma distribution, respectively. λ stands for average arrival intensity in free flowing condition, and Γ is the gamma function. The parameters can be estimated using the Maximum Likelihood Estimation (MLE) method. The likelihood function of Gamma-GQM can be obtained using the following equation:

$$\begin{aligned} LL(t) &= -n \ln \Gamma(\alpha) + \sum_{j=1}^{n} \ln[\theta(\beta t_j)^{\alpha-1} \beta e^{-\beta t_j} + (1-\theta)(\frac{\beta}{\beta-\lambda})^{\alpha} \frac{\gamma[\alpha, t(\beta-\lambda)]}{\Gamma(\alpha)} \lambda e^{-\lambda t}] \\ s.t. & \quad 0 \le \theta \le 1 \end{aligned} \tag{5.4}$$

where n stands for total number of observations, and γ represents incomplete gamma function. The Gamma-GQM parameters can be used for capacity estimation purposes where capacity of a walking facility equals the inverse of minimum pedestrian time headways. The empty zone reflects the minimum time headway that a pedestrian adopts to follow the leaders. Therefore, expected capacity can be estimated by inversing the mean empty zone distribution, assuming that in capacity-flow conditions all pedestrians maintain constrained time headways respect to their leaders.

$$Cap = \frac{1}{W \times E(\mathrm{X})} \tag{5.5}$$

where *W* and *E(X)* stand for average pedestrian lane width [m] and mean empty zone distribution [s], respectively. In fact, inverse of mean empty zone yields the expected capacity per pedestrian lane width unit and it can be converted to capacity per meter unit by dividing to pedestrian lane width. In the proposed method, time headway model can be separately calibrated for each leader type and impacts of different leader types on capacity estimation can be identified using corresponded empty zone distribution. Fig. 5.3 depicts the overall framework of the research.

5.4 Trajectory visualization

Due to the large amount of video data collected from the large-scale controlled experiments, extraction software with a Graphical User Interface (GUI) was developed. This user-friendly GUI is able to manage, process, and visualize the video data collected from the walking experiments. The developed GUI consists of three main components:

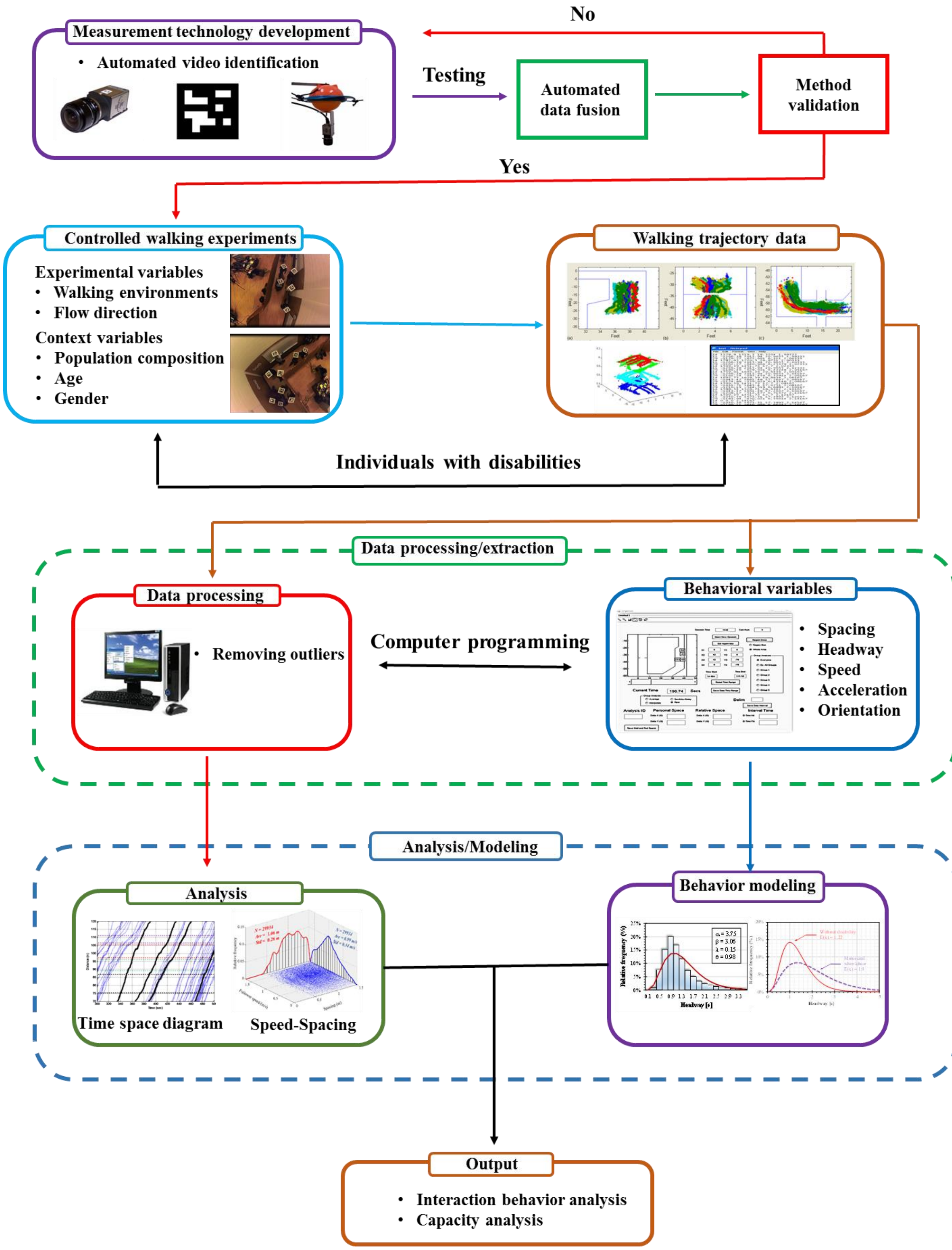


Fig. 5.3. Capacity analysis framework.

visualization, processing, and behavioral data extraction. To visualize the experimental process, a simple CAD drawing of the study area was incorporated into the GUI on which the pedestrian movements are depicted according to their identification IDs during the experiments. The processing component makes it possible to extract the raw trajectory data for a selective area or selected time duration for all pedestrians or for a selective group of pedestrians (e.g. pedestrians with disabilities). In addition, microscopic behavioral variables (e.g., instantaneous speed and acceleration longitudinal and lateral spacing, time headway, orientation, local speed, flow and density) can be extracted using the GUI. The software can extract the behavioral data for all pedestrians or for a particular target pedestrian. Fig. 5.4 presents the GUI components and preliminary trajectory results. The data shows formations consistent with the facility and indicates that pedestrians deviate from a straight path. The deviations are more observable for individuals with disabilities suggesting that their walking behaviors were more affected by the congested condition.

5.5 Fundamental diagrams

To explore how comparable are pedestrian and vehicle traffic flow patterns, fundamental diagrams are investigated. These diagrams show relationship between macroscopic variables such as density, flow, and speed. Definitions of macroscopic variables are relatively straightforward in unidirectional vehicular traffic flow. But it is more complicated to measure these variables in pedestrian traffic flow due to pedestrians' multi-dimensional movements. In this study, the generalization of Edie's definition was adopted (Daamen and Hoogendoorn, 2003). This generalization is a reasonable way to

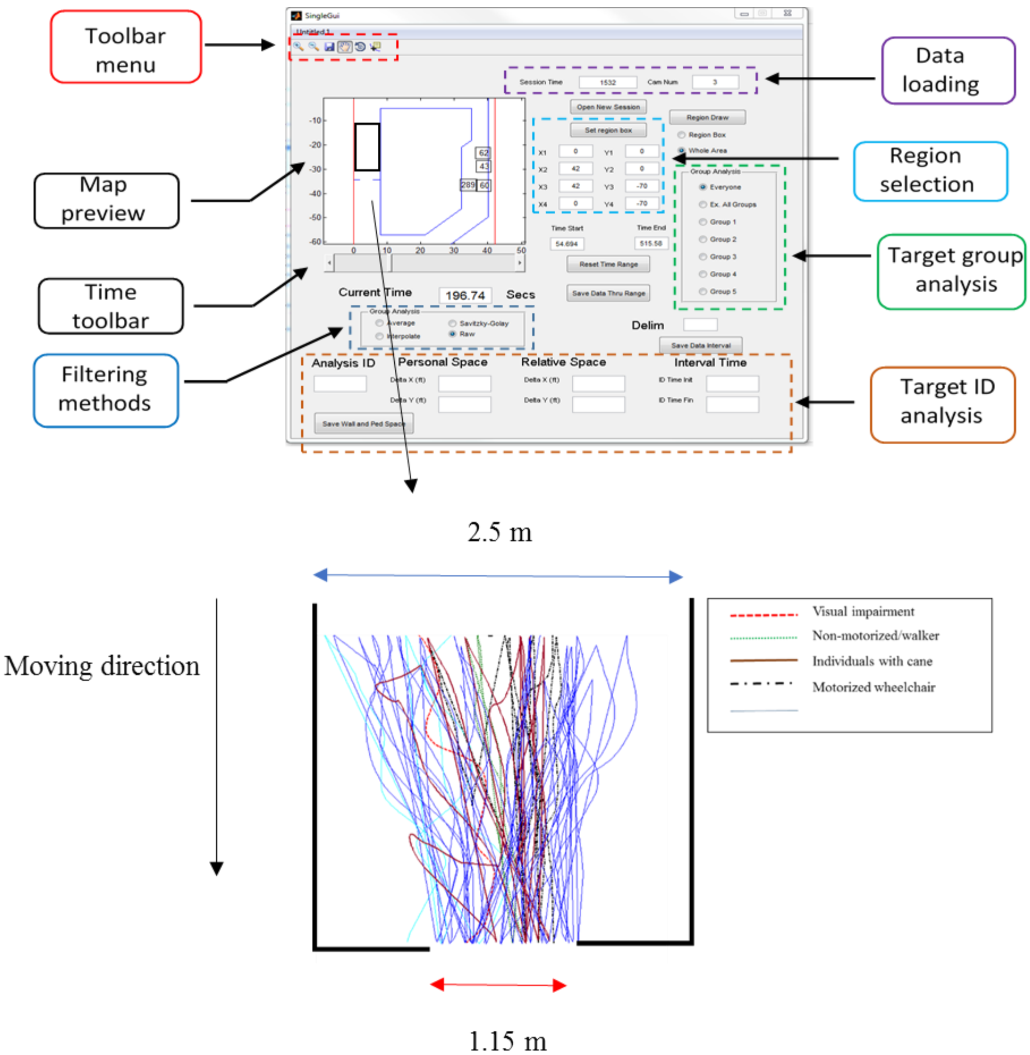


Fig. 5.4. GUI snapshot and trajectory visualization.

extend the vehicular traffic flow definitions for pedestrian traffic flow streams. Generalized density is defined as the sum of walking time spent in the study area divided by multiplication of the area and data extraction time interval:

$$D = \frac{\sum_i TT_i}{AT} \tag{5.6}$$

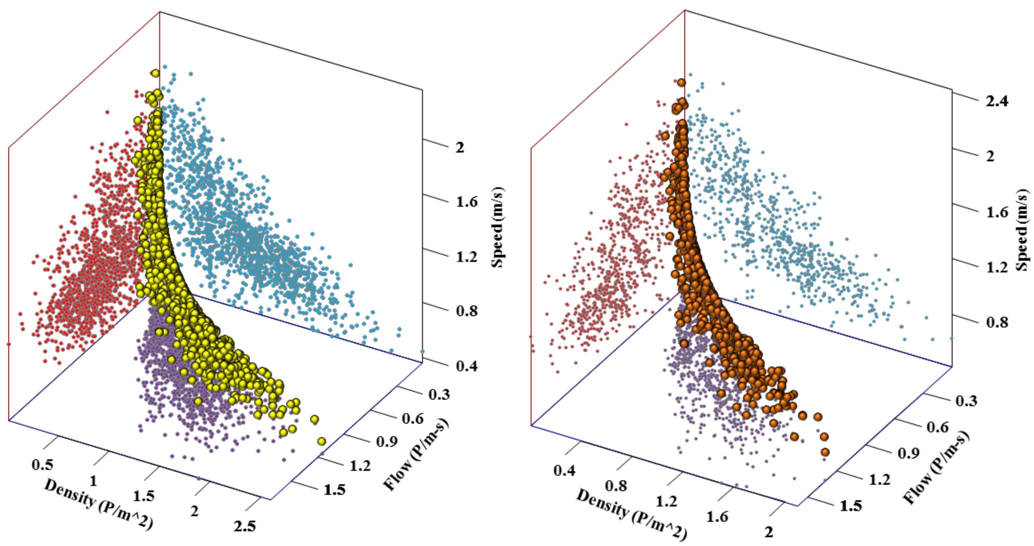
where T is the selected time interval for data extraction, A is area of facility, and TT_i is defined by walking time spent in the study area by pedestrian i. The generalized definition of flow is defined as the sum of walking distances divided by multiplication of the area and data extraction time interval:

$$F = \frac{\sum_i L_i}{AT} \tag{5.7}$$

where L_i is the travelled distance during the time interval. Finally, speed is defined as the sum of distances travelled by pedestrian divided by the sum of travel time:

$$S = \frac{\sum_i L_i}{\sum_i TT_i} \tag{5.8}$$

All session data were combined and fundamental traffic flow variables including density, flow, and speed were extracted using Edie's generalized definitions. Fig. 5.5 shows 3-D fundamental diagrams for homogeneous and heterogeneous scenarios. Each data point in these diagrams represents extracted data for a 1 sec time interval (i.e. T=1 sec). X-Y, X-Z, and Y-Z planes show density-flow, density-speed, and flow-speed relationships respectively. Similar patterns can be observed when comparing pedestrian flow and vehicle traffic flow. The speed-density diagram shows negative correlation between speed and density for all facilities. In other words, pedestrian speed decreases as the density increases. In lower densities dispersion of speed data is higher compared to high densities, implying that pedestrian can walk at their desired speed but are constrained by other pedestrian in high densities and their speed lies in a narrow range. The density-flow diagram also show a parabolic trend between density and flow similar to vehicular flow. The diagram trend indicates that flow increases with increasing density until a threshold density and then it decreases with increases in density.



(a) (b)

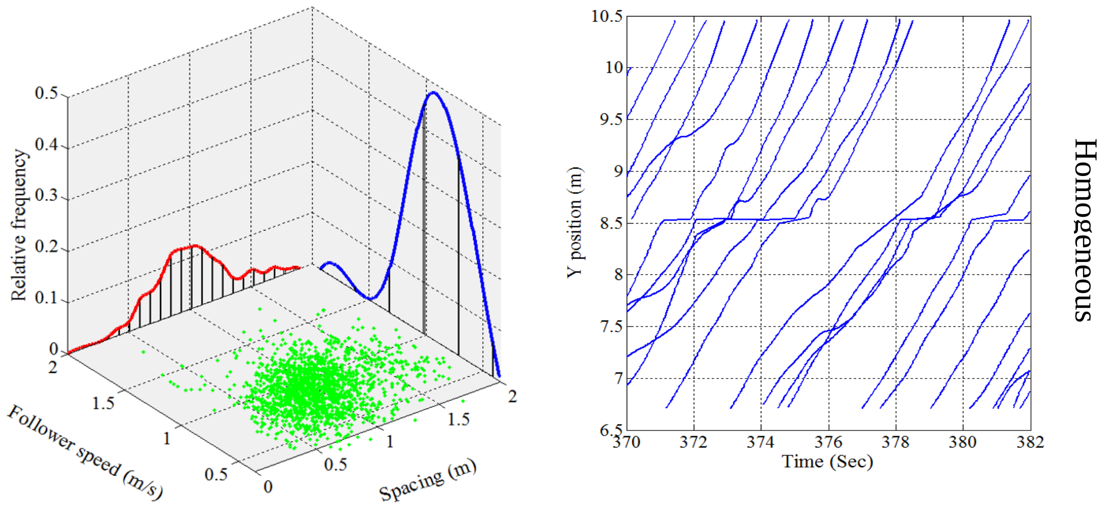
Fig. 5.5. Fundamental diagrams a) homogeneous population b) heterogeneous population.

5.6 Microscopic analysis

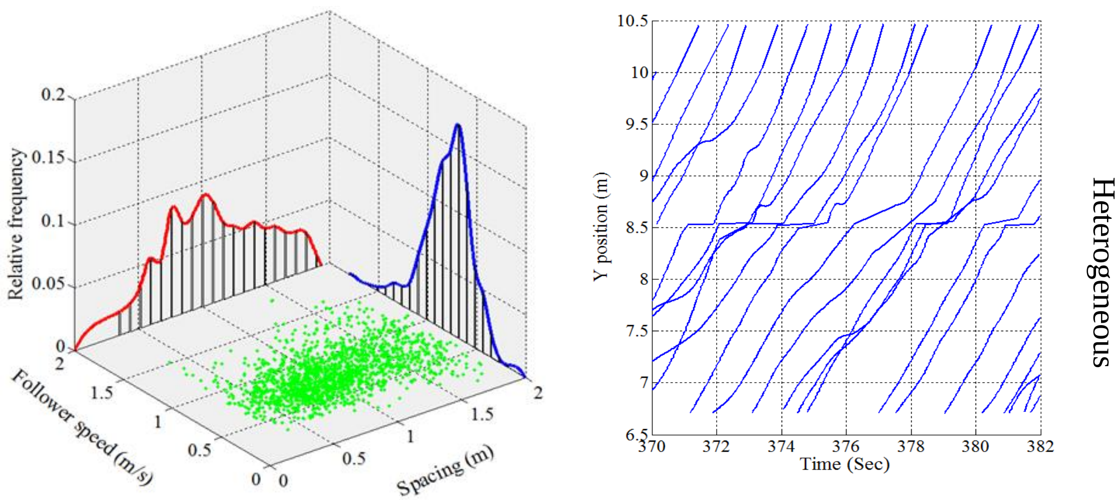
To investigate the walking behavior of different pedestrian groups, follower speeds and spacing data can be examined as the two main components of time headway. Follower speed and spacing show how pedestrians changed their walking behavior with respect to their leaders. The observed distributions and time-space diagrams for different leader types can be found in Fig. 5.6. In the observed distributions, the points on the horizontal surface shows the observed distribution of spacing and follower speed, and the projected histograms show the observed marginal distributions. The figure also shows time-space diagrams presenting position of each pedestrian across time. The vertical distance between two consecutive lines indicates the spacing between the pedestrians, whereas the horizontal distance between two consecutive lines indicates the time headway between pedestrians. In addition, the slope of the trajectories represents the speed of participants with the curved portions indicating speed changes.

The observed distributions show walking behavior changes with respect to different leader types. Table 5.2 presents basic descriptive statistics including number of observations (N), mean, and standard deviation (Std) of followers' speed, spacing, and time headway between leaders and followers. Compared to individuals without disability leaders (i.e., homogeneous scenario), results indicate that followers generally walked with lower mean speed and they maintained higher spacing with respect to their disabled leaders. Table 5.2 shows that followers kept the lowest mean time headway with respect to individuals with non-motorized ambulatory devices and visually impaired and they maintained much greater mean time headway with respect to individuals with mobility canes and individuals who use motorized wheelchair.

The time-space trajectories also confirm that the pattern of walking behaviors changed around individuals with disabilities. The diagrams represent that individuals maintained a more conservative spacing from individuals with disabilities. These behavioral changes are more profound with respect to individuals with motorized wheelchair. The next section examines the hypothesis that these behavior changes have an effect on the capacity of queuing area.

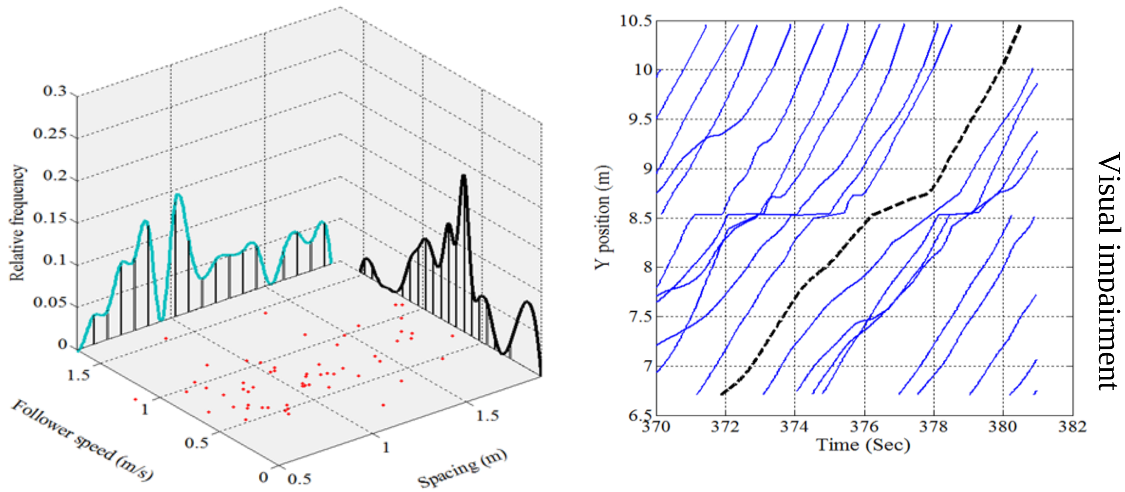


(a)



(b)

Fig. 5.6. Observed follower speed and spacing distributions and time space diagrams for different leader types a) homogeneous b) heterogeneous (continued on next page).



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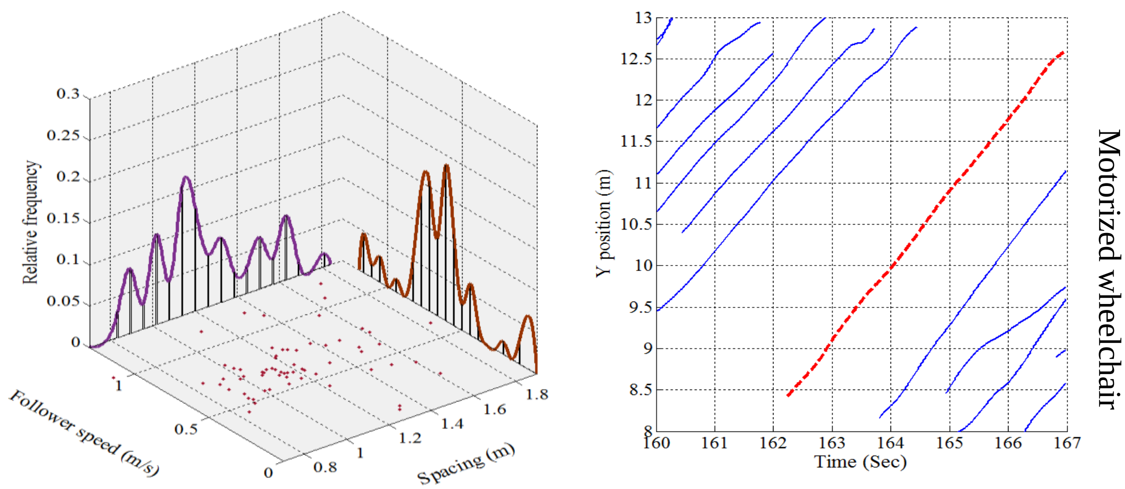
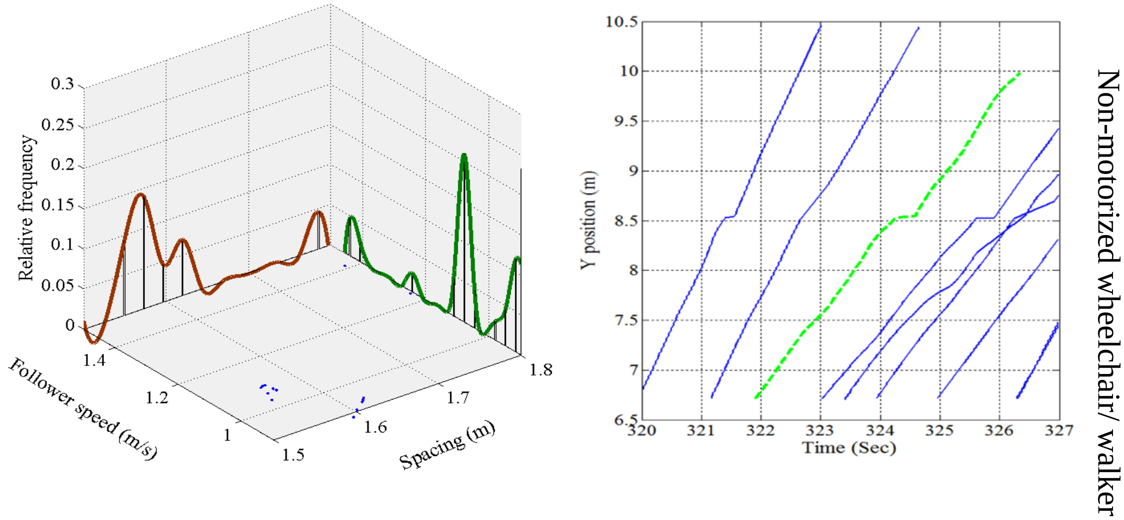


(d)

Fig. 5.6. (continued) Observed follower speed and spacing distributions and time space diagrams for different leader types c) visual impairment d) motorized wheelchair (continued on next page).



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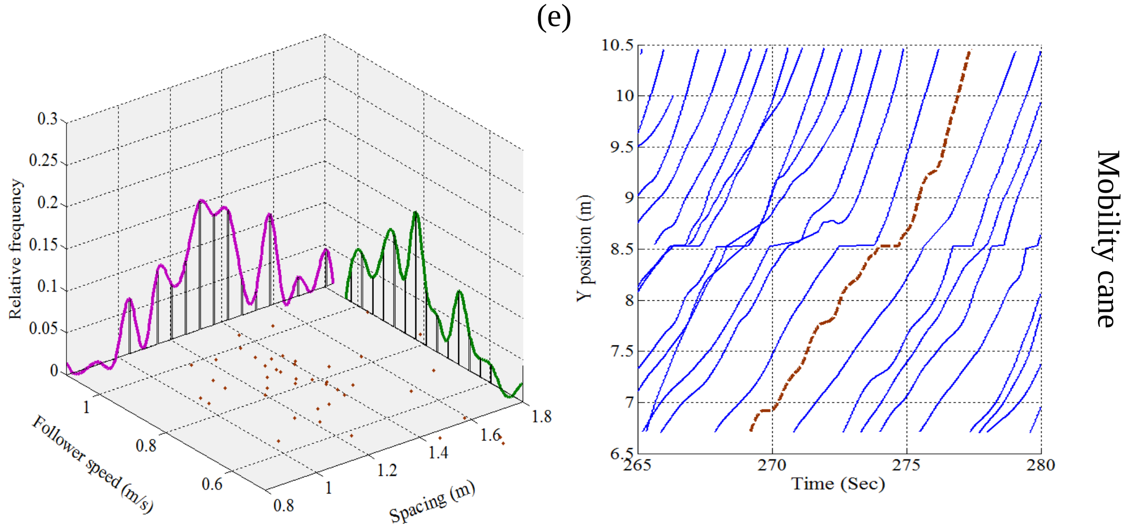


(f)

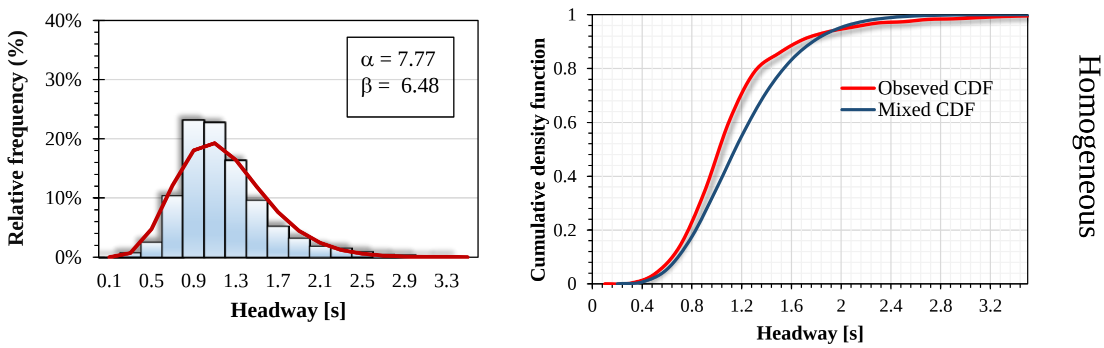
Fig. 5.6. (continued) Observed follower speed and spacing distributions and time space diagrams for different leader types e) non-motorized wheelchair/walker f) mobility canes.

Table 5.2
Followers' speed, spacing, and time headway descriptive statistics.

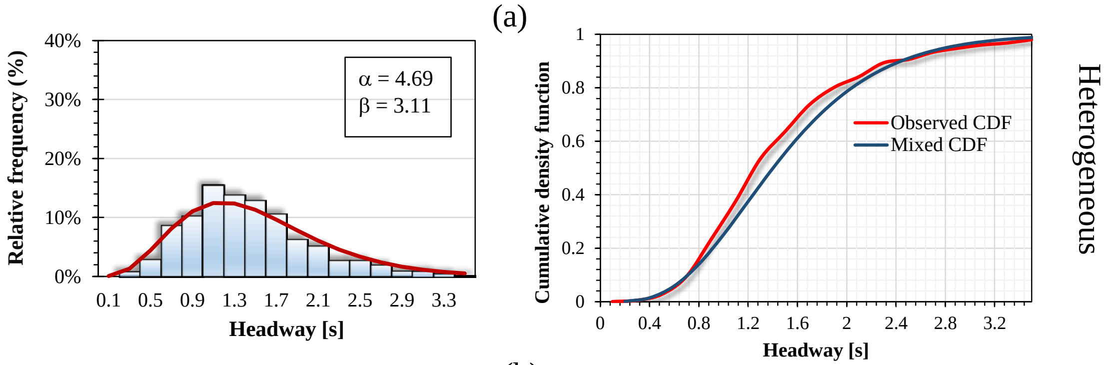
		Followers' speed		Spacing		Time headway	
Leader type	N	Mean (m/s)	Std (m/s)	Mean (m)	Std (m)	Mean (s)	Std (s)
Homogeneous	1852	0.89	0.27	1.01	0.29	1.20	0.45
Heterogeneous	1619	0.78	0.22	1.08	0.38	1.52	0.83
Visual	59	0.79	0.24	1.12	0.36	1.56	0.77
Motorized	64	0.67	0.21	1.22	0.25	2.27	2.21
Non-motorized/walker	43	0.98	0.17	1.49	0.11	1.55	0.21
Cane	46	0.78	0.17	1.34	0.22	1.81	0.62

5.6.1 Time headway modeling and capacity analysis

Gamma-GQM model parameters were estimated using maximum likelihood estimation method. 80% of collected data were used for calibration and 20% of data were reserved for model validation purpose. Specifically, Generalized Reduced Gradient (GRG) was used to maximize the non-linear function presented in Eq. (5.4). Fig. 5.7 shows the results of applying the estimation method across different leader types. The histograms show the observed time headway distribution and the curves present the fitted model. The figures indicate that the model fitted to observed data well for most leader types. A sharp peak can be identified for individuals without disability leader type, while the peak is much flatter and shifted to the right for individuals with disability leaders, suggesting that a larger portion of pedestrians in the queuing area followed individuals without disability leaders in lower time headway ranges compared to disabled leaders. Also, performance of calibrated models are investigated comparing observed and estimated cumulative density function for 20% reserved data. Fig. 5.7 implies that the model had better performance for homogeneous and heterogeneous population probably due to larger number of observations compared to different disabled leader types.



(a)



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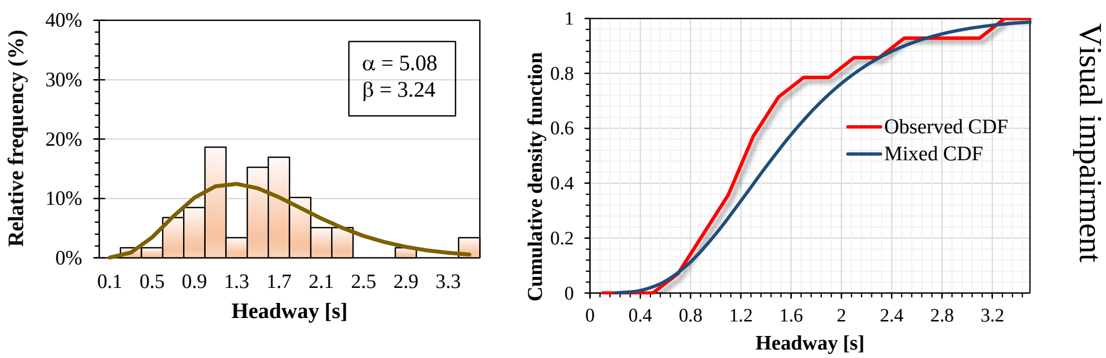
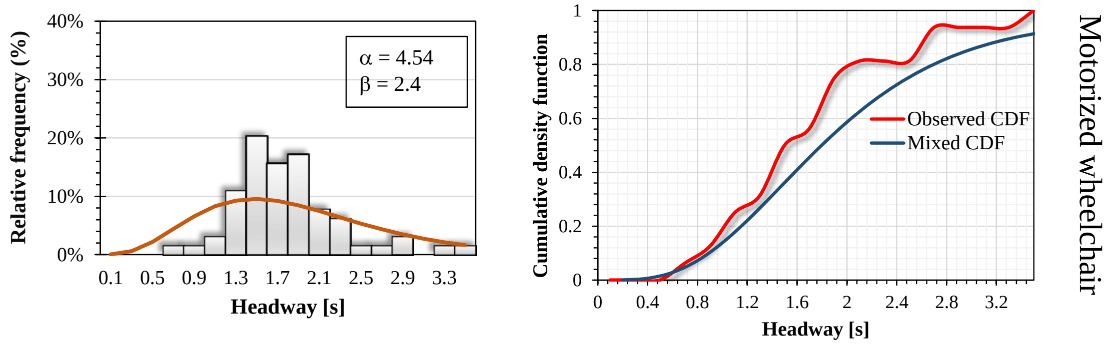


(c)

Fig. 5.7. Results of estimations considering different leader types a) homogeneous b) heterogeneous c) visual impairment (continue on next page).



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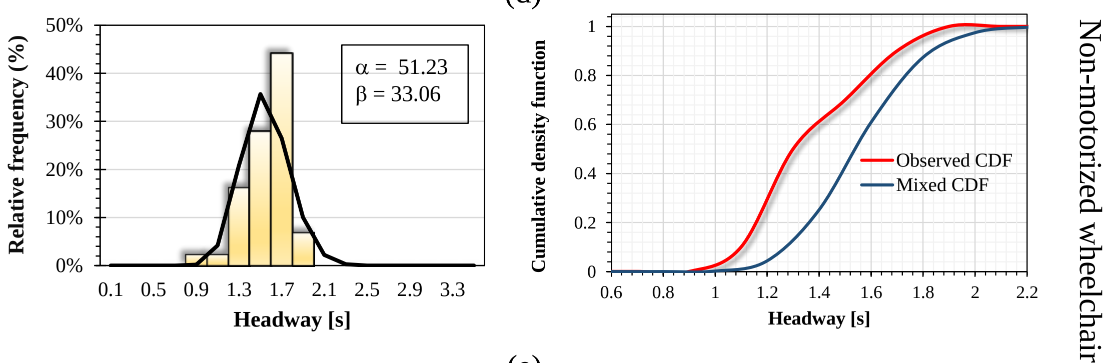

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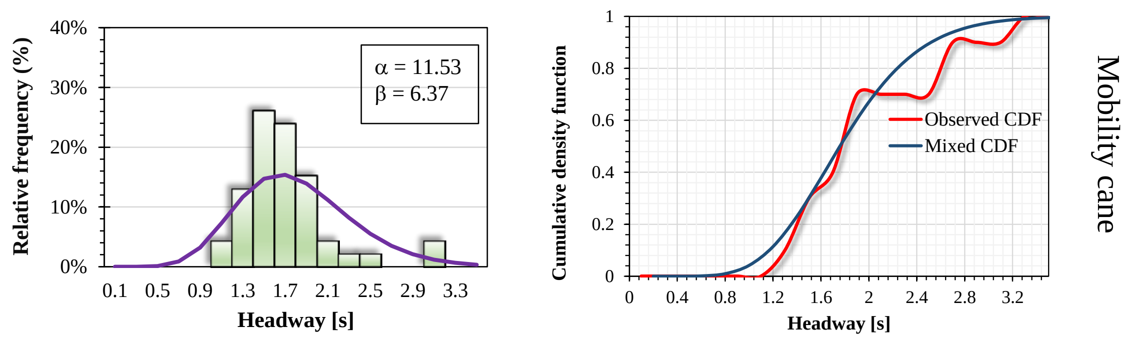

(f)

Fig. 5.7. (continued) Results of estimations considering different leader types d) motorized wheelchair e) non-motorized wheelchair/walker f) mobility canes.

Table 5.3 presents the estimation results of the Gamma-GQM model for different leader types. This Table includes the estimation results including, fraction of constrained time headways (θ), Gamma distribution shape parameter (α), Gamma distribution scale parameter (β), empty zone mean (E(x)) [s], capacity per pedestrian lane width (C) [ped/lane/s], capacity per meter width (Cap) [ped/m/s], and Kolmogorov-Smirnov statistic (K-S statistic). Analysis revealed that constrained time headway fraction is close to 1 in most cases. In other words, follower pedestrians were generally constrained by their leaders. The finding is plausible as we observed congested conditions in the queuing area in most of experimental time duration. Results indicate that there are significant differences in estimated parameters supporting that time headways change significantly with respect to leader types. Note that the estimated shape (α) and scale parameters (β) don't have any straight forward interpretation from a traffic flow point of view (Hoogendoorn and Bovy, 1998) and only indicates that there are statistically significant differences between behaviors with respect to different leader types. To investigate quality of calibrated models, Kolmogorov-Smirnov statistics (K-S statistic) was calculated for the reserved data. This statistics represents the maximum difference between observed and estimated cumulative density functions.

Table 5.3
Summary of Gamma-GQM estimation results.

Leader type	θ	α	β	E(x)	C	Cap	K-S statistic
Homogeneous	1	7.77	6.48	1.20	0.83	1.09	0.07
Heterogeneous	1	4.69	3.11	1.51	0.66	0.87	0.04
Visual	1	5.08	3.24	1.56	0.64	0.84	0.11
Motorized	0.96	4.54	2.4	1.89	0.53	0.7	0.16
Non-motorized	1	51.23	33.06	1.55	0.64	0.84	0.25
Cane	1	11.53	6.37	1.81	0.55	0.72	0.22

Table 5.3 indicates that the mean empty zones for individuals without disability leaders (homogeneous population) were much lower than individuals with disability

leaders in heterogeneous population. Also, results showed that empty zones for different individuals with disability leaders are not similar. For instance, the mean empty zone for individuals with visual impairments and individuals with motorized wheelchairs were 1.56 sec and 1.89 sec, respectively, which supports the observation of how followers changed their behavior with respect to these leader types in the queuing area. Estimated empty zone parameters can be used to estimate the expected capacity of pedestrian lanes. To convert the unit of capacity from lane width to meter width unit, it is necessary to estimate the width of formed lanes (see Eq. (5.5)). Video records showed that pedestrians have limited space to maneuver and formed self-organized lanes. Therefore the lane width was assumed to be equal to the personal lateral space dimension (0.76 m) reflecting minimum lateral space for comfortable movement. Capacity estimation results for homogeneous and heterogeneous populations showed that the queueing area had considerable lower capacity in heterogeneous scenario. The findings suggest that individuals with disabilities have significant on pedestrian flows and it needs to be considered in design plans.

Analysis revealed that individuals with non-motorized ambulatory devices and visually impaired individuals had the least effect, followed by individuals with mobility canes, and individuals with motorized wheelchair. The outcome can be explained by two facts affecting minimum time headway between followers and leaders: Speed of leader groups, and spacing between followers and leaders. Previous study has shown that visually impaired individuals and individuals with non-motorized wheelchairs had the highest, and individuals with motorized wheelchairs and individuals with mobility canes had the lowest walking speed in the queuing area (Sharifi et al., 2016). It indicates that visual impaired and individuals with non-motorized devices may have minimal impacts on the followers' speed leading to lower capacity reductions compared to other groups. On the other hand, followers needed to considerably reduce their speed behind individuals with motorized wheelchair and mobility canes causing remarkable reductions in flow conductibility. Analysis also showed that followers were conservative to keep a safe distance from these two groups, particularly with respect to individuals with mobility canes. Therefore, pedestrian maneuverability is substantially constrained and reduces the capacity of the queuing area.

5.6 Summary and conclusions

This chapter presented a framework to analyze the capacity of a queuing areas when considering heterogeneous pedestrian populations, including individuals with disabilities. Specifically, time headways between different pedestrian groups were examined for one directional homogeneous and heterogeneous pedestrian streams using a mixed time headway distribution model. The model was able to differentiate between constrained and unconstrained time headways and made it possible to use the distribution parameters for capacity estimation purposes.

Results showed that involving individuals in pedestrian stream lead to significant capacity reduction. Analysis also revealed that how pedestrians change their time headways with respect to different disabled groups and how these behavioral changes lead to capacity reductions. The findings suggested that contributions in capacity reductions were not identical for various disabled groups. While individuals with non-motorized ambulatory devices reduced the capacity up to about 25%, individuals with mobility canes reduced the capacity about 40%. Therefore, it is imperative to consider these diverse pedestrian groups as a part of walking infrastructure designs. The findings are expected to enhance current practices for the design of new built environments for heterogeneous populations. Further, the outcomes can be used to calibrate and validate pedestrian traffic flow models capturing the behaviors and interactions of crowds when considering individuals with disabilities.

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CHAPTER 6

PEDESTRIAN PERCEPTIONS ON WALKING FACILITIES LEVEL OF SERVICE AND DESIGN GUIDELINE ASSESSMENTS

6.1 Introduction

Walking facilities are important infrastructure in a community's transportation systems. The pedestrians who use these facilities (e.g. transit transfer stations, shopping malls, urban plazas, etc.) are diverse. Therefore, it is imperative to design and evaluate the effectiveness of these facilities to meet the walking needs of diverse pedestrian groups, including individuals with disabilities who represent a significant population in the United States (12.1% of the total U.S. population) (U.S. Census Bureau, 2010). The Americans with Disabilities Act (ADA) (ADA, 1990) requires that all pedestrian facilities in the public right-of-way should provide equal rights for disabled people. Thus, it is necessary to test existing design and evaluation frameworks to investigate whether they include all pedestrian groups' needs.

Generally, designers use guidelines provided in Highway Capacity Manual (HCM) (HCM, 2010) to assess walking facilitates performances. HCM defines walking facility performance using a qualitative measure describing operational conditions, or level of service (LOS). The six proposed levels of service in the latest version of the HCM are categorized from A to F, in which A represent the best and F represents the worst operational conditions. The HCM's pedestrian LOS thresholds are based on space, average speed, flow rate, and the ratio of volume to capacity; all values for macroscopic pedestrian behavior. How close different pedestrian groups evaluate the walkway quality of service according to these thresholds is questionable. There is little research on diverse pedestrians' behavior and in particular, there is very little empirical study of individuals with disabilities' walking behavior and perceptions. The reason of this shortcoming is mainly related to lack of empirical studies on individuals in disabilities walking behavior.

To overcome the limitations, a controlled large-scaled walking experiment involving individuals with disabilities was conducted at Utah State University (USU) to empirically compare measure perceptions of pedestrian groups involving individuals with disabilities. The purpose of this chapter is to identify how pedestrian groups, which include individuals with disabilities, perceive the walkway quality of service. Specifically, the objectives of this chapter are: (1) to quantify the effects of environment density on walkway level of service evaluations, and (2) to examine and compare different pedestrian groups' perceptions of walking facility performance with existing LOS design guidelines.

6.2 Background

Planners and public agencies extensively use guidelines to assess the design of walking infrastructures. Highway Capacity Manual (HCM) (HCM, 2010), TCRP report 100: Transit Capacity and Quality of Service Manual (TCQSM) (TCQSM, 2010), and Florida Quality/Level of service Handbook (Florida Quality/Level of service Handbook, 2013) are the most common reference manuals in the United States. Generally, these manuals provide LOS definition, thresholds, and estimation methods for various types of walking facilities. These guidelines evaluate walking facility performance using a qualitative measure describing operational conditions, or level of service (LOS). The six proposed levels of are categorized from A to F, in which A represent the best and F represents the worst operational conditions. At LOS A pedestrian can move in desired path with freely selected walking speed. In contrast, pedestrian movements are severely restricted and there is frequent conflict between pedestrians at LOS F.

Chapters 16 and 17 of HCM guideline develop methods for assessing performance measure of urban walking facilities and urban street segments respectively. These environments such as intersections are typically shared by different travel modes (e.g., auto, pedestrian, bicycle, and transit). Thus, the manual proposes a multimodal evaluation framework, considering interactions between different modes. Effective sidewalk width, pedestrian delay at intersection, average space and pedestrian travel speed are key criteria affecting urban walkway performance evaluations. Chapter 23 provides LOS estimation methodologies for off-street pedestrian and bicycle facilities (e.g., walkways separated from highway traffic). Walkway width, pedestrian flow, and average pedestrian space are examined to evaluate performance of exclusive pedestrian facilities.

TCQSM is a comprehensive reference source providing frameworks for designing and assessing public transportation systems. The manual proposes various LOS criteria for various station elements (e.g., walkways, stairs, queuing and waiting area) based on surveys that identified important factors affecting pedestrian perceptions. Similar to the HCM, pedestrian space and flow are considered as key elements for LOS assessments. Quality/Level of service Handbook (Q/LOS Handbook) published by Florida Department of Transportation (FDOT) is another guideline based on local research in Florida. The manual suggests LOS evaluation criteria for different travel modes including auto, transit, bicycle, and pedestrian. Specifically, the guideline only accounts for urban walkways and it considers multiple factors including existence of a sidewalk, lateral separation of pedestrians from motorized vehicles, motorized vehicle volumes, and motorized vehicle speeds for LOS assessments. A statistical model using 1315 observations was developed to evaluate walking systems assigning a score ranging from 0.5 to 6.5. The LOS score was obtained from the following model (NCHRP Report 616, 2008):

$$\text{LOS score} = -1.2276 \ln (W_{ol} + W_l + f_p \times \%OSP + f_b \times W_b + f_{sw} \times W_s) + 0.0091 \left(\frac{Vol_{15}}{L}\right) + 0.00004\, SPD^2 + 6.0468 \tag{6.1}$$

where W_{ol}, W_l, W_b, and W_s represent width of outside lane, width of shoulder or bicycle lane, buffer width, and width of sidewalk respectively. f_p, and f_{sw} indicate on-street parking effect coefficient, and sidewalk presence coefficient respectively. Vol_{15}, L, $\%OSP$, and SPD stand for count of motorized vehicles in the peak 15 minute period, total number of directional through lanes, percent of segment with on-street parking, and average running speed of motorized vehicle traffic in mi/hr. The determined LOS score can be converted to a corresponding LOS letter grade using provided LOS score thresholds.

Several studies in the literature examined walking facilities LOS evaluations and pedestrian LOS perceptions. These studies identified the key variables affecting on LOS perceptions for various walking environments including intersection crossing (Muraleetharan et al., 2004; Chilukuri and Virkler, 2005; Lee et al., 2005; Petritsch et al., 2005; Bullock et al., 2006; Hubbard et al., 2007), sidewalk (Landis et al., 2001; Sisiopiku et al., 2002; Muraleetharan et al., 2004; Hummer et al., 2005; Byrd and Sisiopiku, 2006; Jensen, 2007; Bian et al., 2007; Muraleetharan and Hagiwara, 2007), midblock crossing

(Chu and Baltes, 2001; Chu et al., 2003), and stair (Lee and Lam, 2003). Three survey methods were generally applied to assess the perception and preference of pedestrians on walking facility quality of service: (1) photo/video surveys, (2) visual simulation surveys, and (3) field observations.

In the photo/video survey method, different pictures/video clips showing different conditions are shown to different users and their evaluations are recorded according to HCM LOS definitions. For example, Lee et al. (2005) examined LOS standards for signalized crosswalks in commercial/shopping areas in Hong Kong. They used stated preference interview survey providing a set of five photographs to the pedestrian samples. Respondents were presented with descriptions of the quality of flow and they were requested to choose one of photographs which they felt that it is not according to the descriptions. Their analysis showed that the key variables affecting on LOS evaluations were area density, pedestrian flow, and walking speed. Jensen (2007) studied on pedestrian and bicyclist LOS perceptions on roadway segments in Denmark. He collected perceived LOS from 407 respondents (223 female and 184 male) using video clips recorded from 56 roadway segments. Ordinary generalized linear models were used to identify key determinants of LOS at roadway segments. The developed model revealed that the presence and width of pedestrian and bicycle facilities are the most important factors affecting perceived LOS. While photo/video survey approach is an inexpensive option and interview subjects can expose to wide range of conditions, but obtained perceptions is not coming from pedestrian actual experience.

Simulation survey techniques are similar other than computer simulations of different conditions are used to elicit user evaluations. There are a limited number of studies applied this approach for perception LOS analysis. Miller et al. (2000) applied visualization techniques to collect pedestrian LOS perceptions on improvement options (e.g., adding a level crosswalk, widening the median, etc.) for a suburban intersection in the city of Charlottesville, Virginia. A group of 56 subjects was presented with improvement scenario animations and they were asked to rate each option from A to E and give a numerical score from 1 to 75. The analysis results suggested scale ranges according to different LOS. Although computer-aided visualization approach is more costly than photo/survey method, but it can add more flexibility to survey interviews providing variety of environment situations. However, this approach is not able to record pedestrian perceptions based on their real experiences.

In field observations, after experiencing a pedestrian environment, participants are asked to assess the walkway quality of service. For instance, Muraleetharan et al. (2004) examined key determinants affecting pedestrian LOS at intersections using direct survey method. They selected four different types of intersections in the city of Sapporo, Japan and questionnaires were distributed to pedestrian who crossed the intersections. The respondents were asked to give a score ranging from 0 to 10, in which 0 represent the worst and 10 represents the best operational conditions. Results obtained from 252 surveys revealed that different factors including space at corner, turning vehicles, delay at signals, and pedestrian-bicycle interactions impact on perceived LOS. Landis et al. (2001) used similar approach to measure pedestrian LOS of safety and comforts in sidewalks in

Pensacola, Florida. 75 volunteer participants were asked to walk along a 5-mile (8-km) looped walking course. Then, the participants evaluated the safety/comfort of the walkway system using A-F point scale. Impacts of different factors were identified by developing a stepwise linear regression model. However, human factors were not considered in the study. The field observation method comparing to other approaches has lower initial cost but it is more expensive to set up. However, this method enables to elicit pedestrian perceptions based on their actual experience.

Even though several guidelines and studies have been develop to examine pedestrian perceptions on walking facilities LOS, the literature review revealed that still there are limitations in existing studies. First, existing manuals such as HCM claims to predict LOS based on traveler's prospective. However, there is little evidence to support the claims (NCHRP Report 616, 2008). As a result, how closely pedestrian LOS thresholds provided in guidelines correspond to actual pedestrian perceptions is questionable. Second, there are very limited number of studies used subjects' revealed walking behavior as a part of LOS perception analysis likely due to the lack of walking trajectory. For instance, Kim et al. (2013) collected questionnaire and video recording data from 28 commercial, residential, and leisure locations in South Korea and developed a model connecting pedestrian perceptions with revealed behaviors. Specifically, they examined the effects of personal space and pedestrian evasive movements on perceived LOS, However, they didn't consider pedestrian subjective characteristics (e.g., socio-demographic variables including age, gender, etc.) in their model. Third, the guidelines and majority of existing studies overlooked heterogeneity in pedestrian groups in LOS evaluations. Specifically, there are few studies applicable to individuals with disabilities. Recently, Asadi-Shekari et al. (2013) developed a method to consider individuals with disabilities in LOS evaluations. However, they didn't make use of either preference or reveal behaviors. Therefore, further studies are needed to address the current limitations.

6.3 Survey data collection

To study the walking behavior and the perceptions of different types of individuals with disabilities, a large scale controlled walking experiments was carried out by a multi-disciplinary research group (transportation engineering disability studies, electrical engineering, management information systems and environmental design) at Utah State University (USU). Participants were a mixture of individuals without disabilities and individuals with mobility-related physical, sensory, or other types of disabilities, including hearing, intellectual, and other impairments related to mobility disability. In total, 202 individuals (160 without and 42 with disabilities) were recruited. Among the participants with disabilities, about 26% were visual impaired, 38% were physically impaired, and 36% had other types of disabilities. The study was conducted on a temporary circuit constructed at USU's Motion Laboratory with the necessary walking facilities (e.g., level passageway, right angle, oblique angle, and bottleneck), designed to comply with applicable Americans with Disabilities Act Accessibility Guidelines (ADAAG) and International Building Code (IBC) standards. For each 10-minute experiment session, participants moved at their maximum comfortable speed through the circuit while their position within one footstep (.3 meter) was recorded using an automated video tracking system. One researcher acted as a ramp meter to distribute participants to generate a wide range of crowd density levels and flow directions.

To examine and compare individuals with disabilities' perceptions of walking facility performance with existing LOS design guidelines, individuals with and without disabilities recorded their perceptions prior to, during, and following participation in each experiment session. Prior to each experiment session, participants completed a questionnaire to collect socio-demographic information (e.g. gender, age, walking habits, etc.), each participant's expected grouping behavior (platooning) with regard to individuals with disabilities, and an indication of their spacing behavior toward individuals with disabilities (For example, How comfortable do you feel around individuals with disabilities? Very comfortable, Comfortable, Neutral, Less comfortable, Not very comfortable). During each experiment session, some participants were randomly exited and asked to complete a questionnaire assessing their walking experience. Following each experiment session, all participants were asked to complete the questionnaire assessing their walking experience. This instrument included questions to assess participant's perception of walking facility performance by providing a graphical representation of each HCM LOS to which participants indicated their experience (Fig. 6.1). Additional questions assessed characteristics for LOS thresholds (For example, for the last lap I completed, my ability to maneuver/walk freely was affected by the presence of an individual with a disability in the following areas? Narrow corridor, Wide corridor, where the corridor width changed, Corner, Doorway).

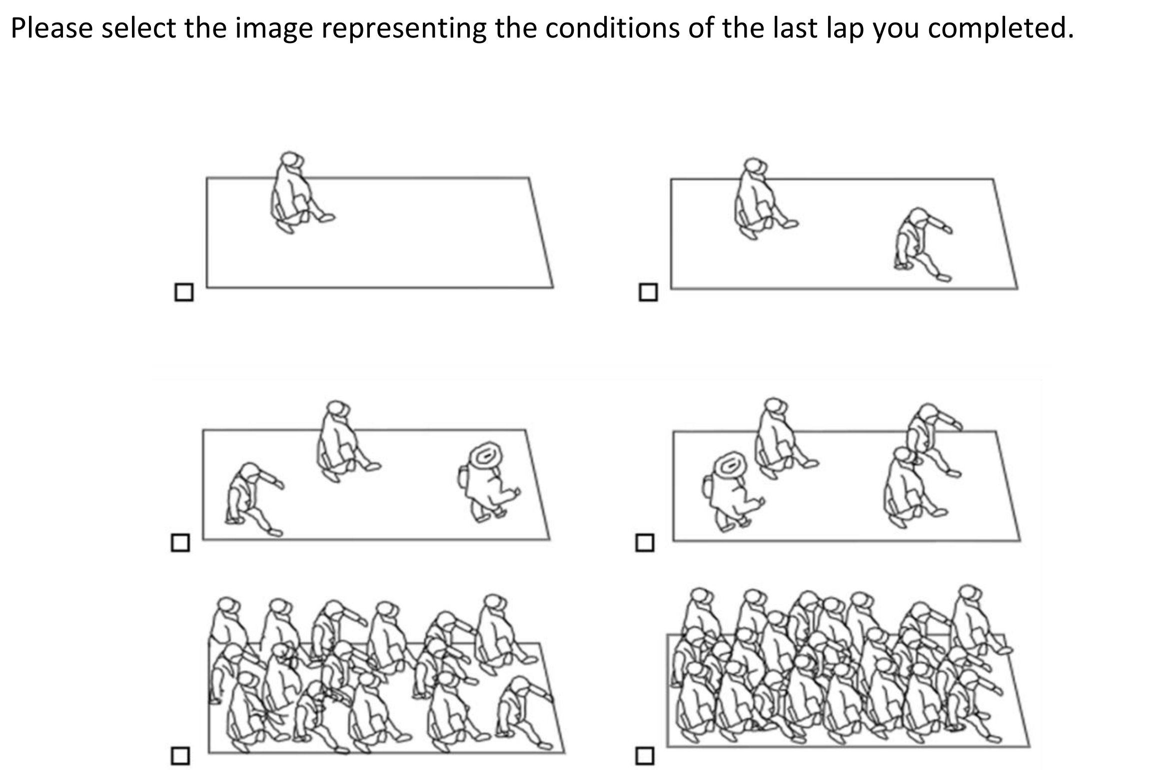


Fig. 6.1. Graphical LOS definitions.

6.4 Methodological approach

The purpose of this study was to understand how density of walking environments effect on walkway level of service evaluations. To achieve the goal, different data sources including video data and survey data were used. Pedestrian socio-demographic variables and their recorded perceptions on quality of service were obtained from the pre-surveys and post-surveys, respectively and circuit density was extracted from collected video data. The conventional way to determine the circuit density is to obtain total number of participants during the survey time duration and divide it by circuit area. But, this method may not reflect the actual experienced density by the surveyed participant. To overcome the limitation, the circuit area was divided to different facilities and density of each facility was calculated during the time that the surveyed individual passed through each facility. The experienced density can be obtained by getting average density of facilities. Fig. 6.2 and Fig. 6.3 present the layout of walking facilities and graphical idea of calculating the experienced density, respectively. Fig. 6.3 shows time-space diagram for a surveyed individual. This time-space diagram was created by plotting the position of each participant, given at a distance from a reference point (e.g., entrance of the circuit) against time. The dashed line shows the trajectory of the surveyed individual during the surveyed time and boxes show the time intervals that the surveyed ID passed through different facilities. Experienced density was obtained by getting average density of different boxes (i.e., different facilities).

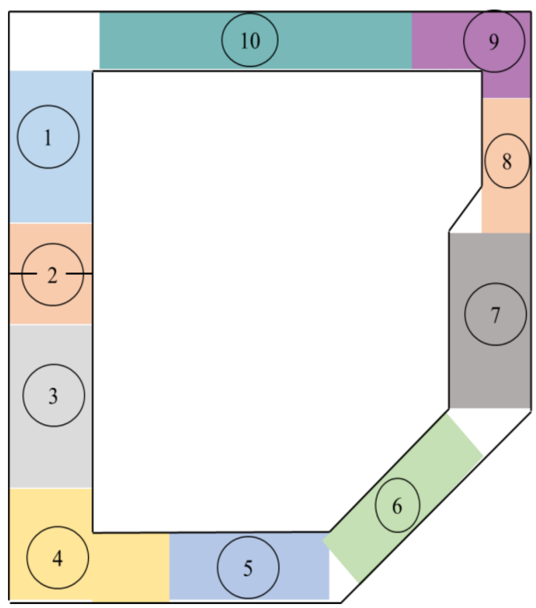


Fig. 6.2. Circuit segmentation.

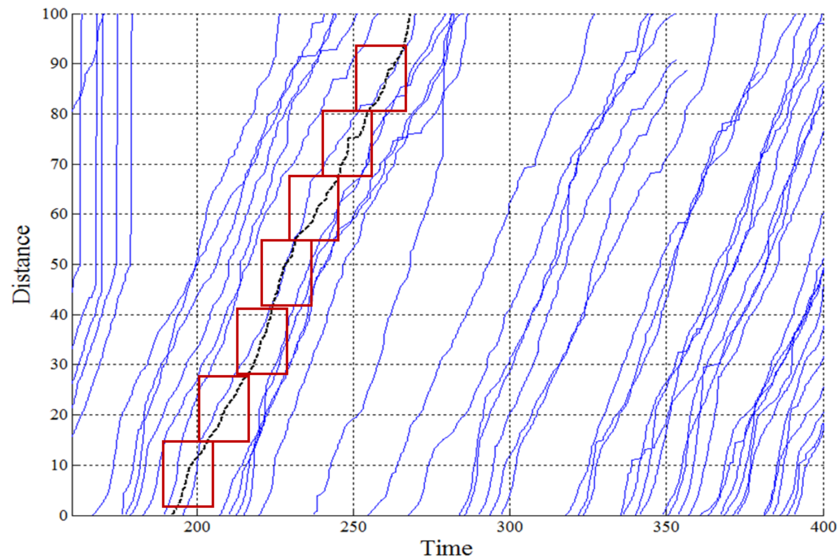


Fig. 6.3. Time-space diagram for a surveyed participant.

To examine how pedestrians perceive LOS, a statistical method is needed to account for both the discrete and ordered nature of responses. Econometric models such as ordered probability approach is an appropriate method widely used in many Transportation Engineering applications (for example see Asgari et al., 2014; Asgari and Jin, 2015; Asgari and Jin, 2016a; Asgari and Jin, 2016b; Asgari, 2015; Baratian and Zhou, 2015; Soltani-Sobh et al, 2016). In this approach, an unobserved variable, *z* is defined that determines the perceptions of LOS as a linear function for each observation *n* such that

$$z_n = \beta X_n + \varepsilon_n \tag{6.1}$$

where X_n is a vector of independent variables like traffic conditions (e.g., density), β is a vector of coefficients and ε_n is a random disturbance. In ordered probit model, random error term is assumed to be normally distributed across observations with mean=0 and variance=1. Using this equation, observed LOS, y_n for each observation is written as (With LOS A, B, C, D, E and F corresponding to y=1, 2, 3, 4, 5, and 6 respectively).

$$
\begin{aligned}
y_n &= 1 \quad \text{if} \quad z_n \le \mu_1 \\
y_n &= 2 \quad \text{if} \quad \mu_1 < z_n \le \mu_2 \\
y_n &= 3 \quad \text{if} \quad \mu_2 < z_n \le \mu_3 \\
y_n &= 4 \quad \text{if} \quad \mu_3 < z_n \le \mu_4 \\
y_n &= 5 \quad \text{if} \quad \mu_4 < z_n \le \mu_5 \\
y_n &= 6 \quad \text{if} \quad z_n \ge \mu_5
\end{aligned}
\tag{6.2}
$$

where μ is the cut-off that defined y_n and it is estimated jointly with the parameter vector β by standard maximum likelihood procedure. It can be shown that μ_1 can be set equal to zero without loss of generality. With these assumptions, an ordered probit model can be written as follow (Choocharukul et al., 2004):

$$
\begin{aligned}
P(y_n = 1) &= \phi(-\beta X_n) \\
P(y_n = 2) &= \phi(\mu_2 - \beta X_n) - \phi(-\beta X_n) \\
P(y_n = 3) &= \phi(\mu_3 - \beta X_n) - \phi(\mu_2 - \beta X_n) \\
P(y_n = 4) &= \phi(\mu_4 - \beta X_n) - \phi(\mu_3 - \beta X_n) \\
P(y_n = 5) &= \phi(\mu_5 - \beta X_n) - \phi(\mu_4 - \beta X_n) \\
P(y_n = 6) &= 1 - \phi(\mu_5 - \beta X_n)
\end{aligned}
\tag{6.3}
$$

where Φ_n is the cumulative normal distribution.

$$\phi(u) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{u} e^{-\frac{1}{2}w^2} dw \tag{6.4}$$

Fig. 6.4 presents an overall framework for the perception LOS analysis.

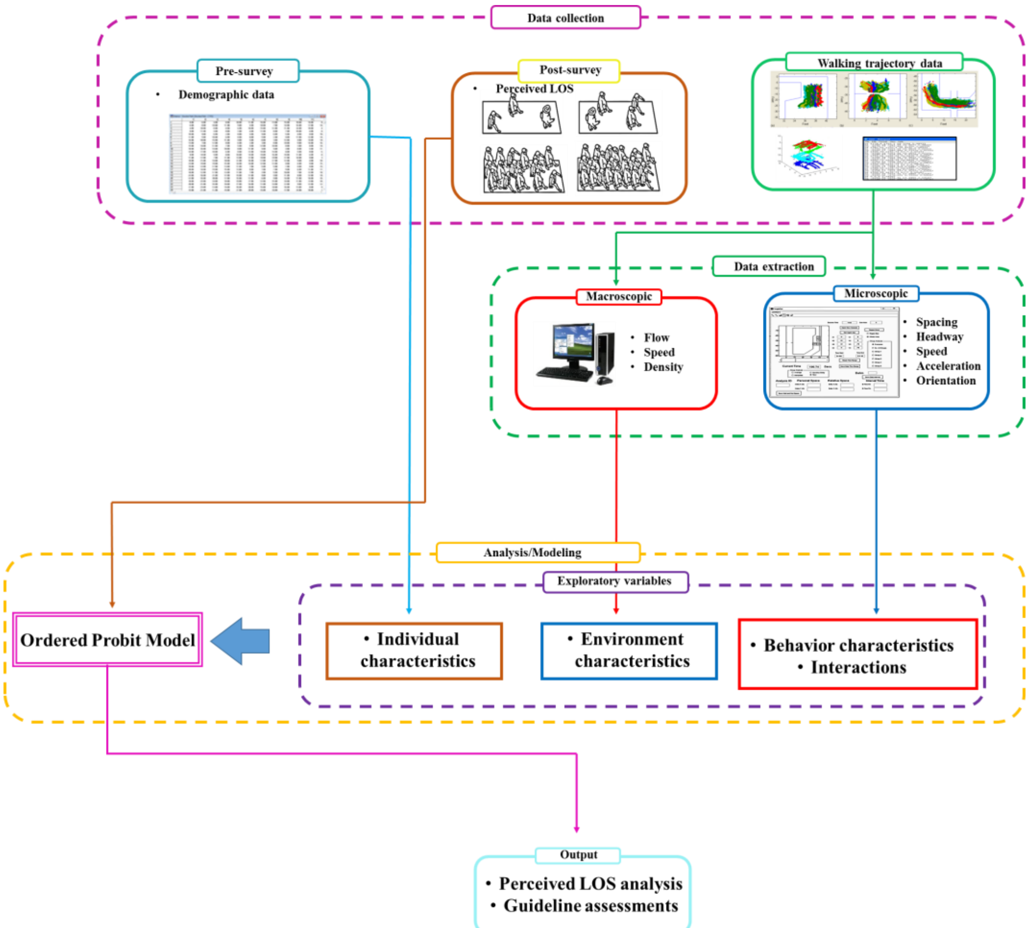


Fig. 6.4. LOS perception analysis framework.

6.5 Analysis and results

A total of 257 valid post-surveys (212 from individuals without disabilities and 45 from individuals) were collected from participants. Fig. 6.5 presents distribution of responses on LOS perceptions. Observations show that most of observations were made at LOS D and E and pedestrian perceptions toward extremely low density level is much less than other groups. Most of participants were surveyed in the middle duration of experimental process where the circuit density was toward higher density levels indicating that the observed results are plausible.

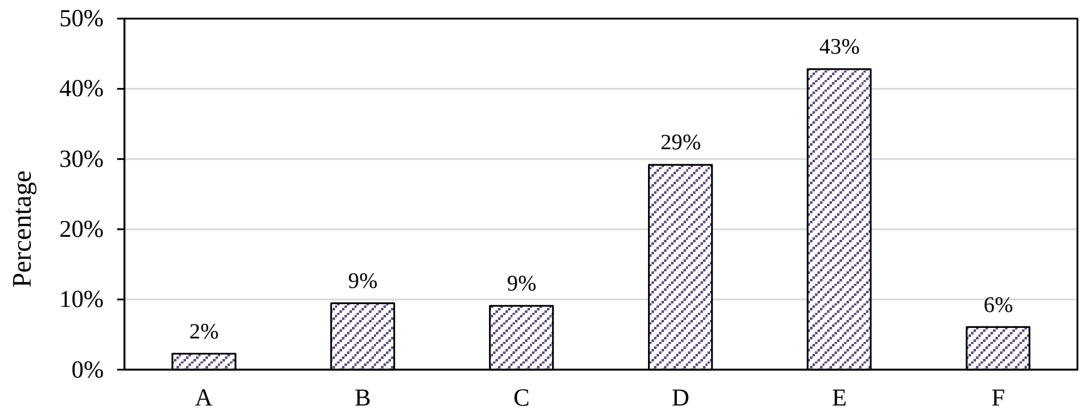
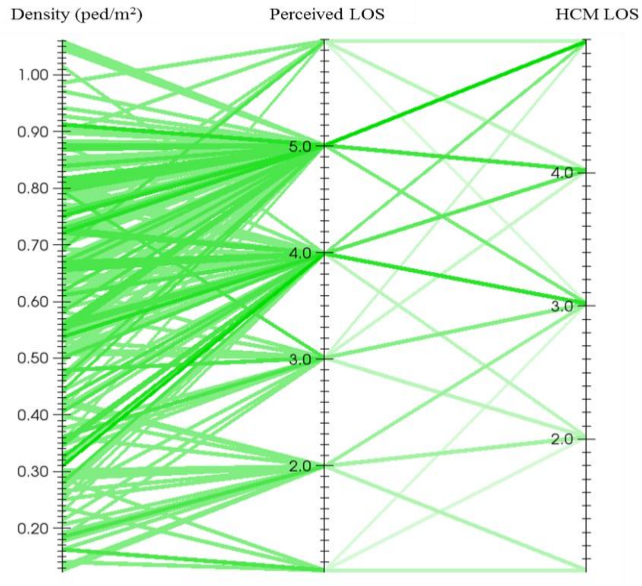
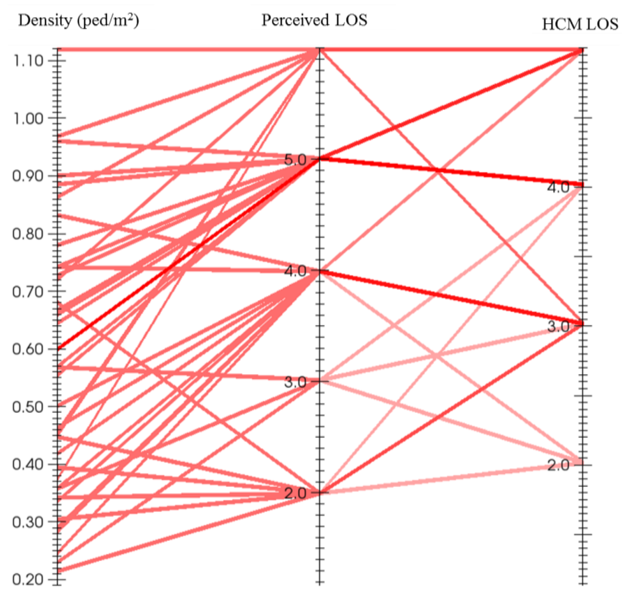


Fig. 6.5. LOS distribution.

To validate collected survey data, data visualization technique was used to show distribution of LOS responses. Fig. 6.6 presents parallel coordinate plots for individuals with and without disability responses. The first axis presents experienced density, the second axis shows individuals' responses on LOS perception (i.e., 1 means LOS A, 2 means LOS B,…), and the third axis shows the corresponding LOS according to HCM guideline. The concentrations of lines show the distribution of collected data. For instance, the figure shows that lines connecting first axis to second axis are ticker in density ranges between 0.5 to 0.9 ped/m^2 for indicating that most of observations were in this density range. The parallel diagrams also indicate that how close were the participants' respondents to actual conditions. Observing lines connecting second and third axes, it can be inferred that although collected perceived LOS responses didn't exactly follow the HCM guideline



(a)



(b)

Fig. 6.6. Survey data visualization for a) without disabilities b) with disabilities.

but they were not too far away implying that participants didn't responded randomly and collected surveys are valid.

SAS statistical software was used to calibrate ordered probit models. Based on initial analysis it was observed that there were not enough collected data for LOS A. Fig. 6.5 shows that only 2% of respondents stated LOS A for their walking condition and treating it as an independent group affect the estimation results. Therefore, LOS A and B were aggregated and five LOS categories were considered in modeling process. 90% of collected data were used for calibration and 10% of data were reserved for model validation purpose. An ordered probit model was calibrated with density as only independent variable for individuals without and with disabilities. Table 6.1 shows the estimation results including constant, coefficients for density variable, and estimated cut-offs and their corresponding statistics including t-statistics. P-values for coefficients and cut-offs are less than 0.01 indicating that coefficients and thresholds are highly significant. Results show that sign of density coefficients are positive for all groups showing that higher values of density levels make it more likely that pedestrians perceive worse LOS.

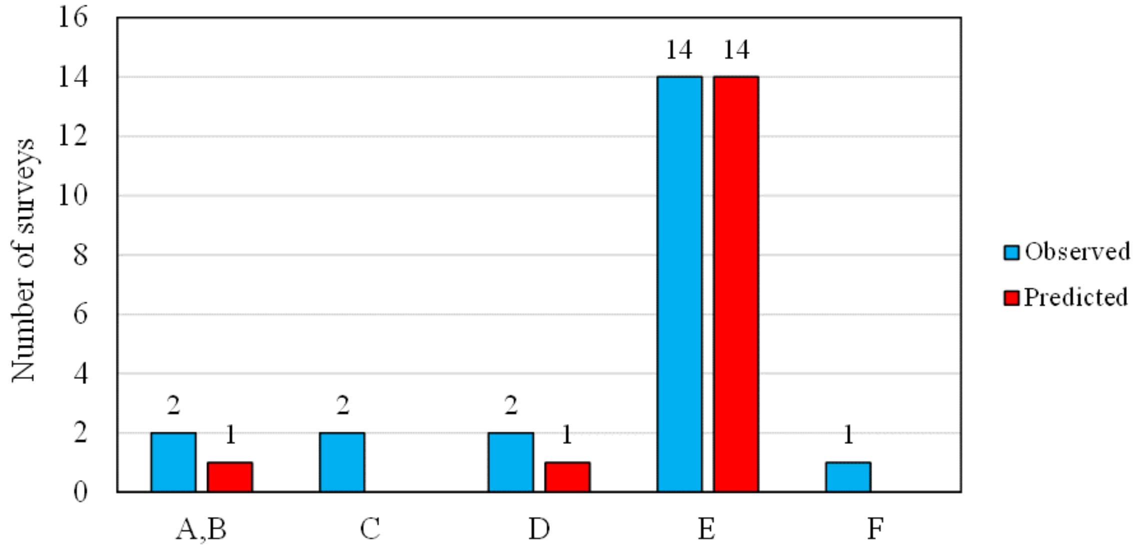
To investigate validity of estimated models, 10% reserved data were used and the models were examined to check how close the models can predict the observations. Specifically, the observed densities were substitute in the models and perceived LOS were predicted. Fig. 6.7 presents results of comparisons between successful prediction of calibrated models and responses of surveyed individuals. It can be observed that the models could predict the LOS responses pretty well. The model for individuals without disabilities

Table 6.1
Model estimation results.

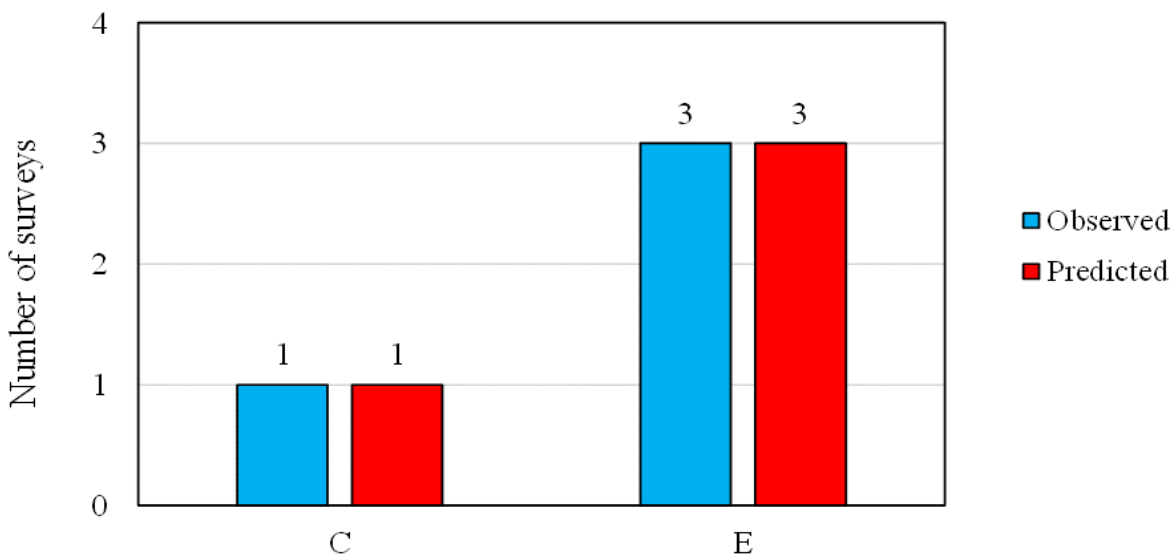
	Model					
	Individuals without disabilities			Individuals with disabilities		
Variables	Coefficients	t-statistics	p-value	Coefficients	t-statistic	p-value
Constant	-0.78	-3.23	0.0015	-0.62	-1.35	0.1835
Density (Ped/m^2)	4.37	9.66	< 0.01	3.35	3.98	< 0.01
Cut-offs						
μ2	0.58	4.46	< 0.01	0.32	1.83	0.074
μ3	1.92	10.45	< 0.01	1.23	4.21	< 0.01
μ4	4.11	14.62	< 0.01	2.46	6.59	< 0.01
Number of observations	191			41		
Log likelihood at convergence	-197.26			-53.17		

predicted almost all of surveys in LOS E and F and calibrated model for individuals with disabilities could predict all of reserved LOS responses. The overall success prediction for individuals without and with disabilities were about 75% and 100%, respectively indicating that the accuracy of models were acceptable.

LOS thresholds can be obtained using estimated coefficients and cut-offs. The thresholds can be calculated as $(\mu_k-\beta_0)/\beta_1$ where k is cut-off values and β_0 and β_1 are intercept and density coefficient, respectively. Fig. 6.8 depicts estimated thresholds for different pedestrian groups (individuals without disabilities, individuals with disabilities, and all participants). Also, proposed LOS thresholds by HCM is provided in the figure to examine and compare different pedestrian groups' perceptions of walking facility performance with existing LOS design guidelines. Fig. 6.8 presents the density ranges for



(a)



(b)

Fig. 6.7. Model validations for a) without disabilities b) with disabilities.

each LOS category. Comparing thresholds for individuals without and with disabilities, it can be found that there is a visible difference between LOS E and F perception thresholds. While individuals with disabilities rated density levels beyond than 0.92 ped/m^2 as LOS F, individuals without disabilities perceived LOS E up to 1.12 ped/m^2 density level indicating that individuals with disabilities had lower tolerance for crowded conditions. LOS thresholds for all surveyed participants can be compared with provided LOS criteria in HCM guideline to investigate that how close the HCM guideline follows the pedestrian perceptions. Results indicate that there are apparent differences between perceptions thresholds and HCM propose values. Surveyed individuals had lower tolerance for all LOS groups. For instance, participants rated density ranges from 0.61 ped/m^2 to 1.07 ped/m^2 as LOS E while HCM considers density ranges from 0.72 ped/m^2 to 1.35 ped/m^2 as LOS E implying that HCM underestimates LOS rates compared to pedestrian perceptions.

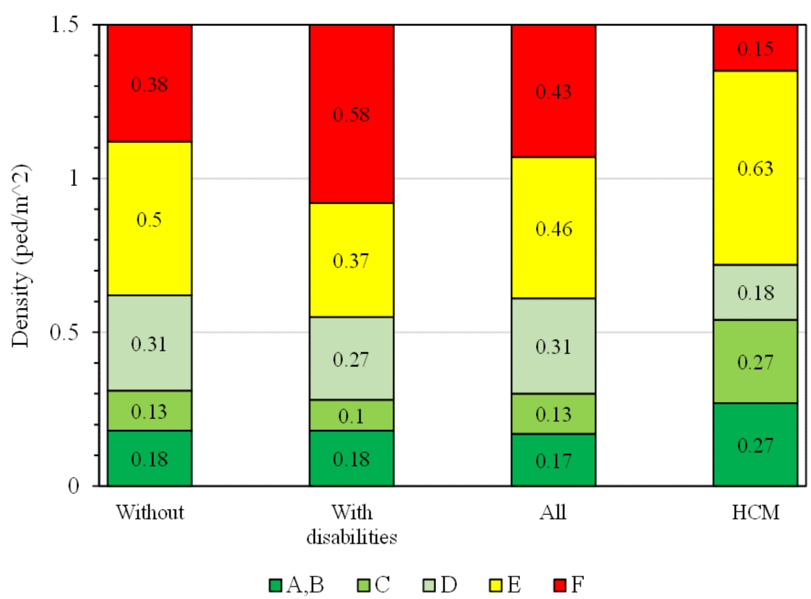


Fig. 6.8. LOS graphical comparisons.

LOS concept is widely used in walking facilities design and evaluations. Given projected demand and length of a walking facility, designers can estimate the minimum required width to achieve desired LOS. Therefore, the findings can be examined to investigate the impacts of overlooking individuals with disabilities in design process. Results show that the minimum required width for individuals without disabilities is about 80% of minimum width for individuals with disabilities to achieve LOS E. Further, effects of overlooking perceptions in design process can be investigated by comparing LOS perception thresholds for all pedestrians and HCM guideline. Results indicate that considering LOS B as the target, design plan based on HCM guideline would be about 63% of minimum width obtained from heterogeneous pedestrian perceptions.

6.6 Summary and conclusions

LOS criteria provided in HCM guideline has been widely used by planners for design and assessment purposes. This chapter examined that whether the guideline is applicable for all pedestrian groups and how close different groups of pedestrian evaluate the walkway quality of service according to guideline recommendations. To achieve the goals, a large scale controlled walking experiments was carried out at Utah State University (USU). Participants were a mixture of individuals without disabilities and individuals with mobility-related physical, sensory, or other types of disabilities. The revealed walking behavior and perceptions on walking environment conditions were observed through video records and survey collection methods. A statistical framework was used to make a connection between the questionnaire and the walking trajectory data to specify how environment density can impact on pedestrians' perceptions of walking facility performance. The results suggest that there are differences between perceptions of individuals without and with disabilities and these differences are more visible in high density levels (i.e., LOS E and F). Also, it was found that pedestrian LOS perception thresholds are lower than HCM LOS implying that the current thresholds provided in HCM guideline don't follow pedestrian perceptions and using them may lead to inappropriate design plans. The findings in this chapter are expected to enhance design of walking environments. Designers can test and evaluate their design plans using the findings in this research to determine how well their design can meet the needs of different users and they can change their plan while changes are possible.

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CHAPTER 7

CONCLUDING REMARKS

7.1 Summary

The goal of this study was to study on walking behaviors of pedestrian groups involving individuals with disabilities in various walking environments. To this end, set of large-scale controlled walking experiments were conducted at Utah State University (USU). This dissertation provided statistical analysis and models to study on operational walking behaviors. The summary and findings of each chapter are discussed as follow:

Chapter 2 provided the literature on trajectory data collection methods, walking speed, and walking facility capacity estimation methods. The properties and limitations of existing approaches were explored in this chapter. Chapter 3 provided an overview of applied experimental methods including experimental design, automated video tracking method, and data processing procedure.

The purpose of chapter 4 was twofold: The first objective was to examine the effect of involving individuals with disabilities on crowd walking speeds in different environments. The findings showed that individuals with disabilities had statistically significant reduction effects in all walking facilities and these differences were more profound in stair, right angle, and passageway facilities. The second objective was to study the walking speed of different types of pedestrians in different walking facilities. Specifically, impacts of different walking facilities on the mean speed of people with and without disabilities were examined using ANOVA. The outcomes suggested that walking speed of individuals with disabilities was lower than individuals with disabilities and these differences were statistically significant. Among individuals with disabilities, visual impaired individuals and individuals with motorized wheelchairs generally had the highest and lowest walking speed, respectively.

The main objectives of chapter 5 were: (1) to model time headway between different individual types using a statistical model, and (2) to describe interaction behaviors between pedestrian groups and to identify implications for queuing area capacity estimations. To achieve the first objective, time headways between leaders and followers were computed using microscopic traffic flow variables such as followers' speed and spacing. Time headways were examined for followers and different leader types and a mixed time headway distribution model was applied to data. Results supported the hypothesis that various leader types had significant changes on time headway distributions. Further, implications of interaction behaviors were investigated on queuing area capacity. Results showed that including individuals with disabilities reduced the capacity of a queuing area. Among individuals with disabilities, individuals with visual impairments and non-motorized ambulatory devices had the minimum and individuals with motorized wheelchairs and individuals with mobility canes had the maximum capacity reduction effects in queuing area.

Chapter 6 provided a statistical framework to identify how pedestrian groups, which include individuals with disabilities, perceive the walkway quality of service. Specifically, the objectives of this chapter were: (1) to explore the effect of walking environment density on walkway level of service evaluations, and (2) to examine and compare different pedestrian groups' perceptions of walking facility performance with existing LOS design guidelines. An ordered probit model were calibrated for individuals with and without disabilities and LOS thresholds were extracted from models. Results indicated that individuals with disabilities were less tolerant to extreme congested environment and comparisons revealed that there are considerable differences between perceived LOS and LOS criteria provided in HCM indicating that the guideline doesn't reflect the actual perceptions.

7.2 Implications

The results of the research informs current understanding of pedestrian walking behaviors involving individuals with disabilities. Specifically, research outcomes can support improved practices for the design and renovation of built environments as follows:

Urban and building design. The outcomes will help designers understand the user/occupant of the designed environment and test the design layout to determine how well it meets the needs of the occupant prior to construction while changes in design are possible. Individuals with disabilities' movement patterns, and their interactions with environments and other pedestrians can largely determine the effectiveness of the design. Further, buildings' interior layouts may involve complex geometries, such as different angles, which should be designed to operate at a satisfactory level. Unfortunately, most existing public building design guidelines, found in the Highway Capacity Manual (HCM) (HCM, 2010) and the International Building Code (IBC) (IBC, 2012), fail to offer adequate consideration for individuals with disabilities. To account for the needs of individuals with disabilities, the Americans with Disabilities Act Accessibility Guidelines (ADAAG, 2002) provide guidelines for the design of pedestrian facilities. This code is based only on physical properties and it does not consider the interactions between people with and without disabilities. The rich data set make it possible to overcome the practice limitations. For example, walking trajectories of individuals with disabilities can be studied to determine minimum required space to negotiate different walking facilities in various occupant load levels. Directly, the results of this study suggest the urban designers, architects, and engineers that design plans based on the walking speed of individuals without disability, or the existing guidelines which do not reflect the heterogeneity of pedestrians, may overlook vulnerable walker needs, as well as creating environments which create walker vulnerability. Complex geometries can significantly reduce the walking speed of heterogeneous populations and urban designers, architects, and engineers should providing more space in walking infrastructures with complex geometries to meet needs of different individual types. Similarly, individuals with disabilities need more space to maintain their preferred speeds, which designers should consider in their planning efforts.

Transportation engineering / policy. The dissertation findings can enhance current practices in transportation engineering. For example, pedestrian walking speed is widely used as input for many transportation engineering applications, such as determining required gap sizes and pedestrian signal timing (Arango and Montufar, 2008). Currently, walking and building design manuals do not differentiate between different walking geometries. The findings of this research can improve the current knowledge and it can help to develop efficient designed plans. Further, given the complexity of walking behavior, one of the most widely applied methods for pedestrian behavior modeling and design evaluation is microsimulation modeling. Many studies used the approach for many applications including signalized crosswalks evaluations (Lu et al., 2015), pedestrian queuing modeling (Kim et al., 2013), and pedestrians' crossing behavior modeling (Lee and Lam, 2008). Current microsimulation models either do not address individuals with disabilities in their simulated populations or simulate 'standard' individuals with disabilities, giving little emphasis to the largest minority demographic of populations, individuals with disabilities. Participants' movement data can be analyzed along with that of the crowd using the collected data. Thereby, microsimulation approaches testing pedestrian facilities may be enhanced to determine how will these facilities meet their intended requirements and reflect occupants with disabilities. Perception analysis pedestrians can be disseminated to augment and refine existing pedestrian LOS thresholds to accommodate the pedestrian needs of a heterogeneous population, which includes individuals with disabilities.

7.3 Directions for future research

The available data, which represents the most extensive examination of the walking behavior of pedestrian groups involving individuals with disabilities, is substantial and will support further research to advance understanding of the pedestrian behaviors. Potential recommendations for future research include the following:

7.3.1 Study on bi-directional pedestrian flow

Bi-directional pedestrian flows can be observed in walking infrastructures such as sidewalks and stairwells. Conflicts in bi-directional flows may have significant effects on pedestrian walking behaviors and consequently on operational performance of walking facilities. Walking experiments were categorized into diverse flow composition scenarios (e.g., one-directional, 90% major stream 10% minor stream, 80 major 20% minor, 70% major 30% minor, 60% major 40% minor, and 50% major 50% minor). However, this study mostly focused on one directional scenario. This study can be further extend to examine effects of flow compositions on walking behaviors at macro and micro levels. For example, Effects of bi-directional flows can be studied on operational capacity of various walking facilities under homogeneous and heterogeneous population scenarios. Examining effects of bi-directional flow on microscopic walking behavior of individuals with disabilities can be considered for future studies. Walking speed, spacing, and time headway between individuals without and with disabilities can be studied under different flow composition scenarios to explore how different individuals react respect to opposite flows.

7.3.2 Microsimulation model development

Given the complexities embedded behind pedestrian behaviors, one of the most widely applied methods of designing and evaluating the walking infrastructures is simulation models. Based on their level of analysis resolution, these approaches can be classified into macroscopic and microscopic models (Ashford et al., 1976; Chalmet et al., 1982; Lovas, 1994; Helbing, 1991; Helbing and Molnar, 1995; Bouvier et al., 1997; Blue and Adler, 2001; Kirchner and Schadshneider, 2002). However, these models need to be calibrated and validated using real observations in order to be considered as reliable tools. Unfortunately, the input parameters used in most microscopic simulation models are only calibrated using macroscopic data on specific pedestrian flow situations (Versluis, 2010). Moreover, current micro-simulation models either do not address individuals with disabilities in their simulated populations or simulate a 'standard' individual with disabilities (Christensen at al., 2013). As a result, most current models do not replicate accurate pedestrian behavior patterns of a heterogeneous population. As such, the walking needs of individuals with disabilities are generally overlooked. The failure to include individuals with disabilities is due in large part to difficulties in obtaining reliable walking behavior data and the lack of studies on the walking behavior characteristics of individuals with disabilities. This research can be further extended to develop new microsimulation models considering individuals with disabilities' behavioral specifications.

7.3.3 Study on crowd collective behaviors

Pedestrian movement patterns are governed by density level of walking facilities. In high density levels, movements are strictly affected by other pedestrians and local interactions among individuals governs crowd dynamic patterns. Examples of these patterns are lane formations and oscillations in pedestrian flows. Understanding of these phenomena can help to predict congestions and consequently it can aid to assess walking infrastructure designs. These phenomena have been studied and many researchers tried to describe the crowd collective behaviors (for example see Helbing and Molnar 1995; Helbing et al., 2001; Ball, 2004; Couzin and Krause, 2003). However, the local mechanisms underlying the formation of collective patterns are not yet known in detail and presented crowd dynamic models still need to be verified by individual-level experiments (Moussaid et al., 2009). Current knowledge can be further extended to study on crowd dynamics of homogeneous and heterogeneous pedestrian stream in various walking facilities under different flow scenarios. Further, proxemics behavior of walking groups have been studied to explore human spatial requirements during social interactions (for example see Gorrini et al., 2014; Koster et al., 2011; Moussaid et al., 2010). However, all of existing studies overlooked heterogeneity in pedestrian populations. Extending current researches to explore proxemics behavior of individuals with disabilities may help to provide efficient design plans to meet individuals with disabilities needs.

7.3.4 GUI improvement

The current version of GUI can process and extract basic traffic flow variables such as speed, acceleration, orientation, spacing, etc. Even the tool is very useful for analysis purposes, but the abilities are still limited. There are many possibilities to enhance the GUI. First, the GUI environment can be improved to be more user friendly and interactive. The visualization tool can be upgraded to visualize trajectories, time-space diagrams, and macro data such as fundamental diagrams. Second, the GUI can be improved to extract and analyze more enhanced microscopic phenomena such as pedestrian group behaviors, self-organization in pedestrian flow, stop and go waves in pedestrian flow, etc. Third, the GUI can be linked to the pre-survey and post-survey data sources to extract and analyze demographic, stated, and reveal behavior data.

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APPENDICES

APPENDIX A

Pre-survey form

1. What is your age?

   ____

2. What is your gender? ☐ Male ☐ Female
3. What is your height?

   ____

4. How would you categorize your disability/impairment?
   - ☐ Vision
   - ☐ Hearing
   - ☐ Physical/Spinal Cord Injury
   - ☐ Intellectual
   - ☐ Other

   ____
   - ☐ None

5. If you possess a disability/impairment, how is your pedestrian movement primarily affected?____

6. In addition to your disability/impairment, do you have a chronic health condition or impairment?

   ____

7. How far do you generally walk each day?
   - ☐ less than 1/4 mile
   - ☐ 1/4 mile to 1/2 mile
   - ☐ 1/2 mile to 1 mile
   - ☐ more than 1 mile

8. How many days per week do you walk at least 10 continuous minutes per day?
   - ☐ 0
   - ☐ 1
   - ☐ 2
   - ☐ 3
   - ☐ 4 or more

9. What is your purpose for walking?
   ☐To work
   ☐To or within school
   ☐To shop
   ☐To exercise/For pleasure
   ☐Other
   ____

10. How comfortable do you feel around **individuals with disabilities** compared with others?
    ☐ Very comfortable
    ☐ Comfortable
    ☐ Neutral
    ☐ Less comfortable
    ☐ Not very comfortable

11. How likely would you be to pass another **individual** when they are walking more slowly than you?
    ☐ Very likely
    ☐ Likely
    ☐ Neutral
    ☐ Not likely
    ☐ Not very likely

12. How likely would you be to pass an **individual with a disability** when they are walking more slowly than you?
    ☐ Very likely
    ☐ Likely
    ☐ Neutral
    ☐ Not likely
    ☐ Not very likely

13. How likely would you be to change your walking behavior toward another **pedestrian with disabilities**? For example, letting them go through the door first or give them extra room.
    ☐ Very likely
    ☐ Likely
    ☐ Neutral
    ☐ Not likely

- ☐ Not very likely

14. How likely would your walking behavior be impacted by encountering an **individual with a disability** in a wide corridor?
    - ☐ Very likely
    - ☐ Likely
    - ☐ Neutral
    - ☐ Not likely
    - ☐ Not very likely

15. How likely would your walking behavior be impacted by encountering an **individual with a disability** in a narrow corridor?
    - ☐ Very likely
    - ☐ Likely
    - ☐ Neutral
    - ☐ Not likely
    - ☐ Not very likely

16. How likely would your walking behavior be impacted by encountering an **individual with a disability** on a wide stairway?
    - ☐ Very likely
    - ☐ Likely
    - ☐ Neutral
    - ☐ Not likely
    - ☐ Not very likely

17. How likely would your walking behavior be impacted by encountering an **individual with a disability** on a narrow stairway?
    - ☐ Very likely
    - ☐ Likely
    - ☐ Neutral
    - ☐ Not likely
    - ☐ Not very likely

18. How likely would your walking behavior be impacted by encountering an **individual with a disability** at a wide doorway?
    - ☐ Very likely
    - ☐ Likely
    - ☐ Neutral

- ☐ Not likely
- ☐ Not very likely

19. How likely would your walking behavior be impacted by encountering an **individual with a disability** at a narrow doorway?
    - ☐ Very likely
    - ☐ Likely
    - ☐ Neutral
    - ☐ Not likely
    - ☐ Not very likely

20. How likely would your walking behavior be impacted by encountering an **individual with a disability** at a wide corner?
    - ☐ Very likely
    - ☐ Likely
    - ☐ Neutral
    - ☐ Not likely
    - ☐ Not very likely

21. How likely would your walking behavior be impacted by encountering an **individual with a disability** at a narrow corner?
    - ☐ Very likely
    - ☐ Likely
    - ☐ Neutral
    - ☐ Not likely
    - ☐ Not very likely

22. Please make any comments or suggestions you feel would be beneficial.

APPENDIX B

Post-survey form

1. For the last lap I completed, I had enough room to maneuver/walk.
   - ☐ Strongly Agree
   - ☐ Agree
   - ☐ Neither disagree or agree
   - ☐ Disagree
   - ☐ Strongly disagree

2. For the last lap I completed, I was able to maintain my desired walking speed.

   - ☐ Strongly Agree
   - ☐ Agree
   - ☐ Neither disagree or agree
   - ☐ Disagree
   - ☐ Strongly disagree

3. For the last lap I completed, my ability to maneuver/walk along the corridors was affected by other people in the environment.
   - ☐ Strongly Agree
   - ☐ Agree
   - ☐ Neither disagree or agree
   - ☐ Disagree
   - ☐ Strongly disagree

   If you strongly agree or agree, what affected your ability to maneuver?

   ____

4. For the last lap I completed, my ability to pass through the doorway was affected by other people in the environment.
   - ☐ Strongly Agree
   - ☐ Agree
   - ☐ Neither disagree or agree
   - ☐ Disagree
   - ☐ Strongly disagree

If you strongly agree or agree, what affected your ability to pass through the doorway?

____

5. For the last lap I completed, my ability to maneuver/walk around the corners was affected by other people in the environment.
   - ☐ Strongly Agree
   - ☐ Agree
   - ☐ Neither disagree or agree
   - ☐ Disagree
   - ☐ Strongly disagree

   If you strongly agree or agree, what affected your ability to maneuver around the corners?

   ____

6. For the last lap I completed, my ability to maneuver/walk when the corridor changed width was affected by other people in the environment.
   - ☐ Strongly Agree
   - ☐ Agree
   - ☐ Neither disagree or agree
   - ☐ Disagree
   - ☐ Strongly disagree

   If you strongly agree or agree, what affected your ability to maneuver when the corridor width changed?

   ____

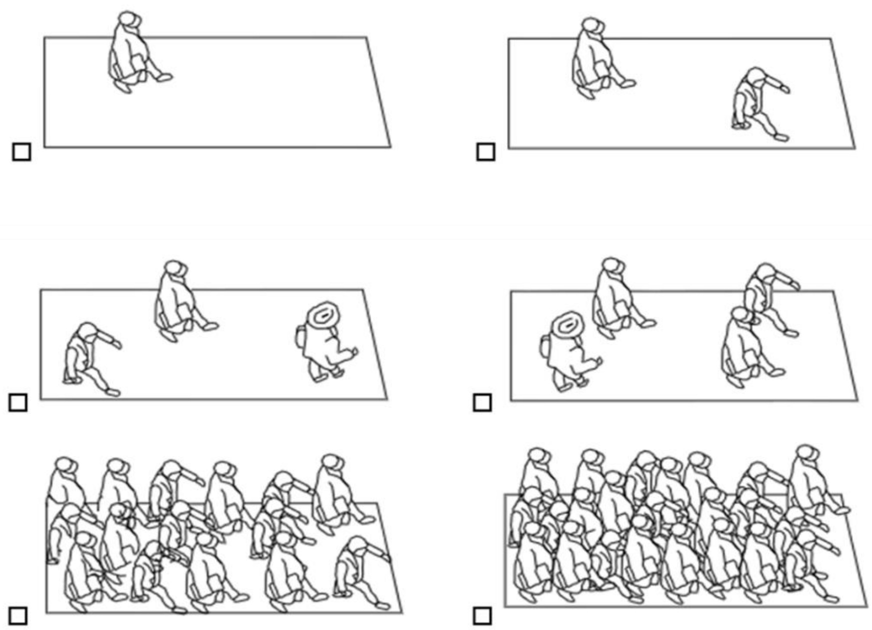
7. My ability to maneuver/walk was affected by obstacles in the environment?
   - ☐ Strongly Agree
   - ☐ Agree
   - ☐ Neither disagree or agree
   - ☐ Disagree
   - ☐ Strongly disagree

   If you strongly agree or agree, what affected your ability to maneuver?

   ____

8. For the last lap I completed, my ability to maneuver/walk freely was affected by the presence of an **individual with a disability** in the following areas?
   - ☐ Narrow corridor
   - ☐ Wide corridor
   - ☐ Where the corridor width changed
   - ☐ Corner
   - ☐ Doorway

9. Please select the image representing the conditions of the last lap you completed.



10. Please make any comments or suggestions you feel would be beneficial.

CURRICULUM VITAE

MOHAMMAD SADRA SHARIFI

(MARCH 2016)

Education

Utah State University (USU), Utah, USA

Ph.D. in Civil Engineering (Transportation Engineering), 2016

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Research Interests

Pedestrian Traffic Flow Theory, Transportation Network Modeling, Traveler Behavior Analysis, Traffic Operations, Intelligent Transportation Systems (ITS), Applications of Operations Research in Transportation Engineering.

Research and Academic Experience

• Research Assistant under projects:

- Experimental research on pedestrian and evacuation behaviors of individuals with disabilities; Theory development necessary to characterize individual-based models funded by the National Institute on Disability and Rehabilitation Research (NIDRR). October 2011 - March 2015.

- Capacity analysis of pedestrian facilities involving individuals with disabilities funded by RITA Tier 1 University Transportation Center- Transportation Research Center for Livable Communities. September 2015 – August 2015.
- Analysis of walking facility performance guidelines for individuals with disabilities. Funded by RITA Tier 1 University Transportation Center- Transportation Research Center for Livable Communities. September 2015 – August 2016.

Teaching Assistant

- Transportation Data/Safety Analysis, Spring 2015, Spring 2016.
- Urban and Regional Transportation (instructor for Cube by Citilabs), Fall 2015, 2014.
- Transportation Systems Analysis, Fall 2015.
- Transportation Network Analysis, Spring 2015.

Courses taught in Transportation Engineering

- Traffic Engineering
- Introduction to Transportation Engineering
- Highway Design
- Advanced Traffic Engineering
- Operations Research
- Transportation Planning
- Railway Engineering
- Transportation Demand Analysis
- Transportation Systems Analysis
- Airport Plan Design
- Transportation Project Evaluation
- Transportation Network Analysis
- Urban and Regional Transportation Planning
- Transportation Data/Safety Analysis

- Categorical Data Analysis
- Design of Experiments
- Public Transportation
- Transportation Logistics Analysis

Software Skills

- Microsoft series: Word, Excel, Power Point, Viso.
- Programming languages: Matlab, Fortran, C#.
- Transportation packages: Cube, TransCad, Synchro, Aimsun, Biogeme, NLogit, ArcGIS.
- Optimization packages: GAMS, CPLEX, LINGO
- Statistical packages: SPSS, SAS, R

Peer-reviewed Journal Publications

1. **Sharifi, M.S**., Stuart, D., Christensen, K.M., Chen, A., Kim, Y.S., Chen, Y. (2015). Analysis of walking speeds involving individuals with disabilities in different indoor walking environments. Journal of Urban Planning and Development 142 (1) (doi: 10.1061/(ASCE)UP.1943-5444.0000288).

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5. **Sharifi, M.S.,** Stuart, D., Christensen, K.M., Chen, A. (2016). Time headway modeling and capacity analysis of pedestrian facilities involving individuals with disabilities. Transportation Research Record: Journal of the Transportation Research Board (in press).

Peer-reviewed Conference Papers

1. Christensen, K.M., **Sharifi, M.S**., Chen, A. (2013). Considering Individuals with Disabilities in Building Evacuation: Agent-Based Simulation Study. Proceeding of the Transportation Research Board 92nd Annual Meeting, Washington DC, January 2013.

2. **Sharifi, M.S**., Stuart, D., Christensen, K.M., Chen, A., Kim, Y.S., Chen, Y. (2014). Analysis of walking speeds involving individuals with disabilities in different walking environments. Proceeding of the Transportation Research Board 93rd Annual Meeting, Washington DC, January 2014.

3. **Sharifi, M.S**., Stuart, D., Christensen, K.M., Chen, A. (2015). Exploring traffic flow characteristics and walking speeds of heterogeneous pedestrian stream involving individuals with disabilities in different walking environment. Proceeding of the Transportation Research Board 94th Annual Meeting, Washington DC, January 2015.

4. Stuart, D., **Sharifi, M.S.,** Christensen, K.M., Chen, A., Kim, Y.S., Chen, Y. (2015) Modeling Different Groups of Pedestrians with Physical Disability, using the Social Force Model and Fractional Order Potential Fields. IDETC/MESA. Proceeding of the ASME 2015 International Design Engineering Technical Conference & Computers and Information in Engineering Conference (IDETC/CIE).

5. **Sharifi, M.S**., Stuart, D., Christensen, K.M., Chen, A. (2016). Time headway modeling and capacity analysis of pedestrian facilities involving individuals with disabilities. Proceeding of the Transportation Research Board 95th Annual Meeting, Washington DC, January 2016.

6. **Sharifi, M.S.,** Stuart, D., Christensen, K.M., Chen, A. (2016). Capacity analysis of pedestrian queuing facilities involving individuals with disabilities. World conference on Transport Research Society, Shanghai, China.

Projects and Presentations

1. Soltani, A., **Sharifi M.S.,** Jackson, K., Butler, J., Fuentes, A. (2011). Utah State University: Romney stadium traffic impact analysis. Utah State University, Logan, Utah.

2. **Sharifi M.S.** (2011). Incorporating safety issues in route choice behavior models for two way road networks. Utah State University, Logan, Utah.

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