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Exploring effects of environment density on heterogeneous populations' level of service perceptions

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Abstract

It is necessary to design and evaluate the effectiveness of walking facilities to accommodate the needs of all pedestrian groups, including individuals with disabilities. The Americans with Disability Act (ADA) standard requires that each facility or part of a facility constructed by, on behalf of, or for the use of a public entity shall be designed and constructed in such manner that the facility or part of the facility is readily usable by individuals with disabilities. The Highway Capacity Manual (HCM) defines walking facility performance using a qualitative measure describing operational conditions, or level of service (LOS). However, how closely pedestrian LOS thresholds correspond to pedestrian groups' perceptions is questionable. To overcome these limitations, a controlled large-scale walking experiment involving individuals with disabilities was conducted at Utah State University (USU). A temporary circuit with the necessary walking facilities was constructed using eight-foot, self-standing walls. In total, 202 (160 without and 42 with disabilities) individuals were recruited to participate in the experiments, with participants asked to pass through the circuit repeatedly. Individuals were tracked using the camera system, and trajectory data extraction was accomplished using a software platform suite. During each experimental session, some participants were randomly selected and asked to complete a questionnaire assessing their walking experience. Using both trajectory and survey data sources, this study explored how a heterogeneous mix of pedestrians perceive and evaluate the operational performance of walking facilities. Specifically, an ordered statistical approach was applied to investigate the effects of environmental density on pedestrians' perceptions. The results indicated that individuals with disabilities were less tolerant of extremely congested environments. Furthermore, the analysis demonstrated that the LOS criteria provided in HCM is inadequate in quantifying the service performance of walking facilities based on the actual perceptions of individuals who participated in the controlled experiment. The findings are expected to improve operational guidelines employed to assess walking facility performance.

1. Introduction

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

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 a possibility of crowd-related disasters. The fact that individuals with disabilities, and the elderly, are disproportionately vulnerable to hazards primarily as a consequence of social disadvantage and structural exclusion is well demonstrated in recent failures in evacuations. According to a recent study, approximately 23% of the individuals evacuating the World Trade Center on September 11, 2001 were affected by a disabling condition impacting their ability to evacuate (Gershon et al., 2012). Therefore, it is imperative that walking facilities are designed effectively to provide a safe environment with preferred level-of-service for all pedestrian groups involving individuals with disabilities. Christensen et al. (2014) conducted a review of the literature with emphasis on individuals with disabilities behaviors in navigating the built environment which found only a few studies considered people with low mobility, including individuals with disabilities. One reason for this lack can be attributed to the absence of empirical studies on pedestrian behavior of individuals with disabilities (Christensen et al., 2013).

Generally, designers use guidelines provided in the Highway Capacity Manual (HCM) to assess walking facility performance (Highway Capacity Manual, 2010). 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, with A representing the best and F representing 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 and these thresholds were set based on engineering judgments. How closely different pedestrian groups evaluate the walkway's quality of service according to these thresholds is questionable. The HCM claims to predict LOS from the traveler's perspective, but there is little evidence to support this claim (Dowling et al., 2008). Specifically, there is very little empirical evidence of the walking behavior and perceptions of individuals with disabilities. The reason for this shortcoming is related to the lack of empirical studies related to the walking behavior of individuals with disabilities.

To overcome these limitations, a controlled, large-scale walking experiment involving individuals with disabilities was conducted at Utah State University (USU) to empirically investigate the perceptions of pedestrian groups, including individuals with disabilities. The purpose of this study is to describe how pedestrian groups, which include individuals with disabilities, perceive the walkway's quality of service. Specifically, the objectives are: (1) to quantify the effects of environmental 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.

2. Background

Planners and public agencies extensively employ guidelines to assess the design of walking infrastructures. The Highway Capacity Manual (HCM) (HCM, 2010), TCRP report 100: Transit Capacity and Quality of Service Manual (TCQSM) (TCQSM, 2010), and the 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 definitions, 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 are categorized from A to F, with A representing the best and F representing the worst operational conditions. At LOS A, pedestrians can move along the desired path at a 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 the HCM guidelines develop methods for assessing performance measures for 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 delays 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 the performance of exclusive pedestrian facilities.

The TCQSM is a comprehensive reference source that provides frameworks for the design and assessment of public transportation systems. The manual proposes different LOS criteria for various station elements (e.g., walkways, stairs, queuing and waiting areas) based on surveys that identify important factors affecting pedestrian perceptions. Similar to the HCM, pedestrian space and flow are considered key elements in LOS assessments. The Quality/Level of Service Handbook (Q/LOS Handbook) published by the 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 (Florida Quality/Level of service Handbook, 2013). Specifically, the guideline only accounts for urban walkways, and it considers multiple factors, including the existence of a sidewalk, the lateral separation of pedestrians from motorized vehicles, motorized vehicle volumes, and motorized vehicle speeds for LOS assessments.

Several studies in the literature examined pedestrians' LOS perceptions. These studies identified the key variables affecting LOS perceptions for various walking environments, including intersection crossing, sidewalk, midblock crossing, and stairs. For example, Kadali and Vedagiri (2015) studied pedestrian crosswalk LOS considering the type of land-use in India. They surveyed pedestrians in different land-use types such as mixed land use, shopping, residential, industrial, and business places. They concluded that perceived safety, crossing difficulty, land-use condition, number of vehicles encountered, median width and number of lanes have a significant effect on pedestrian perceived LOS. Muraleetharan et al. (2005) proposed a method to estimate the overall LOS of pedestrian walkways using total utility concept. Total utility values were used to assign an overall LOS to each sidewalk considering operational and geometrical characteristics. Lee et al. (2005) developed a new LOS standard for signalized crosswalks using interview survey technique. They defined LOS thresholds for different levels of bi-directional flow considering area density, pedestrian flow, and walking speed. In another study, Petritsch et al. (2005) proposed a LOS model for pedestrians at signalized intersections by considering perceived safety and comfort and traffic operations. Hubbard et al. (2007) stated that current procedures for evaluating pedestrian LOS do not adequately reflect the impact of turning vehicles at signalized intersections. They proposed a method for measuring the impact of turning vehicles on pedestrians by assessing thirteen crosswalks. Some studies focused on pedestrian behaviors on sidewalks, such as Kang et al. (2013) who evaluated how pedestrians perceive LOS on sidewalks shared with bicycles using a sample of 114 respondents. They concluded that pedestrian perceptions of LOS are impacted by the pedestrian flow rate, sidewalk width, bicycle flow rate, and speed of bicyclists. Landis et al. (2001) explored effects of safety and comfort in the roadside environment on pedestrians' LOS perceptions. They calibrated a model using 1,250 observations from a roadway walking course in Pensacola, Florida. Hummer et al. (2005) studied pedestrian perceptions on shared paths, surveying 105 volunteers viewing 36 video clips from 10 paths. Their analysis revealed that path operations and the path width had the strongest impacts on the perceptions. And Byrd and Sisiopiku (2006) compared LOS methodologies for pedestrian sidewalks to determine which methods are more reliable.

Three survey methods were generally applied to assess the perceptions and preferences 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 demonstrating various conditions are shown to different users, and their evaluations are recorded according to HCM LOS definitions. For example, Lee et al. (2003) examined LOS standards for signalized crosswalks in commercial/shopping areas in Hong Kong. They employed a stated preference survey by providing a set of five photographs to pedestrian samples. Respondents were presented with descriptions of the quality of flow, and they were then asked to choose one of the photographs which they felt did not meet the descriptions. Their analysis demonstrated that the key variables affecting LOS evaluations were area density, pedestrian flow, and walking speed. Jensen (2007) studied pedestrian and bicyclist LOS perceptions on roadway segments in Denmark, collecting 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 of pedestrians and the width of bicycle facilities are the most important factors affecting perceived LOS. While these photo/video survey approaches are a convenient method for exposing interview subjects to a wide range of conditions, the obtained perceptions are not based upon pedestrians' actual experiences.

Simulation survey techniques use computer simulations of different conditions to elicit user evaluations. 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 the subjects were then asked to rate each option from A to E and provide a numerical score from 1 to 75. The results of the analysis suggested scale ranges according to different LOS. Although a computer-aided visualization approach is more costly than the photo/survey method, it can enhance the flexibility of survey interviews by varying environmental situations. However, this approach is not able to record pedestrian perceptions based on actual experiences.

In field observations, after directly experiencing a pedestrian environment, participants are asked to assess a walkway's quality of service. For instance, Muraleetharan et al. (2004) examined key determinants affecting pedestrian LOS at intersections using the direct survey method. They selected four different types of intersections in the city of Sapporo, Japan, and questionnaires were distributed to pedestrians who crossed the intersections. The respondents were asked to provide a score ranging from 0 to 10, with 0 representing the worst and 10 representing the best operational conditions. Results obtained from 252 surveys revealed that several factors, including space at the corner, turning vehicles, delays at signals, and pedestrian-bicycle interactions, affect perceived LOS. Landis et al. (2001) used a similar approach to measure pedestrian LOS of safety and comfort for sidewalks in Pensacola, Florida. Seventy five volunteer participants were asked to walk along a five-mile (eight-km) looped walking course. The participants then evaluated the safety/comfort of the walkway system using an A-F point scale. The effects of different factors were identified by developing a stepwise linear regression model. However, socio-economic variables were not considered in the study. The field observation method has a lower initial cost compared with other approaches, but it is more intensive to conduct. The benefit of the field observation method is that it elicits pedestrian perceptions based on actual experiences.

Even though several guidelines and studies have been developed to examine pedestrian perceptions on walking facilities' LOS, the literature review revealed that there are still limitations in existing studies. First, existing manuals such as the HCM claim to predict LOS based on travelers' perspectives. However, there is little evidence to support this claim (Dowling et al., 2008). As a result, how closely pedestrian LOS thresholds provided in guidelines correspond to actual pedestrian perceptions is questionable. Second, there is a very limited number of studies that use subjects' revealed walking behavior as part of the LOS perception analysis. For instance, Kim et al. (2014) collected questionnaires 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 pedestrians' evasive movements on perceived LOS. However, they did not consider pedestrians' subjective characteristics (e.g., sociodemographic variables including age, gender, etc.) in their model. Third, the guidelines, as well as the majority of existing studies, overlooked heterogeneity in pedestrian groups for LOS evaluations. Specifically, there are few studies applicable to individuals with disabilities. Asadi-Shekari et al. (2012) developed a method to consider individuals with disabilities in LOS evaluations. However, they did not make use of either preference or reveal behaviors. Therefore, further studies are needed to address the current limitations.

3. Data collection

Although a field survey is the most direct way of measuring LOS it is not without limitations: (1) there is no control over subject's exposure to facility conditions, (2) people do not like to be interrupted while travelling which may yield bias results, and (3) it is difficult to observe extreme conditions (i.e., very high pedestrian density) (Dowling et al., 2008). Therefore, a large-scale, controlled walking experiment was carried out by a multi-disciplinary research group (transportation engineering, disability studies, electrical engineering, management information systems, and environmental design) at USU. Participants were comprised of a mixture of individuals without disabilities and individuals with mobility-related physical, sensory, or other types of disabilities, including hearing and other impairments related to mobility disability. Determining whether an individual meets the criteria for a mobility-related disability was based on the U.S. Census Bureau's American Community Survey (ACS) definition of disability. The recruitment process considered only working age individuals without disabilities who are between 18 and 64 years of age. Excepting an 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 genders.

In total, 202 individuals (160 without and 42 with disabilities) were recruited. As a goal of this study was to observe different density levels from very low to very high. Therefore, the number of invited participants was determined to reach high density levels. Further, as there were approximately 56.7 million people (19% of the population) that had a disability in 2010 according to the U.S. Census in 2012 (U.S. Census, 2012), the proportion of individuals with and without disabilities was determined to be a representative sample of the U.S. population in terms of disability distribution.

Among the participants with disabilities, about 26% were visually impaired, 38% were physically impaired, and 36% had other types of disabilities (e.g., intellectual, hearing). As the focus of the study was to study the impacts of different walking facility environments on pedestrian perceptions, the study was conducted on a temporary circuit constructed in USU's Motion Laboratory. The circuit involved 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. Note that the main objective was to focus on the effects of pedestrian traffic flow variables (i.e., pedestrian density) on LOS perceptions and the effects of the surrounding environment (i.e., attractive views, and walking in a group of friends) were not considered in the study. For each 10-minute experimental session, participants moved at their maximum comfortable speed through the circuit. Augmented reality technology was used for data collection to track participant positions within 0.3 meters or a footstep, enabling tracking and collection of each individual participant's walking trajectory. Augmented reality is the process of injecting virtual objects into an individual's view of reality using video goggles and a camera. ARToolKitPlus (ARTKP) is a software library that allows the tracking of up to 512 identifiable markers at once. To utilize this system, markers were attached to participants using mortar boards, or graduation caps, and were then read by cameras suspended above the experimental area. Power-over-Ethernet (POE) cameras, which only need one cable, 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 full coverage with overlap for the circuit experiments. For detailed information on the experiments and tracking technology, please see Sharifi et al., 2017; Sharifi, 2016 (a); Sharifi, 2016 (b); Sharifi, 2016; Sharifi et al., 2015; Stuart et al., 2013; Gaire et al., 2017. Figure 1 presents a snapshot of the walking experiments, and distribution of gender and age groups of participants. The population of individuals without disabilities was comprised largely of university students, while the population of individuals with disabilities was a sample from the surrounding community.

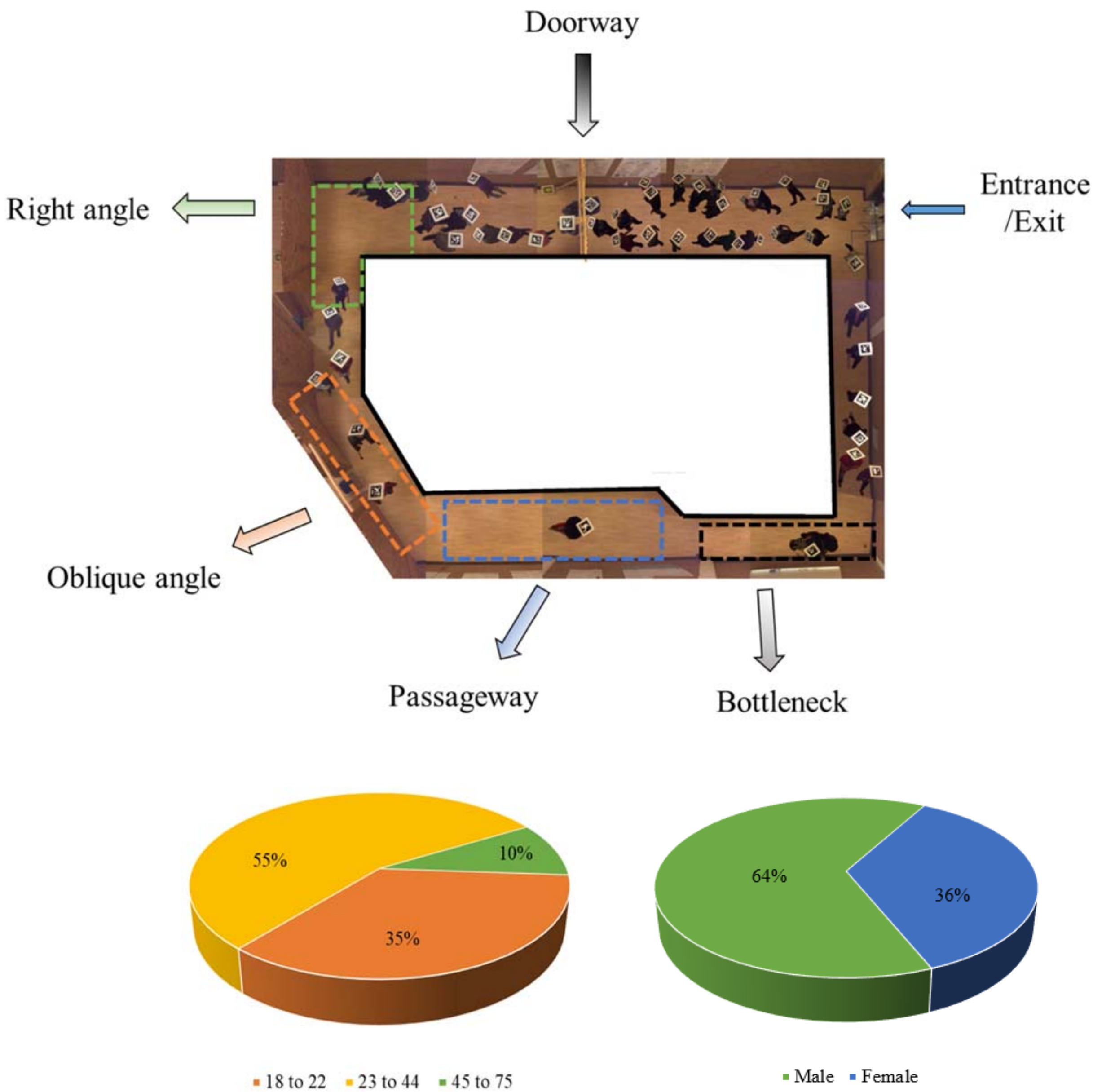


Figure 1. Experimental setting: (a). A snapshot of the walking experiments, (b). All participants' age and gender distribution.

To examine and compare individuals with disabilities' perceptions of walking facility performance with existing LOS design guidelines, individuals with and without disabilities provided their perceptions prior to, during, and following participation in each experimental session. Prior to each experimental session, participants completed a questionnaire to collect sociodemographic 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 spacing behavior toward individuals with disabilities (e.g., How comfortable do you feel around individuals with disabilities? Very comfortable, Comfortable, Neutral, Less comfortable, Not very comfortable). During each experimental session, some participants were randomly selected and asked to complete a questionnaire concerning their walking experiences. The questions included participants' perceptions of walking facility performance by providing a graphical representation of each HCM LOS, by which participants indicated their experiences (Figure 2). Follow-up questions were employed to assess the thresholds of different LOS values (e.g., 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, at a corridor width change, corner, and doorway). The number of surveyed participants was determined to have a large enough sample of both individuals with and without disabilities, in addition to maintaining the representative proportions according to the U.S. Census data.

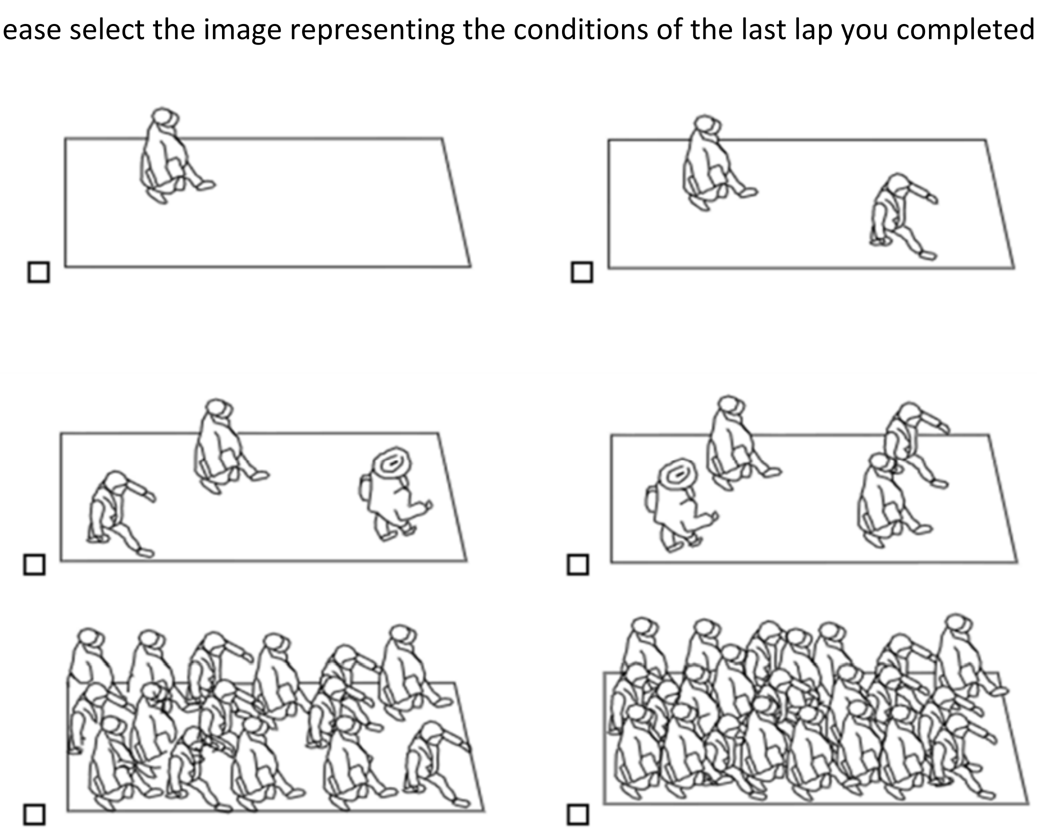


Figure 2. Graphical LOS definitions.

4. Methodological approach

The purpose of this study was to understand how the density of walking environments affects walkway level of service evaluations. According to HCM, density is the primary indicator used to evaluate various transportation infrastructures including walking facilities. For some walking infrastructures such as queuing areas (i.e., areas where people queue for services such as public transfer stations), average pedestrian space (i.e., inverse of density) is the only indicator for LOS descriptions. To achieve this goal, different data sources, including video data and survey data, were used. Pedestrian sociodemographic variables and their stated perceptions on quality of service were obtained from pre-surveys and post-surveys, respectively, and circuit density was extracted from collected video data. To obtain the experienced density by surveyed participants, the circuit area was divided into different walking facilities and density was calculated during the time that a particular surveyed participant passed through each facility. The experienced density can be obtained by calculating the average density of each facility. Figures 3 and 4 present the layout of walking facilities and a graphical representation of the calculation of the experienced density, respectively. Figure 4 shows the time-space diagram for all individuals, with a particular focus on the tracing of a sampled surveyed individual to calculate the experienced density by the 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 the boxes show the time intervals that the surveyed ID passed through different facilities. Density was obtained by calculating the average density of different boxes (i.e., different facilities).

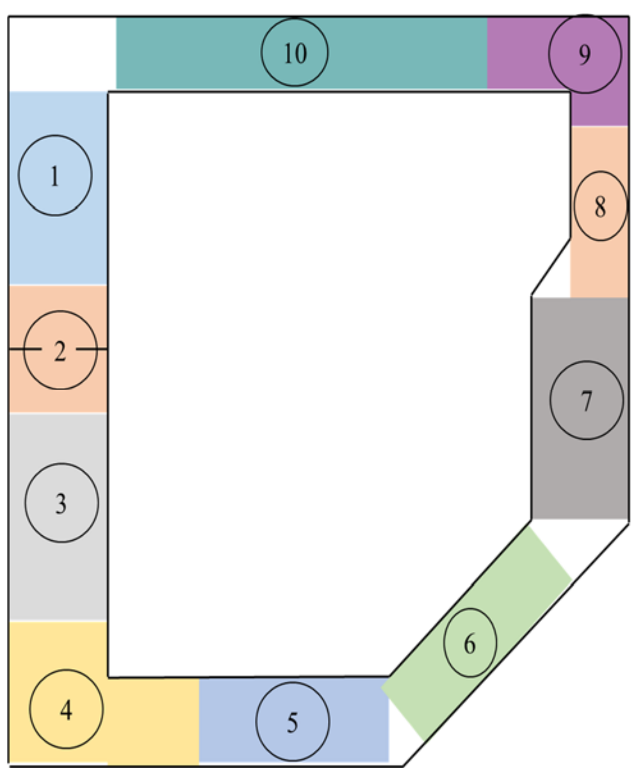


Figure 3. Circuit segmentation.

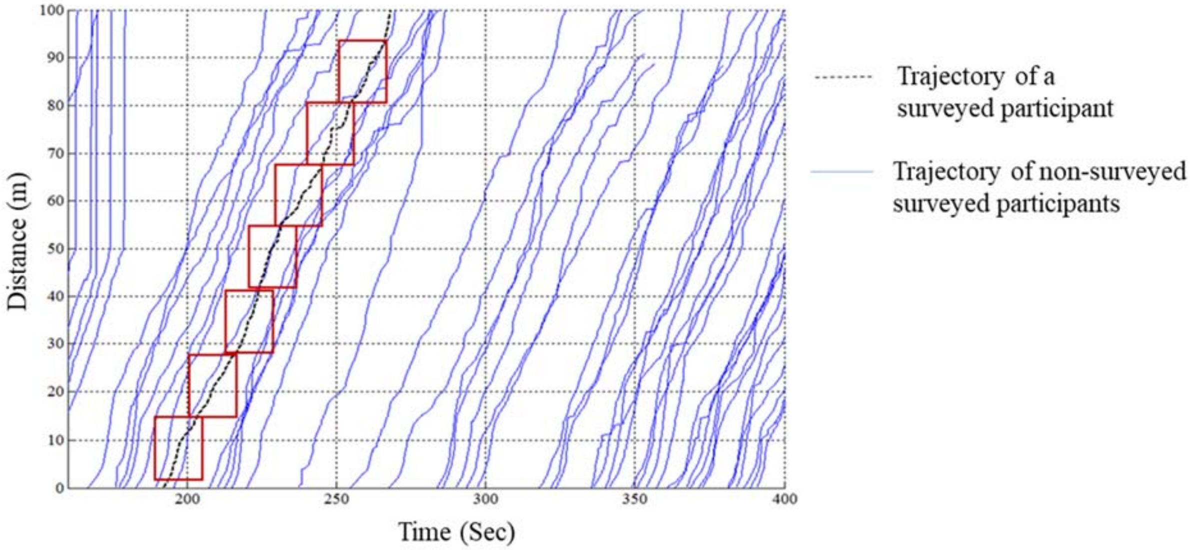


Figure 4. Time-space diagram for a surveyed participant.

To account for both the discrete and ordered nature of the data (e.g., A is better than B, B is better than C and so on), an ordered probability approach is an appropriate modeling choice (Choocharukul et al. 2004). In this modeling approach, an unobserved variable z is defined to represent the perceived LOS as a linear function for each observation n as follows:

$$z_n = \beta X_n + \varepsilon_n \qquad (1)$$

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

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

where μ is the cut-off value that defines y_n. These μ values are jointly estimated with the β coefficents using the maximum likelihood procedure (Washington et al., 2003). Since only the relative values are important, μ_1 can be arbitrarily set to any value (e.g., μ_1=0 for convenience). With this setting, an ordered probit model can be written as follows:

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

where Φ is the cumulative normal distribution.

5. Results

A total of 257 valid post-surveys (212 from individuals without disabilities and 45 from individuals with disabilities) were collected from 202 participants. Note that the number of surveyed individuals were more than the number of participants. Hence, some participants were surveyed more than once. Figure 5 presents the distribution of responses on stated LOS. The figure reveals that most of the stated LOS observed at LOS D and E and the stated LOS toward the extremely low density level is much less than other groups. Most of the participants were surveyed in the middle duration of the experimental process, where the circuit density was toward higher density levels, indicating that the observed results are plausible. To check whether the participants responded rationally to the LOS questions, Figure 6 compares the responses of individuals with LOS thresholds in HCM. Figure 6 presents two parallel coordinate plots for individuals with and without disability responses. The first axis presents experienced density, the second axis shows individual responses to LOS perceptions (i.e., 1 means LOS A, 2 means LOS B, etc.), and the third axis shows the corresponding LOS according to HCM guidelines. The concentration of lines shows the distribution of collected data. For instance, the figure shows that lines connecting the first axis to the second axis are thicker in density ranges between 0.5 to 0.9 ped/m2, indicating that most of the observations were in this density range. The parallel diagrams also indicate how close the participants' responses were to actual conditions. The parallel lines between second and third axes show although collected perceived LOS responses did not exactly follow the HCM guidelines, they were not too far away, implying that participants did not respond randomly, and the collected surveys are valid. Moreover, the lines between second and third axes do not show a dominate upward or downward pattern (i.e., responses were not dominated by optimistic or pessimistic individuals). Therefore it can be deduced that the collected responses were not biased.

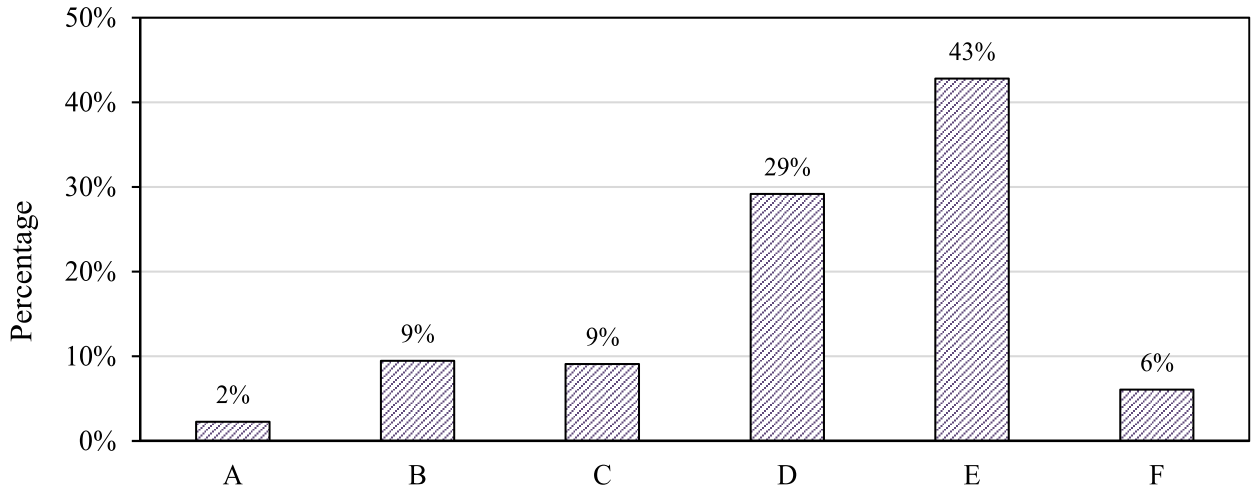
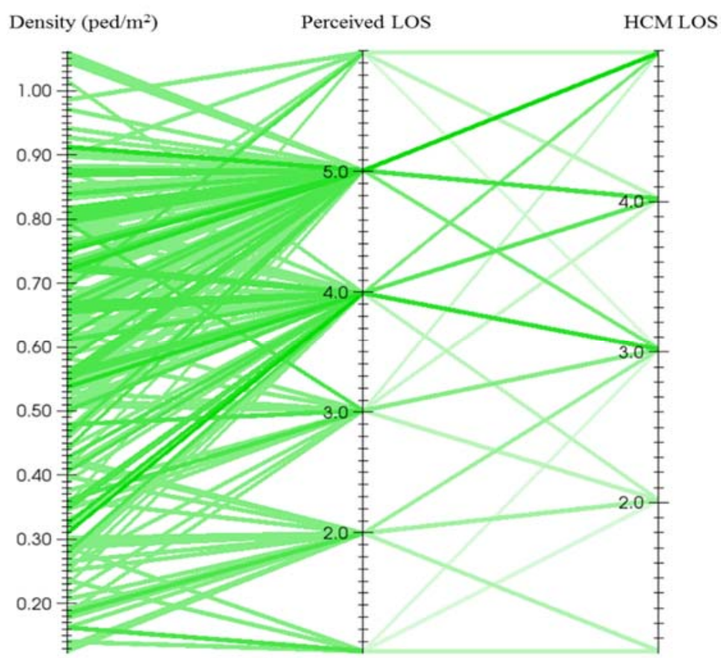
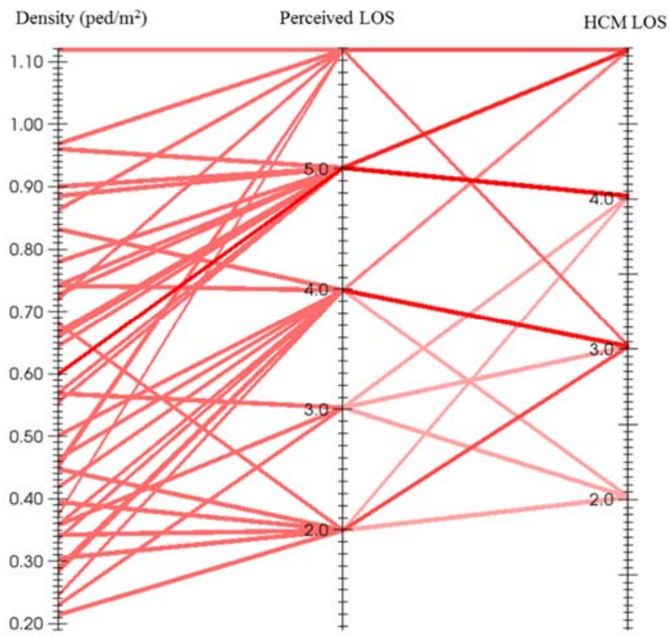


Figure 5. Perceived LOS distribution.



(a)



(b)

Figure 6. Comparing density, perceived LOS, and LOS obtained from HCM for: a) individuals without disabilities, and b) individuals with disabilities.

SAS statistical software was used to calibrate the ordered probit model. Based on the initial analysis, it was observed that there was not enough data collected for LOS A. Figure 5 shows that only 2% of respondents stated LOS A for their walking condition, and therefore treating it as an independent group would affect the significance of the estimation results. As a result, LOS A and LOS B were grouped together as one LOS, which results in five LOS categories in the estimation process. Some 90% of the data were used for calibration, and 10% of the data were reserved for model validation purposes. An ordered probit model was calibrated, with density as the only independent variable for individuals without and with disabilities. In ordered probit regression models there is an assumption regarding ordinal odds. According to the parallel lines assumption, parameters should not be changed for each category. To check the validity of this assumption, score test was conducted. P-values corresponding to χ^2 values are 0.27 and 0.1 for individuals with and without disability models, respectively. A nonsignificant test is taken as evidence that the parallel assumption is valid.

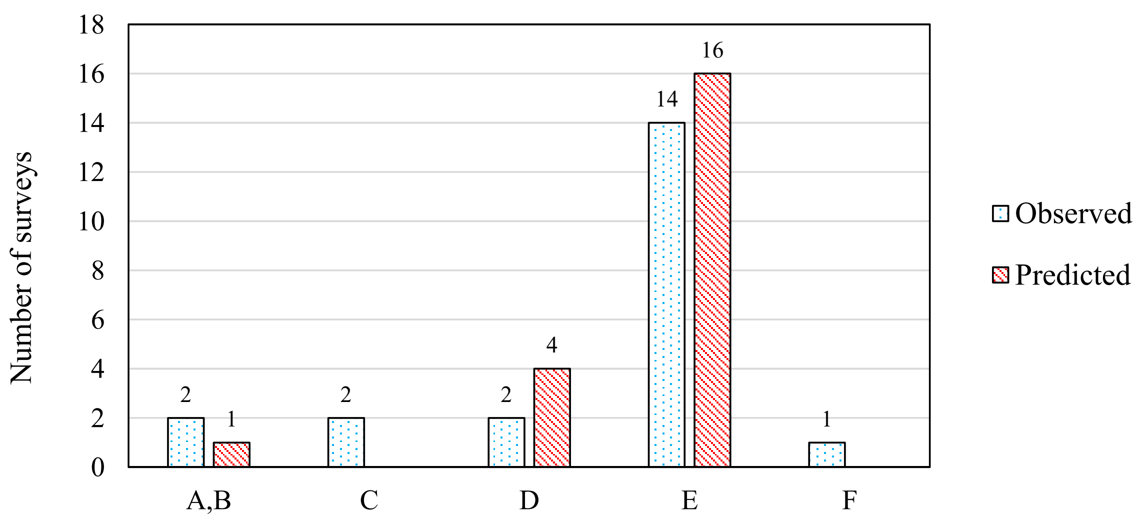
Table 1 shows the estimation results, including constant, coefficient for the density variable, estimated cut-off values, and their corresponding statistics, including t-statistics, and P-values. The table also presents models' performance using likelihood ratio index and likelihood ratio test. All P-values for likelihood ration tests are less than 0.01 indicating that the hypothesis that all coefficients are equal to zero can be rejected at the 1 percent significance level. The P-values for the coefficients (β_0 and β_1) and cut-off values (μ_2, μ_3, μ_4) are less than 0.01, indicating that the coefficients and the thresholds are highly significant. Positive signs for the density variable indicate that all pedestrian groups perceived worse LOS at higher density levels.

To investigate the validity of the estimated models, the 10% of the reserved data were used to determine how closely the model results matched the stated results by individuals. Figure 7 presents the comparison results between the prediction of calibrated models and the responses of surveyed individuals. It can be observed that the models were able to predict the LOS responses relatively accurately. The model for individuals without disabilities predicted almost all of the surveys in LOS E and F, and calibrated model for individuals with disabilities could predict all of the reserved LOS responses. The overall success rates of predictions for individuals without and with disabilities were about 75% and 100%, respectively, indicating that the accuracy of the models was acceptable. Moreover, repeated sampling method was used to test the stability of calibrated coefficients. Different models were calibrated using 50 sets of random samples. Results showed that the maximum Coefficient of Variations (COV) for calibrated coefficients is about 8% implying that the coefficients are stable and the calibrated model is reliable.

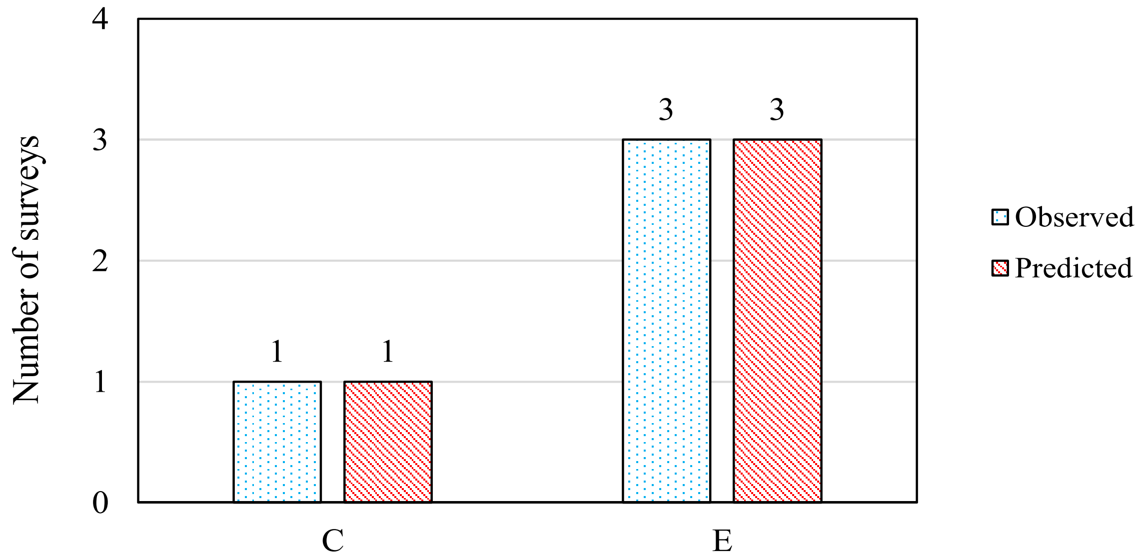
Table 1. Model estimation results.

	Model					
	Individuals without disabilities			Individuals with disabilities		
Variables	Estimated parameter	t-statistics	p-value	Estimated parameter	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						
μ_2	0.58	4.46	< 0.01	0.32	1.83	0.074
μ_3	1.92	10.45	< 0.01	1.23	4.21	< 0.01
μ_4	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		
Likelihood ratio	-149.2			-22.36		
Likelihood ratio test P-value	< 0.01			< 0.01		
McFadden Pseudo R^2	0.27			0.20		

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 the cut-off value and β_0 and β_1 are the intercept and density coefficients, respectively. Figure 8 depicts the estimated thresholds for different pedestrian groups (individuals without disabilities, individuals with disabilities, and all participants). In addition, proposed LOS thresholds by HCM are provided in the figure to examine and compare different pedestrian groups' perceptions with HCM guideline. Figure 8 presents the density ranges for 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 LOS F perception thresholds. While individuals with disabilities rated density levels beyond 0.92 ped/m^2 as LOS F, individuals without disabilities perceived LOS E up to the 1.12 ped/m^2 density level, indicating that individuals with disabilities had lower tolerances for crowded conditions. LOS thresholds for all surveyed participants can be compared with provided LOS criteria in HCM guideline to investigate how closely the HCM guidelines follow pedestrian perceptions. The results indicate that there are apparent differences between perception thresholds and proposed HCM values. Surveyed individuals had lower tolerances 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 when compared to pedestrian perceptions. To examine whether these differences are significant, the estimated density thresholds were compared to presented thresholds in the HCM using ANOVA as shown in Table 2. The table presents 95% confidence intervals for thresholds obtained from the calibrated model. It can be observed that except for LOS A, B thresholds for individuals with disabilities, confidence intervals did not overlap with HCM thresholds indicating that there are statistically significant differences between perceived LOS thresholds and HCM thresholds at 95% confidence.



(a)



(b)

Figure 7. Model validations for: a) individuals without disabilities, and b) individuals with disabilities.

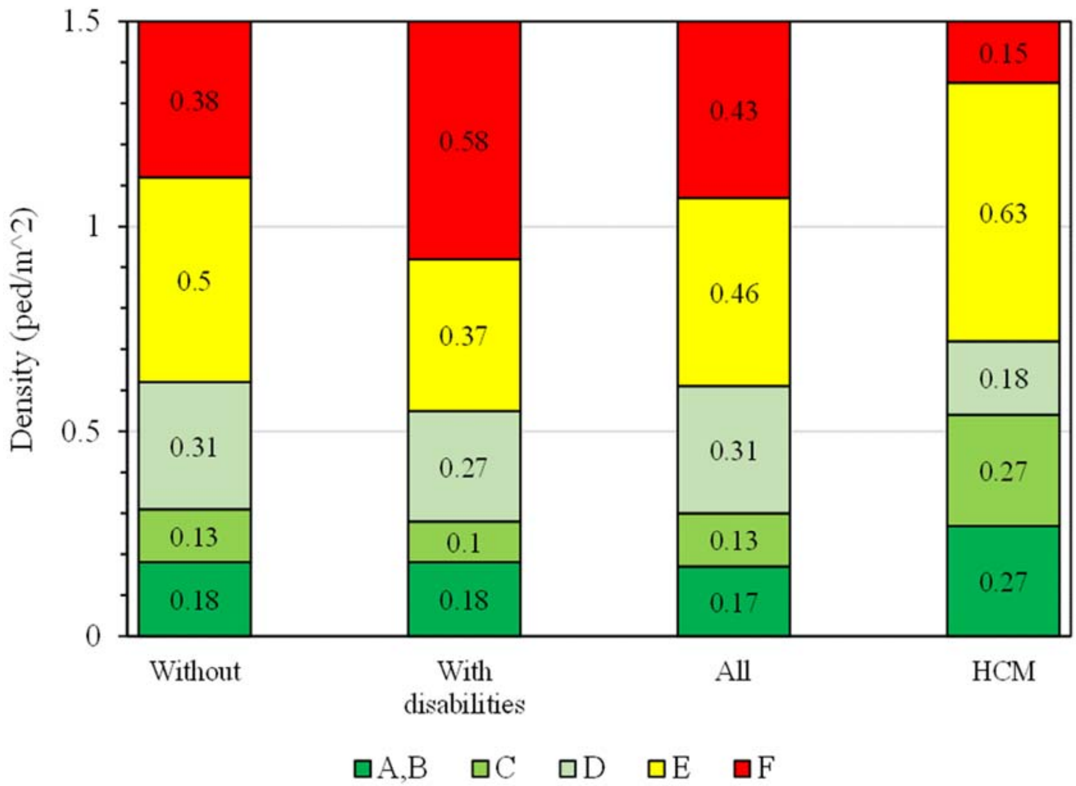


Figure 8. LOS graphical comparisons.

1

Table 2. Statistical test of differences between perceived LOS and LOS obtained from HCM.

Individuals without disabilities					
LOS	Density Threshold	95% lower bound	95% upper bound	HCM Threshold	Significant difference?
A, B	0.18	0.15	0.22	0.27	Yes
C	0.31	0.25	0.37	0.54	Yes
D	0.62	0.53	0.7	0.72	Yes
E	1.12	0.99	1.24	1.35	Yes
Individuals with disabilities					
LOS	Density Threshold	95% lower bound	95% upper bound	HCM Threshold	Significant difference?
A, B	0.18	0.12	0.37	0.27	No
C	0.28	0.17	0.38	0.54	Yes
D	0.55	0.37	0.72	0.72	Yes
E	0.92	0.69	1.14	1.35	Yes

The LOS concept is widely used in walking facility design and evaluation. Given the projected demand and the 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 the design process. Specifically, the required design width to achieve the desired LOS can be obtained by the following equation:

$$w = \frac{Demand}{D_T \times L} \quad (4)$$

where w, D_T, and L stand for width, density threshold of desired LOS, and length of the walking facility, respectively. The results demonstrate that given the projected demand and the length of a walking facility, the minimum required width for individuals without disabilities is about 80% of the minimum width for individuals with disabilities to achieve LOS E, implying individuals with disabilities require wider facility in general. Further, the effects of overlooking perceptions in the design process can be investigated by comparing LOS perception thresholds for all pedestrians and HCM guidelines. The results indicate that considering LOS B as the target, a design plan based on HCM guidelines would be about 63% of the minimum width obtained from heterogeneous pedestrian perceptions. Therefore, considering the perceptions of all individuals can have a significant impact on the current methods used in practice.

To better understand pedestrian groups' perceptions of LOS, two new models were calibrated for individuals with and without disabilities using pedestrian characteristics and pedestrian density. Various models with different combinations of variables were examined and the results of the final models for these two groups are presented in Table 3. Pedestrian density and gender variables were considered for individuals without disabilities. Pedestrian density, gender, and disability type were selected for individuals with disabilities. Note that additional pedestrian stream characteristics including speed and flow were tested. However, the preliminary results showed that only density was the statistical significant variable. This outcome is likely related to the fact that people perceive density (space availability) more clearly than speed or flow. Therefore, those variables were not included in the final models. To include the categorical variables (i.e., gender and disability type), dummy variables were constructed. Specifically, respondents with disabilities were classified into three groups: 1) individuals with physical impairments, 2) individuals with visual constraints, and 3) individuals with other types of disabilities including hearing impairments, intellectual, etc. Male groups and individuals with other types of disabilities were considered as base groups and were not included in the final models.

Table 3. Model estimation results using density and demographic predictors.

	Model			
	Individuals without disabilities		Individuals with disabilities	
Variables	Estimated parameter	t-statistics	Estimated parameter	t-statistic
Constant	0.22	0.79	0.31	0.48
Density (Ped/m^2)	4.36	9.46	4.42	4.45
Gender (1 if female, 0 if male)	0.60	3.36	0.15	2.39
Physical impairments (1 if yes, 0 if no)	-	-	-0.57	-2.24
Visual impairments (1 if yes, 0 if no)	-	-	0.28	1.87
Cut-offs				
μ_2	1.12	4.52	1.38	2.61
μ_3	1.74	6.54	1.74	3.2
μ_4	3.13	10.62	2.78	4.69
μ_5	5.41	14.21	4.19	6.4
Number of observations	190		40	
Log likelihood at convergence	-201.59		-50.65	
Likelihood ratio	-118.06		24.27	
Likelihood ratio test P-value	< 0.01		< 0.01	
McFadden Pseudo R^2	0.23		0.19	

Table 3 presents the estimation results, including constants, coefficient for predictor variables, estimated cut-off values, and their corresponding statistics. The coefficients indicate changes in probability attributed to one-unit increase in the given variable. However, the change in probability is dependent both on the values of the other variables and the value of the given variable. Therefore, interpretation of the coefficients in ordered probit regression is not as straightforward as the interpretations of coefficients in linear regression models. In order to interpret the results, Table 4 provides average marginal effects for each variables on each LOS categories. Average marginal effect is defined as the change in response as a function of the change in the independent variables holding all other variables in their average level. The interpretation of average marginal effect is slightly different for continuous variables (i.e., density) and categorical variables (i.e., gender, disability type). Average marginal effects for continuous variables suggest change in probability when the variable increases by one-unit while other variables are in their average level. Results in Table 4 suggests that one-unit increase in the pedestrian density level would decrease the probability of perceiving LOS A to D, whereas it would increase the probability of perceiving LOS E and F for both individuals with and without disabilities. However, the rate of probability changes show differences. While the increasing probability rates for LOS E and F are 86% and 29% for individuals without disabilities, the probability rates are 49% and 71% for individuals with disabilities. The outcome indicates that participants with disabilities were less tolerant of pedestrian density and they tend to perceive lower quality of service levels.

For categorical variables, the marginal effects show the difference in the predicted probabilities relative to the reference category. Results for gender effect reveal that the marginal effects are negative for LOS A to D and positive for LOS E and F for both individuals with and without disability groups. It means that female groups were less likely to perceive quality of service as being in LOS A to D and more likely to perceive LOS E and F. In other words, female groups were less tolerant compared to male groups. The effect of disability type on perceived LOS also was found to vary across respondents. Trends of marginal effect signs for individuals with physical impairments show that this group tend to give a higher LOS level compared to the reference group (individuals with other types of disabilities). However, individual with visual impairments were less tolerant. This finding can be linked to the fact that these individual groups may have difficulty evaluating the actual conditions and rate the quality of service in a conservative way. The finding confirm the fact that different disabled groups may have different walking needs and individuals with visual impairments need to have more space to have the same perception as other disabled groups.

Table 4. Average marginal effects.

Individuals without disabilities						
Variable	Marginal effects					
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Density	-0.1630	-0.4027	-0.2730	-0.3238	0.8694	0.2931
Gender	-0.0225	-0.0556	-0.0377	-0.0447	0.1201	0.0405
Individuals with disabilities						
Density	-0.1811	-0.6609	-0.1798	-0.1874	0.4921	0.7171
Gender	-0.0062	-0.0230	-0.0062	-0.0065	0.0171	0.0249
Physical impairments	0.0234	0.0856	0.0233	0.0243	-0.0637	-0.0929
Visual impairments	-0.0114	-0.0415	-0.0113	-0.0118	0.0309	0.0450

6. Summary and Conclusions

The LOS criteria provided by the HCM guideline has been widely used by planners for design and assessment purposes. This study examined whether the HCM guideline is applicable for all pedestrian groups, as well as how closely pedestrians' perceptions matched guideline LOS recommendations. To achieve these goals, a controlled large-scale walking experiment was carried out at USU. Participants were comprised of a mixture of individuals without disabilities and individuals with mobility-related physical, sensory, or other types of disabilities. The walking behavior and the perceptions of walking environmental conditions were observed through video records and survey collection methods. An ordered probit model was calibrated to establish a connection between the questionnaire and the walking trajectory data to specify how environmental density can impact pedestrians' perceptions of walking facility performance. Different models were calibrated for individuals with and without disabilities using 90% of data and models were validated with 10% of reserved data. The LOS thresholds obtained from the model revealed two conclusions. First, there are differences between perceptions of individuals without and with disabilities, and these differences are more visible at high density levels (i.e., LOS E and F). Second, the current HCM LOS scale does not map well with pedestrian groups' LOS perceptions. It was observed that both individuals with and without disabilities are less tolerant to congested environments compared to threshold proposed in HCM. This implies that the use of these thresholds may lead to under-estimated design plans for heterogeneous pedestrian groups. Specifically, it was shown that to achieve LOS B given the projected demand and the length of a walking facility, design width using HCM LOS is about 63% of the design width considering LOS perceptions. Therefore, a potential change in HCM LOS levels may reflect pedestrian groups' perceptions in walking facility designs.

The findings in this study are expected to enhance the design of walking environments. Designers can test and evaluate their design plans using the findings in this research to determine how well their designs can meet the needs of different users, allowing designers to modify their plans while changes are still possible. However, there are a number of limitations which can be considered for future studies. First, the focus of this study was to study on the effects of pedestrian traffic flow variables (i.e., pedestrian density) on pedestrian groups' LOS perceptions. The study can be further extended to incorporate other real environmental conditions (i.e., attractive views, walking in a group of friends, etc.). Second, a better approach of data collection would be to have pedestrians express their evaluations of LOS while actually walking. However, this approach is much more difficult to implement and it is very difficult to observe individuals with disabilities in high-density environments. Third, due to regional locations and special assumptions of the study, our conclusions may not be generalized. Therefore, conducting similar experiments in other parts of the U.S. would be valuable.

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